Repairing Hubble's Vision with a New Camera

John Trauger
WFPC2 Principal Investigator
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Paradoxically, astronomical observation of the largest objects and most energetic events in nature requires instruments of exceedingly great sensitivity. Energy radiated by distant stars and galaxies, diminished by astronomical distances, are among the faintest signals ever detected. Yet these distant objects and events reveal the history of our universe, which is unfolding according to the familiar, pervasive laws of physics. There are countless cosmic events scattered across space and time, together these guide us toward a better understanding of the universe, our galaxy, the Solar System, the Earth, and our place within them.

Inevitably, the most intriguing questions in astronomy are those that reside at the very limits of our grasp. Each small advance in our technologies enables further discoveries. Over past centuries, but most importantly in the last few decades, powerful new techniques have been devised at observatories on the ground and in space. The Hubble Space Telescope was designed to reveal details in objects ten times more distant than possible from the ground, a once-in-a-lifetime advance for astronomers that promised fundamental new insights. But to fulfill this promise, the Hubble would have to perform to perfection, near the physical limit for image sharpness known as the "diffraction limit", as determined by the dimensions of the telescope's primary mirror. The Hubble Telescope was designed to take full advantage of its orbit high above the atmosphere, where stars do not shimmer as they do on the Earth. Further, the scientific instruments aboard the Hubble were designed to be sensitive and robust, to work continuously for years in the harsh environment of space without physical maintenance, and to perform at least as well as comparable instruments using ever-advancing technologies at ground~based observatories.

In 1985 the Hubble Telescope was nearly ready for launch (although there would be unexpected delays), and NASA began considering how it would be maintained over its planned 15-year lifetime. Many of the Hubble systems were designed to be serviced by astronauts, since the Space Shuttle would make periodic visits to the orbiting telescope to repair aging components and upgrade the scientific instruments. Hubble contained five scientific instruments, including two cameras: the Wide Field and Planetary Camera (WF/PC) and the European Faint Object Camera; two spectrographs, the Goddard High Resolution Spectrograph and the Faint Object Spectrograph; and the High Speed Photometer. All were designed to be easily replaced. The Wide Field and Planetary Camera 2 (WFPC2) was envisioned in 1985 as a replacement for the original WF/PC, to safeguard and upgrade Hubble's ability to do astronomical imaging. The early starting date anticipated the time required to build and test a new instrument in time for the first Shuttle servicing mission, already scheduled to occur three years after the Hubble launch. Preparations for the Hubble launch were extended and delayed for several years by the grounding of the Shuttle fleet in 1986. By April 1990, when the Hubble was launched, the construction of WFPC2 was already well along, and many subassemblies had been completed.

The first Hubble images were taken with the WF/PC in May 1990, four weeks after launch. NASA had promised the media that they would see the first images, and 70 reporters showed up to observe the "data bits" as they were received at the Goddard Space Flight Center. This would be extraordinary drama! Following years of planning, this would be the first time the Hubble ground control system, Hubble spacecraft and its scientific instruments, and data telemetry systems would all be orchestrated to produce an image of a star (an event known as "first light"), and any number of glitches could be expected in a brand-new operation of this complexity. James Westphal, the principal investigator for the WF/PC instrument, was prepared to narrate the events, and Jeff Hester, a member of his team of scientists, had assembled the computers, programs, and ground-based comparison data needed to deal with any eventuality. The data were received and written on magnetic tape, and the tape was hand-carried to the room where Westphal and Hester were waiting. The first image was displayed on a computer screen. It showed a field of stars and, even though the telescope had not yet been adjusted for best focus, each was sharper than the stars in a comparison image of the same field taken earlier from a ground-based telescope. In a matter of minutes a press-release picture was composed and the media show was over. The picture appeared on the front page of the New York Times the next day. Still there were questions - there was something strange about that field of stars.

Aden and Marjorie Meinel, with a lifetime of experience with astronomical telescopes between them, were curious about the Hubble images. They stopped by the WFPC2 data analysis area at the Jet Propulsion Laboratory (JPL) to take a look. The images were displayed on a computer screen, and after close inspection they commented that the star images appeared distorted by spherical aberration, one of a number of specific errors commonly found in optical systems (but usually in small amounts). As the next few weeks passed by, there was a growing awareness among the scientists and engineers working with the Hubble images that their efforts to focus and align the telescope optics were not going well. Something was wrong. While the origin of the problem had not yet been identified, there were speculations and even scattered optimism. Aden Meinel pointed out that if, indeed, there was spherical aberration in the Hubble's mirrors, that it could in principle be fixed within the WFPC2 by reworking its optics. I worked with optical designer Norm Page over the next few weeks, experimenting with JPL's computer model of the Hubble optical system, to evaluate simple optical corrections that might be built into the WFPC2 with a minimum of changes. Working from an assumption that there were errors in one or both of the Hubble Telescope's mirrors, we quickly established that opposite "errors" in WFPC2 could be used to correct the problem precisely. Better still, the simplest solution corresponded to an error confined to the Hubble primary mirror alone, in which case the shape of a number of small mirrors within WFPC2, and little else, would have to be changed.

Working independently, Chris Burrows, the telescope scientist at the Space Telescope Science Institute who had devoted considerable effort to predicting the telescope's optical characteristics prior to launch, and Jon Holtzman, a young member of the WF/PC science team, had been studying the new Hubble star images, using them as a cosmic eye chart, and had computed early estimates of the nature and magnitude of the Hubble error. Their results showed that the error was dominantly in the form of spherical aberration. The Hubble primary mirror can be envisioned as a very shallow bowl polished to a precise (hyperboloidal) shape, but with an error making it slightly too flat. Nowhere across its diameter of 2.4 meters does it deviate from the correct shape by more than 1/60th of the thickness of a sheet of paper. This may seem a small error, but it is comparable to the wavelength of the light it is intended to focus - a mountain in terms of optical precision, and it rendered the telescope fundamentally unfocusable. Starlight which is normally brought to a sharp focal point, was in this case stretched over a four-centimeter range of focus positions. Subsequent work by many individuals over the following months confirmed the diagnosis and produced an accurate prescription.

Hubble's Science Working Group and its User's Committee, a few dozen astronomers charged with the science oversight of the Hubble program, had planned a joint meeting for late June 1990, and it was clear that the aberration issue would dominate the discussions. The group met in private at Goddard, unusual since these meetings were normally public. As the doors were closed and the meeting was called to order, I recall seeing Mitch Waldrop, a writer for Science magazine, being ushered out. This was to be a candid review of the situation and an assessment of our possible actions. It was at this pivotal meeting that the exact nature of the problem, its impact on the important science programs planned for the Hubble, and the alternative approaches to fix the problem were first brought together. John Bahcall, a Princeton scientist who had long been an advocate of the Hubble program, led a discussion of the consequences the aberration would have on the many science programs already on the books for the first few years of operations, concluding that Hubble imaging science would be largely delayed. The emphasis would likely shift to spectroscopy (which was less affected by the imaging problem and more dependent on Hubble's access to ultraviolet wavelengths) until the telescope could be repaired.

I presented our strategy for a WFPC2 correction of the Hubble aberration, as predicted in the computer model calculations. I held up a nickel to illustrate the size of the mirrors inside WFPC2 on which the imaging correction could be made. Other alternatives were presented as well, mostly modifications to the telescope itself, but a practical method of correcting the four Hubble instruments other than WFPC2 was still to come.

Ed Weiler and Al Boggess, as the chief scientists for the Hubble program at NASA Headquarters and Goddard, respectively, broke news of the problem to the press that afternoon. It didn't take long for the public reaction to register. NBC Television anchor Tom Brokaw began his news program that evening with a provocative statement: "The Hubble Telescope you've heard so much about... it's broken!" The promise of the Hubble program, the application of our best technology to push back the frontiers of astronomy, had been instantly transformed in the public eye to an icon of technical failure. In spite of this, Associate Administrator Lennard Fisk articulated NASA's viewpoint: "We're stubborn and clever. We're going to make the Hubble work," and furthermore, "The measure of our agency is how rapidly we recover from problems."

Who would take responsibility for the Hubble recovery? Individuals across the country would be involved, but at JPL all efforts were focused on obtaining an accurate optical prescription for the Hubble mirror and constructing the corrective WFPC2 camera. Following a technical review in July 1990, plans were made to provide a fully-tested instrument in time for a Shuttle servicing mission scheduled for 1993. Some months later a new program to develop COSTAR was adopted, to provide "eyeglasses" for three of the other Hubble science instruments that could not be replaced on a three-year deadline.

As for most NASA projects, WFPC2 brought together a familiar mix of personalities. There were engineers, schooled by man's first decades in space and the challenges of creating flight hardware required to function without fail in the environmental extremes of space. There were astronomers, thinking ahead to the science questions that Hubble could uniquely answer and always looking for strategies or improvements that would expand the Hubble's science capabilities. Completing the mix were the managers, whose task it was to keep dozens of individuals scattered across the country focused on the sequence of events leading to launch, while balancing the competing realities of fixed budgets and the need to control engineering risk. The underlying differences in experience and perspectives, brought together in a project whose success or failure would be shared by all, created a dynamic and sometimes chaotic working environment.

The WFPC2 instrument is composed of many interlocking electronic, optical, and mechanical components. Inevitably, many of the project staff found themselves having to "guarantee" that a specific mission-ending failure wouldn't happen. The guarantee of success had taken its place among the engineering requirements for the entire Hubble servicing mission. Risk of failure could be understood and quantified for technologies already proven in previous space applications, but eleventh-hour innovations and brand-new technologies were harder to evaluate. "Better is the enemy of good enough" was the NASA mantra.

There were compromises. The original plans for WFPC2 called for eight independent imaging systems. Four of them effectively transformed the Hubble and WFPC2 into a camera with an f/28.3, 68,000 mm focal length lens, known as the "planetary camera." The other four made up a second, wide-angle f/12.9 system, known as the "wide-field camera." The astronomer would have the choice of either the wide-field or planetary configurations for any given exposure. Now there would have to be reductions. Budget, schedule, complexity, labor requirements, and laboratory resources all came under close scrutiny in the fall of 1991, and the WFPC2 project was compelled to reduce the number of internal optical systems from eight to four. The WFPC2 science team was alarmed. WFPC2's wide-field configuration was there for science programs needing coverage of the largest possible area in the sky and for viewing the faintest objects. Key science programs, including one to measure the cosmic distance scale, would be at risk if the wide-field capabilities were lost. But the planetary configuration was there to provide image resolution near the Hubble's diffraction limit and would be required for the sharpest possible \VFPC2 imaging. An agreement was hammered out between the engineers and the science team, and WFPC2 was built with three of the wide-angle f/12.9 systems, and one narrow-angle f/28.3 system, all four aimed at adjacent areas in the sky. Further, mechanisms were added so that each of the four systems could be independently aligned optically with the Hubble telescope. This was the origin of the unusual L-shaped format for the full WFPC2 field of view seen in some of the images of this book. The single planetary camera covers a smaller area with higher resolution, hence the image from it appears smaller than any of the three wide field images when all four are combined into a single WFPC2 image.

A new technology was under consideration for WFPC2. Tiny positioning devices would be needed for three critical mirrors inside the instrument. These would become important elements in our strategy to repair the Hubble's aberration. It seemed that they could be manufactured from a new ceramic material that had been developed only recently and never before used in a spacecraft. They would have to be built and tested within one year, and they would receive all the technical scrutiny and skepticism that NASA engineers could muster. Who would take responsibility for a critical task? Are you lucky? It was, of course, not a question of luck, but rather a recognition of the possibilities and preparation to see it through. The new positioning devices were ultimately launched with WFPC2 to provide the final on-orbit optical adjustments, and Jim Fanson, the young engineer who took charge of the task, proved himself "lucky."

There were other challenges. The WFPC2 corrective optics required "errors" that were precisely as large (but in the opposite direction) as the Hubble aberration. By design, WFPC2 now generated image distortions just as profound as Hubble's. An endless string of novel problems turned up while making and testing the system, not unlike playing a familiar game like baseball in an unfamiliar setting, such as the side of a hill. Jim McGuire and others, camping out at JPL for months without weekends, invented the new techniques needed for alignment and verification of the optical elements. For the technicians, whose hands actually created the hardware, craftsmanship and awareness of the consequences of mistake were daily requirements. For months, Donna Beckert could be found by her microscope as she attached, one-by-one, the hair-width electrical wires that control WFPC2's delicate imaging sensors, knowing that an unnoticed imperfection could cause failure months or years later in space, far beyond the reach of the technician's hands. The sensors themselves, silicon chips the size of postage stamps called CCDs, had been custom designed just one year earlier by Jim Janesick. The collective efforts of many individuals were essential to the development of the WFPC2 hardware that has worked without fail since it was installed in the Hubble Telescope.

Astronaut Jeff Hoffman visited JPL early in 1992 to begin familiarizing himself with the instrument that he and Story Musgrave would be installing during the servicing mission. He arrived at JPL, and a meeting was hastily arranged. A 1/4-scale model of the instrument had been placed on the conference table, and while the participants were shaking hands across the table, the model pickoff mirror was bumped and fell to the table. Was this an omen? The pickoff mirror was the most vulnerable external part on the WFPC2, and we sought assurances that the astronauts fully understood that touching the mirror could misalign a critical optical component and destroy our corrective strategy. In the course of the following year, the full servicing mission astronaut crew visited JPL to become familiar with the instrument and to practice using the tools and fixtures that would be used to remove the original WF/PC instrument and replace it with the new WFPC2 in space.

The Hubble servicing mission was launched on December 2, 1993, in the morning darkness a few hours before sunrise, filling the clear sky with an explosion of light and sound from the Shuttle's rocket engines. While the astronaut crew was surrounded by the violence for the eight minutes required for the Shuttle to reach orbit, we knew that the WFPC2 and its precisely adjusted optical system was receiving its ultimate shake test. An hour after the launch, spectators could watch as the Hubble Telescope itself glided silently across the dark predawn sky, appearing as a bright star passing six hundred kilometers above us and already in sunlight. And in the morning twilight a half hour later, a second "star" passed overhead, but this time it was the Shuttle completing its first orbit around the Earth and already on the chase for the Hubble. Was everything well with WFPC2? We wouldn't know for sure until weeks after the astronauts had returned home.

The Shuttle servicing mission proceeded without delay. One-by-one the planned items were replaced and checked out. Bulky instruments, weightless in orbit, were maneuvered by the astronauts with their fingertips. Anticipated telemetry signatures appeared as each new item was powered on, and the servicing mission concluded successfully. As the Shuttle backed away from the refurbished Hubble Telescope, the large aperture door at the front of the telescope was opened, and the Hubble began functioning once again as an autonomous spacecraft. But it was still too soon to begin full operation of the new scientific instruments; this would have to wait for several weeks while further checks were made.

Our first WFPC2 image was taken on December 18, 1993. This time "first light" took place late on a frigid evening in the basement operations room of the Space Telescope Science Institute in Baltimore. There were no journalists present this time, but the room was filled with scientists waiting for the first image to appear. The target was a bright star named AGK+81°266, and it demonstrated that the new optical system had arrived on-orbit in good health. Using the star image as a guide, the telescope was brought into sharp focus by moving its secondary mirror less than two hundredths of a millimeter (0.016 mm), and WFPC2 was optically aligned with the Hubble Telescope by tilting its pickoff mirror just four hundredths of a degree. For the first time the Hubble Telescope was producing images at the diffraction limit, and it was evident that its science potential was at last at hand. A few months later the WFPC2 was brought into final alignment with a number of even smaller mirror adjustments. After three years of anticipating that moment, and years of pondering the hundreds of potential mistakes that each could cause a failure, the biggest surprise was that there were really no surprises. The Hubble and WFPC2 were working together exactly as predicted, the optical prescription turned out to be correct, the required adjustments were well within expectations, and all WFPC2 systems were working just as they had when we last exercised them on the ground nearly a year earlier.

But it was too soon to declare success. The COSTAR mirrors had not yet been deployed, and during the next two weeks its "shower head" mechanism was extended and its mirrors were adjusted. The first of three instruments to receive the corrective benefits of the COSTAR was the Faint Object Camera, which shortly began producing its own "diffraction limited" images. Happily both Hubble instruments were ready in time for an announcement at the winter meeting of the American Astronomical Society near Washington, D.C., and the first images were released to the public and science community on January 13, 1994.

The Hubble observatory is available to astronomers in the United States and Europe. Their diverse areas of research are reflected in the sampling of images collected and presented in this book.