Hubble Space Telescope

The Hubble Space Telescope (HST) is a NASA space telescope that was carried into orbit by a space shuttle in 1990. Although not the first space telescope, Hubble is one of the largest and most versatile, and is well-known as both a vital research tool and a public relations boon for astronomy. The HST was built by the United States space agency NASA, with contributions from the European Space Agency, and is operated by the Space Telescope Science Institute. It is named after the astronomer Edwin Hubble. The HST is one of NASA's Great Observatories, along with the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Space Telescope.[5]

The Hubble Space Telescope as seen from the departing Space Shuttle Atlantis, flying Servicing Mission 4 (STS-125), the fifth and final human spaceflight to visit the observatory.

Space telescopes were proposed as early as 1923. Hubble was funded in the 1970s, with a proposed launch in 1983, but the project was beset by technical delays, budget problems, and the Challenger disaster. When finally launched in 1990, scientists found that the main mirror had been ground incorrectly, severely compromising the telescope's capabilities. However, after a servicing mission in 1993, the telescope was restored to its intended quality. Hubble's orbit outside the distortion of Earth's atmosphere allows it to take extremely sharp images with almost no background light. Hubble's Ultra Deep Field image, for instance, is the most detailed visible-light image ever made of the universe's most distant objects. Many Hubble observations have led to breakthroughs in astrophysics, such as accurately determining the rate of expansion of the universe.

Hubble is the only telescope ever designed to be serviced in space by astronauts. Four servicing missions were performed from 1993–2002, but the fifth was canceled on safety grounds following the Space Shuttle Columbia disaster. However, after spirited public discussion, NASA administrator Mike Griffin approved one final servicing mission, completed in 2009. The telescope is now expected to function until at least 2014, when its 'successor', the James Webb Space Telescope (JWST), is due to be launched.

Conception, design and aims

Proposals and precursors

In 1923, Hermann Oberth—considered along with Robert H. Goddard and Konstantin Tsiolkovsky fathers of modern rocketry—published Die Rakete zu den Planetenräumen ("The Rocket into Planetary Space"), which mentioned how a telescope could be propelled into Earth orbit by a rocket.[6]

Lyman Spitzer, "father" of the Space Telescope

The history of the Hubble Space Telescope can be traced back as far as 1946, when the astronomer Lyman Spitzer wrote the paper "Astronomical advantages of an extraterrestrial observatory".[7] In it, he discussed the two main advantages that a space-based observatory would have over ground-based telescopes. First, the angular resolution (smallest separation at which objects can be clearly distinguished) would be limited only by diffraction, rather than by the turbulence in the atmosphere, which causes stars to twinkle and is known to astronomers as seeing. At that time ground-based telescopes were limited to resolutions of 0.5–1.0 arcseconds, compared to a theoretical diffraction-limited resolution of about 0.05 arcsec for a telescope with a mirror 2.5 m in diameter. Second, a space-based telescope could observe infrared and ultraviolet light, which are strongly absorbed by the atmosphere.

Spitzer devoted much of his career to pushing for a space telescope to be developed. In 1962 a report by the United States National Academy of Sciences recommended the development of a space telescope as part of the space program, and in 1965 Spitzer was appointed as head of a committee given the task of defining the scientific objectives for a large space telescope.[8]

Space-based astronomy had begun on a very small scale following World War II, as scientists made use of developments that had taken place in rocket technology. The first ultraviolet spectrum of the Sun was obtained in 1946,[9] and NASA launched the Orbiting Solar Observatory to obtain UV, X-ray, and gamma-ray spectra in 1962.[10] An orbiting solar telescope was launched in 1962 by the United Kingdom as part of the Ariel space program, and in 1966 National Aeronautics and Space Administration (NASA) launched the first Orbiting Astronomical Observatory (OAO) mission. OAO-1's battery failed after three days, terminating the mission. It was followed by OAO-2, which carried out ultraviolet observations of stars and galaxies from its launch in 1968 until 1972, well beyond its original planned lifetime of one year.[11]

The OSO and OAO missions demonstrated the important role space-based observations could play in astronomy, and 1968 saw the development by NASA of firm plans for a space-based reflecting telescope with a mirror 3 m in diameter, known provisionally as the Large Orbiting Telescope or Large Space Telescope (LST), with a launch slated for 1979. These plans emphasized the need for manned maintenance missions to the telescope to ensure such a costly program had a lengthy working life, and the concurrent development of plans for the reusable space shuttle indicated that the technology to allow this was soon to become available.[12]

Quest for funding

The continuing success of the OAO program encouraged increasingly strong consensus within the astronomical community that the LST should be a major goal. In 1970 NASA established two committees, one to plan the engineering side of the space telescope project, and the other to determine the scientific goals of the mission. Once these had been established, the next hurdle for NASA was to obtain funding for the instrument, which would be far more costly than any Earth-based telescope. The US Congress questioned many aspects of the proposed budget for the telescope and forced cuts in the budget for the planning stages, which at the time consisted of very detailed studies of potential instruments and hardware for the telescope. In 1974, public spending cuts instigated by Gerald Ford led to Congress cutting all funding for the telescope project.[13]

In response to this, a nationwide lobbying effort was coordinated among astronomers. Many astronomers met congressmen and senators in person, and large scale letter-writing campaigns were organized. The National Academy of Sciences published a report emphasizing the need for a space telescope, and eventually the Senate agreed to half of the budget that had originally been approved by Congress.[14]

The funding issues led to something of a reduction in the scale of the project, with the proposed mirror diameter reduced from 3 m to 2.4 m, both to cut costs [15] and to allow a more compact and effective configuration for the telescope hardware. A proposed precursor 1.5 m space telescope to test the systems to be used on the main satellite was dropped, and budgetary concerns also prompted collaboration with the European Space Agency. ESA agreed to provide funding and supply one of the first generation instruments for the telescope, as well as the solar cells that would power it, and staff to work on the telescope in the United States, in return for European astronomers being guaranteed at least 15% of the observing time on the telescope.[16] Congress eventually approved funding of US$36,000,000 for 1978, and the design of the LST began in earnest, aiming for a launch date of 1983.[14] In 1983 the telescope was named[17] after Edwin Hubble, who made one of the greatest scientific breakthroughs of the 20th century when he discovered that the universe was expanding.[18]

Construction and engineering

Polishing of Hubble's primary mirror begins at Perkin-Elmer corporation, Danbury, Connecticut, May 1979. The engineer pictured is Dr. Martin Yellin, an optical engineer working for Perkin-Elmer on the project.

Once the Space Telescope project had been given the go-ahead, work on the program was divided among many institutions. Marshall Space Flight Center (MSFC) was given responsibility for the design, development, and

construction of the telescope, while the Goddard Space Flight Center was given overall control of the scientific instruments and ground-control center for the mission.[19] MSFC commissioned the optics company Perkin-Elmer to design and build the Optical Telescope Assembly (OTA) and Fine Guidance Sensors for the space telescope. Lockheed was commissioned to construct and integrate the spacecraft in which the telescope would be housed.[20]

Optical Telescope Assembly (OTA)

Optically, the HST is a Cassegrain reflector of Ritchey-Chrétien design, as are most large professional telescopes. This design, with two hyperbolic mirrors, is known for good imaging performance over a wide field of view, with the disadvantage that the mirrors have shapes that are hard to fabricate and test. The mirror and optical systems of the telescope determine the final performance, and they were designed to exacting specifications. Optical telescopes typically have mirrors polished to an accuracy of about a tenth of the wavelength of visible light, but the Space Telescope was to be used for observations from the visible through the ultraviolet (shorter wavelengths) and was specified to be diffraction limited to take full advantage of the space environment. Therefore its mirror needed to be polished to an accuracy of 10 nanometres, or about 1/65 of the wavelength of red light.[21] On the long wavelength end, the OTA was not designed with optimum IR performance in mind — for example, the mirrors are kept at stable (and warm, about 15 C) temperatures by heaters. This limits Hubble's performance as an infrared telescope.[22]

Perkin-Elmer intended to use custom-built and extremely sophisticated computer-controlled polishing machines to grind the mirror to the required shape.[20] However, in case their cutting-edge technology ran into difficulties, NASA demanded that PE sub-contract to Kodak to construct a back-up mirror using traditional mirror-polishing techniques.[23] (The team of Kodak and Itek also bid on the original mirror polishing work. Their bid called for the two companies to double-check each other's work, which would have almost certainly caught the polishing error that later caused such problems.[24]) The Kodak mirror is now on permanent display at the Smithsonian Institution.[25] An Itek mirror built as part of the effort is now used in the 2.4 m telescope at the Magdalena Ridge Observatory.[26]

Construction of the Perkin-Elmer mirror began in 1979, starting with a blank manufactured by Corning from their ultra-low expansion glass. To keep the mirror's weight to a minimum it consisted of inch-thick top and bottom plates sandwiching a honeycomb lattice. Perkin-Elmer simulated microgravity by supporting the mirror on both sides with 138 rods that exerted varying amounts of force. This ensured that the mirror's final shape would be correct and to specification when finally deployed. Mirror polishing continued until May 1981. NASA reports at the time questioned Perkin-Elmer's managerial structure, and the polishing began to slip behind schedule and over budget. To save money, NASA halted work on the back-up mirror and put the launch date of the telescope back to October 1984.[27] The mirror was completed by the end of 1981; it was washed using 2,400 gallons of hot, deionized water and then received a reflective coating of aluminium 65 nm-thick and a protective coating of magnesium fluoride 25 nm-thick.[22][28]
Construction of Hubble. The optical metering truss and secondary baffle are visible.

Doubts continued to be expressed about Perkin-Elmer's competence on a project of this importance as their budget and timescale for producing the rest of the OTA continued to inflate. In response to a schedule described as "unsettled and changing daily", NASA postponed the launch date of the telescope until April 1985. Perkin-Elmer's schedules continued to slip at a rate of about one month per quarter, and at times delays reached one day for each day of work. NASA was forced to postpone the launch date until first March and then September 1986. By this time the total project budget had risen to US$1.175 billion.[29]

Spacecraft systems

The spacecraft in which the telescope and instruments were to be housed was another major engineering challenge. It would have to adequately withstand frequent passages from direct sunlight into the darkness of Earth's shadow, which would generate major changes in temperature, while being stable enough to allow extremely accurate pointing of the telescope. A shroud of multi-layer insulation keeps the temperature within the telescope stable, and surrounds a light aluminum shell in which the telescope and instruments sit. Within the shell, a graphite-epoxy frame keeps the working parts of the telescope firmly aligned.[30] Because graphite composites are hygroscopic, there was a risk that water vapor absorbed by the truss while in Lockheed's clean room would later be expressed in the vacuum of space; the telescope's instruments would be covered in ice. To reduce that risk, a nitrogen gas purge was performed prior to launching the telescope into space.[31]
Exploded view of the Hubble Telescope.

While construction of the spacecraft in which the telescope and instruments would be housed proceeded somewhat more smoothly than the construction of the OTA, Lockheed still experienced some budget and schedule slippage, and by the summer of 1985, construction of the spacecraft was 30% over budget and three months behind schedule. An MSFC report said that Lockheed tended to rely on NASA directions rather than take their own initiative in the construction.[32]

Initial instruments

Main articles: Wide Field and Planetary Camera, Goddard High Resolution Spectrograph, High Speed Photometer, Faint Object Camera, and Faint Object Spectrograph

Photometer, Faint Object Camera, and Faint Object Spectrograph

When launched, the HST carried five scientific instruments: the Wide Field and Planetary Camera (WF/PC), Goddard High Resolution Spectrograph (GHRS), High Speed Photometer (HSP), Faint Object Camera (FOC) and the Faint Object Spectrograph (FOS). WF/PC was a high-resolution imaging device primarily intended for optical observations. It was built by NASA's Jet Propulsion Laboratory, and incorporated a set of 48 filters isolating spectral lines of particular astrophysical interest. The instrument contained eight charge-coupled device (CCD) chips divided between two cameras, each using four CCDs. The "wide field camera" (WFC) covered a large angular field at the expense of resolution, while the "planetary camera" (PC) took images at a longer effective focal length than the WF chips, giving it a greater magnification.[33]

The GHRS was a spectrograph designed to operate in the ultraviolet. It was built by the Goddard Space Flight Center and could achieve a spectral resolution of 90,000.[34] Also optimized for ultraviolet observations were the FOC and FOS, which were capable of the highest spatial resolution of any instruments on Hubble. Rather than CCDs these three instruments used photon-counting digicons as their detectors. The FOC was constructed by ESA, while the University of California, San Diego and the Martin Marietta corporation built the FOS.[33]

The final instrument was the HSP, designed and built at the University of Wisconsin–Madison. It was optimized for visible and ultraviolet light observations of variable stars and other astronomical objects varying in brightness. It could take up to 100,000 measurements per second with a photometric accuracy of about 2% or better.[35]

HST's guidance system can also be used as a scientific instrument. Its three Fine Guidance Sensors (FGS) are primarily used to keep the telescope accurately pointed during an observation, but can also be used to carry out extremely accurate astrometry; measurements accurate to within 0.0003 arcseconds have been achieved.[36]

Ground support

Main article: Space Telescope Science Institute

Hubble's low orbit means many targets are visible for somewhat less than half of elapsed time, since they are blocked from view by the Earth for one-half of each orbit.

The Space Telescope Science Institute (STScI) is responsible for the scientific operation of the telescope and delivery of data products to astronomers. STScI is operated by the Association of Universities for Research in Astronomy (AURA) and is physically located in Baltimore, Maryland on the Homewood campus of Johns Hopkins University, one of the 33 US universities and 7 international affiliates that make up the AURA consortium. STScI was established in 1983 after something of a power struggle between NASA and the scientific community at large. NASA had wanted to keep this function "in-house", but scientists wanted it to be based in an academic establishment.[37][38] The Space Telescope European Coordinating Facility (ST-ECF), established at Garching bei München near Munich in 1984, provides similar support for European astronomers.

One rather complex task that falls to STScI is scheduling observations for the telescope.[39] Hubble is situated in a low-Earth orbit so that it can be reached by the space shuttle for servicing missions, but this means that most astronomical targets are occulted by the Earth for slightly less than half of each orbit. Observations cannot take place when the telescope passes through the South Atlantic Anomaly due to elevated radiation levels, and there are also sizable exclusion zones around the Sun (precluding observations of Mercury), Moon and Earth. The solar avoidance angle is about 50°, which is specified to keep sunlight from illuminating any part of the OTA. Earth and Moon avoidance is to keep bright light out of the FGSs and to keep scattered light from entering the instruments. If the FGSs are turned off, however, the Moon and Earth can be observed. Earth observations were used very early in the program to generate flat-fields for the WFPC1 instrument. There is a so-called continuous viewing zone (CVZ), at roughly 90 degrees to the plane of Hubble's orbit, in which targets are not occulted for long periods. Due to the precession of the orbit, the location of the CVZ moves slowly over a period of eight weeks. Because the limb of the Earth is always within about 30° of regions within the CVZ, the brightness of scattered earthshine may be elevated for long periods during CVZ observations.

Because Hubble orbits in the upper atmosphere, its orbit changes over time in a way that is not accurately predictable. The density of the upper atmosphere varies according to many factors, and this means that Hubble's predicted position for six weeks' time could be in error by up to 4,000 km. Observation schedules are typically finalized only a few days in advance, as a longer lead time would mean there was a chance that the target would be unobservable by the time it was due to be observed.[40]

Engineering support for HST is provided by NASA and contractor personnel at the Goddard Space Flight Center in Greenbelt, Maryland, 48 km south of the STScI. Hubble's operation is monitored 24 hours per day by four teams of flight controllers who make up Hubble's Flight Operations Team.[41]

Challenger disaster, delays, and eventual launch

In early 1986, the planned launch date of October that year looked feasible, but the Challenger accident brought the U.S. space program to a halt, grounding the space shuttle fleet and forcing the launch of Hubble to be postponed for several years. The telescope had to be kept in a clean room, powered up and purged with nitrogen, until a launch could be rescheduled. This costly situation (about $6 million per month) pushed the overall costs of until a launch could be rescheduled. This costly situation (about $6 million per month) pushed the overall costs of the project even higher. On the other hand, engineers used this time to perform extensive tests, swap out a possibly failure-prone battery, and make other improvements.[42] Furthermore, the ground software needed to control Hubble was not ready in 1986, and in fact was barely ready by the 1990 launch.[43]

Eventually, following the resumption of shuttle flights in 1988, the launch of the telescope was scheduled for 1990. On April 24, 1990, shuttle mission STS-31 saw Discovery launch the telescope successfully into its planned orbit.[44]

From its original total cost estimate of about US$400 million, the telescope had by now cost over $2.5 billion to construct. Hubble's cumulative costs up to this day are estimated to be several times higher still, with US expenditure estimated at between $4.5 and $6 billion, and Europe's financial contribution at €593 million (1999 estimate).[45]
Shuttle mission STS-31 lifts off, carrying Hubble into orbit.
Hubble is deployed from Discovery.

Flawed mirror

Within weeks of the launch of the telescope, the returned images showed that there was a serious problem with the optical system. Although the first images appeared to be sharper than ground-based images, the telescope failed to achieve a final sharp focus, and the best image quality obtained was drastically lower than expected. Images of point sources spread out over a radius of more than one arcsecond, instead of having a point spread function (PSF) concentrated within a circle 0.1 arcsec in diameter as had been specified in the design criteria.[46] The detailed performance is shown in graphs from STScI illustrating the mis-figured PSFs compared to post-correction and ground-based PSFs.[47]

Analysis of the flawed images showed that the cause of the problem was that the primary mirror had been ground to the wrong shape. Although it was probably the most precisely figured mirror ever made, with variations from the prescribed curve of only 10 nanometers,[21] it was too flat at the edges by about 2200 nanometers (2.2 microns).[48] This difference was catastrophic, introducing severe spherical aberration, a flaw in which light reflecting off the edge of a mirror focuses on a different point from the light reflecting off its center.[49]

The effect of the mirror flaw on scientific observations depended on the particular observation—the core of the aberrated PSF was sharp enough to permit high-resolution observations of bright objects, and spectroscopy was largely unaffected. However, the loss of light to the large, out of focus halo severely reduced the usefulness of the telescope for faint objects or high contrast imaging. This meant that nearly all of the cosmological programs were essentially impossible since they required observation of exceptionally faint objects.[49] NASA and the telescope became the butt of many jokes, and the project was popularly regarded as a white elephant. (For instance, in the movie The Naked Gun 2½: The Smell of Fear, the Hubble was pictured with the Titanic, the Hindenburg, and the Edsel).[50] Nonetheless, during the first three years of the Hubble mission, before the optical corrections, the telescope still carried out a large number of productive observations. The error was well characterized and stable, enabling astronomers to optimize the results obtained using sophisticated image processing techniques such as deconvolution.[51]

Origin of the problem
An extract from a WF/PC image shows the light from a star spread over a wide area instead of being concentrated on a few pixels.

A commission headed by Lew Allen, director of the Jet Propulsion Laboratory, was established to determine how the error could have arisen. The Allen Commission found that the main null corrector, a device used to measure the exact shape of the mirror, had been incorrectly assembled—one lens was wrongly spaced by 1.3 mm.[52] During the polishing of the mirror, Perkin-Elmer had analyzed its surface with two other null correctors, both of which correctly indicated that the mirror was suffering from spherical aberration. The company ignored these test results as it believed that the two null correctors were less accurate than the primary device that was reporting that the mirror was perfectly figured.[53]

The commission blamed the failings primarily on Perkin-Elmer. Relations between NASA and the optics company had been severely strained during the telescope construction due to frequent schedule slippage and cost overruns. NASA found that Perkin-Elmer did not review or supervise the mirror construction adequately, did not assign its best optical scientists to the project (as it had for the prototype), and in particular did not involve the optical designers in the construction and verification of the mirror. While the commission heavily criticized Perkin-Elmer for these managerial failings, NASA was also criticized for not picking up on the quality control shortcomings such as relying totally on test results from a single instrument.[54]

Design of a solution
The correctly ground backup mirror built by Eastman Kodak for the Hubble space telescope (the mirror was never coated with a reflective surface, hence its inner support structure can be seen). It now resides in the National Air

and Space Museum in Washington, DC.[55]

The design of the telescope had always incorporated servicing missions, and astronomers immediately began to seek potential solutions to the problem that could be applied at the first servicing mission, scheduled for 1993. While Kodak and Itek had each ground back-up mirrors for Hubble, it would have been impossible to replace the mirror in orbit, and too expensive and time-consuming to bring the telescope temporarily back to Earth for a refit. Instead, the fact that the mirror had been ground so precisely to the wrong shape led to the design of new optical components with exactly the same error but in the opposite sense, to be added to the telescope at the servicing mission, effectively acting as "spectacles" to correct the spherical aberration.[56][57]

The first step was a precise characterization of the error in the main mirror. Working backwards from images of point sources, astronomers determined that the conic constant of the mirror as built was −1.01390±0.0002, instead of the intended −1.00230.[58][59] The same number was also derived by analyzing the null corrector used by Perkin-Elmer to figure the mirror, as well as by analyzing interferograms obtained during ground testing of the mirror.[60]

Because of the way the HST's instruments were designed, two different sets of correctors were required. The design of the Wide Field and Planetary Camera 2, already planned to replace the existing WF/PC, included relay mirrors to direct light onto the eight separate CCD chips making up its two cameras. An inverse error built into their surfaces could completely cancel the aberration of the primary. However, the other instruments lacked any intermediate surfaces that could be figured in this way, and so required an external correction device.[61]

The system designed to correct the spherical aberration for light focused at the FOC, FOS, and GHRS was called the "Corrective Optics Space Telescope Axial Replacement" (COSTAR) and consisted essentially of two mirrors in the light path, one of which would be figured to correct the aberration.[62] To fit the COSTAR system onto the telescope, one of the other instruments had to be removed, and astronomers selected the High Speed Photometer to be sacrificed.[61]

By 2002 all of the original instruments requiring COSTAR had been replaced by instruments with their own corrective optics, rendering it redundant.[63] COSTAR was removed and returned to Earth in 2009, its space taken by the Cosmic Origins Spectrograph.

Servicing missions and new instruments

Servicing Mission 1
Astronauts installing corrective optics during SM1

Improvement in Hubble images after SM1
Astronauts replacing gyroscopes during SM3A

Hubble on the payload bay just prior to release during SM3B
Main article: STS-61

The telescope had always been designed so that it could be regularly serviced, but after the problems with the mirror came to light, the first servicing mission assumed a much greater importance, as the astronauts would have to carry out extensive work on the telescope to install the corrective optics. The seven astronauts selected for the mission were trained intensively in the use of the hundred or more specialized tools that would be needed.[64] The Space Shuttle Endeavour mission STS-61 took place in December 1993, and involved installation of several instruments and other equipment over a total of 10 days.

Most importantly, the High Speed Photometer was replaced with the COSTAR corrective optics package, and WFPC was replaced with the Wide Field and Planetary Camera 2 (WFPC2) with its internal optical correction system. In addition, the solar arrays and their drive electronics were replaced, as well as four of the gyroscopes used in the telescope pointing system, two electrical control units and other electrical components, and two magnetometers. The onboard computers were upgraded, and finally, the telescope's orbit was boosted, to compensate for the orbital decay from 3 years of drag in the tenuous upper atmosphere.[48]

On January 13, 1994, NASA declared the mission a complete success and showed the first of many much sharper images.[65] At the time, the mission had been one of the most complex ever undertaken, involving five lengthy periods of extra-vehicular activity, and its resounding success was an enormous boon for NASA, as well as for the astronomers who now had a fully capable space telescope.

Servicing Mission 2
Main article: STS-82

Servicing Mission 2, flown by Discovery (STS-82) in February 1997, replaced the GHRS and the FOS with the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), replaced an Engineering and Science Tape Recorder with a new Solid State Recorder, repaired thermal insulation and again boosted Hubble's orbit.[66] NICMOS contained a heat sink of solid nitrogen to reduce the thermal noise from the instrument, but shortly after it was installed, an unexpected thermal expansion resulted in part of the heat sink coming into contact with an optical baffle. This led to an increased warming rate for the instrument and reduced its original expected lifetime of 4.5 years to about 2 years.[67]

Servicing Mission 3A
Main article: STS-103

Servicing Mission 3A flown by Discovery (STS-103), took place in December 1999, and was a split-off from Servicing Mission 3 after three of the six onboard gyroscopes had failed. (A fourth failed a few weeks before the mission, rendering the telescope incapable of performing science observations.) The mission replaced all six gyroscopes, replaced a Fine Guidance Sensor and the computer, installed a Voltage/temperature Improvement Kit (VIK) to prevent battery overcharging, and replaced thermal insulation blankets.[68] Although the new computer is hardly a powerhouse (a 25 MHz radiation hardened Intel 486 with two megabytes of RAM), it is still 20 times faster, with six times more memory, than the DF-224 it replaced. The new computer increases throughput by moving some computing tasks from the ground to the spacecraft, and saves money by allowing the use of modern programming languages.[69]

Servicing Mission 3B
Main article: STS-109

Servicing Mission 3B flown by Columbia (STS-109) in March 2002 saw the installation of a new instrument, with the FOC (the last original instrument) being replaced by the Advanced Camera for Surveys (ACS). This meant that COSTAR was no longer required since all new instruments had correction for the main mirror aberration built in.[63]

The mission also saw the revival of NICMOS, which had run out of coolant in 1999. A new cooling system was installed that reduced the instrument's temperature enough for it to be usable again. Although not as cold as its original design called for, the temperature is more stable, in many ways a better tradeoff.[67] ACS in particular enhanced Hubble's capabilities; it and the revived NICMOS together imaged the Hubble Ultra Deep Field.

The mission replaced the solar arrays for the second time. The new arrays were derived from those built for the Iridium comsat system and were only two-thirds the size of the old arrays, resulting in less drag against the tenuous reaches of the upper atmosphere while providing 30 percent more power. The additional power allowed all instruments on board the HST to be run simultaneously, and reduced a vibration problem that occurred when the old, less rigid arrays entered and left direct sunlight. Hubble's Power Distribution Unit was also replaced in order to correct a problem with sticky relays, a procedure that required the complete electrical power down of the spacecraft for the first time since it was launched.[70]

Servicing Mission 4
Main article: STS-125
Wikinews has related news: NASA launches Space Shuttle Atlantis
Astronauts work on Hubble during SM4
Hubble floats free from Atlantis after SM4.

Servicing Mission 4 (SM4), was the last scheduled shuttle mission (STS-125) for the Hubble Space Telescope in May 2009.[71] The servicing mission was first planned for October 14, 2008.[72] However on 27 September 2008, the Science Instrument Command and Data Handling (SI C&DH) unit on HST failed. All science data pass through this unit before they can be transmitted to Earth. Although it has a backup unit, if the backup were to fail, the HST's useful life would be over.[73] Therefore, on 29 September 2008, NASA announced the launch of SM4 was postponed until 2009 so this unit could be replaced as well.[74] SM4, with a replacement SI C&DH unit,[75] was launched aboard Space Shuttle Atlantis on May 11, 2009.[76]

On SM4 astronauts, over the course of five spacewalks, installed two new instruments, Wide Field Camera 3 (WFC3), and the Cosmic Origins Spectrograph (COS). WFC3 will increase Hubble's observational capabilities in the ultraviolet and visible spectral ranges by up to 35 times due to its higher sensitivity and wider field of view. The telephone-booth sized COS assembly replaced the Corrective Optics Space Telescope Axial Replacement (COSTAR) that was installed in 1993 to correct Hubble's spherical aberration problems. (COSTAR was no longer needed after the replacement of the FOC in 2002, the last original instrument without the necessary correction built in.[63]) The COS will do observations in the ultraviolet parts of the spectrum, complementing the measurements done by the repaired STIS system. The service mission repaired two instruments that had failed, the Advanced Camera for Surveys (ACS) and the Space Telescope Imaging Spectrograph (STIS). They also performed other component replacements including: all three Rate Sensor Units (each containing two gas-bearing gyroscopes); one of three Fine Guidance Sensor (FGS) units used to help keep pointing accuracy and increase platform stability; the SI C&DH unit; all six of the 125-pound (57 kg) nickel-hydrogen batteries used to provide all Hubble's electrical power to support operations during the night portion of its orbit; and three New Outer Blanket Layer (NOBL) thermal insulation protective blankets. The batteries had never been replaced and were more than 13 years over their original design life.[77] After testing and calibration, Hubble resumed routine operation in September 2009.[78] These efforts are expected to keep the telescope fully functioning at least into 2014 and perhaps longer.[79]

Hubble was originally designed to be returned to earth on board a shuttle. With the retirement of the shuttle fleet this will no longer be possible. NASA engineers developed the Soft Capture and Rendezvous System (SCRS), a ring-like device that was attached to Hubble's aft bulkhead which will enable the future rendezvous, capture, and safe disposal of Hubble by either a crewed or robotic mission.[80] Atlantis released the Hubble Space Telescope on May 19, 2009 back into space after all repairs were successfully made. The next mission will be to deorbit Hubble at the end of its service life.

Scientific results

Important discoveries
One of Hubble's most famous images, Pillars of Creation shows stars forming in the Eagle Nebula

Hubble has helped to resolve some long-standing problems in astronomy, as well as turning up results that have required new theories to explain them. Among its primary mission targets was to measure distances to Cepheid variable stars more accurately than ever before, and thus constrain the value of the Hubble constant, the measure of the rate at which the universe is expanding, which is also related to its age. Before the launch of HST, estimates of the Hubble constant typically had errors of up to 50%, but Hubble measurements of Cepheid variables in the Virgo Cluster and other distant galaxy clusters provided a measured value with an accuracy of 10%, which is consistent with other more accurate measurements made since Hubble's launch using other techniques.[81]

While Hubble helped to refine estimates of the age of the universe, it also cast doubt on theories about its future. Astronomers from the High-z Supernova Search Team and the Supernova Cosmology Project[82] used the telescope to observe distant supernovae and uncovered evidence that, far from decelerating under the influence of gravity, the expansion of the universe may in fact be accelerating. This acceleration was later measured more accurately by other ground-based and space-based telescopes, confirming Hubble's finding. The cause of this acceleration remains poorly understood;[83] the most common cause attributed is dark energy.[84]

The high-resolution spectra and images provided by the HST have been especially well-suited to establishing the prevalence of black holes in the nuclei of nearby galaxies. While it had been hypothesized in the early 1960s that black holes would be found at the centers of some galaxies, and work in the 1980s identified a number of good black hole candidates, it fell to work conducted with Hubble to show that black holes are probably common to the centers of all galaxies.[85][86][87] The Hubble programs further established that the masses of the nuclear black holes and properties of the galaxies are closely related. The legacy of the Hubble programs on black holes in galaxies is thus to demonstrate a deep connection between galaxies and their central black holes.
Main article: Comet Shoemaker-Levy 9

The collision of Comet Shoemaker-Levy 9 with Jupiter in 1994 was fortuitously timed for astronomers, coming just a few months after Servicing Mission 1 had restored Hubble's optical performance. Hubble images of the planet were sharper than any taken since the passage of Voyager 2 in 1979, and were crucial in studying the dynamics of the collision of a comet with Jupiter, an event believed to occur once every few centuries.

Other major discoveries made using Hubble data include proto-planetary disks (proplyds) in the Orion Nebula;[88] evidence for the presence of extrasolar planets around sun-like stars;[89] and the optical counterparts of the still-mysterious gamma ray bursts.[90] HST has also been used to study objects in the outer reaches of the Solar System, including the dwarf planets Pluto[91] and Eris.[92]
Main articles: Hubble Deep Field and Hubble Ultra Deep Field

A unique legacy of Hubble are the Hubble Deep Field and Hubble Ultra Deep Field images, which utilized Hubble's unmatched sensitivity at visible wavelengths to create images of small patches of sky that are the deepest ever obtained at optical wavelengths. The images reveal galaxies billions of light years away, and have generated a wealth of scientific papers, providing a new window on the early Universe.

The non-standard object SCP 06F6 was discovered by the Hubble Space Telescope (HST) in February 2006.[93][94]

Impact on astronomy
Distant galaxies in deep space in a Hubble Ultra Deep Field photograph

Many objective measures show the positive impact of Hubble data on astronomy. Over 8,000 papers based on Hubble data have been published in peer-reviewed journals,[95] and countless more have appeared in conference proceedings. Looking at papers several years after their publication, about one-third of all astronomy papers have no citations, while only 2% of papers based on Hubble data have no citations. On average, a paper based on Hubble data receives about twice as many citations as papers based on non-Hubble data. Of the 200 papers published each year that receive the most citations, about 10% are based on Hubble data.[96]

Although the HST has clearly had a significant impact on astronomical research, the financial cost of this impact has been large. A study on the relative impacts on astronomy of different sizes of telescopes found that while papers based on HST data generate 15 times as many citations as a 4 m ground-based telescope such as the

William Herschel Telescope, the HST costs about 100 times as much to build and maintain.[97]

Making the decision between investing in ground-based versus space-based telescopes in the future is complex. Even before Hubble was launched, specialized ground-based techniques such as aperture masking interferometry had obtained higher-resolution optical and infrared images than Hubble would achieve, though restricted to targets about 108 times brighter than the faintest targets observed by Hubble.[98][99] Since then, advances in adaptive optics have extended the high-resolution imaging capabilities of ground-based telescopes to the infrared imaging of faint objects. The usefulness of adaptive optics versus HST observations depends strongly on the particular details of the research questions being asked. In the visible bands, adaptive optics can only correct a relatively small field of view, whereas HST can conduct high-resolution optical imaging over a wide field. Only a small fraction of astronomical objects are accessible to high-resolution ground-based imaging; in contrast Hubble can perform high-resolution observations of any part of the night sky, and on objects that are extremely faint.

Usage

The Hubble Space Telescope as seen from Space Shuttle Discovery during its second servicing mission (STS-82).

Anyone can apply for time on the telescope; there are no restrictions on nationality or academic affiliation.[100] Competition for time on the telescope is intense, and the ratio of time requested to time available (the oversubscription ratio) typically ranges between 6 and 9.[101]

Calls for proposals are issued roughly annually, with time allocated for a cycle lasting approximately one year. Proposals are divided into several categories; 'general observer' proposals are the most common, covering routine observations. 'Snapshot observations' are those in which targets require only 45 minutes or less of telescope time, including overheads such as acquiring the target; snapshot observations are used to fill in gaps in the telescope schedule that cannot be filled by regular GO programs.[102]

Astronomers may make 'Target of Opportunity' proposals, in which observations are scheduled if a transient event covered by the proposal occurs during the scheduling cycle. In addition, up to 10% of the telescope time is designated Director's Discretionary (DD) Time. Astronomers can apply to use DD time at any time of year, and it is typically awarded for study of unexpected transient phenomena such as supernovae.[103] Other uses of DD time have included the observations that led to the production of the Hubble Deep Field and Hubble Ultra Deep Field, and in the first four cycles of telescope time, observations carried out by amateur astronomers.

Amateur observations

The first director of STScI, Riccardo Giacconi, announced in 1986 that he intended to devote some of his Director Discretionary time to allowing amateur astronomers to use the telescope. The total time to be allocated was only a few hours per cycle, but excited great interest among amateur astronomers.[104]

Proposals for amateur time were stringently peer reviewed by a committee of leading amateur astronomers, and time was awarded only to proposals that were deemed to have genuine scientific merit, did not duplicate proposals made by professionals, and required the unique capabilities of the space telescope. In total, 13 amateur astronomers were awarded time on the telescope, with observations being carried out between 1990 and 1997. One such study was Transition Comets — UV Search for OH Emissions in Asteroids. The very first proposal, A Hubble Space Telescope Study of Post Eclipse Brightening and Albedo Changes on Io, was published in Icarus, [105] a journal devoted to solar system studies. After that time, however, budget reductions at STScI made the support of work by amateur astronomers untenable, and no further amateur programs have been carried out.[106]

Hubble data

Transmission to Earth
Hubble Control Center, Goddard Space Flight Center

Hubble data was initially stored on the spacecraft. When launched, the storage facilities were old-fashioned reel-to-reel tape recorders, but these were replaced by solid state data storage facilities during servicing missions 2 and 3A. Approximately twice daily, The Hubble Space Telescope radios data to a satellite in the geosynchronous Tracking and Data Relay Satellite System (TDRSS).[107] The TDRSS then downlinks the science data to one of two 60-foot (18-meter) diameter high gain microwave antennas located at the White Sands Test Facility in White Sands, New Mexico.[107] From there they are sent to the Goddard Space Flight Center and finally to the Space Telescope Science Institute for archiving.[108]

These data are then transmitted to the Space Telescope Operations Control Center (STOCC) located in Greenbelt, Maryland.[107]

Archive

All Hubble data is eventually made available via the archives of STScI.[109] Data is usually proprietary—available only to the principal investigator (PI) and astronomers designated by the PI—for one year after being taken. The PI can apply to the director of the STScI to extend or reduce the proprietary period in some circumstances.[110]

Observations made on Director's Discretionary Time are exempt from the proprietary period, and are released to the public immediately. Calibration data such as flat fields and dark frames are also publicly available straight away. All data in the archive is in the FITS format, which is suitable for astronomical analysis but not for public use.[111] The Hubble Heritage Project processes and releases to the public a small selection of the most striking images in JPEG and TIFF formats.[112]

Pipeline reduction

Astronomical data taken with CCDs must undergo several calibration steps before they are suitable for astronomical analysis. STScI has developed sophisticated software that automatically calibrates data when they are requested from the archive using the best calibration files available. This 'on-the-fly' processing means that large data requests can take a day or more to be processed and returned. The process by which data are calibrated automatically is known as 'pipeline reduction', and is increasingly common at major observatories. Astronomers may if they wish retrieve the calibration files themselves and run the pipeline reduction software locally. This may be desirable when calibration files other than those selected automatically need to be used.[113]

Data analysis

Hubble data can be analysed using many different packages. STScI maintains the custom-made STSDAS (Space Telescope Science Data Analysis System) software, which contains all the programs needed to run pipeline reduction on raw data files, as well as many other astronomical image processing tools, tailored to the requirements of Hubble data. The software runs as a module of IRAF, a popular astronomical data reduction program.[114]

Outreach activities
In 2001, NASA polled internet users to find out what they would most like Hubble to observe; they overwhelmingly selected the Horsehead Nebula.

It has always been important for the Space Telescope to capture the public's imagination, given the considerable contribution of taxpayers to its construction and operational costs.[115] After the difficult early years when the faulty mirror severely dented Hubble's reputation with the public, the first servicing mission allowed its rehabilitation as the corrected optics produced numerous remarkable images.

Several initiatives have helped to keep the public informed about Hubble activities. The Hubble Heritage Project was established to produce high-quality images for public consumption of the most interesting and striking objects observed. The Heritage team is composed of amateur and professional astronomers, as well as people with backgrounds outside astronomy, and emphasizes the aesthetic nature of Hubble images. The Heritage Project is granted a small amount of time to observe objects which, for scientific reasons, may not have images taken at enough wavelengths to construct a full-color image.[116]

In addition, STScI maintains several comprehensive websites for the general public containing Hubble images and information about the observatory.[117][118][119][120] The outreach efforts are coordinated by the Office for Public Outreach, which was established in 2000 to ensure that US taxpayers saw the benefits of their investment in the space telescope program.
A small scale replica of the Hubble Space Telescope in Marshfield, Missouri

Since 1999, the leading Hubble outreach activities group in Europe has been the Hubble European Space Agency Information Centre (HEIC).[121] This office was established at the Space Telescope - European Coordinating Facility (ST-ECF) in Munich, Germany. HEIC's mission statement is to fulfill the Hubble Space Telescope outreach and education tasks for the European Space Agency (ESA). The work is centered on the production of news and photo releases that highlight interesting Hubble science results and images. These are often European in origin, and so not only increase the awareness of ESA’s Hubble share (15%), but the contribution of European scientists to the observatory. The group also produces video releases and other innovative educational material.

There is a replica of the Hubble Telescope on the courthouse lawn in Marshfield, Missouri, the hometown of namesake Edwin P. Hubble.

Future

Equipment failure
A WFPC2 image of a small region of the Tarantula Nebula in the Large Magellanic Cloud

Past servicing missions have exchanged old instruments for new ones, both avoiding failure and making possible new types of science. Without servicing missions, all of the instruments will eventually fail. In August 2004, the power system of the Space Telescope Imaging Spectrograph (STIS) failed, rendering the instrument inoperable. The electronics had originally been fully redundant, but the first set of electronics failed in May 2001.[122] This

The electronics had originally been fully redundant, but the first set of electronics failed in May 2001.[122] This power supply was fixed during servicing mission 4 in May 2009. Similarly, the main camera (the ACS) primary electronics failed in June 2006, and the power supply for the backup electronics failed on January 27, 2007.[123] Only the instrument's Solar Blind Channel (SBC) was operable using the side-1 electronics. A new power supply for the wide angle channel was added during SM 4, but quick tests revealed this did not help the high resolution channel.[124] As of late May 2009, tests of both repaired instruments are still ongoing.

HST uses gyroscopes to stabilize itself in orbit and point accurately and steadily at astronomical targets. Normally, three gyroscopes are required for operation; observations are still possible with two, but the area of sky that can be viewed would be somewhat restricted, and observations requiring very accurate pointing are more difficult.[125] There are further contingency plans for science with just one gyro,[126] but if all gyros fail, continued scientific observations will not be possible. In 2005, it was decided to switch to two-gyroscope mode for regular telescope operations as a means of extending the lifetime of the mission. The switch to this mode was made in August 2005, leaving Hubble with two gyroscopes in use, two on backup, and two inoperable.[127] One more gyro failed in 2007.[128] By the time of the final repair mission, during which all six gyros were replaced (with two new pairs and one refurbished pair), only three gyros were still working. Engineers are confident that they have identified the root causes of the gyro failures, and the new models should be much more reliable.[129]

In addition to predicted gyroscope failure, Hubble eventually required a change of nickel hydrogen batteries. A robotic servicing mission including this would be tricky, as it requires many operations, and a failure in any might result in irreparable damage to Hubble. Alternatively, the observatory was designed so that during shuttle servicing missions it would receive power from a connection to the space shuttle, and this capability could have been utilized by adding an external power source (an additional battery) rather than changing the internal ones.[130] In the end, however the batteries were simply replaced during service mission 4.

Orbital decay

Hubble orbits the Earth in the extremely tenuous upper atmosphere, and over time its orbit decays due to drag. If it is not re-boosted by a shuttle or other means, it will re-enter the Earth's atmosphere sometime between 2019 and 2032, with the exact date depending on how active the Sun is and its impact on the upper atmosphere. The state of Hubble's gyros also affects the re-entry date, as a controllable telescope can be oriented to minimize atmospheric drag. Not all of the telescope would burn up on re-entry. Parts of the main mirror and its support structure would probably survive, leaving the potential for damage or even human fatalities (estimated at up to a 1 in 700 chance of human fatality for a completely uncontrolled re-entry).[131] With the success of STS-125, the natural re-entry date range has been extended further as the mission replaced its gyroscopes, even though Hubble was not re-boosted to a higher orbit.

NASA's original plan for safely de-orbiting Hubble was to retrieve it using a space shuttle. The Hubble telescope would then have most likely been displayed in the Smithsonian Institution. This is no longer considered practical because of the costs of a shuttle flight, the mandate to retire the space shuttles by 2010, and the risk to a shuttle's crew. Instead NASA looked at adding an external propulsion module to allow controlled re-entry.[132] The final decision was not to attach a de-orbit module on STS-125, but to add a grapple fixture so a robotic mission could more easily attach such a module later.[133]

Debate over final servicing mission

Columbia was originally scheduled to visit Hubble again in February 2005. The tasks of this servicing mission would have included replacing a fine guidance sensor and two broken gyroscopes, placing protective "blankets" on top of torn insulation, replacing the Wide Field and Planetary Camera 2 with a new Wide Field Camera 3 and installing the Cosmic Origins Spectrograph (COS). However, then-NASA Administrator Sean O'Keefe decided that, in order to prevent a repeat of the Columbia accident, all future shuttles must be able to reach the 'safe-haven' of the International Space Station (ISS) should an in-flight problem develop that would preclude the shuttle from landing safely. The shuttle is incapable of reaching both the Hubble Space Telescope and the International Space Station during the same mission, and so future manned service missions were canceled.[134]

This decision was assailed by numerous astronomers, who felt that Hubble was valuable enough to merit the human risk. HST's successor, the James Webb Space Telescope (JWST), will not be ready until well after the 2010 scheduled retirement of the space shuttle. While Hubble can image in the ultraviolet and visible wavelengths, JWST is limited to the infrared. The break in space-observing capabilities between the decommissioning of Hubble and the commissioning of a successor is of major concern to many astronomers, given the great scientific impact of HST taken as a whole.[135] The consideration that the JWST will not be located in low Earth orbit, and therefore cannot be easily repaired in the event of an early failure, only makes these concerns more acute. Nor can JWST's instruments be easily upgraded. On the other hand, many astronomers felt strongly that the servicing of Hubble should not take place if the costs of the servicing come from the JWST budget.

In January 2004, O'Keefe said he would review his decision to cancel the final shuttle servicing mission to HST due to public outcry and requests from Congress for NASA to look for a way to save it. On 13 July 2004 an official panel from the National Academy of Sciences made the recommendation that the HST should be preserved despite the apparent risks. Their report urged "NASA should take no actions that would preclude a space shuttle despite the apparent risks. Their report urged "NASA should take no actions that would preclude a space shuttle servicing mission to the Hubble Space Telescope". In August 2004, O'Keefe requested the Goddard Space Flight Center to prepare a detailed proposal for a robotic service mission. These plans were later canceled, the robotic mission being described as "not feasible".[136] In late 2004, several Congressional members, led by Sen. Barbara Mikulski (D-MD), held public hearings and carried on a fight with much public support (including thousands of letters from school children across the country) to get the Bush Administration and NASA to reconsider the decision to drop plans for a Hubble rescue mission.[137]

The arrival in April 2005 of the new NASA Administrator, Michael D. Griffin, changed the status of the proposed shuttle rescue mission. At the time, Griffin stated he would reconsider the possibility of a manned servicing mission. Soon after his appointment, he authorized Goddard Space Flight Center to proceed with preparations for a manned Hubble maintenance flight, saying he would make the final decision on this flight after the next two shuttle missions. In October 2006 Griffin gave the final go-ahead for the mission. The 11-day STS-125 mission by Atlantis was scheduled for launch in October 2008.[138][139] However, the main data-handling unit failed in late September 2008, halting all reporting of scientific data. This unit has a backup, and on October 25, 2008 Hubble was successfully rebooted and was reported to be functioning normally.[140] However, since a failure in the backup unit would now leave the HST helpless, the service mission was postponed to allow astronauts to repair this problem. This mission got underway on May 11, 2009[141] and completed all the long planned replacements as well as additional repairs, including replacing the main data-handling unit.

Successors

Main articles: James Webb Space Telescope and Advanced Technology Large-Aperture Space Telescope

Several space telescopes are claimed to be successors to Hubble, and some ground based astronomy lays claim to higher optical achievements.

The James Webb Space Telescope (JWST) is a planned infrared space observatory, and lays claim to being a planned successor of Hubble.[142] The main scientific goal is to observe the most distant objects in the universe, beyond the reach of existing instruments. JWST is a NASA-led international collaboration between NASA, the European Space Agency and the Canadian Space Agency. Formerly called the Next Generation Space Telescope (NGST), it was renamed after NASA's second administrator, James E. Webb, in 2002. The telescope's launch is planned for no earlier than June 2014. It will be launched on an Ariane 5 rocket.[143]

Another similar effort is the European Space Agency's Herschel Space Observatory, launched on May 14, 2009. Like JWST, Herschel has a mirror substantially larger than Hubble's, but observes only in the far-infrared.

Much further out is the Advanced Technology Large-Aperture Space Telescope (AT-LAST)[144] is a proposed 8 to 16-meter (320 to 640-inch) optical space telescope that if approved, built, and launched (using the planned Ares V rocket slated for Project Constellation flights to the Moon), would be a true replacement and successor for the Hubble Space Telescope (HST); with the ability to observe and photograph astronomical objects in the optical, ultraviolet, and Infrared wavelengths, but with substantially better resolution than Hubble.

Existing ground based telescopes, and various proposed Extremely Large Telescopes, certainly exceed the HST in terms of sheer light gathering power, due to their much larger mirrors. In some cases, they may also be able to match or beat Hubble in resolution by using adaptive optics (AO). However, AO on large ground-based reflectors will not make Hubble and other space telescopes obsolete. Most AO systems sharpen the view over a very narrow field – Lucky Cam, for example, produces crisp images just 10" to 20" wide, whereas Hubble's cameras are super sharp across a 2½' (150") field. Furthermore, space telescopes can study the heavens across the entire electromagnetic spectrum, most of which is blocked by Earth's atmosphere. Finally, the background sky is darker in space than on the ground, because air absorbs solar energy during the day and then releases it at night, producing a faint—but nevertheless discernible—airglow that washes out faint, low-contrast astronomical objects."[145]

See also

* List of largest optical reflecting telescopes

References

* "Hubble Space Telescope Primer for Cycle 17" (PDF). STScI. http://www.stsci.edu/hst/proposing/documents/cp/primer.pdf.
* Allen, Lew (1990). "The Hubble Space Telescope Optical Systems Failure Report" (PDF). NASA Technical Report NASA-TM-103443. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19910003124_1991003124.pdf. The definitive report on the error in the Hubble mirror.

* Dunar, A. J.; S. P. Waring (1999). Power To Explore—History of Marshall Space Flight Center 1960–1990. U.S. Government Printing Office. ISBN 0-16-058992-4. Chapter 12, The Hubble Space TelescopePDF (260 KB). Covers the development of the telescope.
* Logsdon, John M.; Amy Paige Snyder, Roger D. Launius, Stephen J. Garber, and Regan Anne Newport (PDF).

NASA SP-2001-4407: Exploring the Unknown — Selected Documents in the History of the U.S. Civil Space Program. Volume V: Exploring the Cosmos. NASA. http://history.nasa.gov/SP-4407/vol5/ExploreUnknown.pdf. . Contains many of the primary documents such as Spitzer's 1946 article, the Wood's Hole report on STScI autonomy, and the ESA memorandum of understanding. Also includes other NASA astronomy programs.
* Spitzer, Lyman S (1979). "History of the Space Telescope". Quarterly Journal of the Royal Astronomical Society 20: 29–36. PDF version here [146]PDF. Covers the early history of precursors and proposals.
* Tatarewicz, Joseph N. "Chapter 16: The Hubble Space Telescope Servicing Mission". NASA. http://history.nasa.gov/SP-4219/Contents.html. From the book SP-4219: From Engineering Science To Big Science. A detailed account of the first servicing mission.
* Zimmerman, Robert F. The Universe in a Mirror — The Saga of the Hubble Space Telescope and the Visionaries Who Built It, publ. Princeton UP (2008, 2010)

Notes

1. ^ Lynn Jenner, Brian Dunbar. "The Hubble Story (page 2)". NASA. http://www.nasa.gov/mission_pages/hubble/story/the_story_2.html. Retrieved 2010-06-02.
2. ^ HST Program Office (2003) (PDF). Hubble Facts: HST Orbit Decay and Shuttle Re-boost. Goddard Space Flight Center. http://hubble.nasa.gov/a_pdf/news/facts/sm3b/fact_sheet_reboost.pdf. Retrieved 2009-05-12.
3. ^ Amiko Kauderer (26 March 2009). "Space Shuttle Mission Overview — STS-125: The Final Visit". NASA. http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/hst_sm4/overview.html. Retrieved 2009-05-02.
4. ^ SYNPHOT User's Guide, version 5.0, Space Telescope Science Institute, p. 27
5. ^ "NASA's Great Observatories". NASA. http://www.nasa.gov/audience/forstudents/postsecondary/features/F_NASA_Great_Observatories_PS.html. Retrieved 2008-04-26.
6. ^ H. Oberth (1923). Die Rakete zu den Planetenräumen. R. Oldenbourg-Verlay.
7. ^ Spitzer, L., "Report to Project Rand: Astronomical Advantages of an Extra-Terrestrial Observatory", reprinted in NASA SP-2001-4407: Exploring the Unknown, Chapter 3, Document III-1, p. 546.
8. ^ "Lyman Spitzer, Jr.". Caltech. http://www.spitzer.caltech.edu/about/spitzer.shtml. Retrieved 2008-04-26.
9. ^ Baum, W. A. and Johnson, F. S. and Oberly, J. J. and Rockwood, C. C. and Strain, C. V. and Tousey, R. (November 1946). "Solar Ultraviolet Spectrum to 88 Kilometers". Phys. Rev (American Physical Society) 70 (9–10): 781–782. doi:10.1103/PhysRev.70.781.
10. ^ "Up close and personal — physicsworld.com". physicsworld.com. Institute of Physics (www.iop.org). 2 March 2009. http://physicsworld.com/cws/article/print/37981. Retrieved 20 April 2009. [dead link]
11. ^ "OAo". NASA. http://nasascience.nasa.gov/missions/oao. Retrieved 2008-04-26.
12. ^ Spitzer, History of the Space Telescope, p. 32.
13. ^ Spitzer, History of the Space Telescope, pp. 33–34.
14. ^ a b Spitzer, History of the Space Telescope, p. 34.
15. ^ Andersen, Geoff (2007). The telescope: its history, technology, and future. Princeton University Press. p. 116. ISBN 0691129797.
16. ^ "Memorandum of Understanding Between The European Space Agency and The United States National Aeronautics and Space Administration", reprinted in NASA SP-2001-4407: Exploring the Unknown, Chapter 3, Document III-29, p. 671.
17. ^ "A Chronology of the Hubble Space Telescope". NASA. http://history.nasa.gov/hubble/chron.html. Retrieved 2008-04-26.
18. ^ "The path to the Hubble Space Telescope". NASA. Archived from the original on May 08, 2008. http://web.archive.org/web/20080508195855/http://hubble.nasa.gov/overview/conception-part3.php. Retrieved 2008-04-26.
19. ^ Dunar, pp. 487–488.
20. ^ a b Dunar, p. 489.
21. ^ a b "Hubble: The Case of the Single-Point Failure" (PDF). Science Magazine. 1990-08-17. http://www.sciencemag.org/cgi/reprint/249/4970/735.pdf. Retrieved 2008-04-26.
22. ^ a b Robberto, M. and Sivaramakrishnan, A. and Bacinski, J.J. and Calzetti, D. and Krist, J.E. and MacKenty, J.W. and Piquero, J. and Stiavelli, M. (2000). "The Performance of HST as an Infrared Telescope" (PDF). Proc. SPIE 4013: 386–393. doi:10.1117/12.394037. http://www.stsci.edu/hst/wfc3/documents/published/spie4013386.pdf.
23. ^ Allen report, page 3–4.
24. ^ "Losing Bid Offered 2 Tests on Hubble". Associated Press. 1990-07-28. http://query.nytimes.com/gst/fullpage.html?res=9C0CEEDF1731F93BA15754C0A966958260. Retrieved 2008-04-26.
25. ^ "Hubble Space Telescope Stand-in Gets Starring Role". NASA. 2001-09-21. http://www.gsfc.nasa.gov/news-release/releases/2001/h01-185.htm. Retrieved 2008-04-26.

26. ^ "2.4m Observatory Technical Note". New Mexico Institute of Mining and Technology. 2008-01-01. http://www.mro.nmt.edu/2.4m/doc-public/OTN-Overview.html. Retrieved 2008-04-26.
27. ^ Dunar, p. 496
28. ^ Ghitelman, David, The Space Telescope, Michael Friedman Publishing, New York, 1987, p.32

29. ^ Dunar, p. 504.
30. ^ "Hubble Space Telescope Systems". Goddard Space Flight Center. http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/hst3-01/hubble_space_telescope_systems.htm. Retrieved 2008-04-26.
31. ^ Ghitelman, David, The Space Telescope, Michael Friedman Publishing, New York, 1987, p. 50
32. ^ Dunar, p. 508.
33. ^ a b Hall, Donald N.B., ed. (1982). The Space Telescope Observatory. Technical Report NASA CP-2244. 40 MB PDF file.
34. ^ Brandt J.C. et al. (1994). "The Goddard High Resolution Spectrograph: Instrument, goals, and science results" (PDF). Publications of the Astronomical Society of the Pacific 106: 890–908. doi:10.1086/133457. http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1994PASP..106..890B&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf.
35. ^ Bless R.C., Walter L.E., White R.L. (1992), High Speed Photometer Instrument Handbook, v 3.0, STSci
36. ^ Benedict, G. Fritz; McArthur, Barbara E. (2005). "High-precision stellar parallaxes from Hubble Space Telescope fine guidance sensors". in D.W. Kurtz (ed.). Proceedings of IAU Colloquium #196,. Transits of Venus: New Views of the Solar System and Galaxy. Cambridge University Press. pp. 333–346. http://adsabs.harvard.edu/abs/2005tvnv.conf..333B.
37. ^ Dunar, pp. 486–487.
38. ^ Nancy Grace Roman, "Exploring the Universe: Space-Based Astronomy and Astrophysics", in NASA SP-2001-4407: Exploring the Unknown Chapter 3, p. 536.
39. ^ Primer, Chapter 2.
40. ^ Diane Karakla, Editor and Susan Rose, Technical Editor (2004). HST Primer for Cycle 14.
41. ^ "Hubble Space Telescope Servicing Mission 4 Space Telescope Operations Control Center" (PDF). NASA. http://www.nasa.gov/pdf/206047main_STOCC-FS-2007-09-090_12_4.pdf.
42. ^ Tatarewicz, SP-4219, p. 371.
43. ^ John Wilford (April 9, 1990). "Telescope Is Set to Peer at Space and Time". New York Times. http://query.nytimes.com/gst/fullpage.html?res=9C0CE3D6153AF93AA35757C0A966958260&sec=&spon=&pagewanted=all. Retrieved 2009-01-19.
44. ^ "STS-31". NASA. http://science.ksc.nasa.gov/shuttle/missions/sts-31/mission-sts-31.html. Retrieved 2008-04-26.
45. ^ "The European Homepage for the NASA/ESA Hubble Space Telescope — Frequently Asked Questions". http://www.spacetelescope.org/about/faq.html. Retrieved 2007-01-10.
46. ^ Burrows C.J. et al. (1991). "The imaging performance of the Hubble Space Telescope". Astrophysical Journal 369 (part 2): L21. doi:10.1086/185950. http://ucp.uchicago.edu/cgi-bin/resolve?doi=10.1086/185950.
47. ^ "Effects of OTA Spherical Aberration". STScI. http://www.stsci.edu/itt/review/ihb_cy14/WFPC2/ch5_psf2.html. Retrieved 2008-04-26.
48. ^ a b "Servicing Mission 1". NASA. http://hubble.nasa.gov/missions/sm1.php. Retrieved 2008-04-26.
49. ^ a b Tatarewicz, SP-4219, p. 375.
50. ^ "The Naked Gun 2½: The Smell of Fear". Internet Movie Database. http://www.imdb.com/title/tt0102510/. Retrieved 2008-04-26.
51. ^ Dunar, pp. 514–515.
52. ^ Allen, The Hubble Space Telescope Optical Systems Failure Report, chapter VII. The spacing of the field lens in the corrector was to have been done by laser measurements off the end of an invar bar. Instead of illuminating the end of the bar, however, the laser in fact was reflected from a worn spot on a black-anodized metal cap placed over the end of the bar to isolate its center (visible through a hole in the cap). The technician who performed the test noted an unexpected gap between the field lens and its supporting structure in the corrector and filled it in with an ordinary metal washer.
53. ^ Dunar, p. 512.
54. ^ Allen report, p. 9–3.
55. ^ "Mirror, Primary Backup, Hubble Space Telescope.". National Air and Space Museum. http://collections.nasm.si.edu/code/emuseum.asp?profile=objects&newstyle=single&quicksearch=A20010288000. Retrieved 2008-04-26.
56. ^ Chaisson, Eric (1994) The Hubble Wars; Astrophysics Meets Astropolitics in the Two-Billion-Dollar Struggle Over the Hubble Space Telescope. Harper Collins Publishers, ISBN 0-06-017114-6, p. 184.
57. ^ Arthur Fisher (October 1990). "The Trouble with Hubble". Popular Science: 100.
58. ^ M. M. Litvac. "Image inversion analysis of the HST OTA (Hubble Space Telescope Optical Telescope Assembly), phase A". TRW. http://adsabs.harvard.edu/abs/1991trw..rept.....L.
59. ^ David Redding, Sam Sirlin, Andy Boden, Jinger Mo, Bob Hanisch, Laurie Furey (July 1995). "Optical Prescription of the HST". JPL. http://hdl.handle.net/2014/31621.
60. ^ Allen, The Hubble Space Telescope Optical Systems Failure Report, appendix E.
61. ^ a b Tatarewicz, SP-4219, p. 376.
62. ^ Jedrzejewski R.I., Hartig G., Jakobsen P., Crocker J.H., Ford H. C. (1994). "In-orbit performance of the COSTAR-corrected Faint Object Camera" (abstract). Astrophysical Journal Letters 435: L7–L10. doi:10.1086/187581. http://adsabs.harvard.edu/abs/1994ApJ...435L...7J.
63. ^ a b c "Corrective Optics Space Telescope Axial Replacement". STSci. http://www.stsci.edu/hst/HST_overview/index_html#costar.
64. ^ Tatarewicz, SP-4219, p. 384–387.

64. ^ Tatarewicz, SP-4219, p. 384–387.
65. ^ Trauger J.T., Ballester G.E., Burrows C.J., Casertano S., Clarke J.T., Crisp D.. et al. (1994). "The on-orbit performance of WFPC2" (abstract). Astrophysical Journal Letters 435: L3–L6. doi:10.1086/187580. http://adsabs.harvard.edu/abs/1994ApJ...435L...3T.
66. ^ "Servicing Mission 2". NASA. http://hubble.nasa.gov/missions/sm2.php. Retrieved 2008-04-26.
67. ^ a b "NICMOS Temperature History". STSI. http://www.stsci.edu/hst/nicmos/performance/temperature. Retrieved 2008-04-26.
68. ^ "Servicing Mission 3A Overview". NASA. http://sm3a.gsfc.nasa.gov/overview.html. Retrieved 2008-04-26.
69. ^ Lockheed Martin Missiles and Space. "Hubble Space Telescope Servicing Mission 3A Media Reference Guide" (PDF). NASA. http://hubble.nasa.gov/a_pdf/news/SM3A-MediaGuide.pdf. Retrieved 2008-04-27. Page 5-9 and Section 7.1.1.
70. ^ "Servicing Mission 3". NASA. http://hubble.nasa.gov/missions/sm3b.php. Retrieved 2008-04-26.
71. ^ Hubble Space Telescope Servicing Mission 4, NASA. Retrieved 29 September 2008.
72. ^ "Media Advisory: M08-181: NASA Announces New Target Launch Dates, Status News Conference". NASA. http://www.nasa.gov/home/hqnews/2008/sep/HQ_M08-181_New_launch_dates.html. Retrieved 2008-09-25.
73. ^ "Hubble suddenly quiet". Science News, September 29, 2008.
74. ^ Dunn, Marcia. "NASA delays repair mission to Hubble telescope". Yahoo news, September 29, 2008.
75. ^ "Hubble Space Telescope Servicing Mission 4" (PDF). NASA. http://www.nasa.gov/pdf/252452main_FS_SM4_Summary.pdf. Retrieved 2009-05-12.
76. ^ Morris, Jefferson. "Shuttle Blasts Off To Repair Hubble". Aviation Week, May 11, 2009.
77. ^ Hubble Nickel Hydrogen Batteries. NASA. Accessed 20 May 2009
78. ^ "Sen. Mikulski Unveils First Images from Rejuvenated Hubble". September 9, 2009. http://www.nasa.gov/home/hqnews/2009/sep/HQ_09-205_New_Hubble_Images.html.
79. ^ "Servicing Mission 4". NASA. http://www.nasa.gov/mission_pages/hubble/servicing/SM4/main/index.html. Retrieved 2008-09-21.
80. ^ Soft Capture and Rendezvous System. NASA. Accessed 20 May 2009
81. ^ W. L. Freedman, B. F. Madore, B. K. Gibson, L. Ferrarese, D. D. Kelson, S. Sakai, J. R. Mould, R. C. Kennicutt, Jr., H. C. Ford, J. A. Graham, J. P. Huchra, S. M. G. Hughes, G. D. Illingworth, L. M. Macri, P. B. Stetson (2001). "Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant". The Astrophysical Journal 553 (1): 47–72. doi:10.1086/320638. http://adsabs.harvard.edu/cgi-bin/nph-bib_query?2001ApJ...553...47F. . Preprint available here.
82. ^ "Supernova Cosmology Project". Lawrence Berkeley Laboratory. http://supernova.lbl.gov/. Retrieved 2008-04-26.
83. ^ "Does Dark Energy Exist?". Scientific American. http://www.scientificamerican.com/article.cfm?id=does-dark-energy-exist. Retrieved 2009-06-16.
84. ^ Charles Seife (20 June 2003). "Dark Energy Tiptoes Toward the Spotlight". Science 300 (5627): pp. 1896–1897. doi:10.1126/science.300.5627.1896.
85. ^ "Hubble Confirms Existence of Massive Black Hole at Heart of Active Galaxy". Goddard Space Flight Center, NASA. 1994-05-25. http://nssdc.gsfc.nasa.gov/photo_gallery/caption/hst_blkhole.txt. Retrieved 2008-04-26.
86. ^ Gebhardt, K. and Bender, R. and Bower, G. and Dressler, A. and Faber, SM and Filippenko, A.V. and Green, R. and Grillmair, C. and Ho, L.C. and Kormendy, J. and others (2000). "A Relationship between Nuclear Black Hole Mass and Galaxy Velocity Dispersion". The Astrophysical Journal 539 (1): L13–L16. doi:10.1086/312840. Preprint here [1].
87. ^ Ferrarese, Laura; Merritt, David (2000). "A Fundamental Relationship between Supermassive Black Holes and their Host Galaxies". The Astrophysical Journal 539 (1): L9–L12. doi:10.1086/312840. http://adsabs.harvard.edu/abs/2000ApJ...539L...9F.
88. ^ "Hubble Confirms Abundance of Protoplanetary Disks around Newborn Stars". STScI. 1994-06-13. http://hubblesite.org/newscenter/archive/releases/1994/24/text/. Retrieved 2008-04-26.
89. ^ "Hubble Finds Extrasolar Planets Far Across Galaxy". NASA. 2006-10-04. http://www.nasa.gov/mission_pages/hubble/exoplanet_transit.html. Retrieved 2008-04-26.
90. ^ "Autopsy of an Explosion". NASA. 1999-03-26. http://science.nasa.gov/newhome/headlines/ast26mar99_1.htm. Retrieved 2008-04-26.
91. ^ "APOD: March 11, 1996 – Hubble Telescope Maps Pluto". NASA. http://apod.nasa.gov/apod/ap960311.html. Retrieved 2008-04-26.
92. ^ "Astronomers Measure Mass of Largest Dwarf Planet". NASA. 2007-06-14. http://hubblesite.org/newscenter/archive/releases/2007/24/full/. Retrieved 2008-04-26.
93. ^ How they wonder what you are, Nature News, 19 September 2008
94. ^ Gänsicke et al.: SCP06F6: A carbon-rich extragalactic transient at redshift z~0.14. Preprint, 2008.
95. ^ "HST Publication Statistics". Space Telescope Science Institute (STScI). http://archive.stsci.edu/hst/bibliography/pubstat.html. Retrieved 2009-09-09.
96. ^ STSCi newsletter, v. 20, issue 2, Spring 2003
97. ^ Benn C.R., Sánchez S.F. (2001). "Scientific Impact of Large Telescopes". Publications of the Astronomical Society of the Pacific 113: 385. doi:10.1086/319325. . arXiv preprint.
98. ^ Haniff, C. A.; Mackay, C. D.; Titterington, D. J.; Sivia, D.; Baldwin, J. E., (August 1987). "The first images from optical aperture synthesis". Nature 328: 694. doi:10.1038/328694a0. http://ukads.nottingham.ac.uk/cgi-bin/nph-bib_query?bibcode=1987Natur.328..694H&db_key=AST.

99. ^ Buscher, D. F.; Baldwin, J. E.; Warner, P. J.; Haniff, C. A. (July 1990). "Detection of a bright feature on the surface of Betelgeuse". Monthly Notices Royal Astronomical Society 245: 7. http://ukads.nottingham.ac.uk/abs/1990MNRAS.245P...7B.
100. ^ "Cycle 17 Announcement Page". Space Telescope Science Institute. 2007-12-03. http://www.stsci.edu/hst/proposing/docs/cycle17announce. Retrieved 2008-04-26.
101. ^ Hubble Space Telescope Call for Proposals for Cycle 14, (2004), eds. Neill Reid and Jim Younger
102. ^ "Hubble Space Telescope Call for Proposals" (PDF). STScI. http://www.stsci.edu/hst/proposing/documents/cp/cp.pdf. Retrieved 2008-04-26. Chapter 3.
103. ^ Hubble Space Telescope Call for Proposals, Chapter 3.7, Director's Discretionary (DD) Time Proposals.
104. ^ "Amateur Astronomers Will Use NASA's Hubble Space Telescope". STScI. 1992-09-10. http://hubblesite.org/newscenter/archive/releases/1992/1992/23/text/. Retrieved 2008-04-26.
105. ^ Secosky, J and M. Potter. 1994. A Hubble Space Telescope Study of Posteclipse Brightening and Albedo Changes on Io. Icarus. 111: 73–78.
106. ^ O'Meara S. (1997), The Demise of the HST Amateur Program, Sky and Telescope, June 1997, p.97.
107. ^ a b c "The Hubble Program — Hubble Operations — Capturing Images". NASA. 8 July 2008. http://hubble.nasa.gov/operations/capture-image.php. Retrieved 14 May 2009. Click on the web page image to retrieve information.
108. ^ Primer, Section 7.
109. ^ "The Hubble Telescope". STScI. http://archive.stsci.edu/hst. Retrieved 2008-04-26.
110. ^ Primer, Section 7.2
111. ^ Primer, Chapter 7.
112. ^ "The Hubble Heritage Project". STScI. http://heritage.stsci.edu/. Retrieved 2008-04-26.
113. ^ Primer, Section 7.2.1
114. ^ Primer, Section 7.1.1
115. ^ "National Aeronautics and Space Administration 2003 Strategic Plan" (PDF). NASA. http://www1.nasa.gov/pdf/1968main_strategi.pdf.
116. ^ "The Hubble Heritage Project". STScI. http://heritage.stsci.edu/commonpages/infoindex/ourproject/moreproject.html. Retrieved 2008-04-26.
117. ^ "HubbleSite". STScI. http://hubblesite.org/. Retrieved 2008-04-26.
118. ^ "NewsCenter". STScI. http://hubblesite.org/newscenter/. Retrieved 2008-04-26.
119. ^ "News Release Archive: Entire Collection". STScI. http://hubblesite.org/newscenter/archive/. Retrieved 2008-04-26.
120. ^ "Hubble Public Talks". STScI. http://hubblesite.org/about_us/public-talks.shtml. Retrieved 2008-04-26.
121. ^ "The European Homepage For The NASA/ESA Hubble Space Telescope". ESA. http://www.spacetelescope.org/. Retrieved 2008-04-26.
122. ^ "Space Telescope Imaging Spectrograph". STScI. http://www.stsci.edu/instruments/stis/. Retrieved April 26, 2008.
123. ^ "Engineers Investigate Issue on One of Hubble's Science Instruments". NASA. http://www.nasa.gov/home/hqnews/2007/jan/HQ_0715_Hubble_ACS.html. Retrieved April 26, 2008.
124. ^ "Advanced Camera for Surveys". Space Telescope Science Institute. http://www.stsci.edu/hst/acs. Retrieved May 21, 2009.
125. ^ Sembach, K. R., et al. 2004, HST Two-Gyro Handbook, Version 1.0, (Baltimore: STScI)
126. ^ "NASA Hubble Space Telescope Daily Report # 4537". http://www.spaceref.com/news/viewsr.html?pid=26874. Retrieved January 6, 2009.
127. ^ "NASA/ESA Hubble Space Telescope Begins Two-Gyro Science Operations". SpaceRef.com. http://www.spaceref.com/news/viewpr.html?pid=17700. Retrieved January 9, 2009.
128. ^ Jeff Hecht. "Hubble telescope loses another gyroscope". New Scientist. http://www.newscientist.com/article/dn12600-hubble-telescope-loses-another-gyroscope-.html. Retrieved January 6, 2009.
129. ^ William Harwood. "Endeavour to go Nov. 14; Hubble slips deeper into '09". Spaceflight Now. http://spaceflightnow.com/shuttle/sts125/081030hubble. Retrieved January 6, 2009.
130. ^ Whitehouse, Dr. David (April 23, 2004). "NASA optimistic about Hubble fate". BBC News. http://news.bbc.co.uk/2/hi/science/nature/3652627.stm. Retrieved January 10, 2007.
131. ^ Whitehouse, Dr. David (2004-01-17). "Why Hubble is being dropped". BBC News. http://news.bbc.co.uk/2/hi/science/nature/3406079.stm. Retrieved 2007-01-10.
132. ^ Cowing, Keith (2005-07-22). "NASA Considering Deletion of Hubble Deorbit Module". SpaceRef. http://www.spaceref.com/news/viewnews.html?id=1050. Retrieved 2007-01-10.
133. ^ Leonard David (2005-09-14). "Health Checkup: Engineers Work to Stall Hubble's Death". space.com. http://www.space.com/businesstechnology/050914_hubble_health.html. Retrieved 2008-04-28.
134. ^ "Servicing Mission 4 Cancelled". STScI. 16 January 2004. http://www.stsci.edu/resources/sm4meeting.html. Retrieved 28 April 2008.
135. ^ "2004 Annual Report" (PDF). Astronomy and Astrophysics Advisory Committee. http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2004_report.pdf. Section 3.1 – The Scientific Impact of the HST SM4 Cancellation.
136. ^ Gugliotta, Guy (12 April 2005). "Nominee Backs a Review Of NASA's Hubble Decision". The Washington Post. http://www.washingtonpost.com/wp-dyn/content/article/2005/04/12/AR2005041201646.html. Retrieved 10

January 2007.
137. ^ Barbara Mikulski (7 February 2005). "Mikulski Vows To Fight For Hubble". Press release. http://mikulski.senate.gov/record.cfm?id=231696. Retrieved 2008-04-26.
138. ^ "Servicing Mission 4". NASA. http://www.nasa.gov/mission_pages/hubble/servicing/SM4/main/index.html. Retrieved 21 September 2008.
139. ^ Boyle, Alan (31 October 2006). "NASA gives green light to Hubble rescue". MSNBC. http://www.msnbc.msn.com/id/15489217/. Retrieved 2007.
140. ^ "Hubble re-opens an eye". New Scientist. 28 October 2008. http://space.newscientist.com/article/dn15056-hubble-reopens-an-eye.html. Retrieved 29 October 2008.
141. ^ "NASA Sets Target Shuttle Launch Date for Hubble Servicing Mission". NASA. 4 December 2008. http://www.nasa.gov/home/hqnews/2008/dec/HQ_08-320_Hubble_May2009.html. Retrieved 2008-12-05.
142. ^ John Matson (May 8, 2009). "Last Dance with the Shuttle: What's in Store for the Final Hubble Servicing Mission". Scientific American. http://www.scientificamerican.com/article.cfm?id=hubble-servicing-mission-shuttle. Retrieved May 18, 2009.
143. ^ "About JWST'S Launch". NASA. http://www.jwst.nasa.gov/launch.html. Retrieved 2006-11-04.
144. ^ "What Will Astronomy Be Like in 35 Years? Astronomy magazine, August, 2008
145. ^ Fienberg, Rick (2007-09-14). "Sharpening the 200-inch (5,100 mm)". News. Sky and Telescope magazine. http://www.skyandtelescope.com/news/9785152.html. Retrieved 2008-07-01.
146. ^ "1979QJRAS..20...29S Page 29". Articles.adsabs.harvard.edu. http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1979QJRAS..20...29S&data_type&#61PDF_HIGH&whole_paper&#61YES&type&#61PRINTER&filetype&#61.pdf. Retrieved 2010-04-25.

External links

* HubbleSite, Hubble website for the public (operated by the Space Telescope Science Institute)
* Hubble Heritage Project
* NASA Hubble pages
* Where's Hubble now..., an interactive map of Hubble's current location and orbital track
* Spacetelescope, ESA's public Hubble pages
* "A Brief History of the Hubble Space Telescope" from the NASA History Office
* Hubble data archive
* The transition from Hubble to JWSTPDF (182 KB) (August 2003 report)
* Hubblecast video from Dailymotion
* Amateur observations with Hubble, and a related press report
* Hubble's current position, via Google Maps
* Hubble at 20 - slideshow by The First Post
* Hubble's first 20 years with Professor Alec Boksenberg from the Institute of Astronomy in Cambridge