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The New and Improved Hubble Space Telescope

by Sally Stephens, Astronomical Society of the Pacific

The small room at the Space Telescope Science Institute in Baltimore was packed, even though it was the middle of the night. Astronomers and technicians strained to get a good view of the monitor that would soon show them the first picture taken with the newly "fixed" Hubble Space Telescope (HST). At 1:00 a.m., on Dec. 18, 1993, the image was radioed from the telescope to the ground. Tension gave way to cheers and exuberant shouts as the image of a star appeared on the monitor, a star without any of the smeared light astronomers had come to expect from the telescope's flawed main mirror. According to Edward Weiler, Hubble Space Telescope Program Scientist, the HST had not only been fixed, but "fixed beyond our wildest expectations."

What Had Happened?

When it was launched in 1990, astronomers expected to use the telescope to see farther into space and with greater clarity than had ever been possible. Circling 580 kilometers (360 miles) above the Earth's surface, the Hubble Space Telescope would float high above our turbulent atmosphere, which blurs the vision of even the largest telescopes on the ground. With the orbiting HST, astronomers hoped to see objects ten times more clearly than possible from the ground.

But the telescope's 2.4-meter (94-inch) main mirror had been ground to the wrong specifications, and was too flat near the edge by about 1/50th the width of a human hair. This miniscule error meant that only a small fraction, about 15 percent, of the light gathered by the HST was properly focused to a sharp point. The remaining 85 percent was spread out into a large, fuzzy halo and was essentially unusable. This problem, well known to astronomers, is called spherical aberration.

Astronomers quickly devised computer programs to remove this wasted light from images taken by the telescope, and the Hubble produced spectacular pictures of dust rings in the centers of galaxies that may be hiding massive black holes from view, peered into the heart of clusters of stars, and followed a storm on Saturn. But many projects, especially those involving faint objects, could not be done, and astronomers were haunted by the idea of discoveries that might have been made had the mirror not been flawed.

The Fix

Recognizing that all telescopes need periodic upgrades in equipment, NASA designed the Hubble Space Telescope to be serviced by space shuttle astronauts about every three years throughout its planned 15-year lifetime. The first servicing mission was scheduled for 1993. Scientists had already begun work on improved versions of its scientific instruments before HST was even launched.

For example, astronomers had always planned to replace the HST's Wide Field and Planetary Camera (abbreviated WF/PC, and usually called "Wiff-Pick"), designed to look at relatively bright objects with a wide field of view, during the first servicing mission. The new instrument would have "faster" electronic detectors, which, because they capture the same amount of light in half the time, can image fainter objects. After the HST mirror's aberration was discovered, scientists realized they could polish the mirrors in the new camera to a different "prescription" than originally planned to properly refocus the light. Replacing the old WF/PC would correct the HST mirror's problem, but only for that one instrument.

Unfortunately, replacements were not readily available for the other Hubble instruments, since they had not been scheduled for early upgrades. So scientists and engineers devised COSTAR (Corrective Optics Space Telescope Axial Replacement), with three small mirrors, about the size of dimes and quarters, each polished to compensate for the main mirror's flaw. After installation, a set of mechanical arms, no longer than a human hand, would put one of the mirrors in front of the opening that admits light into each of the other three scientific instruments, properly refocusing the light entering each one. In a sense, COSTAR put "eyeglasses" in front of each instrument to correct the telescope's vision, although the eyeglasses were mirrors, not lenses.

To make space for COSTAR, the shuttle astronauts had to remove one of the original Hubble instruments, the phonebooth-sized High Speed Photometer, which measured the brightness of celestial objects. This instrument was chosen to be sacrificed because it did proportionally less science than any of the other four instruments.

The Repair Mission

In the early morning hours of Dec. 2, 1993, the space shuttle Endeavour rocketed off into space, beginning the most difficult and challenging satellite repair mission ever attempted. For two days, the shuttle chased after the Hubble Space Telescope, slowly closing the gap between the two. When the two were finally side by side, astronaut Claude Nicollier grabbed the telescope with the shuttle's robotic arm, and placed it upright on a special turntable at the back of Endeavour's cargo bay.

Working in pairs on alternating days, four spacewalking shuttle astronauts worked on the Hubble Space Telescope. Jeffrey Hoffman and Story Musgrave installed the new WF/PC and replaced two pairs of faulty gyroscopes. The HST needs three gyros to point at and "track" stars during observations. It originally carried six gyroscopes. But the failure of three gyros since launch left the telescope with no back-ups. The repair gave the Hubble a full complement of healthy gyros.

Astronauts Kathryn Thornton and Tom Akers gently installed COSTAR, and replaced the HST's solar power panels. Shortly after launch, scientists discovered that the Hubble's solar panels expanded and contracted more than expected every time the telescope passed from the warmth of day into the cold of night and vice versa. This happened twice during every 96-minute orbit, and caused a "jitter" in the telescope that interfered with its ability to point at stars correctly for a short time after each temperature change. As a temporary fix, engineers created special computer programs that compensated for almost all of the jitter, allowing the telescope to function normally.

Still, scientists worried that the jitter would weaken the solar panels, causing them to break before the telescope's mission was done. Without enough power, the telescope could not operate. This concern prompted the astronauts to replace the solar panels with new ones designed to reduce the amount of jitter caused by the extreme temperature changes in Earth orbit.

The five spacewalks went so smoothly that the astronauts were frequently an hour ahead of the timeline established beforehand for each repair. Moving with extreme care and precision, the astronauts accomplished all of the tasks asked of them. On Dec. 13, 12 days after launch, the shuttle returned to Earth, its mission completed. At the time, one scientist said, "We have just completed eye surgery on the Hubble Space Telescope. It will be a matter of six to eight weeks before we can remove the bandages, figuratively speaking, from the patient and determine whether the operation was a success or not."

First astronomers had to calibrate the new gyroscopes, allow the WF/PC's new electronic detectors to cool to operating temperatures and align the Hubble's secondary mirror to make sure light properly entered the improved WF/PC. Then they would focus on aligning COSTAR's mirrors.

To their delight, astronomers found that the astronauts had been extraordinarily gentle to the telescope and its instruments; nothing had been bumped out of place. The corrective optics, which had been tested, retested, and tested again on the ground behaved exactly as expected. The telescope worked, in the words of one scientist, "like a dream." Astronomers and engineers worked feverishly for very long hours over the holiday season, aligning mirrors and analyzing information sent down by the telescope. About a month after the servicing mission, much sooner than expected, astronomers knew that the repairs had succeeded.

"The Trouble with Hubble is Over"

On Thursday, Jan. 13, 1994, NASA officials and HST scientists faced a standing-room-only crowd of journalists jammed into a room at NASA Goddard Space Flight Center, in Greenbelt, Md. Sen. Barbara Mikulski (D-Md.) held up two pictures of an otherwise nondescript star -- one taken by HST before the repair, the other after it. "The trouble with Hubble is over," she exclaimed. Where before there had been a large, fuzzy halo, there was now a sharply focused star. "We got everything just right," David Lekrone, senior project scientist, exulted. The spherical aberration had disappeared.

As astronomers analyzed data sent from Hubble throughout December, they were surprised at how good the images really were. There is a limit to how sharp light in a telescope can be made to focus. This so-called diffraction limit is based on the fact that light waves will inevitably spread out when they encounter an object in their path, like a mirror. This limit is different for every telescope and depends solely on the width of the main mirror and the wavelength of light under consideration. The resolution of most telescopes (the degree to which fine detail can be observed, or resolved) is normally much higher than the diffraction limit, due to the blurring of light by the Earth's atmosphere and imperfections in the optics.

The Hubble's spherical aberration spread a star's light out into a fuzzy halo four arc seconds across. [One arc second is 1/3600 of a degree, and corresponds to how far apart the headlights on a car would look if the car was 480 kilometers (300 miles) away.] Now, with the corrective optics in place, 60-70 percent of the light is concentrated within 1/10 of an arc second, very near the sharpest focus possible for a 2.4-meter telescope, essentially at the telescope's diffraction limit.

According to James Crocker, COSTAR team leader, the new Hubble images are "as perfect as engineers can achieve and as physical laws will allow." In fact, the corrected Hubble's vision is so precise that, if the telescope were in Washington, D.C., with an hour-and-a-half-long observation (the length of one HST orbit), it could detect the light from a firefly in Tokyo, half a world away. "And," Crocker continued, "if they were ten feet apart, we could see there were two fireflies."

Crystal-clear images

After a few minor adjustments to the focus and mirror alignment, astronomers tested the refurbished telescope by aiming it at the beautiful spiral galaxy, M100 (it is the 100th entry in a catalog of "fuzzy-appearing" objects compiled by the 18th-century comet-hunter Charles Messier, hence its name). At 10 p.m. on New Year's Eve, the telescope sent back a dramatic, crystal-clear image, taken with the new WF/PC.

For the first time, astronomers could follow the galaxy's spiral arms into the innermost regions of the galaxy. And, because of the clearer image, they were able to see extremely faint stars in M100's outer regions that will allow them to accurately determine its distance. The faint glow of these stars had always been swamped by light from nearby brighter stars blurred by the Earth's atmosphere. But with the repaired Hubble's sharp focus, the brighter stars looked like true points of light, allowing astronomers to see their fainter neighbors for the first time.

Another Hubble test image revealed thousands of stars in a cluster of young, hot stars, where before astronomers had only been able to detect the hundred or so brightest stars. And these were just "raw" images, with no computer enhancements of any kind. The telescope's new-found ability to see faint objects and structure within a few tenths of an arc second of bright stars delighted scientists. The telescope is now every bit as good as it was supposed to be when it was launched. In fact, in some ways it's even better; the improved WF/PC detectors make that instrument more sensitive than the original.

During the coming year, 1,200 to 1,500 astronomers will use the refurbished telescope to learn more about the universe in which we live. They will look for evidence of massive black holes in the centers of galaxies, continue the search for planets around other stars, and begin to calibrate the distance scale to far-away galaxies. Given the extraordinary success of the repair mission, astronomers have high hopes that the Hubble will finally deliver on its promise to revolutionize our understanding of astronomy.

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Activity: "Name That Angle"

(an activity to explain and explore angular resolution)

by Scott Hildreth, Astronomical Society of the Pacific/Chabot College

We can help students grasp the significance of Hubble's extremely keen eye, and learn a bit about angles and math in the process, with the following in-class activity.

Background

Picture the sky overhead as a large bowl, spanning 180 degrees from one horizon to the other. One degree on the sky then represents 1/180th of the visible hemispherical bowl. The Sun and Moon each span about one-half of one degree in our sky. Looking through binoculars or telescopes allows us to magnify a small section of the sky. To measure sizes or distances in that small section, astronomers divide a degree into 60 smaller pieces called *arcminutes,* and further subdivide minutes into 60 smaller sections called *arcseconds.* One second of arc on the sky is 1/3600th of one degree.

Activity overview

Place a ruler on the classroom wall, have students stand a fixed distance away, and determine the smallest things that they can see from that distance. Translate the size of the object and its distance to an equivalent "angular resolution." Within the classroom, most students will be able to see small shiny objects about 0.5 centimeter (1/4 inch) in diameter from 10 meters (30 feet) away. These objects represent an angle of about 1.7 arcminutes. A grain of sand or salt, seen from 10 meters away with binoculars or a small telescope, represents an angle of about 10 arcseconds. Compare this to the HST's resolution of 0.1 arcseconds, which is 1,000 times sharper!

Materials

A meter stick or ruler (with big numbers if possible), tape, a tape measure, and an assortment of very small items (which students can be asked to bring), such as single grains of dust, Cream of Wheat, salt, sand, coarse pepper, white pepper corns, small white peas or beans, coins, marbles, and balls.

Suggested procedure

Fold a long piece of tape in two, or put a piece of double-sided tap along the ruler, under the markings so that the small objects will adhere temporarily to its surface. Place the ruler on a wall, at eye-level for the students. Have students work in small groups, with two members acting as independent observers, and the rest of the group as judges who evaluate whether the observers correctly identify where on the ruler an object is placed. Judges place an object somewhere along the tape "in secret," and then ask the observers to view the ruler from 10 meters, and separately write down where the object is located on the ruler. For larger objects, the observers should agree with each other, and with the judges. For smaller objects, at the limit of the student's resolution, observers may disagree slightly with each other, and with the judges, so repeated measurements should be taken.

Use Table 1 to translate the size of the target to an equivalent angular size at 10 meters (30 feet). For small angles, like these, under 2 degrees, you can safely interpolate between the values in the table for target objects with sizes between those listed. For example, a grain of rice 3 millimeters wide held 10 meters away has an angular resolution of (3) x (20.6 arc seconds) = 61.8 arc seconds -- just about one minute of arc.

Once the limit of a student's resolution is reached, students can then walk forward slowly toward the ruler, ultimately reaching a distance where the smaller objects can be located. Measurements of this distance can then be used to calculate the angular size of the target, using the following approximate formulae. Please note that size and distance need to be expressed in the same units, that is, both in inches, or both in centimeters.

Angle (in degrees) = (57.3) x Size/Distance
Angle (in minutes) = (3440) x Size/Distance
Angle (in seconds) = (206,400) x Size/Distance

Extensions with more math

Once students have gathered data on what angle they can resolve, have them use mathematical ratios to create an "analogy" expressing the angle using much larger distances and more common objects. For example, something with a resolution of one arc second means that an observer could see a dime held about two miles away.

Help students create their analogies by developing a ratio equation:

Angular Size (of smaller object @ distance 1) = Angular Size (of larger object @ distance 2)

As older students develop their skills and comfort with ratios and units, you can encourage them to make reasonable estimates of distances as they answer questions like:

- If you can just resolve an angle of 1 arcminute, how far away is an automobile seen at night when its headlights just appear as two separate sources? (Use an approximate distance of two meters, or six feet, between the headlights.)
- If you were using a telescope with resolution like HST's, how close would you have to be to Earth to resolve:
    1. a city
    2. a football stadium
    3. a house
    4. a person

  Make assumptions about the typical size for each of these objects. What do your results tell you about the ability of robot spacecraft to detect intelligent life, or life of any kind, through photographs taken from hundreds or thousands of miles away?

Table 1. Conversion of linear diameters to angles

English			Metric		
12 inches	@ 30 feet =	1.9 degrees	10 cm	@ 10 meter =	34.4 minutes
1"	@ 30 feet =	9.55 minutes	2 cm	@ 10 meter =	6.87 minutes
1/8"	@ 30 feet =	1.2 minutes	1 cm	@ 10 meter =	3.43 minutes
1/16"	@ 30 feet =	36 seconds		@ 10 meter =	
1/32"	@ 30 feet =	18 seconds	1 mm	@ 10 meter =	20.6 seconds

1/64"	@ 30 feet =	9 seconds	0.1 mm	@ 10 meter =	2.1 seconds
1/1000"	@ 30 feet =	1.1 seconds	0.01 mm	@ 10 meter =	0.21 seconds
1/10,000"	@ 30 feet =	0.1 seconds	0.005 mm	@ 10 meter =	0.1 seconds