Mission: optometrist

When the patient is a million miles out in deep space, the optometrist needs to get his refraction spot on. **David Baker** explains

Space exploration, aeronautics research, astrophysics: NASA is an acknowledged expert in these and other scientific endeavours. But optometry? By its own account NASA likened itself to an optometrist when faced with the mother of all awkward 'non-tolerance' cases. The patient was the Hubble Space Telescope (HST), which had been given the wrong prescription and was orbiting 569km above the Earth at a velocity of 28,000km/h.

The 13.2m long, 4.2m wide HST, weighing over 11,000kg, was launched on 24 April 1990 by space shuttle Discovery and deployed a day later. The images HST started sending back, while better than anything a ground-based telescope could produce, were of a lower quality than had been expected: a diagnosis of spherical aberration was quickly made. This was a crushing blow for a project that was first sketched out by NASA in 1969 and embarked upon in earnest in conjunction with the European Space Agency in 1975. Astronaut training for the launch mission, using mock-ups in deep-water tanks, had begun as far back as 1979. So how did such a carefully-planned project go wrong, and how was it to be fixed?

The telescope is a reflector of the Ritchey-Chretien Cassegrain type, which consists of a large, concave, primary mirror that collects light and reflects it to a smaller, convex, secondary mirror. From here the light is reflected back through an aperture in the centre of the primary mirror and focused. HST is designed to house several instruments that can be moved individually into the focal plane of the mirror system. Investigations found the problem to lie with the 2.4m diameter primary mirror, ultimately caused by faulty assembly of the device used to measure its curvature.

This mirror needed to have its reflecting surface ground with a curvature accurate to within 0.032 microns (μm); were the mirror the diameter of the Earth, the curve could deviate from true by only 15cm. Made of ultra-low expansion glass, and kept at a constant temperature of about 21°C to avoid warping, its surface is coated with a 0.076μm layer of pure aluminium covered by a 0.025μm layer of highly UV-reflective magnesium flouoride. The fault in the mirror was determined to be an excess flattening of the peripheral curve of 2.2μm. This may only be one-fiftieth the thickness of a human hair, but in terms of the accuracy required it was devastating.

By retracing the steps of manufacture of the primary mirror, it was found that the contractor had relied on just a single test to confirm the accuracy of curvature (a mistake NASA learned the hard way not to repeat). This was a cylindrical instrument comprising two mirrors and a lens called a 'null corrector'; through which a laser beam is passed and reflected back from the mirror under test to produce an interferogram – a pattern of black and white lines which allows analysis of the mirror's curve. Unfortunately one of the null corrector's optical elements had been positioned incorrectly by 1.3mm, which then guided technicians to grind the peripheral curve erroneously. It was fortunate indeed that the contractor's null corrector had sat untouched in their plant for 10 years so that, together with the data from HST's fuzzy images, the problem could be traced.

Where did NASA go from here? In its own words, 'NASA approached the correction of Hubble's nearsightedness as would an optometrist. The agency first diagnosed the telescope's vision problem, determined a prescription to fix the ailment and monitored the development of corrective optics to make sure the telescope's sight would be restored to the fullest extent possible.' So the diagnosis had been made. NASA now established a committee, the Hubble Independent Optical Review Panel (HIORP), to work out the prescription.

Using all available data, HIORP came up with a 'conic constant' that described accurately the mirror's aberrant shape. New astronomical instruments being developed for HST could then have their optics corrected by, in effect, the inverse of that conic constant to make them compatible with the mirror. But for the three instruments already on board HST, a different solution would be required. A plan was devised to insert a series of coin-sized mirrors, designed to the inverse conic constant, behind the primary mirror on HST. The engineering problems with achieving this in practice were complex, but eventually an assembly of mirrors on mechanical arms which would be unfolded when *in situ*, the size of a telephone box, was developed. And so the Corrective Optics Space Telescope Axial Replacement (COSTAR) was born.

In light of the testing debacle that led to the original problem, NASA concurrently set about establishing committees and design teams to devise several pieces of testing and verification equipment, which in turn were to be subjected to their own inspection regimes in order to ensure they were properly set up. The development of, and analysis by, these instruments took the best part of two years.

Finally COSTAR was ready to be deployed. It was carried by space shuttle Endeavour on Servicing Mission 1, launched on December 2 1993. Along with COSTAR there was a replacement Wide Field Planetary Camera, with built-in correction for HST's defect, along with new solar arrays, gyroscopes and other equipment. Servicing Mission 3B, launched on March 1 2002, removed the last of the three instruments that COSTAR had been designed to keep in focus and marked the end of its useful life. So, as part of Servicing Mission 4 (actually the fifth servicing mission, as Servicing Mission 3 was split into two parts), lasting from May 11-24 2009, it was finally returned to Earth on board the shuttle Atlantis. It now resides in the Smithsonian's National Air and Space Museum in Washington DC where it is on permanent public display.

Successful as HST has turned out to be, its replacement is already under construction. In fact, manufacture of the Webb Space Telescope (WST) began in 2004 and is expected to be completed by 2013. This tennis court-sized instrument is an infra-red (IR) telescope designed to detect cooler, more distant objects than HST (which uses visible light) and to be able to penetrate interstellar dust clouds. It will have an 18-segment beryllium parabolic primary mirror 6.5m at its widest part, with a focal length of 131.4m and an optical resolution of 0.07 arc seconds. It will be coated with 24 carat gold, increasing its reflectivity of IR from 85 per cent to 98 per cent and will have an operating temperature of 40K (-233.2C).

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If WST is half as successful as HST, it will have done its job. Among other things, HST has allowed astronomers to set the age of the universe at 13.7 billion years with a high degree of certainty; has detected distant light from the universe when aged just 600 million years; has proved the existence of massive black holes; and has proved the existence of dark energy. WST will have a special orbit beyond the moon, 1.5 million km from Earth, at the Second Lagrange Point, a location that enables a stable distant orbit using the Earth's and the Sun's gravity in harness.

There will be no visits possible by the now-decommissioned shuttles, or any other manned craft given the distance involved. Returning to the analogy of NASA as optometrist, it had better take extra care to get its refraction spot-on first time; and when the 'job' comes back from the lab, it should be mighty careful in checking the work before sending the patient out into deep space.

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