Development of the Second Generation Wide Field Planetary Camera for HST

By Arthur H. Vaughan and David H. Rodgers

With the launch of Space Shuttle Endeavour early next month, the fate of NASA's Hubble Space Telescope will rest in the skilled hands of five experienced astronauts whose demanding tasks will include installing corrective optics made necessary by the telescope's precisely polished, but tragically flawed, 2.4 m diameter main mirror. The corrective optics for the telescope's centrally located instrument, the Wide Field Planetary Camera (WFPC), are incorporated in an entirely new version of the 280 kg (618 lb.) instrument. Like its perfectly-functioning predecessor, WFPC II will re-image the focal plane of the telescope onto large-format electronic detector arrays through a selection of 48 spectral filters ranging from far-ultraviolet to near-infrared wavelengths, and will offer a choice of two magnifications. The second generation instrument was already under construction as a backup when the telescope was launched in 1990.

When NASA discovered that HST's main mirror was flawed, engineers, scientists, and managers at NASA's Jet Propulsion Laboratory (JPL) turned their attention to configuring WFPC II so that its optical system would have a clear focus despite the mirror defect. The main components of WFPC II are illustrated in Figure 1. This article traces the history of its development.

Early History

The concept of a large astronomical telescope orbiting above the Earth's atmosphere^2 was first proposed by Princeton University's Lyman Spitzer, Jr. (then at Yale University) in the late 1940s. A telescope operating above the atmosphere has many inherent advantages over ground-based observatories: Resolution is not degraded by atmospheric turbulence, and thus can approach a limit imposed only by diffraction; and the accessible spectral region can be extended far into the vacuum ultraviolet below 330 nm. This region is inaccessible to ground-based observatories because the atmosphere is opaque at these wavelengths. An orbiting observatory can also operate around the clock.

After the formation of NASA, the concept was studied extensively in the 1960s and early 1970s. First conceived as the "Large Space Telescope" (LST) with an aperture of up to 5 m, its name was later shortened to Space Telescope (ST) when the Space Shuttle became the launch vehicle of choice in 1972 , and the ST's aperture had to be constrained to fit within the cargo bay of the Shuttle. When the ST Project was approved for flight under the direction of the Marshall Space Flight Center in late 1976, the baseline design called for a 2.4-m diameter primary mirror with a small secondary mirror magnifying its focal length to 57.6 m. The telescope would carry five scientific instruments. In addition to all the necessary spacecraft engineering and control systems, a high performance pointing system featuring a set of Fine Guidance Sensors (collectively called the FGS) was needed. The FGS is capable of stabilizing the observatory to within ±0.007 arcsec for extended periods of time.

An additional and unique constraint (for a scientific observatory) was the requirement imposed on the ST that it be designed to be serviced in space, to avoid the prohibitive cost of returning the observatory to the ground and re-launching it. The first demonstration of this fortunate capability will be the upcoming Servicing Mission.

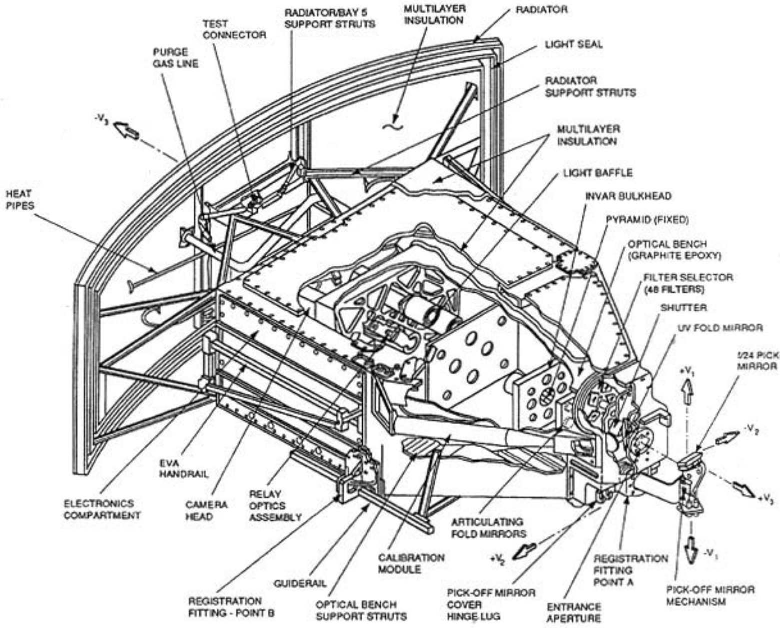

Figure 1. Cut-away view, showing interior, of the Wide Field Planetary Camera

The First Generation WFPC

The instrument that became WFPC I was selected on a competitive basis through an Announcement of Opportunity issued by NASA in 1975. James A. Westphal (Caltech) and his team (including JPL) were selected in 1977 to develop WFPC I as the prime imaging instrument. According to the NASA schedule, the camera was to be delivered in 1980 for a 1982 launch.

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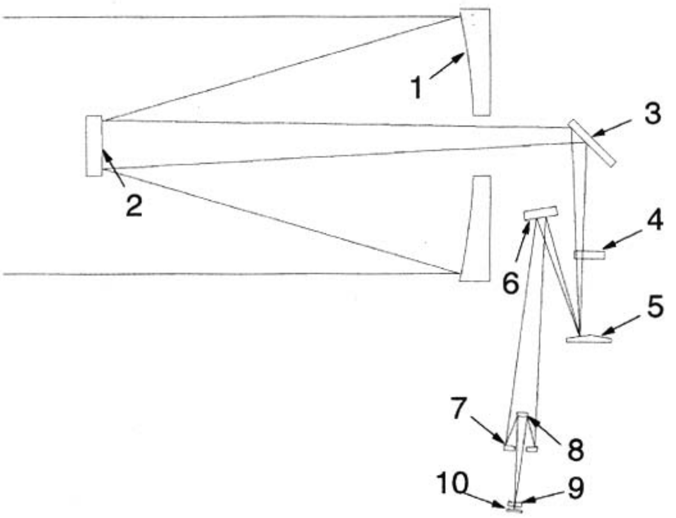


Figure 2. Schematic optical layout of HST (elements 1 and 2); WFPC II pickoff mirror, filter, and pyramid mirror (3,4, and 5); and one relay channel of WFPC II consisting of fold mirror, two-mirror relay, field flattener, and CCD detector (6,7,8,9, and 10). The pyramid (5) is weakly concave. Elements 2-7 serve to form an image of the flawed HST primary (1) onto the relay secondary mirror (8), whose prescription in WFPC II contains a compensating correction.

The camera's design evolved rapidly after proposal phases of its design, ultimately acquiring the dual magnification that led to the name Wide Field (F/12.9) and Planetary (F/30) Camera.

Replacement instruments were to be available to support Servicing Missions at five-year intervals. Delays and changes in the shuttle development program caused delays in the development of both the ST and the scientific instruments associated with it. This resulted in delays to both the launch and the initiation of the development of "second generation" scientific instruments. In 1984 with the ST scheduled for launch in 1986, a decision was made to build a duplicate—or "clone"—of the first WFPC to ensure that the ST's imaging capability could be restored if problems arose in the original instrument. This second camera was scheduled for delivery in 1988.[3] With Space Shuttle Challenger's disastrous accident of January 1986, the ST's launch was postponed until 1989. Clearly, the second camera would not be required as early as 1988; hence, its development was stretched out to preserve resources. In the interim, significant technical improvements were schieved that enhanced the camera's performance, particularly at ultraviolet wavelengths.

The ST—officially renamed the Hubble Space Telescope (HST) after the astronomer Edwin P. Hubble whose observations in the 1920s showed that the universe is expanding—was launched on April 24, 1990, from the Kennedy Space Center. At that time, the second WFPC was scheduled for delivery in the 1995 timeframe.

Spherical Aberration

The HST's first images in May 1990 exhibited abnormal characteristics and various difficulties were encountered in "fine tuning" the telescope's performance. From extensive examination of the images, Westphal's science team and workers at JPL and the Space Telescope Institute reached the conclusion that the HST's images could not be brought into sharp focus because of a flaw built into the telescope's optical system.

It was recognized almost immediately that if HST's main mirror happened to be the cause of the problem (as the result of having an incorrect shape), the fix would be relatively straightforward, at least for WFPC. This was because of the fortuitous circumstance that, inside WFPC's optical system, miniature images of HST's main mirror are formed almost exactly on top of elements (a set of convex mirrors about a centimeter in diameter) that are used in relaying the telescopic images to the detectors. Therefore, a defect in the HST primary could be compensated by introducing an equal but opposite "defect" on these small elements. This is illustrated in Figure 2.

It was not initially known whether the defect could be ascribed to the main mirror alone or was caused wholly or partly by errors in the smaller secondary mirror of the telescope. If significant errors in the HST secondary mirror were involved, a simple fix in WFPC would not correct the problem, except within a limited field of view—too small to be useful. The exact nature of the defect and the fact that it was restricted to the HST's main mirror were eventually well established by extensive studies in the year after the HST problem was discovered.[4-6]

The Second Generation WFPC

At the time HST was launched, and its optical flaw discovered, many parts of WFPC II, including its optical components, had already been fabricated. However, the instrument was still about four years away from its planned date of completion. Under pressure to recover from the defect of HST, the schedule to complete WFPC II was accelerated, and to its list of functional requirements was added the requirement that its optical system be modified to correct the spherical aberration of the telescope to the fullest possible extent.

This would require not only that the components be manufactured and aligned to very tight tolerances in the instrument, but that the instrument itself be aligned with excruciating precision within the telescope—a precision more exacting than the telescope's instrument-mounting latches were designed to provide. If the requisite precision of alignment could not be maintained, the HST's ability to detect and resolve the faintest astronomical sources would not be restored.

Fixing the Aberration

To make the conceptual fix a reality, much work was needed. Several integral tasks were envisioned early on. The initial plan of attack included three key elements:

- to deduce accurately and with high confidence the actual error built into the HST optical system;
- to produce an appropriately revised optical prescription for WFPC II that would correct the HST aberra-

tion; and

- to accelerate the development of WFPC II by three years to meet a newly planned 1993 servicing mission launch date.

These tasks occupied the attention of many workers at JPL, the Space Telescope Institute, Goddard Space Flight Center, and those in industry for almost a year. Two approaches were possible. The first involved a painstaking series of investigations of the tooling and test procedures used in manufacturing and testing the HST primary and secondary mirrors. The second approach involved diagnosing the optical system's performance using star images recorded by the orbiting observatory. It was clear that high confidence in the conclusions of these diagnoses would be possible only if the two approaches led to essentially the same answers.

In fact, "reverse engineering" of a flawed optical system was an ill-posed mathematical problem whose solution required the invention of new methods. A variety of technical approaches were investigated. A series of observations with the HST was undertaken to acquire a variety of stellar images for use in these analyses.

Meeting New and Tighter Alignment Tolerances

During the winter of 1990 and the summer of 1991, great efforts were made to both predict and measure the alignment stability of the camera within the telescope. The assembled evidence showed that slight movements might be taking place within the orbiting observatory, or within WFPC I, which in WFPC II could (in the worst case) prevent the corrective optics from restoring the HST's performance to the necessary degree.

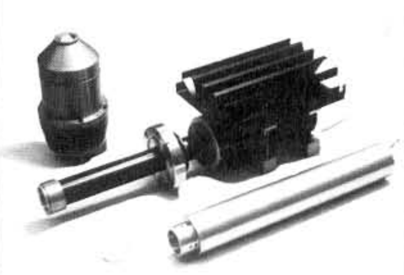
The ramifications were extensive. First, to allow for the known alignment uncertainty caused by the instrument's mounting within the telescope, it was decided early in the program to provide an active tip-tilt mechanism to adjust the pickoff mirror to permit any anticipated latch error to be corrected by remote control from the ground.

Tighter alignment tolerances also posed a potential problem for WFPC II: Could the camera maintain its alignment internally to the required level of accuracy, both during launch and in flight? Evidence suggested that WFPC I's internal alignment in orbit was slightly different from the alignment that had been documented just before launch. This would not have been a problem in WFPC I (had the HST been perfect), but might indicate the possibility of a problem in WFPC II because of its new function of compensating for the HST's flawed mirror.

As a result of such considerations, JPL and the science team decided in September 1991 to recommend that a second level of active optics be implemented in WFPC II, in the form of actively tip-tilt controlled fold mirrors in all but one of the relay optics channels of the instrument. To compensate for the added cost to develop and build the Active Fold Mirrors (AFMs), the decision was also made to eliminate four of the original eight channels of WFPC. In the resulting configuration, three of the channels would carry Wide Field Camera optics, while the fourth would carry Planetary Camera optics. In this arrangement, the active pickoff mirror would guarantee alignment of the channel having a fixed fold mirror. The three AFMs would guarantee alignment of the remaining channels. These recommendations were accepted and the task undertaken with utmost urgency.

In June 1991, before the above measures were discussed, JPL, in collaboration with Litton ITEK Optical Systems, studied a conceptual approach that allowed active control of the WFPC II pupil alignment on-orbit. The approach would capitalize on ITEK's proven electrostrictive actuator technology. This study demonstrated that active pupil control would be technically feasible. To make it a reality required, however, that ITEK and JPL work closely together to develop, flight qualify, and deliver a set of flight articulated flight mirrors in nine months. This required a significant resource commitment and a radically different approach to implementation. The development of the articulating fold mirrors was successful both technically and programmatically: The mirrors were available when needed to support the camera buildup; they were completed within cost; and they performed as advertised.

Another modification also stemmed from the very tight alignment



tolerances in WFPC II. One of the possible causes of the on-orbit alignment variations suspected in WFPC I was the highly complex pyramid mirror mechanism. In WFPC I, this mechanism provided two capabilities: Focusing the instrument relative to the telescope and "switching" between the telescope's lower and higher magnification relay channels. The "switching" capability was no longer needed in the WFPC II configuration. Moreover, the four-channel focus capability could no longer be used in WFPC II, because if the pyramid mirror was moved axially, the resulting misalignment of the corrective optics relative to the telescope would blur the images. On the other hand, if small adjustments in the focus of WFPC II relative to the other instruments proved necessary in orbit, the necessary capability exists in the HST and in the corrective optics space telescope axial replacement (COSTAR) to adjust the focus. For these reasons, the decision was finally reached to replace the original pyramid mechanism by a fixed mounting so as to eliminate, insofar as possible, all risk of optical misalignment in the instrument.

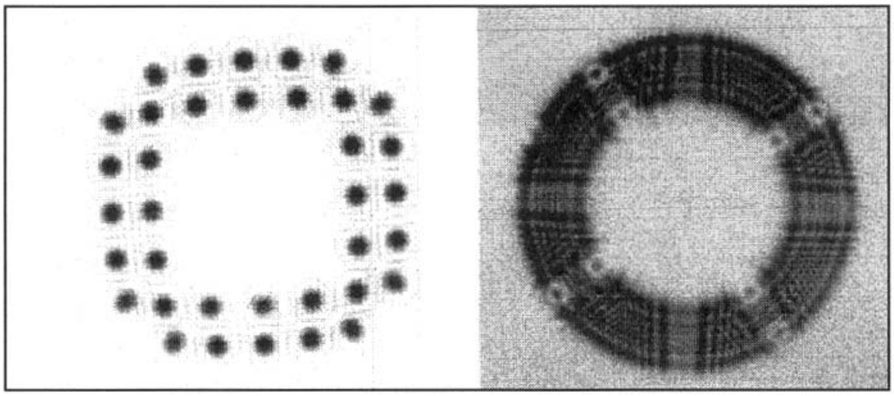


Figure 3. Negative prints of out-of-focus diffraction patterns created by the Stimulus with a classical Hartmann mask of 36 holes in a rectangular array (left) and a complementary mask (right), consisting of eight opaque disks supported by thin vanes. Spherical aberration is manifest by the pincushion distortion of the Hartmann pattern on the left. Diffraction gives rise to bright "spots of Arago" at the centers of the shadows of the opaque disks, visible on the right. The "Arago" mask was used to perform non-interfering focus tests of the Stimulus during environmental testing of WFPC II. The illumination has a 5 nm bandwidth at 633 nm. The near-vertical, horizontal, and diagonal linear features are caused by secondary mirror support structures in the Stimulus and WFPC II.

Stimulating the Telescope

To test WFPC I, an optical simulator of the Space Telescope had been designed and built at Caltech and JPL in the 1980s to feed light into the instrument in the same way that the actual telescope would supply images to it. To test WFPC II, the simulator (or "Stimulus," as it was called) was redesigned and rebuilt to reproduce as faithfully as possible the aberrated images delivered by the "as-flown" HST optical system, a task that required almost two years to complete. The new Stimulus became the ultimate gauge-block against which the flight instrument could be tested in a simulated space environment prior to launch. As such, it was subjected to extensive testing and validation, which established that the Stimulus performed to well within its very tight allowable tolerances.

To assure that WFPC II would meet its allowable rms wavefront error tolerance of $\lambda/14$ (at 633 nm), the Stimulus itself was required to meet a wavefront error tolerance of $\lambda/20$ relative to the wavefront it is designed to produce. But the new Stimulus is designed to produce highly aberrated images, the result of a specific amount (about 0.4λ rms) of spherical aberration in the HST.

This circumstance gave rise to difficulties of two kinds. First, the question of how to define the meaning of "focus" of a highly spherically aberrated system is complicated by the fact that the focal length of the system varies (by several centimeters in this case) between paraxial and marginal zones. Consequently, in specifying and in validating focus, it is necessary to specify correctly the zone of reference. Second, as much as 0.4λ rms of spherical aberration was found to be beyond the capability of industry-standard optical interferometers to measure reliably, although such instruments are routinely capable of high precision when aberrations are near zero, as is usually the case. It is possible, of course, to construct a null lens to cancel the spherical aberration of the Stimulus, and this was done to facilitate alignment and wavefront validation of the Stimulus. From double-pass interferometry of the Stimulus with its three-element null lens, an rms wavefront accuracy approaching $\lambda/40$ was consistently demonstrated.

However, as experience in the manufacture of the HST's primary mirror made painfully clear, a null lens might itself introduce error. To avoid this risk, the decision was made to base the fundamental validation of the Stimulus upon the classical Hartmann test, in which no null lens is needed. Suitable high-precision masks were fabricated by photolithography, to be located at the entrance pupil of the Stimulus under test. The Stimulus was illuminated by a point source on axis. The resulting light patterns were recorded by a LORAL 800 × 800 pixel CCD at an accurately known out-of-focus distance. These are illustrated in Figure 3. The positions of the centroids of the light-bundles at the CCD were compared differentially with the positions predicted by ray-tracing, based upon the intended optical prescription of the system. The method provides a focus uncertainty of about +0.13 mm (+0.005 in.) as compared with a conservative focus tolerance of twice as much for the Stimulus. The method also yields a measurement of third-order spherical aberration with a formal precision corresponding to about $\lambda/100$ rms, slightly better than the accuracy with which the actual spherical aberration of the HST is believed to be known. The use of Hartmann tests and interferometric tests using the null lens (as well as other "sanity" checks also performed) were in accordance with an adopted policy of requiring at least two independent methods of verification of all critical parameters relating to WFPC II.

Round-the-clock testing of the assembled WFPC II in a simulated space environment in JPL's 3.9 m (13 ft) vacuum test chamber began in late April of this year and occupied about a month, as planned. During this time, the integration and test engineering team put the instrument through all of its paces, while the science team tested and calibrated the instrument. Test targets fabricated by E-beam lithography in JPL's Microdevices Laboratory and an array of ultraviolet and visible light sources in the Stimulus were used to evaluate WFPC II's imaging capability and photometric response. Although a few minor problems were encountered and solved in the ground support test equipment, WFPC II passed all of its exacting tests, leaving no doubt that once in the telescope, it will perform to perfection.

On June 2, with an exhaustive preship readiness review of WFPC II successfully completed, the instrument and its retinue of ground support equipment began a three-day road journey in specially instrumented and air-conditioned moving vans to Goddard Space Flight Center in Maryland, where further tests were made in a high-fidelity simulator of the instrument bay of HST to confirm that the instrument would be compatible with COSTAR. By mid-August, on schedule, WFPC II was ready to be moved again, this time to Kennedy Space Center at Cape Canaveral for final installation and alignment of its delicate pickoff mirror.

The flight of WFPC II, along with COSTAR and other systems planned for installation in HST, will be an exciting adventure whose success will restore the long-awaited deep-space vision of the HST. We should not expect, however, that the full capabilities of the newly serviced Hubble Space Telescope can or will be demonstrated in the first few days or weeks after the Endeavour's mission. Bringing the telescope and its array of scientific instruments safely and surely back to life after the planned five-day Servicing Mission will be as painstaking and exacting a task as was building them.

Acknowledgments

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ARTHUR H. VAUGHAN *and* **DAVID H. RODGERS** *are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif.*

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HST Postscript

During last-minute testing, the beleaguered Hubble Space Telescope (HST) project experienced another aberration. Final pre-flight testing at Goddard Space Flight Center, Greenbelt, Md. revealed a focusing problem on the Wide Field Planetary Camera II (WFPC II). One test showed the WFPC II out of focus by 8 mm. A follow-up test showed WFPC II within 1-2 mm of the Corrective Optics Space Telescope Axial Replacement (COSTAR). NASA determined that the camera used to determine WFPC II's focus was "out of whack," according to space agency spokesman Jim Elliott. To ensure WFPC II's focusing problems are no greater than 1-2 mm, NASA devised yet another test for WFPC II that was scheduled for the middle of October.

"We're all sure it will be okay," says Elliott. "We just want to make sure the optical bench can take care of any focusing problems." If the discrepancy between WFPC II and COSTAR remains at 1-2 mm, NASA scientists can correct the situation by adjusting COSTAR's positioning on orbit.

Should testing reveal a last minute difficulty with WFPC II, NASA scientists may choose to ground the camera but launch the other replacement and corrective instruments.

In a related matter, the U.S. Justice Department has settled out of court with Hubble manufacturer Perkin-Elmer and Hughes Danbury Optical Systems, a subsidiary of Hughes Aircraft Corp. The three parties reached a $25 million settlement after a three-year investigation by the Justice Department and NASA's Inspector General.

The federal government contended that Perkin-Elmer knew or should have known of the defect in the HST's main mirror. In exchange for the payment, the government is releasing the companies from further liability claims.

According to the settlement agreement, the government will receive $15 million in cash and $3.5 million in waived fees under the telescope contract. Hughes Danbury Optical Systems will perform $6.5 million of continuing work on HST without reimbursement by the government.

Based on the terms of the settlement agreement, the parties agree that neither Perkin-Elmer nor Hughes Danbury Optical Systems admits "any liability whatsoever for any defect in the Hubble Space Telescope."

Watch for a Hubble update in an upcoming issue of *Optics & Photonics News*.

—*Susan Reiss*