Engineering the COSTAR

By James H. Crocker

At NASA's request, Riccardo Giacconi, Director of the Space Telescope Science Institute, convened a panel of experts in the summer of 1990 to identify and assess strategies for recovering the HST's capabilities degraded by spherical aberration. This panel included astronomers, optical scientists, astronauts, and engineers from industry, academia, and government. The European Space Agency (ESA)—a partner with NASA in the HST program—contributed significant expertise in optics and space astronomy. The Strategy Panel studied the problem and developed and evaluated solutions during the late summer and fall of 1990 during a series of meetings in the U.S. and Europe. The panel concluded the optical problem was well enough understood to design highly effective optical correctors. After investigating numerous solutions, it was decided that corrective mirrors with precisely the same amount of spherical aberration as the HST's primary mirror, but with the opposite mathematical sign, would pose the best approach.[1-3] A key element of the feasibility of this approach rests on packaging these corrector mirrors in a standard HST science instrument enclosure for the ascent to orbit and subsequent deployment and alignment. This package with the corrective optics is called the Corrective Optics Space Telescope Axial Replacement (COSTAR).

Figure 1 shows the location of the axial science instruments in a cut-away view of the telescope. Packing the corrective system in one of these standard enclosures allows the optical correction to be accomplished in an identical manner to the planned servicing scenarios. COSTAR replaces the High Speed Photometer (HSP), the least used of the science instruments. COSTAR corrects the wave front presented to the European Faint Object Camera (FOC), the Goddard High Resolution Spectrograph (GHRS), and the Faint Object Spectrograph (FOS) by placing a pair of reflective correctors in front of each instrument channel. Because the Wide Field Planetary Camera (WFPC) is located in a different area of the HST, it cannot be serviced by COSTAR. Fortunately, NASA was already building a replacement for the WFPC to fly on the first servicing mission. Plans were quickly put in place to install a corrector system similar to COSTAR's internal to this new camera. With both the COSTAR and WFPC II installed on the first servicing mission, the scientific functionality expected at launch can be restored.

In addition to providing better detail without resorting to computer enhancements, the FOC, GHRS, and the FOS will be able to detect and analyze light from faint objects at much greater distances. The two spectrographs will be able to better isolate objects in crowded fields since the light from near by objects will no longer contaminate the object under investigation. Because the amount of light entering the small slits of the spectrographs will be increased, the exposure times for observation will be significantly reduced. Ball Aerospace and Communications Group in Boulder, Colo., was selected as the prime contractor for COSTAR's construction.

How COSTAR Restores HST

COSTAR is designed to place small pairs of mirrors in front of each channel of the three axial science instruments (ASI). As illustrated in Figure 2, the M2 mirror is first placed in front of the instrument aperture to block the aberrated light currently entering the instrument. The M1 mirror of each mirror pair, a simple sphere, directs light from a new location in the telescope's field of view onto the M2 mirror. The M2 mirror prescription contains the same magnitude as the error in the HST primary mirror but with the opposite mathematical sign, thus canceling the spherical aberration. The great challenge of COSTAR was in these mirrors—first fabricating them to the requirements and then placing them in front of each instrument channel. Figure 3 shows the major elements of COSTAR. The enclosure is a standard HST instrument design. The optics are mounted on the Deployable Optical Bench: Seven of the mirrors are mounted on arms that deploy in front of the science instruments while three mirrors are located within the deployable bench. During the ascent to orbit, this deployable bench is stowed inside of COSTAR. Once installed into the HST, the bench is raised by ground command into the focal plane area just behind HST's primary mirror. The arms containing the optics are deployed into the correct positions in front of each instrument aperture. In Figure 3, the deployable

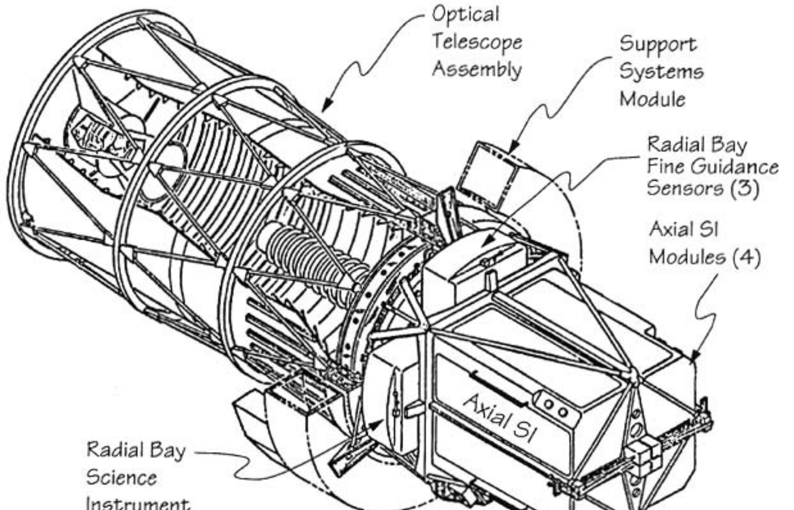

Figure 1. Cut-away view of HST showing axial science instruments. COSTAR replaces one of the axial science instrument modules to provide optical correction to the remaining three.

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optics bench is shown raised into the area behind the primary mirror and in front of the science instruments. The rays shown in Figure 4 illustrate the light path for the GHRS. For this channel, the M1 mirror is located inside of the COSTAR bench. Light is reflected from the M1 located in the deployable bench through an opening to the M2, where it is corrected and directed into the GHRS aperture. Small actuators are located behind the M1 mirrors to allow for fine alignment of the pupil formed by M1 onto the M2 corrector. Adjustment of this articulatable M1 controls field-dependent coma and astigmatism.

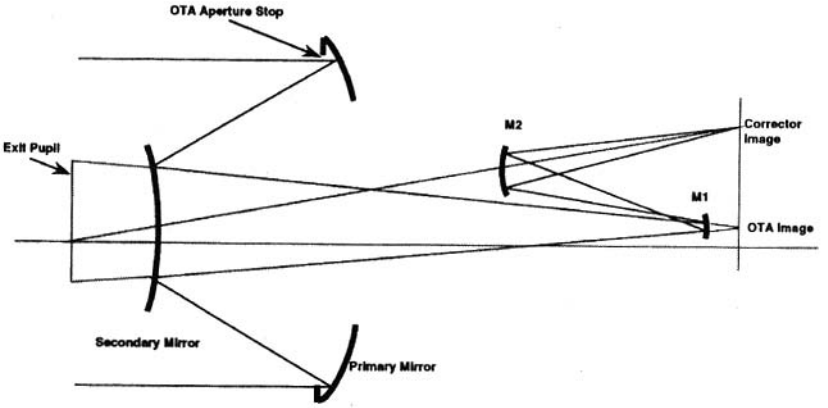

Figure 2. COSTAR corrector principle. The field mirror M1 images the telescope primary mirror at M2. The surface of M2 is figured to compensate for the spherical aberration in the primary.

COSTAR Optics

Fabrication of the small, high quality, complex COSTAR optics required to correct the aberrated HST images was a significant challenge. Physical constraints on the mirror locations, limited deployment options, and the demanding image quality specifications imposed by a defraction limited 2.4-m telescope resulted in a design that requires fourth-order aspheric surfaces superimposed with a toroidal, astigmatism-compensating figure. To achieve the encircled energy and Strehl ratio requirements, each of the optics required a surface figure of $\lambda/100$ wave rms (at 633 nm). Furthermore, the requirement to maintain image quality and optimal throughput in the far ultraviolet drove the requirement on the surface quality specification to 10 Å rms ripple at spatial scales at or below 1 mm. While the M1 mirrors are simple spheres, the M2 are complex fourth-order aspheres. This means that the surface of the M2 is shaped like a Schmidt corrector with different curvatures in two directions. Fabrication was further complicated due to the small size of the optics, which range from 17 mm to 25 mm—about the size of a dime and a quarter, respectively. Because the mirror specifications required state-of-the-art polishing techniques, there was considerable uncertainty regarding their timely procurement, so three vendors were selected to fabricate these challenging optics.

Only one of the three vendors was able to produce the optics in a timely fashion. To their credit, Tinsley Laboratories (Richmond, Calif.) produced all of the COSTAR flight optics on time, within budget, and exceeding all of the requirements. The quality of the Tinsley mirrors was so good that a single prescription for the red and blue channel for the FOS (originally a compromise since the difference in the optimal prescriptions was thought to be beyond current manufacturing capability) was modified to separately optimize the two channels. The flight optics were delivered on schedule in May 1992, along with a complete set of spares.

The second challenge with the optics was to coat them to provide high reflectance in the ultraviolet (down to 1216 Å). Because the ultraviolet is critical to the science performed with the corrected HST and because COSTAR placed two additional reflections in the light path of the instruments, it was imperative that the reflectance be kept as high as possible. The optics were aluminum overcoated with 20 Å of magnesium fluoride in a special coating facility at NASA's Goddard Space Flight Center. The results were excellent, with a throughput per surface of 85% at 1216 Å, very near the theoretical maximum for this coating and significantly greater than expectations. The smoothness of the optics was maintained in the coating process with a final surface quality between 2 and 4 Å rms. Stringent environmental controls were used throughout the COSTAR manufacturing process to ensure high reflectivity.

Packaging

The packaging challenge for COSTAR was driven by the small area in the focal plane through which the optical bench must be deployed. This area is roughly one fourth of a 15 cm (6 in.) radius circle. While the standard science instrument enclosure is about the size of a telephone booth, all of the optics and most of the motors and alignment mechanisms must be packaged into the smaller deployable bench. The deployable bench contains the 10 optics, 4 beryllium arms that place the optics in front of the respective science instrument, 12 motors to deploy the arm and align the mirrors, and a myriad of sensors and wires to provide telemetry on the placement of the optics and bench as well as temperatures, voltages, and currents.

Another challenge was enabling each channel to operate independently. Because of the plans to install new science instruments on future missions, each of the channels on COSTAR were designed to be individually retractable so that future instruments could be installed without affecting the remaining instruments. Current plans call for replacing two of the science instruments later in the decade with a new spectrograph and infrared camera. A new UV-visible camera is anticipated shortly after the year 2000. These new instruments will have the aberration correction built into their internal optics and will not require COSTAR. When these new instruments are installed, the corresponding COSTAR arm and its

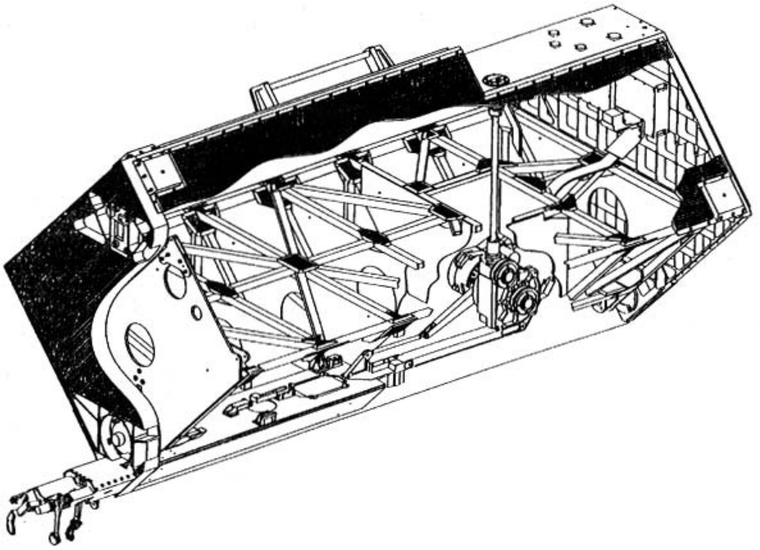

Figure 3. COSTAR is shown with the optical bench deployed. For assent and insertion into HST, this bench is retracted into the COSTAR enclosure with the arm that carry the optics folded up.

attached optics will be stowed to provide a clear line of sight for the new instruments.

COSTAR was designed with a "do no harm" philosophy. Unlike many of the proposals that were rejected by the Strategy Panel, COSTAR was designed with reversibility in mind. Even in the unlikely event of a total system failure, COSTAR can be readily removed from the HST allowing the installation of future instruments with COSTAR-type corrections built in. In addition to typical dual redundancy on electronics and motor windings, COSTAR uses a unique manual retraction mechanism. Should all of the COSTAR motors and electrical systems fail, a manual retraction device enables astronauts to retract the COSTAR deployable bench from the hub area. A special fitting located on the connector panel of COSTAR is provided to implement manual retraction. The same power ratchet tool used to latch COSTAR into HST fits this special fitting. Rotating this fitting stows the deployable optical bench. Special guides built into the COSTAR fold up the arms as the bench retracts into the enclosure.

Stability

COSTAR's optical performance depends on the stability of the corrector optics, on both short time scales (line-of-sight jitter) and over longer periods (alignment drift). Alignment drift can affect both image quality and image location. While the motors and mechanisms provide optical alignment with precision required to achieve the restored optical performance of HST, the mechanical structure guarantees that the optics do not move and thus degrade the optical performance once this alignment is achieved. Like all of the science instruments, COSTAR is attached to HST using a three-point kinematics mounting system to automatically register the instrument and to permit stability over the HST temperature environment. Within COSTAR a combination of materials and thermal controls assure this stability is maintained. Both the main structure and the deployable bench are fabricated from graphite epoxy. Graphite epoxy was selected due to its extremely low coefficient of thermal expansion and high stiffness. Each of the COSTAR deployable arms are manufactured from beryllium and maintained at a precise temperature by a thermal control system. This thermal control system keeps the arms temperature to within 1° C. In addition to withstanding thermal disturbances, COSTAR must hold its alignment precisely in the presence of mechanical disturbances from systems on the HST. These include mechanical motion of the reaction wheels, tape recorders, solar arrays, and communication antennas. The stiffness and low mass of the graphite epoxy and beryllium ensure these mechanical disturbances can be tolerated. The optics must resist both thermal and mechanical disturbances to about 1 µm rms. This stability is required due to the small size of the corrector optics. The image of the HST primary mirror pupil is formed by the COSTAR M1 mirror on the M2 mirror where the correction is performed. The image formed at M2 is about 200 times smaller than the primary mirror pupil. To correct the spherical aberration, this small image of the primary must be placed precisely and then held to the 1 µm tolerance to properly cancel out the error in the primary. Testing at Ball Aerospace has demonstrated that the COSTAR exceeds its requirement for thermal and mechanical stability.

Optical Testing

A key element of the COSTAR program has been redundant optical testing scheduled throughout the development period to ensure the improvement to Hubble's optical performance will be achieved on orbit. At the component level, two independent fig-

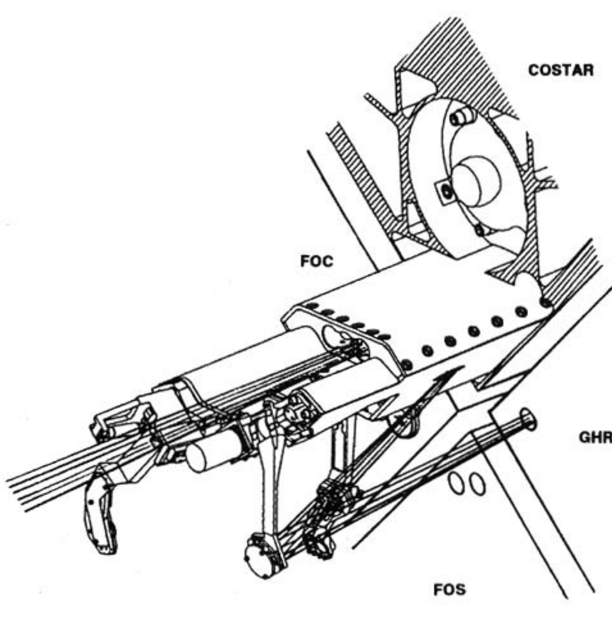

Figure 4. The optical bench is shown deployed into the area in front of the science instrument apertures. The light path for the Goddard High Resolution Spectrograph is shown.

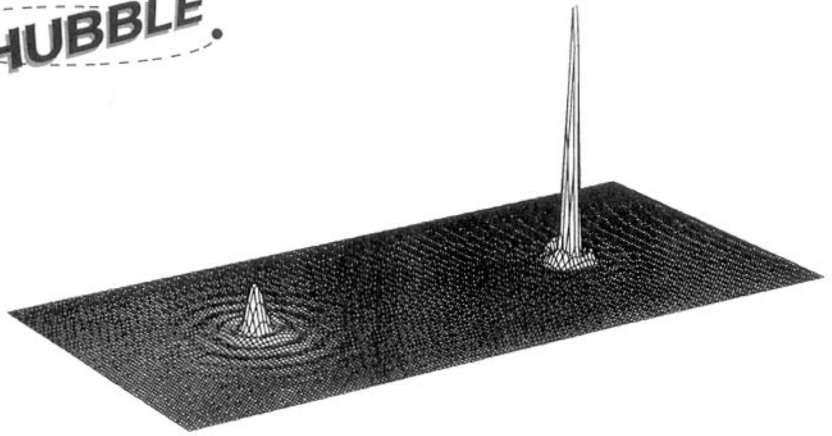

Figure 5. Point spread function taken with and without COSTAR. The engineering model of the Faint Object Camera was used to compare the aberrated and COSTAR corrected image.

ure characterization measurements were used. A computer-generated hologram technique was used for the in-process measurements of the aspheres, and a null lens test was used for the final acceptance. Results from the two tests correlated well, typically within $\lambda/100$ at 633 nm. Surface quality was also independently measured at Goddard Space Flight Center and shows good agreement with those measured at Tinsley, 2-5 Å rms. At the system level, a full field optical and mechanical simulator of the aberrated HST was fabricated to provide a final end-to-end demonstration of COSTAR performance. This simulator was developed from the HST optical model, assuming an aberrated primary mirror with a conic constant of -1.0139, as adopted by the HST Independent Optical Review Panel.[4] This simulator, which was independently verified by Ball and the Goddard Independent Verification Team, closely approximates the HST, with residual rms wavefront error of less than $\lambda/40$ at 633 nm. This is considerably less than the uncertainty in the actual HST wavefront. The mechanical portion of the simulator contains the flight type latches to properly align the COSTAR with the optical axis. Interferometric testing yielded values well within specification.

Expected Performance

Testing indicates that the optical performance of the COSTAR corrected instrument will be outstanding and should exceed specification. All six channels exceed the specification for encircled energy. Currently the aberrated HST delivers only about 15% encircled energy into a 0.1 arcsec radius. The COSTAR-corrected images should exceed the 60% in a 0.1 arcsec radius requirement. The original telescope specification was 70% encircled energy in a 0.1 arcsec radius. Figure 5 illustrates the magnitude of the expected improvement. On the left of the figure is the current performance, the point spread function, of one channel of the FOC. On the right is an actual image of the same aberrated source taken through the COSTAR with the engineering model FOC. This performance is essentially identical to the performance that would have been achieved had spherical aberration not occurred. Performance on orbit similar to those demonstrated in testing will result in the HST's full science capability being restored.

Installation

COSTAR will be installed during the first HST servicing mission scheduled for December 1993. Carried to orbit in a protective enclosure, it will be installed into HST by one of the two Extra Vehicular Activity (EVA) teams. During the 11-day mission, one of these teams of two astronauts will remove the High Speed Photometer and install the COSTAR into the axial science instrument bay of the HST. After opening the access door, the HSP's electrical connectors—specially designed to be easily removed by suited astronauts—will be disconnected. Next, the mechanical latches that hold the HSP in the telescope will be released. At this point the HSP is free to slide out. The HSP will be placed on a temporary fixture while the COSTAR is removed from its protective enclosure. After insertion into the bay vacated by the HSP, the astronauts will engage the latches and attach the electrical connections. They will then close the access doors and place the HSP in the COSTAR protective enclosure for the return to Earth. Engineers on the ground will begin a check-out process to ensure that all of the connections were properly made. Deployment of the COSTAR optics and the subsequent alignment and recalibration will occur in an eight-week period after Endeavour has landed.

Conclusion

The efforts by the scientists, engineers, and technicians at Ball Aerospace, NASA, ESA, and the Space Telescope Science Institute to conceive, design, build, and test the COSTAR in the 28 months required to support the launch of the first servicing mission is an outstanding achievement. Typically, instruments of this nature have usually taken four or more years to complete. The redundant testing of all aspects of the optical system should ensure the expected on-orbit performance. With the restoration of the HST by COSTAR and the WFPC II, we can expect the rich promise of HST to be fulfilled. Far from an example of failure, the HST will become an example of what can be accomplished when failure is deemed unacceptable. The motivation and successes of the people involved in restoring HST will long remain a tribute to their perseverance and creativity.

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