Hubble Space Telescope

(Most Versatile Space Telescope)

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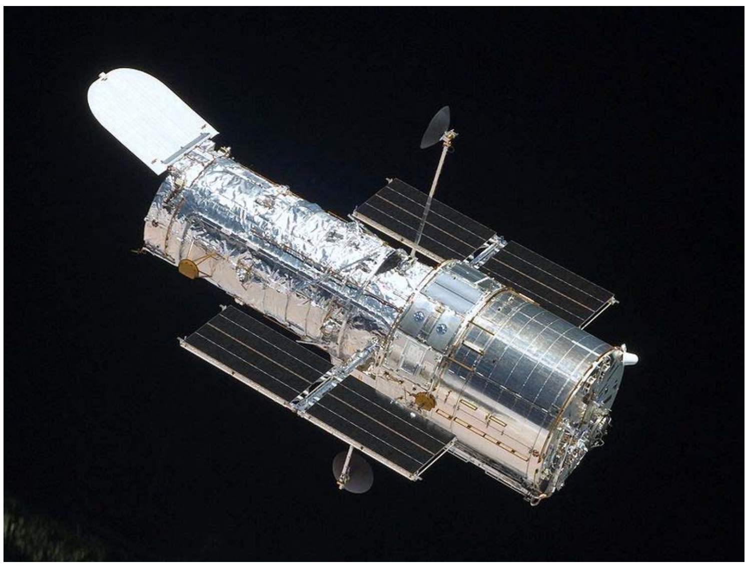
Introduction to Hubble Space Telescope

Hubble Space Telescope



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.

General information

NSSDC ID	1990-037B
Organization	NASA / ESA / STScI
Launch date	April 24, 1990, 8:33:51 am EDT
Launch vehicle	Space Shuttle Discovery, (STS-31)
Mission length	20 years, 5 months, and 19 days elapsed

Deorbited	due ~2013–2021
Mass	11,110 kg (24,500 lb)
Type of orbit	Near-circular low Earth orbit
Orbit height	559 km (347 mi)
Orbit period	96–97 minutes (14-15 periods per day)
Orbit velocity	7,500 m/s (25,000 ft/s)
Acceleration due to gravity	8.169 m/s^2 (26.80 ft/s^2)
Location	Low Earth orbit
Telescope style	Ritchey-Chrétien reflector
Wavelength	Optical, ultraviolet, near-infrared
Diameter	2.4 m (7 ft 10 in)
Collecting area	4.5 m^2 (48 sq ft)
Focal length	57.6 m (189 ft)
Instruments	
NICMOS	infrared camera/spectrometer
ACS	optical survey camera (partially failed)
WFC3	wide field optical camera
COS	ultraviolet spectrograph
STIS	optical spectrometer/camera
FGS	three fine guidance sensors

The **Hubble Space Telescope** (**HST**) is a 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.

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 to 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.

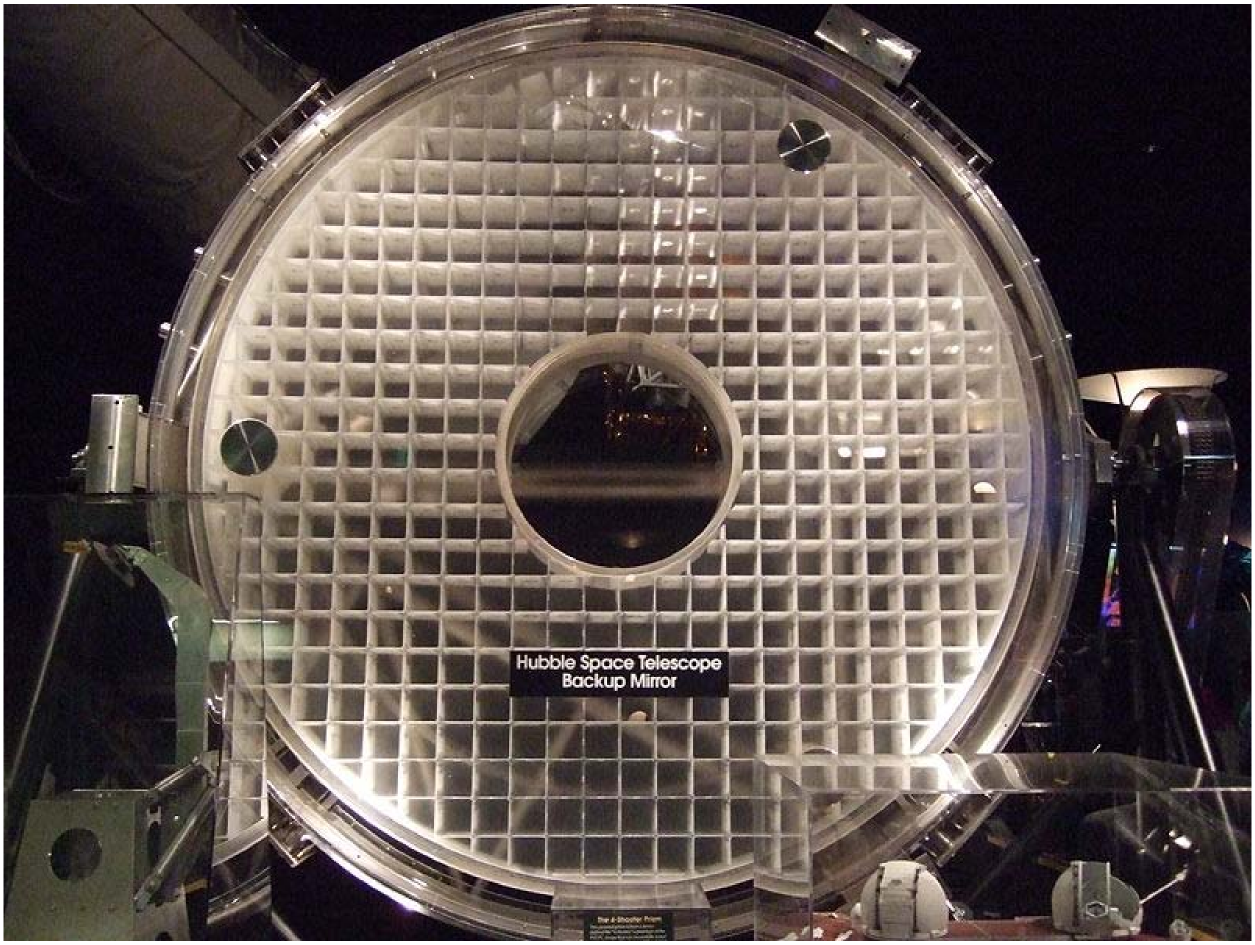
Flawed mirror

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. The detailed performance is shown in graphs from STScI illustrating the mis-figured PSFs compared to post-correction and ground-based PSFs.

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, it was too flat at the edges by about 2200 nanometers (2.2 microns). 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.

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. 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). 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.

Origin of the problem



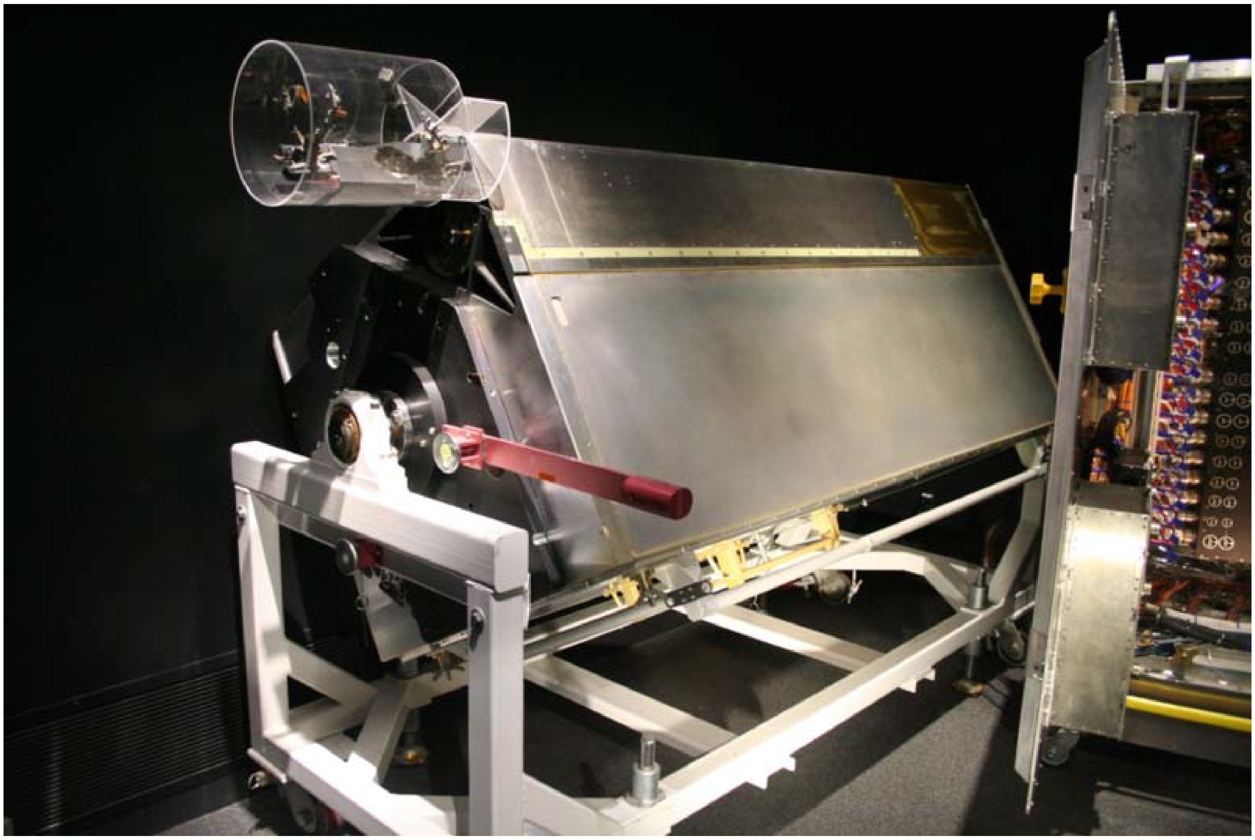
The correctly ground backup mirror built by Eastman Kodak for the Hubble space telescope (the mirror was never coated with a reflective surface, hence its inner support structure can be seen). It now resides in the National Air and Space Museum in Washington, DC.

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. 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.

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.

Design of a solution



COSTAR on display at the National Air and Space Museum

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.

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. 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.

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.

The Corrective Optics Space Telescope Axial Replacement (COSTAR) system was designed to correct the spherical aberration for light focused at the FOC, FOS, and GHRS. It consists of two mirrors in the light path with one ground to correct the aberration. 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. By 2002 all of the original instruments requiring COSTAR had been replaced by instruments with their own corrective optics. COSTAR was removed and returned to Earth in 2009 where it is exhibited at the National Air and Space Museum. The area previously used by COSTAR is now occupied by the Cosmic Origins Spectrograph.

Usage

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

To consummate Hubble Telescope's 20th Birthday, NASA, along with ESA and Space Telescope Institute, released a findings from Hubble.

Anyone can apply for time on the telescope; there are no restrictions on nationality or academic affiliation. 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.

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.

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. 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.

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, 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.

20th birthday

The Hubble Telescope celebrated its 20th birthday on April 22, 2010. To consummate the celebration, NASA, ESA, and Space Telescope Institute (STScI) released an image from the Carina Nebula.

Hubble data

Transmission to Earth

Hubble Control Center, Goddard Space Flight Center, 1999

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). 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. From there they are sent to the Goddard Space Flight Center and finally to the Space Telescope Science Institute for archiving.

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

Archive

All Hubble data is eventually made available via the archives of STScI. Data is usually proprietary—available only to the principal investigator (PI) and astronomers designated by the

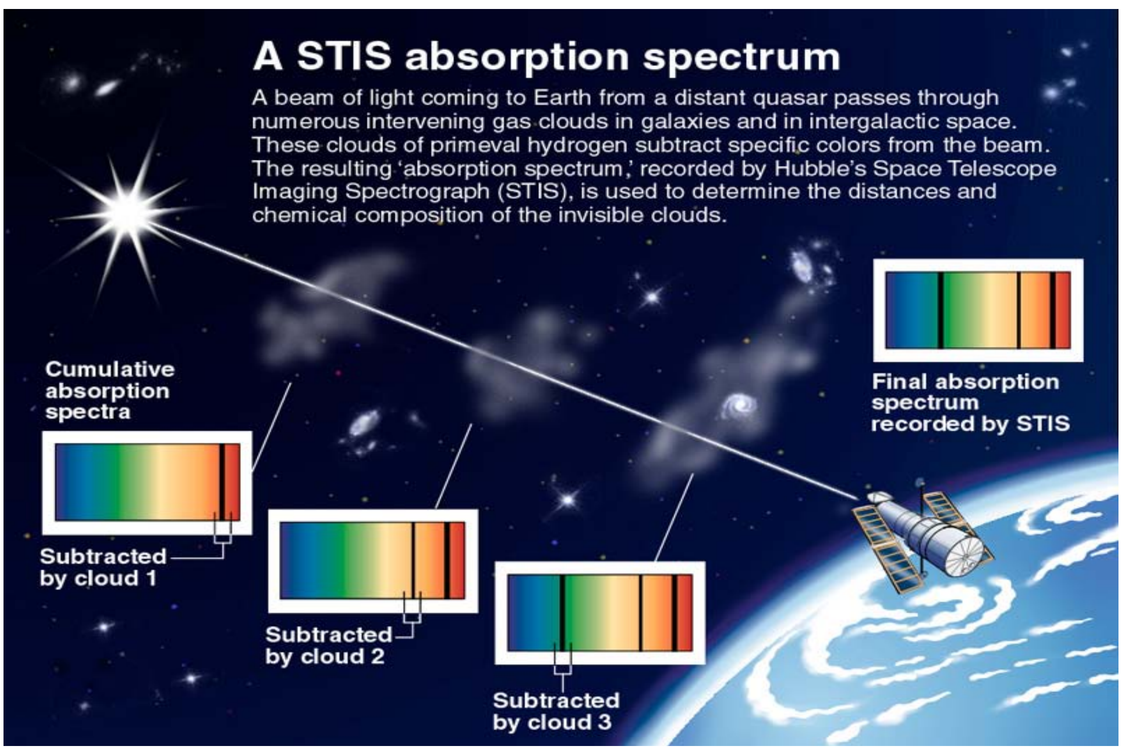
PI—for one year after being taken. The PI can apply to the director of the STScI to extend or reduce the proprietary period in some circumstances.

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. The Hubble Heritage Project processes and releases to the public a small selection of the most striking images in JPEG and TIFF formats.

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.

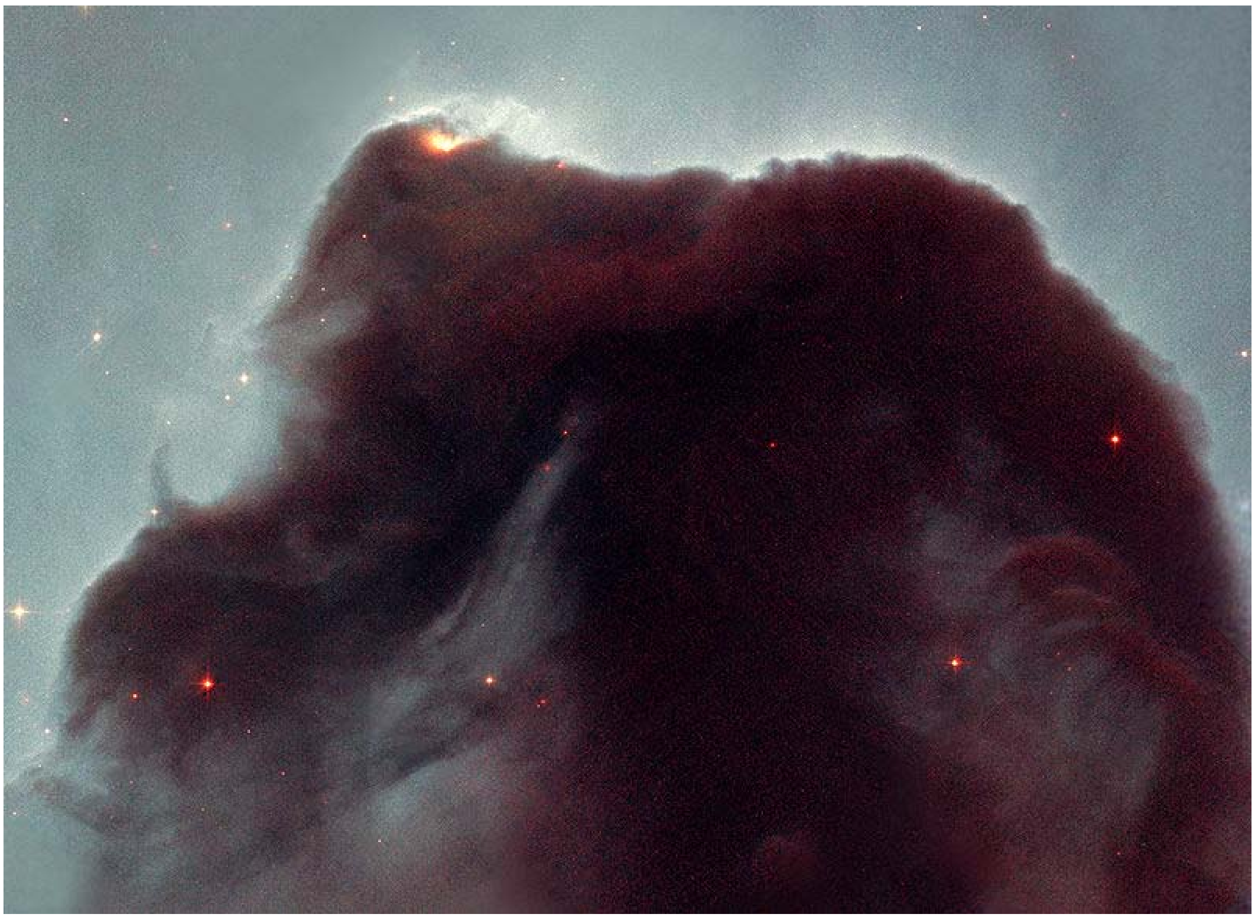
Data analysis



Data analysis of a spectrum reveals the chemistry of hidden clouds

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.

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. 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.

In addition, STScI maintains several comprehensive websites for the general public containing Hubble images and information about the observatory. 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). 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.

The Space Foundation has twice honored the Hubble Space Telescope with its Space Achievement Award. In 2010, the Hubble Space Telescope Repair Mission Team was honored and, in 2001, the initial Hubble Space Telescope Team was honored.

Hubblecast

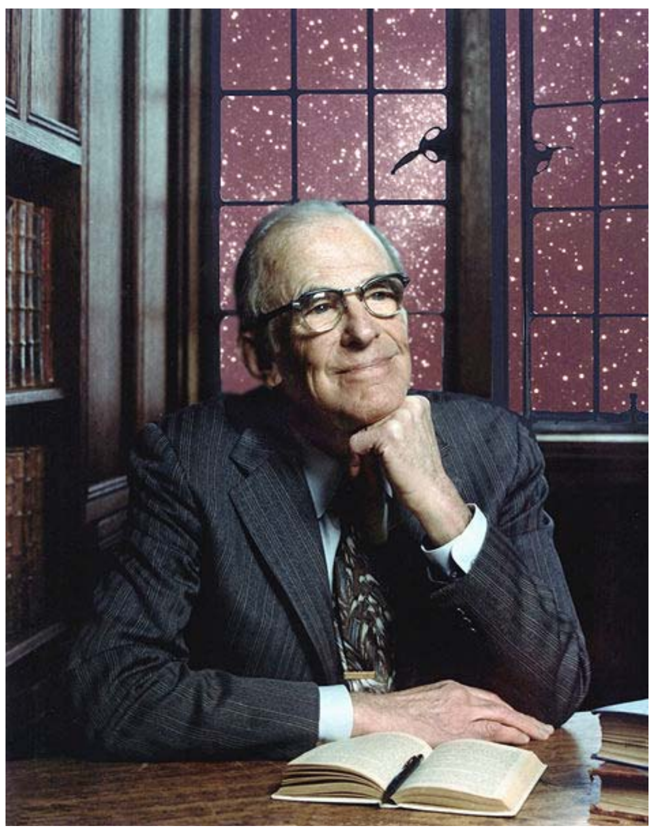
The Hubblecast is a vodcast series made by the ESA's Hubble team to bring world-class science news to everyone about Hubble's latest discoveries. Hosted by "Dr. J" *(Joe Liske)* who is a research scientist at ESO. The episodes are available in several formats and resolutions for different platforms.

Chapter- 2

Conception, Design and Aims of HST

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.



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". 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.

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, and NASA launched the Orbiting Solar Observatory to obtain UV, X-ray, and gamma-ray spectra in 1962. 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.

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.

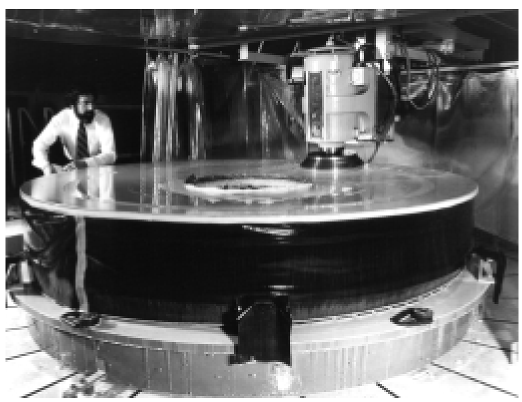
Quest for funding

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.

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.

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 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. 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. In 1983 the telescope was named after Edwin Hubble, who made one of the greatest scientific breakthroughs of the 20th century when he discovered that the universe was expanding.

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.

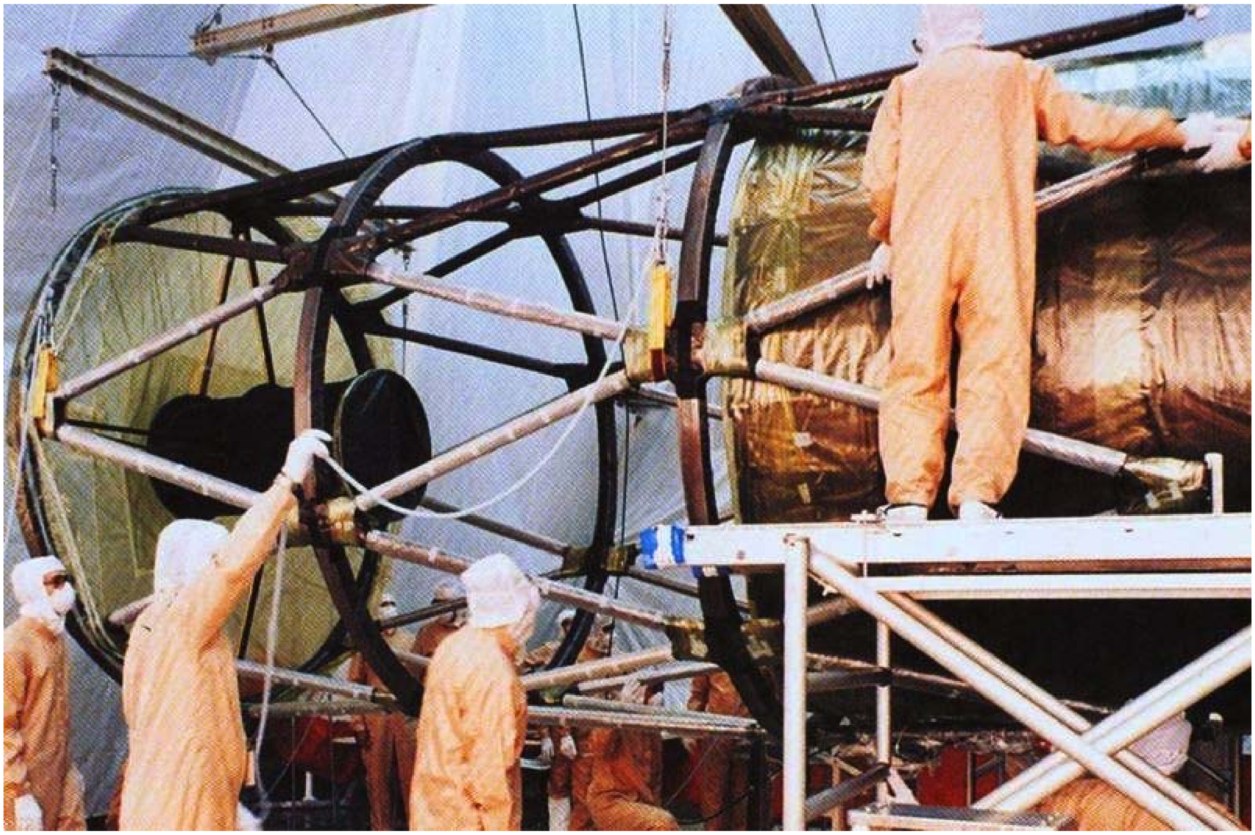
Once the Space Telescope project had been given the go-ahead, work on the program was divided among many institutions. Marshall Space Flight Center (MSFC) was given responsibility for the design, development, and construction of the telescope, while the Goddard Space Flight Center was given overall control of the scientific instruments and ground-control center for the mission. 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.

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. 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.

Perkin-Elmer intended to use custom-built and extremely sophisticated computer-controlled polishing machines to grind the mirror to the required shape. 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. (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.) The Kodak mirror is now on permanent display at the Smithsonian Institution. An Itek mirror built as part of the effort is now used in the 2.4 m telescope at the Magdalena Ridge Observatory.

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. 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.

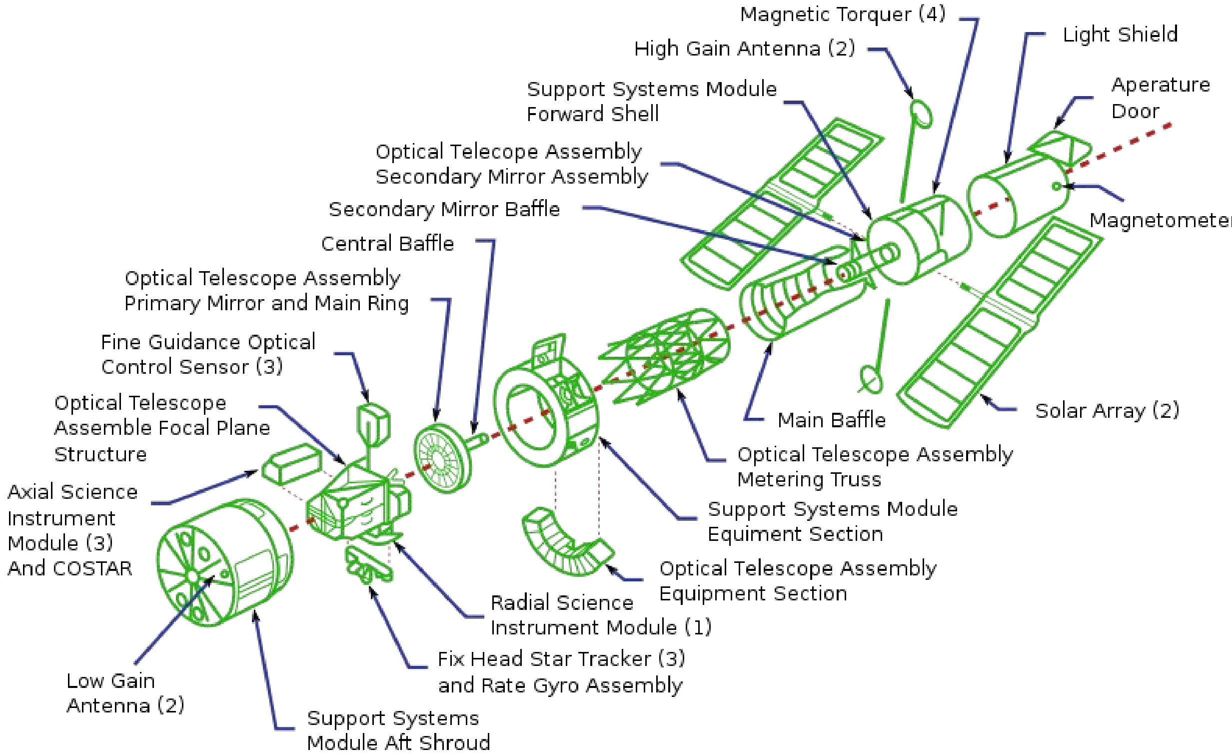


Construction of Hubble. The optical metering truss and secondary baffle are visible

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.

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. 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.



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.

Wide Field and Planetary Camera

WFPC image of Messier 100 (NGC 4321)

On the left, an un-corrected WFPC image of M100 in November 1993, next to an image by its replacement instrument with corrected optics

The **Wide Field/Planetary Camera** (**WFPC**) (pronounced as wiffpick) was a camera installed on the Hubble Space Telescope until December 1993. It was one of the instruments on Hubble at launch, but its functionality was severely impaired by the defects of the main mirror optics which afflicted the telescope. However, it produced uniquely valuable high resolution images of relatively bright astronomical objects, allowing for a number of discoveries to be made by HST even in its aberrated condition.

WFPC was proposed by James A. Westphal, a professor of planetary science at Caltech, and was designed, constructed, and managed by JPL. At the time it was proposed, 1976, CCDs had barely been used for astronomical imaging. However, their high sensitivity offered such promise that many astronomers strongly argued that they should be considered for Hubble Space Telescope instrumentation.

This first WFPC consisted of two separate cameras, each comprising 4 800x800 pixel Texas Instruments CCDs arranged to cover a contiguous field of view. The Wide Field camera had a 0.1 arcsecond pixel scale and was intended for the panoramic observations of faint sources at the cost of angular resolution. The Planetary Camera had a 0.043 arcsecond pixel scale and was intended for high-resolution observations. Selection between the two cameras was done with a four-facetted pyramid that rotated by 45 degrees.

As part of the corrective service mission (STS-61 in December 1993) the WFPC was swapped out for a replacement version. The Wide Field and Planetary Camera 2 improved on its predecessor and incorporated corrective optics needed to overcome the main mirror defect. To avoid potential confusion, the WFPC is now most commonly referred to as WFPC1.

On its return to Earth, the WFPC was disassembled and parts of it were used in Wide Field Camera 3, which was installed in Hubble on May 14, 2009 as part of Servicing Mission 4, replacing WFPC2.

Goddard High Resolution Spectrograph

GHRS being removed during Servicing Mission 2

The **Goddard High Resolution Spectrograph** (GHRS or HRS) was a spectrograph installed on the Hubble Space Telescope. It was replaced by the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) in 1997.

GHRS facts

- **Instrument type**: Ultraviolet spectrograph
- **Wavelength range**: 1050 to 3200 Å (105 to 320 nm)
- **Resolving Power** at 1200 Å (120 nm)
    - Low - 2,000 (0.6 Å or 60 pm, or a Doppler effect of 150 km/s)
    - Medium - 20,000 (0.06 Å or 6 pm, 15 km/s)
    - High - 100,000 (0.012 Å or 1.2 pm, 3 km/s)

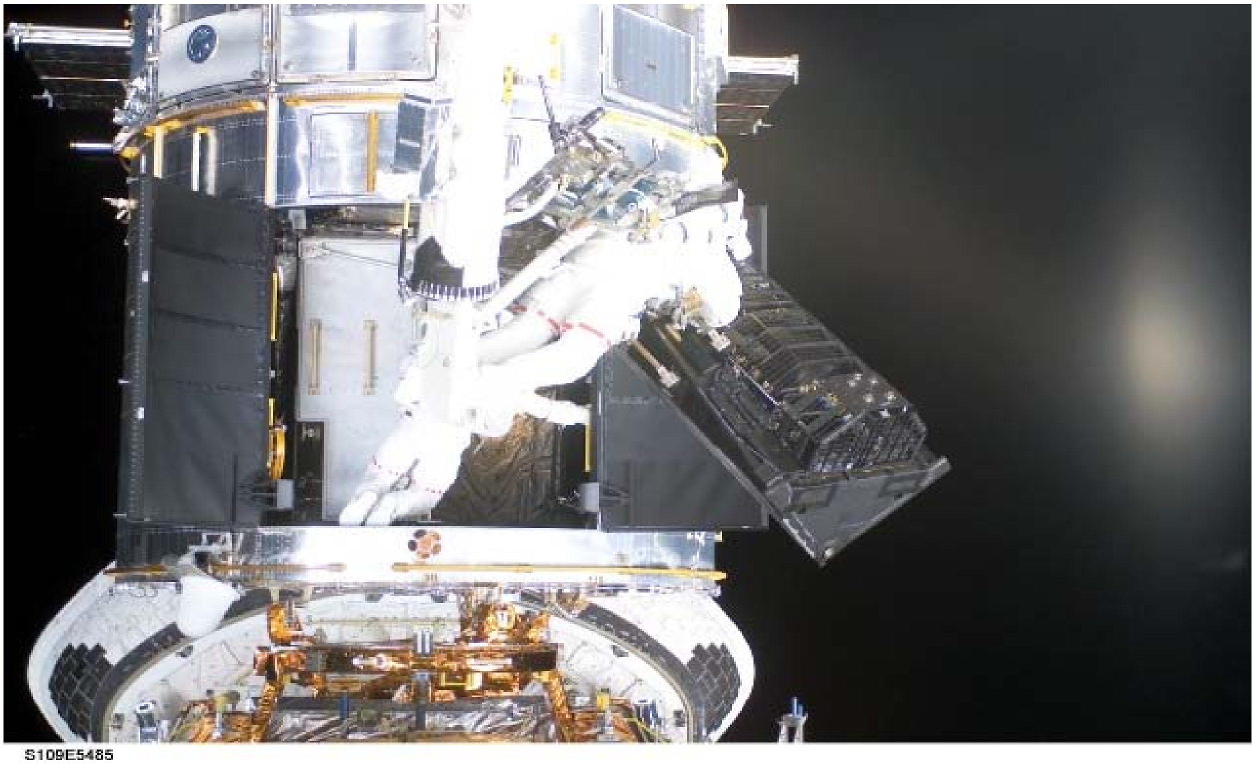
A technical description of the construction and operation of the GHRS can be found in NASA technical report CP-2244.

High Speed Photometer

The **High Speed Photometer** (**HSP**) was a scientific instrument installed on the Hubble Space Telescope. The HSP was designed to measure the brightness and polarity of rapidly varying celestial objects. It could observe in ultraviolet, visible light, and near infrared at a rate of one measurement per 10 microseconds. The design was novel in that despite being able to view through a variety of filters and apertures, it had no moving parts.

The HSP was one of the instruments on Hubble at launch but could not be used successfully due to the optical problems with the telescope. During the first servicing mission, in December 1993, it was replaced by the Corrective Optics Space Telescope Axial Replacement (COSTAR), which corrected the optical problem for the remaining instruments.

Faint Object Camera



Astronauts remove the FOC to make room for the ACS

An image of Pluto and its moon Charon revealed by the Hubble Faint Object Camera

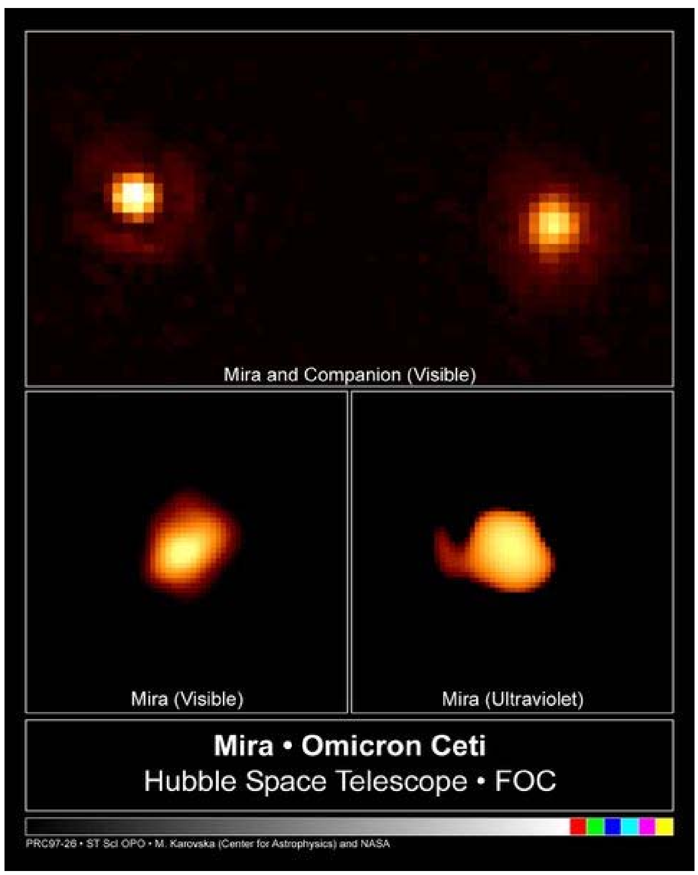
The **Faint Object Camera** (**FOC**) was a camera installed on the Hubble Space Telescope from launch in 1990 until 2002. It was replaced by the Advanced Camera for Surveys.

The camera was built by Dornier GmbH and was funded by the European Space Agency. The unit actually consists of two complete and independent camera systems designed to provide extremely high resolution, exceeding 0.05 arcseconds. It is designed to view very faint UV light from 115 to 650 nanometers in wavelength.

The camera was designed to operate at low, medium, or high resolution. The angular resolution and field of view at each resolution were as follows:

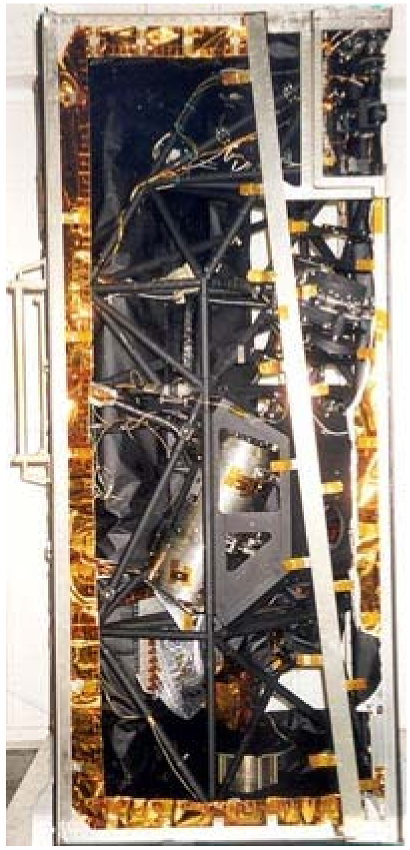
	Angular resolution	**Field of view**
Low resolution (f/48)	0.043 arcseconds	22 arcseconds
Medium resolution (f/96)	0.022 arcseconds	11 arcseconds
High resolution (f/288)	0.0072 arcseconds	3.6 arcseconds

Mira



Hubble + FOC red giant star Mira A (right), officially called Omicron Ceti in the constellation Cetus, and its companion on the left. Taken on December 11, 1995

Faint Object Spectrograph



The Faint Object Spectrograph (FOS). This picture was taken after FOS was brought back to the Earth again. Credit: NASA/ESA.

The **Faint Object Spectrograph** (FOS) was a spectrograph installed on the Hubble Space Telescope. It was replaced by the Space Telescope Imaging Spectrograph in 1997, and is now on display in the National Air and Space Museum in Washington DC.

FOS facts

- **Instrument type**: Spectrograph
- **Wavelength range**: 115 to 850 nm

A technical description of the construction and operation of the FOS can be found in NASA technical report CP-2244. The instrument used two digicon detectors, 'blue' and 'red', and had a spectral resolution of about 1300 over the 115nm to 850nm range. It had a number of apertures of varying size, but the aberration of the HST mirror meant that, until COSTAR was installed, the smallest apertures suffered very serious loss of light; even the largest 4.3-arcsecond aperture collected only 70% of the light from a point source.

The digicons suffered from inadequate magnetic shielding, which meant that a static image was smeared over several pixels; the red digicon suffered most from this. Also, either the blue detector or one of the mirrors in the system was contaminated in such a way as to remove sensitivity below 150nm; this was a serious problem since it makes the Lyman-alpha line at 121.6nm inaccessible.

Space Telescope Science Institute

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

The **Space Telescope Science Institute** (**STScI**) is the science operations center for the Hubble Space Telescope (HST; in orbit since 1990) and for the James Webb Space Telescope (JWST; scheduled to be launched in 2014). STScI is located on the **Johns Hopkins University** Homewood campus in Baltimore, Maryland and was established in 1981 as a community-based science center that is operated for NASA by the Association of Universities for Research in Astronomy (AURA). Today, in addition to performing continuing science operations of HST and preparing for scientific exploration with JWST, STScI manages and operates the Multi-mission Archive at Space Telescope (MAST), the Data Management Center for the Kepler mission and a number of other activities benefiting from its expertise in and infrastructure for supporting the operations of space-based astronomical observatories. Most of the funding for STScI activities comes from contracts with NASA's Goddard Space Flight Center but there are smaller activities funded by NASA's Ames Research Center, NASA's Jet Propulsion Laboratory, and the European Space Agency (ESA). The staff at STScI consists of scientists (mostly astronomers and astrophysicists), software engineers, data management and telescope operations personnel, education and public outreach experts, and administrative and business support personnel. There are approximately 100 Ph.D. scientists working at STScI, 15 of which are ESA staff who are on assignment to the HST project. The total STScI staff consists of about 450 people.

STScI operates its missions on behalf of NASA, the worldwide astronomy community, and the general public. The science operations activities directly serve the astronomy community, primarily in the form of HST (and eventually JWST) observations and grants, but also include distributing data from other NASA missions (e.g., Far Ultraviolet Spectroscopic Explorer, Galaxy Evolution Explorer) and ground-based sky surveys. The ground system development activities create and maintain the software systems that are needed to provide these services to the astronomy community. STScI's public outreach activities provide a wide range of information, on-line media, and programs for formal educators, planetariums and science museums, and the general public. STScI's award-winning public outreach websites receive millions of hits per month. STScI also serves as a source of guidance to NASA on a range of optical and UV space astrophysics issues.

The STScI staff interacts and communicates with the professional astronomy community through a number of channels, including participation at the bi-annual meetings of the American Astronomical Society, publication of quarterly STScI newsletters and the STScI website, hosting user committees and science working groups, and holding several scientific and technical symposia and workshops each year. These activities enable STScI to disseminate information to the telescope user community as well as enabling the STScI staff to maximize the scientific productivity of the facilities they operate by responding to the needs of the community and of NASA.

STScI activities

Telescope science proposal selection

The STScI conducts all activities required to select, schedule, and implement the science programs of HST. The first step in this process is to support the annual community-led selection of the scientific programs that will be performed with HST. This begins with publishing of the annual Call for Proposals, which specifies the currently supported science instrument capabilities, proposal requirements and the submission deadline. Anyone is eligible to submit a proposal. All proposals are critically peer-reviewed by the Time Allocation Committee (TAC). The TAC consists of about 100 members of the U.S. and international astronomical community, selected to represent a broad range of research expertise needed to evaluate the proposals. Each proposal cycle typically involves reviewing 700 to 1100 proposals. Only 15 - 20% of these proposals will eventually be selected for implementation. The TAC reviews several categories of observing time, as well as proposals for archival, theoretical, and combined research projects between HST and other space-based or ground-based observatories (e.g., Chandra X-ray Observatory and the National Optical Astronomy Observatories). STScI provides all technical and logistical support for these activities. The annual cycle of proposal calls is occasionally altered in duration in years when a HST servicing mission is scheduled.

Proposers fortunate enough to be awarded telescope time, referred to as General Observers (GOs), must then provide detailed requirements needed to schedule and implement their observing programs. This information is provided to STScI on what is called a Phase II proposal. The Phase II proposal specifies instrument operation modes, exposure times, telescope orientations, and so on. The STScI staff provide the web-based software called Exposure Time Calculators (ETCs) that allow GOs to estimate how much observing time any of the onboard detectors will need to accumulate the amount of light required to accomplish their scientific objectives. In addition, the STScI staff carries out all the steps necessary to implement each specific program, as well as plan the entire ensemble of programs for the year. For HST, this includes finding guide stars, checking on bright object constraints, implementing specific scheduling requirements, and working with observers to understand and factor in specific or any non-standard requirements they may have.

Observation scheduling

Once the Phase II information is gathered, a long-range observing plan is developed that covers the entire year, finding appropriate times to schedule individual observations, and at the same time ensuring effective and efficient use of the telescope through the year. Detailed observing schedules are created each week, including, in the case of HST operations, scheduling the data communication paths via the Tracking and Data Relay Satellite System (TDRSS) and generating the binary command loads for uplink to the spacecraft. Adjustments can be made to both long-range and weekly plans in response to Targets of Opportunity (e.g., for transient events like supernovae or coordination with one-of-a-kind events such as comet impact spacecraft). The STScI uses the Min-conflicts algorithm to schedule observation time on the telescope. The STScI is currently developing similar processes for JWST, although the operational details will be very different due to its different instrumentation and spacecraft constraints, and its location at the Sun-Earth L2 Lagrange point (~1.5 million km from Earth) rather than the low Earth orbit (~565 km) used by HST.

Flight operations

Flight Operations consists of the direct support and monitoring of HST functions in real-time. Real-time daily flight operations for HST include about 4 command load uplinks, about 10 data downlinks, and near continuous health and safety monitoring of the observatory. Real-time operations are staffed around the clock. Flight operations activities for HST are done at NASA's GSFC in Greenbelt, Maryland.

Science data processing

Science data from HST arrive at the STScI a few hours after being downlinked from TDRSS and subsequently passing through a data capture facility at NASA's Goddard Space Flight Center. Once at STScI, the data are processed by a series of computer algorithms that convert its format into an internationally accepted standard (known as FITS: Flexible Image Transport System), correct for missing data, and perform final calibration of the data by removing instrumental artifacts. The calibration steps are different for each HST instrument, but as a general rule they include cosmic ray removal, correction for instrument/detector non-uniformities, flux calibration, and application of world coordinate system information (which tells the user precisely where on the sky the detector was pointed). The calibrations applied are the best available at the time the data pass through the pipeline. The STScI is working with instrument developers to define similar processes for Kepler and JWST data.

Science data archiving and distribution

All HST science data are permanently archived after passing through the calibration pipeline. NASA policy mandates a one-year proprietary period on all data, which means that only the initial proposal team can access the data for the first year after it has been obtained. Subsequent to that year, the data become available to anyone who wishes to access it. Data sets retrieved from the archive are automatically re-calibrated to ensure that the most up-to-date calibration factors and software are applied. The STScI serves as the archive center for all of NASA’s optical/UV space missions. In addition to archiving and storing HST science data, STScI holds data from 13 other missions including the International Ultraviolet Explorer (IUE), the Extreme Ultraviolet Explorer (EUVE), the Far Ultraviolet Spectroscopic Explorer (FUSE), and the Galaxy Evolution Explorer (GALEX). Kepler and JWST science data will be archived and retrieved in similar fashions. The internet serves as the primary user interface to the data archives at STScI. The archive currently holds over 30 terabytes of data. Each day about 11 gigabytes of new data are ingested and about 85 gigabytes of data are distributed to users. The Hubble Legacy Archive, currently in development, will act as a more integrated and user-friendly archive. It will provide raw Hubble data as well as higher-level science products (color images, mosaics, etc.).

Science instrument calibration and characterization

STScI is responsible for in-flight calibration of the science instruments on HST and JWST. For HST, a calibration plan for the observatory is developed each year. This plan is designed to support the selected GO observation programs for that cycle, as well as to provide a basic calibration that spans the lifetime of each instrument. The calibration program includes measurements that are made relative to on-board calibration sources or to assess internal detector noise levels as well as observations of astronomical standard stars and fields, needed to determine absolute flux conversions and astrometric transformations. The external calibrations on HST typically total 5-10% of the GO observing program, with more time required when an instrument is still relatively new. HST has had a total of 12 science instruments to date, 6 of which are currently active. Two new instruments were installed during the May 2009 HST servicing mission STS-125. Electronic failures in STIS (in 2001) and in the ACS Wide-Field Channel (in 2007) were also repaired on-orbit in May 2009, bringing these instruments back to active status. All 12 HST instruments plus the 4 planned for JWST are summarized in the table below. HST instruments can detect light with wavelengths from the ultraviolet through the near infrared. JWST instruments will operate from the red-end of optical wavelengths (~6000 Angstroms) to the mid-infrared (5 to 27 micrometres). Instruments listed as decommissioned are no longer on board.

Instrument name (and abbreviation)	Instrument function	Instrument Status	Telescope
High Speed Photometer (HSP)	Rapid Timescale Photometry	Decommissioned in 1993	HST
Wide Field and Planetary Camera (WFPC)	UV/Optical Imaging	Decommissioned in 1993	HST
Faint Object Spectrograph (FOS)	UV/Optical Spectroscopy	Decommissioned in 1997	HST
Goddard High Resolution Spectrograph (GHRS)	UV/Optical Spectroscopy	Decommissioned in 1997	HST
Faint Object Camera (FOC)	UV/Optical Imaging	Decommissioned in 2002	HST
Wide Field and Planetary Camera 2 (WFPC2)	UV/Optical Imaging	Decommissioned in 2009	HST
Fine Guidance Sensor (FGS)	Precision Astrometry	Active	HST
Space Telescope Imaging Spectrograph (STIS)	UV/Optical Spectroscopy	Active (repaired)	HST
Near Infrared Camera and Multi-Object Spectrometer (NICMOS)	NIR Imaging and grism Spectroscopy	Active	HST
Advanced Camera for Surveys (ACS)	UV/Optical Imaging and grism Spectroscopy	SBC and WFC (repaired) Active; HRC Inactive	HST
Cosmic Origins Spectrograph (COS)	UV Spectroscopy	Active	HST
Wide Field Camera 3 (WFC3)	UV/Optical/Near-IR Imaging and grism Spectroscopy	Active	HST
Near Infrared Camera (NIRCam)	Optical/Near-IR Imaging	Pre-flight (2014)	JWST
Near Infrared Spectrograph	Near-IR Spectroscopy	Pre-flight (2014)	JWST

(NIRSpec)			
Mid-Infrared Instrument (MIRI)	Mid-IR Imaging & Spectroscopy	Pre-flight (2014)	JWST
Tunable Filter Imager (FGS-TFI)	Near to Mid-IR Medium-band Imaging	Pre-flight (2014)	JWST

STScI staff develops the calibration proposals, shepherd them through the scheduling process, and analyze the data they produce. These programs provide updated calibration and reference files to be used in the data processing pipeline. The calibration files are also archived so users can retrieve them if they need to manually recalibrate their data. All calibration activity and results are documented, usually in the form of Instrument Science Reports posted to the public website, and occasionally in the form of published papers. Results are also incorporated into the Data Handbooks and Instrument Handbooks.

In addition to calibration of the instruments, STScI staff characterizes and documents the performance of the instrument, so users can better understand how to interpret their data. These are generally effects that are not automatically corrected for in the pipeline (because they vary with time or depend on the brightness of the source). They include global effects, such as charge transfer efficiency in the charge coupled devices, as well as effects specific to modes and filters, such as filter "ghosts" (caused by subtle scattering of light within an instrument). Awareness of these effects can come from STScI staff as they analyze calibration programs, or from observers who find oddities in their data and provide feedback to STScI.

The STScI staff also performs the characterization and calibration of the telescope itself. In the case of HST, this has evolved to primarily be a matter of monitoring and adjusting focus, and monitoring and measuring point spread functions. (In the early 1990s, the STScI was responsible for accurate measurement of the spherical aberration, necessary for the corrective optics of all subsequent instruments). In the case of JWST, the STScI will be responsible for using the wavefront sensor system developed by JPL and Northrop Grumman Space Technology (NGST, the NASA contractor building the observatory) to monitor and adjust the segmented telescope.

Post observation support

The post observation support includes a HelpDesk that users can contact to answer their questions about any aspect of observing – from how to submit a proposal to how to analyze the data.

Science community service

The STScI performs large HST science programs on behalf of the community. These are programs with broad scientific applications. To date, these programs include the Hubble Deep Field (HDF), the Hubble Deep Field South (HDFS), and the Ultra Deep Field (UDF). The raw and processed data for these observations are made available to the astronomy community nearly immediately. These products have then been used by many astronomers in pursuit of their own research topics, and have motivated a great deal of follow-up work.

Ground systems

STScI is responsible for developing, enhancing, and maintaining most of the ground systems used to carry out our Hubble science operations described above. These systems originally (1980s, early 1990s) came from several sources, including in-house STScI developments and work done under NASA contracts with various vendors. Over HST's lifetime substantial work has been done on these systems - even while they were supporting daily operations of Hubble. They have been integrated into a more effective and easier to operate end-to-end system. They have been through major technology upgrades (e.g., improved operating systems and computer hardware, higher capacity archive storage media). They have also been modified to support the succession of instruments installed in the telescope. In the last several years, they have been modified to support WFC3 and COS, the two new instruments that will be installed during the next HST servicing mission, and to support the 2-Gyroscope mode of HST operations. STScI also provides subsets of ground system services to other astronomy missions, including FUSE, Kepler, and JWST. STScI's software engineers maintain about 7,900,000 source lines of code.

Mission development and operations support

STScI routinely participates with NASA and industry system engineers and scientists in developing the overall mission architecture. For HST, this includes helping to determine and prioritize servicing mission activities and development of the servicing strategy. For JWST, this includes participating in the definition of high-level science requirements and the overall architecture for the mission. In both cases, the STScI focuses on the scientific capabilities of the mission, and also the requirements for smooth and efficient operations of the observatory.

Scientific research activities

STScI manages the selection of the Hubble Fellowship Program. Hubble Fellowships support outstanding postdoctoral scientists whose research is broadly related to the scientific mission of the Hubble Space Telescope. The research may be theoretical, observational, or instrumental. Each year, since HST's launch in 1990, 8 to 12 fellowships are awarded. STScI also sponsors a summer student intern program that allows talented undergraduate students from around the world to work with the Institute's scientific staff, providing these students with hands-on experience in state-of-the-art astronomical research. STScI's full-time scientific staff conducts original research spanning a broad range of astrophysics including investigations of the solar system, exoplanet detection and characterization, star formation, galaxy evolution, and cosmology. STScI hosts an annual scientific symposium held each spring as well as several smaller scientific workshops. The employment of an active scientific staff at STScI helps to ensure that HST, and eventually JWST, perform at peak capability.

Public outreach

The STScI's Office of Public Outreach (OPO) provides a wide array of products and services designed to share and communicate the science and discoveries of HST (and eventually JWST) with the general public. OPO's efforts focus on meeting the needs of four communities: the news media, web users, the formal education community and informal science education venues.

OPO's News Branch produces approximately 40 new press releases each year featuring HST discoveries and science results. These media packages include news stories, Hubble images, explanatory artwork, animations, and supplementary information for use by print, broadcast, and on-line media. The branch also conducts press conferences called "NASA Science Updates" for particularly newsworthy discoveries. Science Writers' Workshops and other special events bring reporters to the Institute for in-depth sessions with scientists working on current astrophysical research problems.

The Formal Education Branch develops standards-based and rigorously evaluated educational products and lessons for use in K-14 curricula throughout the country. Many of the branch's products are incorporated in its award-winning web site called Amazing Space where lessons and exercises are readily accessible by both teachers and students and is used in more than 200 school districts and in all 50 states.

The Informal Education Branch creates a variety of Hubble-related products and features for use in informal venues including museums, science centers, planetariums, and libraries. These include ViewSpace, a multimedia display system providing a series of educational features on the science of Hubble and other missions using imagery, text, and music. A short film called "Hubble: Galaxies Across Space and Time" which features a three-dimensional fly-through of the Hubble Ultra Deep Field has been produced for IMAX theaters and adapted for use in planetariums. The group also provides materials for conferences and workshops, manages Hubble traveling exhibits for national distribution, and creates video compilations of Hubble imagery and features.

OPO's Online Branch develops, improves and maintains a series of HST and JWST related web sites including the award-winning HubbleSite, which contains an image gallery of nearly 900 Hubble images that have been released for public consumption over the telescope's lifetime.

Challenger disaster, delays, and eventual launch

By 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 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. Furthermore, the ground software needed to control Hubble was not ready in 1986, and in fact was barely ready by the 1990 launch.

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.

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).

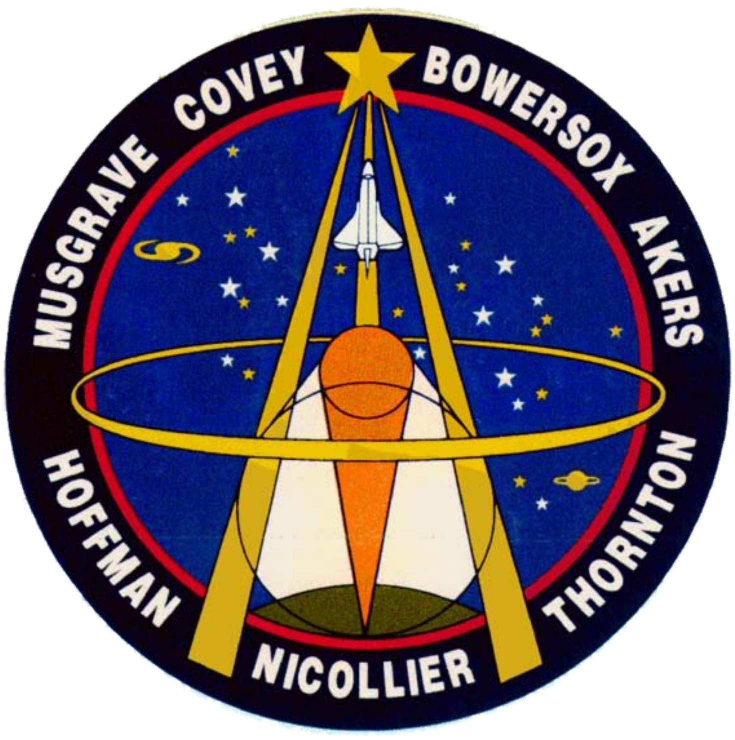
Chapter- 3

Servicing Missions and Instruments of HST

STS-61

STS-61

Mission insignia



Mission statistics

Mission name	STS-61
Space shuttle	*Endeavour*
Launch pad	39-B

Launch date	December 2, 1993, 4:26 a.m. EST
Landing	December 13, 1993, 12:26.25 a.m. EST, Runway 33, KSC
Mission duration	10/19:58:37
Number of orbits	163
Orbital altitude	321 nautical miles (594 km)
Orbital inclination	28.45 degrees
Distance traveled	4,433,772 miles (7,135,464 km)

Crew photo

Related missions

Previous mission	**Subsequent mission**
STS-58 	STS-60 

STS-61 was the first Hubble Space Telescope servicing mission, and the fifth flight of the Space Shuttle *Endeavour*. The mission launched on December 2, 1993 from Kennedy Space Center in Florida.

Crew

Position	Astronaut
Commander	Richard O. Covey Fourth spaceflight
Pilot	Kenneth D. Bowersox Second spaceflight
Mission Specialist 1	F. Story Musgrave Fifth spaceflight Payload Commander
Mission Specialist 2	Kathryn C. Thornton Third spaceflight
Mission Specialist 3	Claude Nicollier, ESA Second spaceflight
Mission Specialist 4	Jeffrey A. Hoffman Fourth spaceflight
Mission Specialist 5	Thomas D. Akers Third spaceflight

Mission parameters

- **Mass:**
  - *Orbiter landing with payload:* 94,972 kg (209,380 lb)
  - *Payload:* 10,949 kg (24,140 lb)
- **Perigee:** 291 kilometres (181 mi)
- **Apogee:** 576 kilometres (358 mi)
- **Inclination:** 28.5°
- **Period:** 93.3 min

Spacewalks

- ***Musgrave and Hoffman*** - EVA 1
  - **EVA 1 Start**: December 5, 1993 - 03:44 UTC
  - **EVA 1 End**: December 5–11:38 UTC
  - **Duration**: 7 hours, 54 minutes
- ***Thornton and Akers*** - EVA 2
  - **EVA 2 Start**: December 6, 1993 - 03:29 UTC
  - **EVA 2 End**: December 6–10:05 UTC
  - **Duration**: 6 hours, 36 minutes
- ***Musgrave and Hoffman*** - EVA 3
  - **EVA 3 Start**: December 7, 1993 - 03:35 UTC
  - **EVA 3 End**: December 7–10:22 UTC
  - **Duration**: 6 hours, 47 minutes

- ***Thornton and Akers*** - EVA 4
    - **EVA 4 Start**: December 8, 1993 - 03:13 UTC
    - **EVA 4 End**: December 8–10:03 UTC
    - **Duration**: 6 hours, 50 minutes
- ***Musgrave and Hoffman*** - EVA 5
    - **EVA 5 Start**: December 9, 1993 - 03:30 UTC
    - **EVA 5 End**: December 9–10:51 UTC
    - **Duration**: 7 hours, 21 minutes

Mission highlights

The STS-61 crew servicing the Hubble Space Telescope while docked to *Endeavour*'s cargo bay

Launch

With its very heavy workload, the STS-61 mission was one of the most sophisticated in the Shuttle's history. It lasted almost 11 days, and crew members made five EVAs, an all-time record. Even the retrieval of Intelsat IV on STS-49 in May 1992 required only four. The flight plan allowed for two additional EVAs, which could have raised the total number to seven EVAs. The final two contingency EVAs were not made. In order to complete the mission without too much fatigue, the five extravehicular working sessions were shared between two alternating shifts of two astronauts.

The mission was originally scheduled for launch from Pad 39A, and the shuttle was rolled out and placed on that pad, but due to contamination, a "rollaround" to Pad 39B was made.

After launch on December 2, 1993, the astronauts carried out a series of checks on the vehicle and went to sleep seven and a half hours after liftoff.

Flight Day 2

Endeavour performed a series of burns that allowed the shuttle to close in on the Hubble Space Telescope at a rate of 60 nautical miles (110 km) per 95-minute orbit. The crew made a detailed inspection of the payload and checked out both the robot arm and the spacesuits. All of *Endeavour*'s systems functioned well as the crew got a full day's sleep in preparation for the evening's rendezvous. At the end of Flight Day 2, *Endeavour* was 190 nautical miles (350 km) behind HST and closing.

Flight Day 3

HST was sighted by astronaut Jeffrey A. Hoffman using binoculars and he noted that the right-hand solar array was bent in a 90 degree angle. These 12-meter (39 ft) solar arrays, built by the European Space Agency, are planned to be replaced during the second spacewalk because they wobble 16 times a day each time the telescope heats up and cools off as it passes from the dark side of the Earth to its light side and vice versa.

The closing speed remained the same until the next reaction control system firing, at 8:34 p.m. CST (MET 1/17:07). The NH burn changed the shuttle's velocity by 4.6 feet per second (1.4 m/s), adjusting the high point of *Endeavour*'s orbit and fine-tuning its course toward a point 40 miles (64 km) behind HST. The next burn, an orbital maneuvering system firing designated NC3, was scheduled for 9:22 p.m. (MET 1/17:55) and changed *Endeavour*'s velocity by 12.4 feet per second (3.8 m/s). *Endeavour*'s catch-up rate was adjusted to about 16 nautical miles (30 km) per orbit and put it eight nautical miles (15 kilometres (9.3 mi)) behind HST two orbits later. A third burn of just 1.8 ft/s (550 mm/s), called NPC and designed to fine tune two spacecrafts' ground tracks, at for 9:58 p.m. CST (MET 1/18:31). The multiaxis RCS terminal initiation or "TI" burn, which places Endeavour on an intercept course with HST and set up Commander Dick Covey's manual control of the final stages of the rendezvous, occurred at 12:35 a.m. (MET 1/21:08). Covey maneuvered *Endeavour* within 30 feet (9.1 m) of the free-flying HST before Mission Specialist Claude Nicollier used *Endeavour*'s robot arm to grapple the telescope at 3:48

a.m. EST, when the orbiter was several hundred kilometers east of Australia over the South Pacific. Nicollier berthed the telescope in the shuttle's cargo bay at 4:26 a.m. EST. Everything was on schedule for the first planned spacewalk scheduled for 11:52 p.m. EST. After capture, additional visual inspections were performed using the camera mounted on the 50-foot (15 m)-long shuttle remote manipulator arm.

Earlier in the day, controllers at the Space Telescope Operations Control Center at the Goddard Space Flight Center uplinked commands to stow HST's two high-gain antennas. Controllers received indications that both antennas had nested properly against the body of the telescope, but microswitches on two latches of one antenna and one latch on the other did not send the "ready to latch" signal to the ground. Controllers decided not to attempt to close the latches, as the antennas were in a stable configuration. The situation was not expected to affect plans for rendezvous, grapple and servicing of the telescope.

Spacewalk #1 (Flight Day 4)

Hubble Telescope images before and after the STS-61 mission

Story Musgrave and Jeffrey A. Hoffman started the first EVA about an hour earlier than scheduled by stepping into the cargo bay at 10:46 p.m. EST. They began by unpacking tools, safety tethers and work platforms. Hoffman then installed a foot restraint platform onto the end of the shuttle's remote manipulator arm, which he then snapped into his feet. Nicollier drove the arm from within the shuttle and moved Hoffman around the telescope. Meanwhile, Musgrave installed protective covers on Hubble's aft low gain antenna and on exposed voltage bearing connector covers. The astronauts then opened the HST equipment bay doors and installed another foot restraint inside the telescope. Musgrave assisted Hoffman into the restraint and Hoffman proceeded to replace two sets of Remote Sensing Units. These units contain gyroscopes that help keep Hubble pointed in the right direction. By 12:24 EST Hoffman had finished swapping out RSU-2 (containing Gryos 2-3 and 2-4) and then swapped out RSU-3 (containing Gryos 3-5 and 3-6). The astronauts then spent about 50 minutes preparing equipment for use during the second space walk and then replaced a pair of electrical control units (ECU3 and ECU1) that control RSUs 3 and 1. The astronauts also changed out eight fuse plugs that protect the telescope's electrical circuits. Hubble now had a full set of six healthy gyroscopes.

The astronauts struggled with the latches on the gyro door when two of four gyro door bolts did not reset after the astronauts installed two new gyro packages. Engineers who evaluated the situation speculated that when the doors were unlatched and opened, a temperature change might have caused them to expand or contract enough to keep the bolts from being reset.

With the efforts of determined astronauts in *Endeavour*'s payload bay and persistent engineers on the ground, all four bolts finally latched and locked after the two spacewalkers worked simultaneously at the top and bottom of the doors. Musgrave anchored himself at the bottom of the doors with a payload retention device which enabled him to use some body force against the doors. Hoffman, who was attached to the robot arm, worked at the top of the doors. The duo successfully latched the doors when they simultaneously latched the top and bottom latches.

The spacewalkers also set up the payload bay for mission specialists Tom Akers and Kathy Thornton who would replace the telescope's two solar arrays during the second spacewalk. In anticipation of that spacewalk, Musgrave and Hoffman prepared the solar array carrier which is located in the forward portion of the cargo bay, and attached a foot restraint on the telescope to assist in the solar array replacement.

Musgrave and Hoffman's spacewalk became the second longest spacewalk in NASA history lasting 7 h 50 min. The longest spacewalk occurred on STS-49 in May 1992 during *Endeavour*'s maiden flight. Spacewalking crew members during that flight were Thomas D. Akers, Richard J. Hieb and Pierre J. Thuot. A number of spacewalks have since surpassed these.

In spite of the kink in array (about a panel and a half from the end), after a review by HST program managers, flight controllers decided to continue with the pre-flight plan and attempt to roll up and retract the solar arrays at the end of the first EVA. The stowage of the solar arrays is a two step process with the initial step involving the rolling up of the solar arrays and the second step involving the actual folding up of the arrays against the telescope. Each array stands on a four foot mast that supports a retractable wing of solar panels 12 m long and 2.5 m wide. They supply the telescope with 4.5 kW of power.

Spacewalk #2

Flight Day 5 began on Sunday night (December 5, 1993) at 10:35 EST. Astronauts Thomas D. Akers and Kathryn C. Thornton replaced HST's solar arrays during the second planned EVA (Thornton had red dashed stripes on her spacesuit while Tom Akers had diagonal red dashed stripes, which helped flight controllers tell the two spacewalkers apart.) At the start of the EVA, the pressure in Thornton's vent garment was 0.2 psi (1.4 kPa) instead of the normal pressure of 4 to 6 psi (28 to 41 kPa). This was due to a possible ice plug in the suit's plumbing which shortly melted. Thornton then topped off her suit. There were also other problems with Thornton's EVA suit. Her communications receiver malfunctioned in a way that allowed her to communicate to Akers but not to Mission Control. The crew decided to use a technique of relaying all commands for Thornton via Akers instead of switching to the backup comm channel. The backup channel is used for suit biomedical telemetry and would have limited Mission Control's ability to monitor that telemetry.

Akers started the EVA by installing a foot restraint on the RMA for Thornton and proceeded to begin disconnecting three electrical connectors and a clamp assembly on the solar array. He had a slight problem with the clamp assembly but had the connectors demated by 11:17 p.m. EST. Thornton held the array in place so that it would not drift freely after being detached. The solar arrays weigh 160 kilograms (350 lb) and are 5 meters (16 ft) long when folded. The astronauts dismounted the damaged array at 11:40 p.m. EST above the Sahara (during a nighttime pass to minimize electrical activity), and Thornton held the array until the next daylight pass (approximately 12 min) before throwing it overboard at 11:52 p.m. EST over Somalia. The jettison during daylight allowed the astronauts and flight controllers to accurately track its position and relative velocity. The release by Thornton imparted zero velocity to the arrays and then the orbiter did a small burn to put some distance between it and the array. The array, moving away from Endeavour at 5 feet per second (1.5 m/s), separated about 11 to 12 miles (18 to 19 km) each orbit. The crew then installed a new array, (finishing around 1:40 EST) and rotated the telescope 180 degrees. They then replaced the second solar array which was stowed away for return to ESA. After the 6.5 hour EVA, successful functional tests were performed by the Space Telescope Operations Control Center (STOCC) on four of HST's six gyros. Gyros 1 and 2 were not able to be tested due to the orientation of the telescope and were tested during the crew sleep period Monday afternoon (December 6, 1993).

Spacewalk #3 (Flight Day 6)

The third EVA began December 6, 1993 at 10:34 p.m. EST while Endeavour was over Australia. Hoffman installed guide studs on the Wide Field Planetary Camera (WFPC) and prepared the WFPC for removal while Musgrave setup a work platform and worked on opening an access door to allow observation of WFPC status lights. Hoffman attached the support handle to the WFPC and, with assistance by Claude Nicollier on the arm and a free floating Story Musgrave, removed the WFPC during the night pass starting at 11:41 p.m. EST. The WFPC was clear of the telescope by 11:48 p.m. EST and moved back into its storage container. A protective hood was then removed on the new WFPC (protecting its fragile external mirror) and the new 620-pound (280 kg) WFPC was then installed at 1:05 a.m. EST. Ground controllers then ran an Aliveness Test and 35 minutes later reported that the new camera successfully performed its series of initial tests. The new Wide Field and Planetary Camera had a higher rating than the previous model, especially in the ultraviolet range, and included its own spherical aberration correction system.

Following the WFPC installation, Hoffman changed out two magnetometers on board HST. The magnetometers, which are located at the top of the telescope, are the satellite's "compass". They enable HST to find its orientation with respect to the Earth's magnetic field. Both original units were suffering from problems of background noise. During installation, two pieces peeled off the magnetometers. The EVA lasted 6 hours and 47 minutes.

Spacewalk #4 (Flight Day 7)

The fourth EVA began on December 7, 1993, while *Endeavour* was flying over Egypt at 10:13 p.m. EST with Thornton and Akers. The primary task of the EVA was to replace HST's High Speed Photometer (HSP) with a device called COSTAR. This acronym stands for the Corrective Optics Space Telescope Axial Replacement system and the unit corrected HST's spherical aberration of the main mirror for all instruments except the WFPC-II camera, which had its own built-in corrective optics. Akers received a go for the opening of HST's -V2 aft shroud doors at 10:45 p.m. EST. The doors were scheduled to be opened during a night pass to minimize thermal changes and reduce the possibility of out-gassing of components that could contaminate the optics. The High Speed Photometer (HSP) was powered down at 10:54 p.m. EST and the door opening started at 10:57 EST. Shortly after partially opening the door, the astronauts practiced reclosing the door. The door exhibited the same reluctance upon closing that was experienced on different doors during previous EVAs. The doors were fully opened by 11:00 p.m. EST and four power and data connectors plus one ground strap were disconnected from the HSP. The HSP was removed at 11:27 p.m. EST and then reinserted to practice for the COSTAR installation. HSP was then parked on the side of the payload bay while COSTAR was removed from stowage and successfully installed in the HST by about 12:35 a.m. EST. The astronauts closed out the HST equipment bay doors and stowed the HSP. At 2:25 a.m. EST they started upgrading HST's onboard computer by bolting on an electronics package containing additional computer memory and a co-processor. The computer system was then reactivated and passed its aliveness and functional tests at 4:41 a.m. EST. The EVA was 100% successful and lasted for 6 h 50 min.

Pilot Kenneth D. Bowersox, using *Endeavour*'s RCS system, performed two orbital manueuvers and boosted HST from a 321-by-317-nautical-mile (594 by 587 km) orbit to a 321.7-by-320.9-nautical-mile (595.8 by 594.3 km) circular orbit at 9:14 p.m. EST. COSTAR functional tests were also completed. There was some concern about the health of the onboard HST DF-224 computer and recently installed memory and co-processor when a memory dump failed. After much analysis by a team at the GSFC, it was determined that the dump failure was due to noise on the communications link between the spacecraft and the ground.

Spacewalk #5 (Flight Day 8)

Story Musgrave, anchored on the end of the Remote Manipulator System arm, prepares to be elevated to the top of the Hubble Space Telescope to install protective covers on the magnetometers.

The fifth EVA began on December 8, 1993 at 10:14 p.m. with a "go" for airlock depress over the Indian Ocean with Musgrave and Hoffman performing the EVA. Musgrave's EVA suit failed its initial leak check, and Musgrave performed steps on the 5 psi (34 kPa) contingency checklist. He rotated the EVA suit's lower arm joints and the suit passed two subsequent leak checks. The EVA started at 10:30 EST and lasted 7 h 21 min.

Musgrave's and Hoffman's first task was to replace the solar array drive electronics and they began the SADE operation while ground controllers initiated the first step in solar array deployment by commanding the Primary Drive Mechanism (PDM). *Endeavour* was placed in free drift to disable any RCS firings that could disrupt the solar arrays and the PDM motors were engaged at 10:48 p.m. The latches were unlocked but the arrays failed to rotate to the deploy position. No motion was detected and the STOCC sent commands to drive a single array with two motors with no success. Finally, the astronauts cranked the deployment mechanism by hand and deploy was successful. After the SADE was swapped out, the crew fitted an electrical connection box on the Goddard High Resolution Spectrograph at 3:30 a.m. EST and it passed its aliveness test. The crew then installed some covers on the magnetometers, fabricated onboard by Claude Nicollier and Kenneth D. Bowersox. These covers would contain any debris caused by the older magnetometers that showed some signs of UV decay. The EVA ended at 5:51 a.m. EST bringing the total EVA time for this mission to 35 h 28 min. The HST High Gain Antenna (HGA) was deployed at 6:49 a.m. EST and completed by 6:56 a.m. EST. Release time for HST was set for 2:08 a.m. EST.

Release of Hubble and Landing

Flight Day 9 began on December 9, 1993, but concerns about one of HST's four onboard Data Interface Units (DIU's) delayed release. The DIUs are 35 pounds (16 kg) electronic units that transfer data between HST's main computer, solar arrays and other critical systems. A failure on Side An of DIU #2 experienced erratic current fluctuations and some data dropouts. Controllers at the STOCC and mission control came up with a troubleshooting procedure to determine the extent of the problem. HST was transferred to internal power and disconnected from its power umbilical at 11:43 p.m. EST. Controllers then switched channels on the DIU from the A side to the B side and then back to the A side. They determined HST should be deployed. The drum brakes on the new Solar Array were applied to prevent them from vibrating during future observations. Claude Nicollier then took hold of the satellite with the robot arm. The satellite was then lifted and moved away from Endeavour. The telescope's aperture door was then reopened (a 33-minute procedure) and then released at 5:26 a.m. EST. Commander Dick Covey and pilot Kenneth D. Bowersox fired *Endeavour*'s small maneuvering jets and moved the shuttle slowly away from HST. Landing of the Shuttle occurred at Kennedy Space Center on Runway 33 at 12:26 a.m. on December 13, 1993.

Trivia

- This mission was the first to use a computer-controlled space tool, the Power Ratchet Tool (PRT).
- The crew of this mission appeared on *Tool Time* in a 1994 episode of *Home Improvement*.
- An IMAX camera was carried on this mission to film the repairs to Hubble, and this film ultimately appeared in the IMAX film Destiny in Space.
- STS-61 had the highest calculated risk (1 in 150) of a catastrophic failure due to space debris or micrometeorite impact. Article from Wired Science

STS-82

STS-82

Mission insignia

Mission statistics

Mission name	STS-82
Space shuttle	*Discovery*
Launch pad	39-A
Launch date	February 11, 1997, 3:55:17 am EST
Landing	February 21, 1997, 3:32 am EST, KSC, Runway 33
Mission duration	9 days, 23 hours, 38 minutes, 09 seconds
Number of orbits	149
Orbital altitude	360 miles (580 km)
Orbital inclination	28.45 degrees
Distance traveled	6,500,000 miles (10,460,000 km)

Crew photo

Related missions

Previous mission	**Subsequent mission**
STS-81	STS-83

STS-82 was a Hubble Space Telescope servicing mission by Space Shuttle *Discovery*. The mission launched from Kennedy Space Center, Florida, on February 11, 1997 and returned to earth on February 21, 1997 at Kennedy Space Center.

Crew

Position	Astronaut
Commander	Kenneth D. Bowersox Fourth spaceflight
Pilot	Scott J. Horowitz Second spaceflight
Mission Specialist 1	Joseph R. Tanner Second spaceflight
Mission Specialist 2	Steven A. Hawley Fourth spaceflight
Mission Specialist 3	Gregory J. Harbaugh Fourth spaceflight

Mission Specialist 4	Mark C. Lee Fourth spaceflight
Mission Specialist 5	Steven L. Smith Second spaceflight

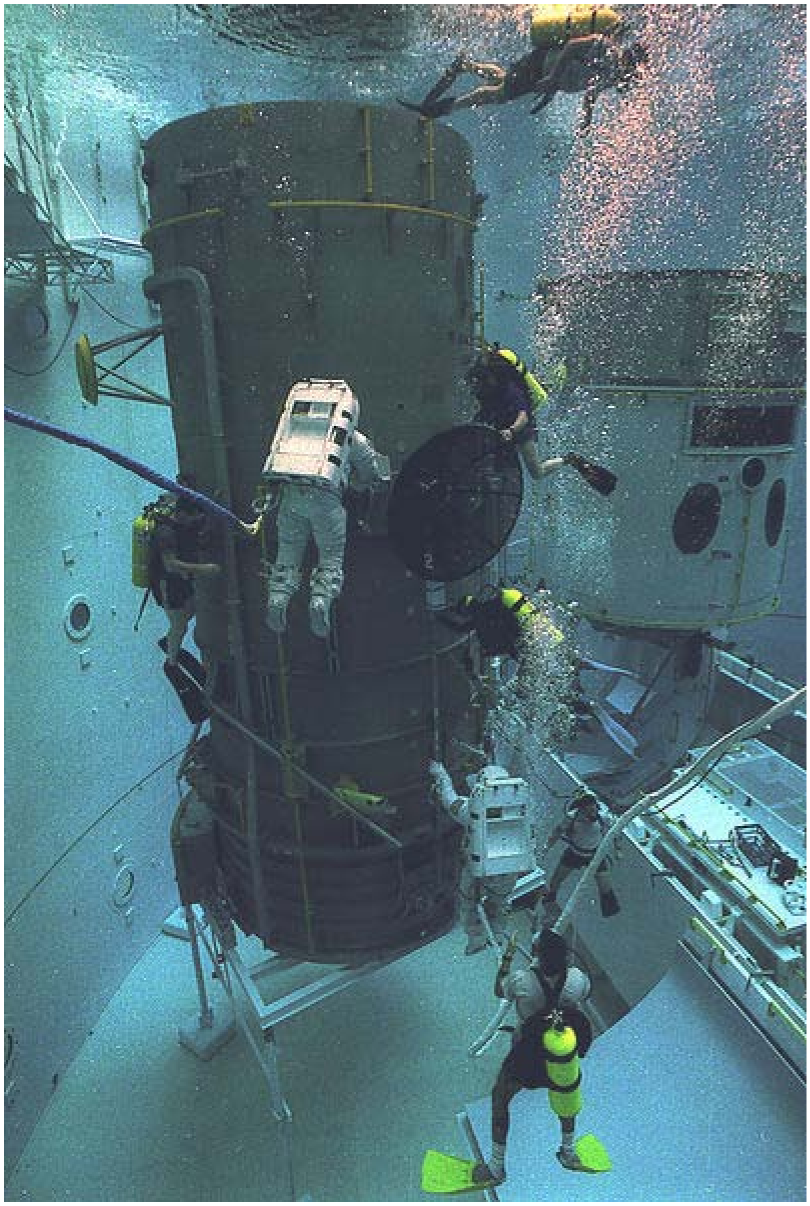
Mission parameters

- **Mass:** 83,122 kilograms (183,250 lb)
- **Perigee:** 475 kilometres (295 mi)
- **Apogee:** 574 kilometres (357 mi)
- **Inclination:** 28.4698°
- **Period:** 95.2 min

Space walks

- ***Lee and Smith*** - EVA 1
- **EVA 1 Start**: February 14, 1997 - 04:34 UTC
- **EVA 1 End**: February 14, - 11:16 UTC
- **Duration**: 6 hours, 42 minutes
- ***Harbaugh and Tanner*** - EVA 2
- **EVA 2 Start**: February 15, 1997 - 03:25 UTC
- **EVA 2 End**: February 15, - 10:52 UTC
- **Duration**: 7 hours, 27 minutes
- ***Lee and Smith*** - EVA 3
- **EVA 3 Start**: February 16, 1997 - 02:53 UTC
- **EVA 3 End**: February 16, - 10:04 UTC
- **Duration**: 7 hours, 11 minutes
- ***Harbaugh and Tanner*** - EVA 4
- **EVA 4 Start**: February 17, 1997 - 03:45 UTC
- **EVA 4 End**: February 17, - 10:19 UTC
- **Duration**: 6 hours, 34 minutes
- ***Lee and Smith*** - EVA 5
- **EVA 5 Start**: February 18, 1997 - 03:15 UTC
- **EVA 5 End**: February 18, - 18:32 UTC
- **Duration**: 5 hours, 17 minutes

Mission Objectives



Astronauts train in the Neutral Buoyancy Lab with a mockup of the HST

The STS-82 mission was the second in a series of planned servicing missions to the orbiting Hubble Space Telescope (HST). HST was placed in orbit on April 24, 1990 by the Space Shuttle Discovery on STS-31. The first servicing mission was done by Space Shuttle Endeavour on STS-61. Work performed on the telescope significantly upgraded the scientific capabilities of the HST and helped to keep the telescope functioning smoothly until the next scheduled servicing missions, which were STS-103 in 1999 and STS-109 in 2002.

Starting on the third day of the mission, the seven-member crew were to conduct four spacewalks (also called Extra-vehicular Activities or EVAs) to remove two older instruments and install two new astronomy instruments, as well as other servicing tasks. The two older instruments being replaced are the Goddard High Resolution Spectrograph and the Faint Object Spectrograph. Replacing these instruments are the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). HST's current complement of science instruments includes two cameras, two spectrographs, and fine guidance sensors.

In addition to installing the new instruments, astronauts will replace other existing hardware with upgrades and spares. Hubble received a refurbished Fine Guidance Sensor, an optical device that is used on HST to provide pointing information for the spacecraft and is used as a scientific instrument for astrometric science. The Solid State Recorder (SSR) will replace one of HST's current reel-to-reel tape recorders. The SSR provides much more flexibility than a reel-to-reel recorder and can store ten times more data. One of Hubble's four Reaction Wheel Assemblies (RWA) will be replaced with a refurbished spare. The RWA is part of Hubble's Pointing Control Subsystem. The RWAs use spin momentum to move the telescope into position. The wheels also maintain the spacecraft in a stable position. The wheel axes are oriented so that the telescope can provide science with only three wheels operating, if required.

Mission Results

Joseph Tanner performing maintenance on the Hubble Space Telescope

STS-82 demonstrated anew the capability of the Space Shuttle to service orbiting spacecraft as well as the benefits of human spaceflight. The crew completed servicing and upgrading of the Hubble Space Telescope during four planned extravehicular activities (EVAs) and then performed a fifth unscheduled space walk to repair insulation on the telescope.

HST deployed in April 1990 during STS-31. It was designed to undergo periodic servicing and upgrading over its 15-year lifespan, with first servicing performed during STS-61 in December 1993. Hawley, who originally deployed the telescope, operated the orbiter Remote Manipulator System arm on STS-82 to retrieve HST for second servicing at 3:34 a.m. EST, Feb. 13, and positioned it in payload bay less than half an hour later.

Relying on more than 150 tools and crew aids, Lee and Smith performed EVAs 1, 3 and 5, and Harbaugh and Tanner did EVAs 2 and 4. EVA 1 began at 11:34 p.m. EST, February 13, and lasted six hours, 42 minutes. One of Hubble's solar arrays was unexpectedly disturbed by gust of air from Discovery's airlock when it was depressurized, but was not damaged. Lee and Smith removed two scientific instruments from Hubble, the Goddard High Resolution Spectrograph (GHRS) and Faint Object Spectrograph (FOS), and replaced them with the Space Telescope Imaging Spectrograph (STIS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS), respectively. STIS expected to shed further light on supermassive black holes. NICMOS features more capable infrared detectors and will give astronomers their first clear view of the universe at near infrared wavelengths between 0.8 and 2.5 micrometers.

EVA 2 began at 10:25 p.m., February 14, and lasted seven hours, 27 minutes. Harbaugh and Tanner replaced a degraded Fine Guidance Sensor and a failed Engineering and Science Tape Recorder with new spares. Also installed a new unit called the Optical Control Electronics Enhancement Kit, which will further increase the capability of the Fine Guidance Sensor. During this EVA astronauts noted cracking and wear on thermal insulation on side of telescope facing sun and in the direction of travel.

EVA 3 began at 9:53 p.m., February 15, and lasted seven hours, 11 minutes. Lee and Smith removed and replaced a Data Interface Unit on Hubble, as well as an old reel-to-reel- style Engineering and Science Tape Recorder with a new digital Solid State Recorder (SSR) that will allow simultaneous recording and playback of data. Also changed out one of four Reaction Wheel Assembly units that use spin momentum to move telescope toward a target and maintain it in a stable position. After this EVA, mission managers decided to add EVA 5 to repair the thermal insulation on HST.

EVA 4 began at 10:45 p.m., February 16, and lasted six hours, 34 minutes. Harbaugh and Tanner replaced a Solar Array Drive Electronics package which controls the positioning of Hubble's solar arrays. Also replaced covers over Hubble's magnetometers and placed thermal blankets of multi-layer material over two areas of degraded insulation around the light shield portion of the telescope just below the top of the observatory. Meanwhile, inside Discovery Horowitz and Lee worked on the middeck to fabricate new insulation blankets for HST.

Final space walk, EVA 5, lasted five hours, 17 minutes. Lee and Smith attached several thermal insulation blankets to three equipment compartments at the top of the Support Systems Module section of the telescope which contain key data processing, electronics and scientific instrument telemetry packages. STS-82 EVA total of 33 hours, 11 minutes is about two hours shy of total EVA time recorded on first servicing mission.

Discovery's maneuvering jets fired several times during mission to reboost telescope's orbit by eight nautical miles. Hubble redeployed on Feb. 19 at 1:41 a.m. and is now operating at the highest altitude it has ever flown, a 335-nautical-mile (620 km) by 321-nautical-mile (594 km) orbit. Initial checkout of new instruments and equipment during mission showed all were performing nominally. Calibration of two new science instruments was to take place over a period of several weeks with first images and data anticipated in about eight to 10 weeks.

Wake-up calls

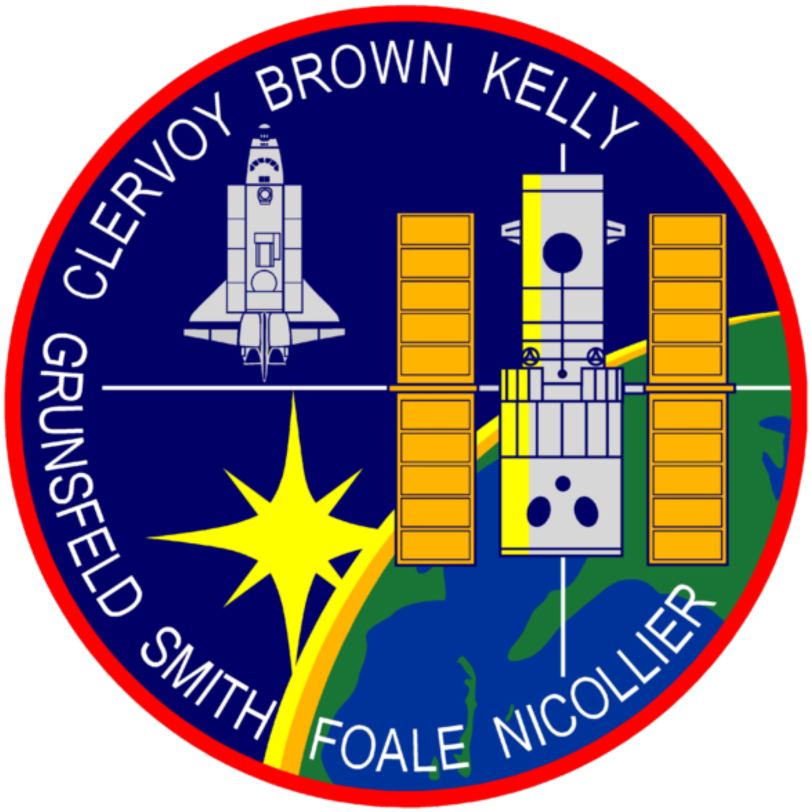
NASA began a tradition of playing music to astronauts during the Gemini program, which was first used to wake up a flight crew during Apollo 15. Each track is specially chosen, often by their families, and usually has a special meaning to an individual member of the crew, or is applicable to their daily activities.

Flight Day	Song	Artist/Composer
Day 2	*Magic Carpet Ride*	Steppenwolf
Day 3	*These Are Days*	10,000 Maniacs
Day 4	*Two Princes*	Spin Doctors
Day 5	*Higher Love*	Steve Winwood
Day 6	*The Packerena*	WMYX-FM
Day 7	*Shiny Happy People*	R.E.M.
Day 8	*Dreams*	The Cranberries
Day 9	*That Thing You Do*	The Wonders
Day 10	*Five Hundred Miles Away From Home*	Reba McEntire
Day 11	*Born to Be Wild*	Steppenwolf

STS-103

STS-103

Mission insignia



Mission statistics

Mission name	STS-103
Space shuttle	*Discovery*
Launch pad	39-A
Launch date	19 December 1999 19:50:00 EST
Landing	27 December 1999 19:01:34 EST, KSC, Runway 33
Mission duration	7 days, 23 hours, 11 minutes 34 seconds
Orbital altitude	587 kilometres (365 mi)
Orbital inclination	28.45 degrees
Distance traveled	5,230,000 kilometres (3,250,000 mi)

Crew photo

Related missions

Previous mission	Subsequent mission
STS-93 	STS-99 

STS-103 was a Hubble Space Telescope servicing mission by Space Shuttle *Discovery*. The mission launched from Kennedy Space Center, Florida, on 19 December 1999.

Crew

Position	Astronaut
Commander	Curtis L. Brown Sixth spaceflight
Pilot	Scott J. Kelly First spaceflight
Mission Specialist 1	Steven L. Smith Third spaceflight
Mission Specialist 2	Jean-François Clervoy, ESA Third spaceflight
Mission Specialist 3	John M. Grunsfeld Third spaceflight

Mission Specialist 4	C. Michael Foale Fifth spaceflight
Mission Specialist 5	Claude Nicollier, ESA Fourth spaceflight

Mission parameters

- **Mass:**
    - *Orbiter Liftoff:* 112,493 kilograms (248,000 lb)
    - *Orbiter Landing:* 95,768 kilograms (211,130 lb)
- **Perigee:** 563 kilometres (350 mi)
- **Apogee:** 609 kilometres (378 mi) (highest Shuttle orbit on record)
- **Inclination:** 28.5°
- **Period:** 96.4 min

Space walks

- ***Smith and Grunsfeld*** - EVA 1
- **EVA 1 Start**: 22 December 1999 - 18:54 UTC
- **EVA 1 End**: 23 December 1999- 03:09 UTC
- **Duration**: 8 hours, 55 minutes
- ***Foale and Nicollier*** - EVA 2
- **EVA 2 Start**: 23 December 1999 - 19:06 UTC
- **EVA 2 End**: 24 December 1999 - 03:16 UTC
- **Duration**: 8 hours, 10 minutes
- ***Smith and Grunsfeld*** - EVA 3
- **EVA 3 Start**: 24 December 1999 - 19:17 UTC
- **EVA 3 End**: 25 December 1999 - 03:25 UTC
- **Duration**: 8 hours, 08 minutes

Mission highlights

Astronauts Steven L. Smith, and John M. Grunsfeld are replacing rate sensor units

The primary objective of STS-103 was the Hubble Servicing Mission 3A. STS-103 had four scheduled Extravehicular Activity (EVA) days where four crew members will work in pairs on alternating days to renew and refurbish the telescope.

NASA officials decided to move up part of the servicing mission that had been scheduled for June 2000 after three of the telescope's six gyroscopes failed. Three gyroscopes must be working to meet the telescope's very precise pointing requirements, and the telescope's flight rules dictated that NASA consider a "call-up" mission before a fourth gyroscope failed. Four new gyros were installed during the first servicing mission (STS-61) in December 1993 and all six gyros were working during the second servicing mission (STS-82) in February 1997. Since then, a gyro failed in 1997, another in 1998 and a third in 1999. The Hubble team believes they understand the cause of the failures, although they cannot be certain until the gyros are returned from space. Having fewer than three working gyroscopes would preclude science observations, although the telescope would remain safely in orbit until a servicing crew arrived.

In addition to replacing all six gyroscopes on the December flight, the crew will replace a guidance sensor, the spacecraft's computer and install a voltage/temperature kit for the spacecraft's batteries. A new transmitter, solid state recorder and thermal insulation blankets will also be installed.

Hubble's gyros spin at a constant rate of 19,200 rpm on gas bearings. This wheel is mounted in a sealed cylinder, which floats in a thick fluid. Electricity is carried to the motor by thin wires (approximately the size of a human hair). It is believed that oxygen in the pressurized air used during the assembly process caused the wires to corrode and break. The new gyros were assembled using nitrogen instead of oxygen. Each gyroscope is packaged in a Rate Sensor assembly. The Rate Sensors are packaged in pairs into an assembly called a Rate Sensor Unit (RSU's). It is the RSU's that the STS-103's astronauts will be changing. The RSU's each weigh 11.0 kilograms (24 lb) and are 12.8 by 10.5 by 8.9 inches (325 by 267 by 226 mm) in size.

In addition to replacing all six gyroscopes on the December flight, the crew will replace a Fine Guidance Sensor (FGS) and the spacecraft's computer. The new computer will reduce the burden of flight software maintenance and significantly lower costs. The new computer is 20 times faster and has six times the memory of the DF-224 computer previously used on Hubble. It weighs 32.0 kilograms (71 lb) and is 18.8 by 18 by 13 inches (478 by 457 by 330 mm) in size. The FGS being installed is a refurbished unit that was returned from Servicing Mission 2. It weighs 217 kilograms (480 lb) and is 5.5 by 4 by 2 feet (1.68 by 1.22 by 0.61 m) in size.

A voltage/temperature improvement kit (VIK) will be also be installed to protect spacecraft batteries from overcharging and overheating when the spacecraft goes into safe mode. The VIK modifies the charge cutoff voltage to a lower level to prevent battery overcharging and associated overheating. The VIK weighs about 1.4 kilograms (3.1 lb).

The repair mission will also install a new S-Band Single Access Transmitter (SSAT). Hubble has two identical SSATs onboard and can operate with only one. The SSATs send data from Hubble through NASA's Tracking Data Relay Satellite System (TDRSS) to the ground. The new transmitter will replace one that failed in 1998. The SSAT weighs 3.9 kilograms (8.6 lb) and is 14 by 8 by 2¾ inches (356 by 203 by 70 mm).

A spare solid state recorder will also be installed to allow efficient handling of high-volume data. Prior to the second servicing mission, Hubble used three 1970s style reel-to-reel tape recorders. During the second servicing mission one of these mechanical recorders was replaced with a digital solid state recorder. During this mission a second mechanical recorder will be replaced by a second Solid State Recorder. The new recorder can hold approximately 10 times as much data as the old unit (12 gigabytes instead of 1.2 gigabytes). The recorder weighs 11.3 kilograms (25 lb) and is 12 by 9 by 7 inches in size.

Finally, the EVA crew will replace the telescopes outer insulation that has degraded. The insulation is necessary to control the internal temperature on the Hubble. The New Outer Blanket Layer (NOBL) and Shell/Shield Replacement Fabric (SSRF) will help protect Hubble from the harsh environment of space. It protects the telescope from the severe and rapid temperature changes it experiences during each 90 minute orbit as it moves from sunlight to darkness.

STS-103 will also carry hundreds of thousands of student signatures as part of the Student Signatures in Space (S3) program. The unique project provides elementary schools (selected on a rotating basis) with special posters to be autographed by students, then scanned onto disks and carried aboard a NASA Space Shuttle mission.

On STS-103, the shuttle Discovery reached the highest orbit ever flown in the program's history, at the apogee of 609 kilometers (378 miles) above Earth.

STS-103 was the shuttle Discovery's last solo spaceflight. All later missions by Discovery were International Space Station missions.

Attempt	Planned	Result	Turnaround	Reason	Decision point	Weather go %	Notes
1	6 Dec 1999, 2:37:00 am	scrubbed	---	technical			additional wiring inspection
2	16 Dec 1999, 9:18:00 pm	scrubbed	10 days, 18 hours, 41 minutes	technical			concern about fuel line welds
3	18 Dec 1999, 8:21:00 pm	scrubbed	1 days, 23 hours, 3 minutes	weather			
4	19 Dec 1999, 7:50:00 pm	success	0 days, 23 hours, 29 minutes			60%	

Trivia

Astronaut John Grunsfeld, who was one of the mission specialists on this mission, brought a "Planet Mars Flag" aboard shuttle *Discovery*.

The Mars flag

Wake-up calls

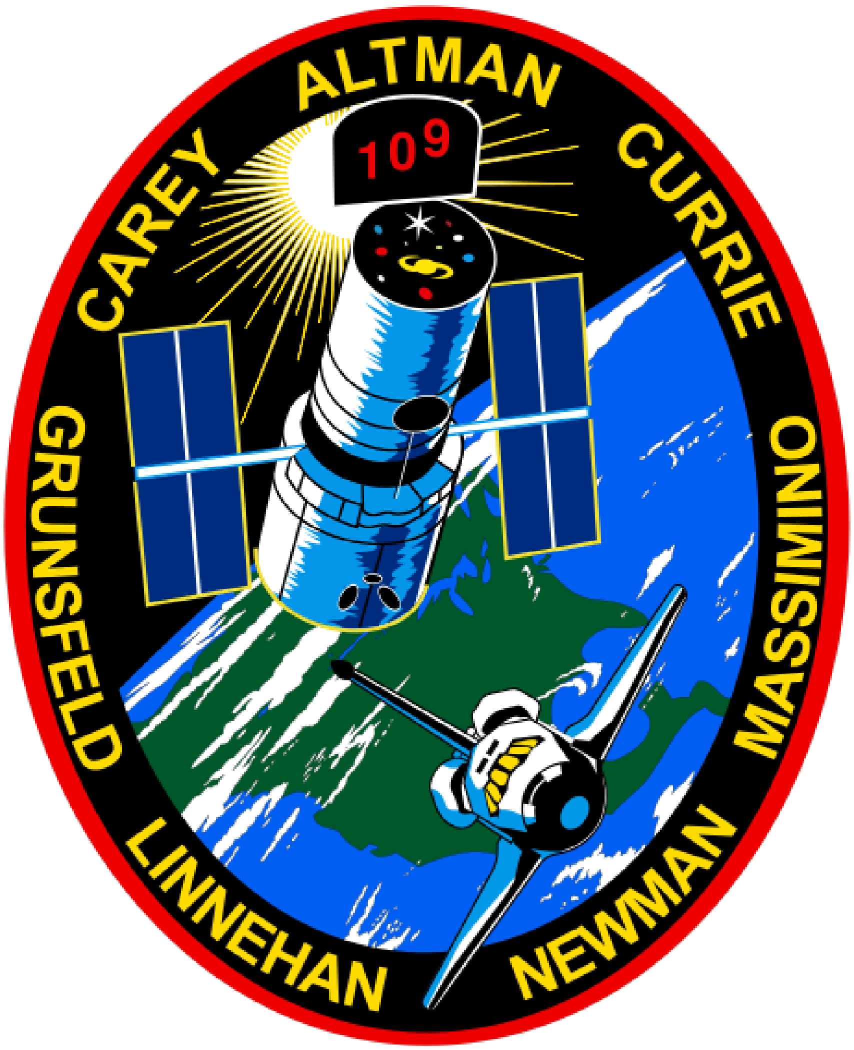
NASA began a tradition of playing music to astronauts during the Gemini program, which was first used to wake up a flight crew during Apollo 15. Each track is specially chosen, often by their families, and usually has a special meaning to an individual member of the crew, or is applicable to their daily activities.

Flight Day	Song	Artist/Composer
Day 2	*Takin' Care of Business*	Bachman-Turner Overdrive
Day 3	*Rendezvous*	Bruce Springsteen
Day 4	*Hucklebuck*	Beau Jocque and the Zydeco Hi-Rollers
Day 6	*Magic Carpet Ride*	Steppenwolf
Day 7	*I'll Be Home for Christmas*	Bing Crosby
Day 8	*We're So Good Together*	Reba McEntire
Day 9	*The Cup of Life*	Ricky Martin

STS-109

STS-109

Mission insignia



Mission statistics

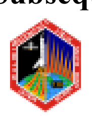
Mission name	STS-109
Space shuttle	*Columbia*
Crew size	7
Launch pad	39-A
Launch date	March 1, 2002 11:22:02 UTC

Landing	March 12, 2002 9:33:10 UTC KSC Runway 33
Mission duration	10d 22h 11m 09s
Number of orbits	165
Orbital altitude	570 kilometres (310 nmi)
Orbital inclination	28.5 degrees
Distance traveled	6,300,000 kilometres (3,910,000 mi)

Crew photo

(L-R): Michael J. Massimino, Richard M. Linnehan, Duane G. Carey, Scott D. Altman, Nancy J. Currie, John M. Grunsfeld and James H. Newman.

Related missions

Previous mission	**Subsequent mission**
STS-108 	STS-110 

STS-109 (SM3B) was a Space Shuttle mission that launched from the Kennedy Space Center on March 1, 2002. It was the 108th mission of the Space Shuttle program, the 27th flight of the orbiter *Columbia* and the fourth servicing of the Hubble Space Telescope. It was also the last successful mission of the orbiter *Columbia* before the ill-fated STS-107 mission, which culminated in the *Columbia* Disaster.

The Hubble Space Telescope (HST) was placed in orbit during mission STS-31 on April 25, 1990. Initially designed to operate for 15 years, plans for periodic service and refurbishment were incorporated into its mission from the start. After the successful completion of the second planned service mission (SM2) by the crew of STS-82 in February 1997, three of HST's six gyroscopes failed. NASA decided to split the third planned service mission into two parts, SM3A and SM3B. A fifth and final servicing mission, STS-125 (SM4) launched May 11, 2009 The work performed during SM4 is expected to keep HST in operation through 2014. Further plans for servicing after SM4 are ambiguous as NASA is planning to launch HST's successor, the James Webb Space Telescope in 2014.

Crew

Position	Astronaut
Commander	Scott D. Altman Third spaceflight
Pilot	Duane G. Carey First spaceflight
Mission Specialist 1	John M. Grunsfeld Fourth spaceflight Payload Commander
Mission Specialist 2	Nancy J. Currie Fourth spaceflight
Mission Specialist 3	Richard M. Linnehan Third spaceflight
Mission Specialist 4	James H. Newman Fourth spaceflight
Mission Specialist 5	Michael J. Massimino First spaceflight

Mission parameters

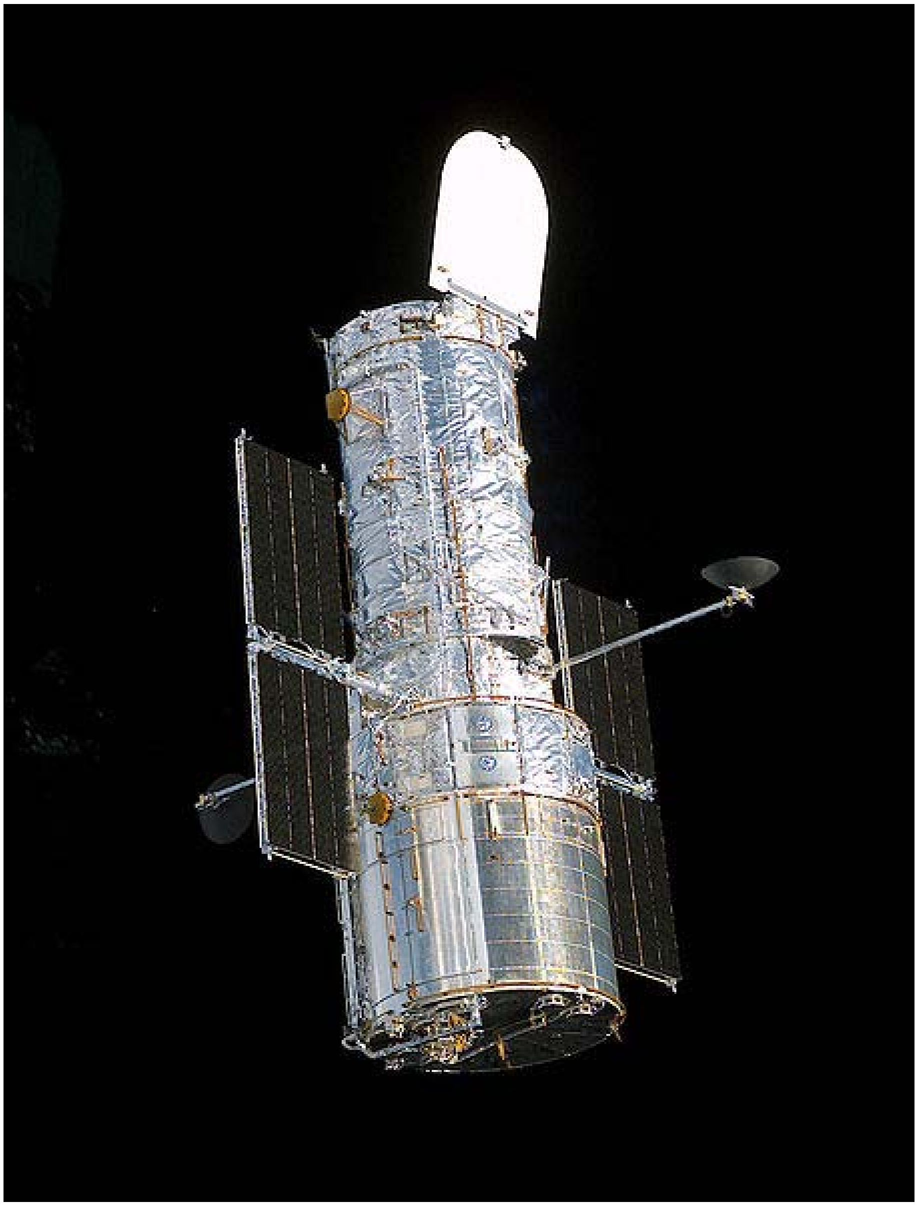
- **Mass:**
  - *Orbiter liftoff:* 116,989 kg (257,920 lb)
  - *Orbiter landing:* 100,564 kg (221,710 lb)
- **Perigee:** 486 km (302 mi)
- **Apogee:** 578 km (359 mi)
- **Inclination:** 28.5°
- **Period:** 95.3 min

Spacewalks

Hubble Space Telescope sporting new solar arrays during SM3B

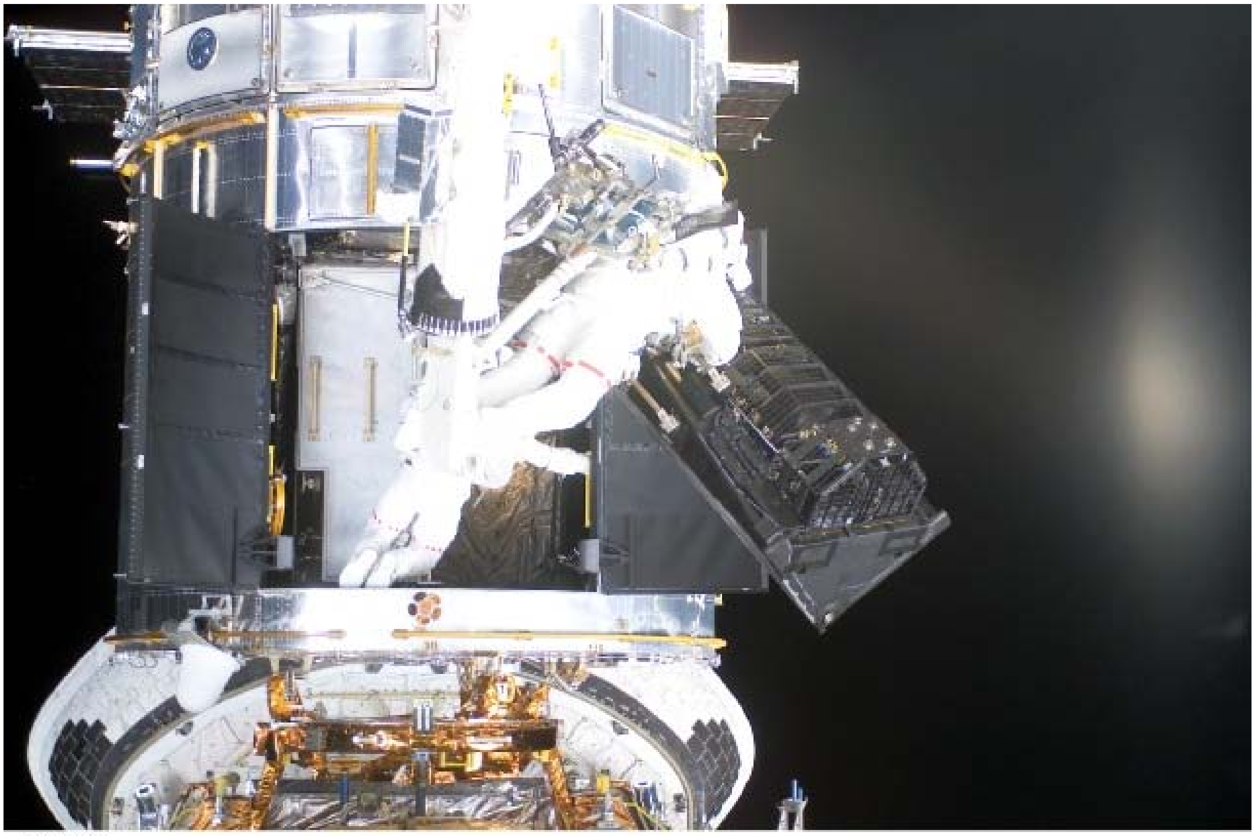
EVA	Team	Start - UTC	End - UTC	Duration
1	Grunsfeld Linnehan	March 4, 2002, 06:37	March 4, 2002, 13:38	7:01
2	Newman Massimino	March 5, 2002, 06:40	March 5, 2002, 13:56	7:16
3	Grunsfeld Linnehan	March 6, 2002, 08:28	March 6, 2002, 15:16	6:48
4	Newman Massimino	March 7, 2002, 09:00	March 7, 2002, 16:18	7:18
5	Grunsfeld Linnehan	March 8, 2002, 08:46	March 8, 2002, 16:18	7:32

Mission highlights



Hubble Space Telescope after servicing by the crew of STS-109

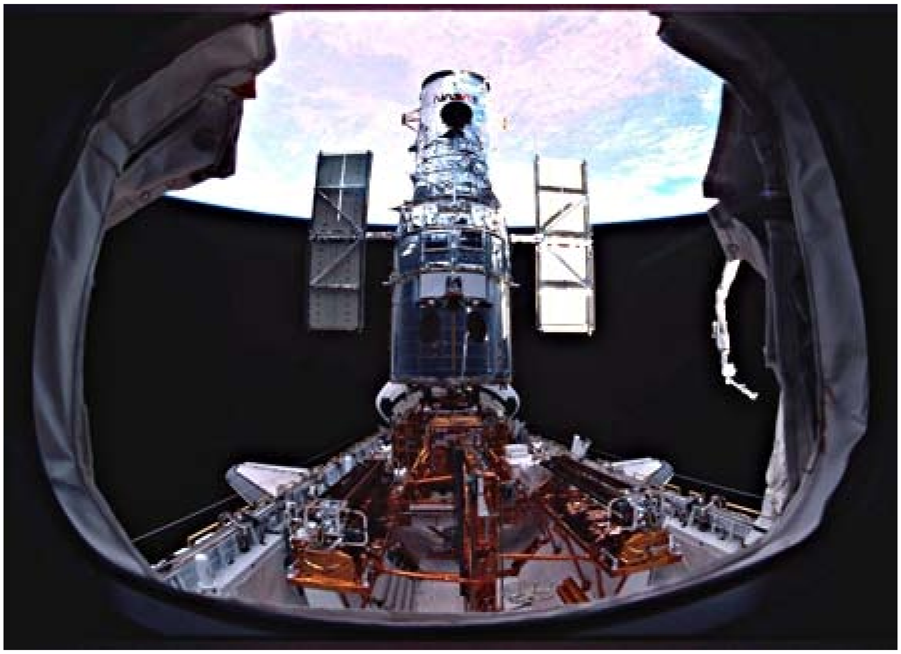
The purpose of **STS-109** was to service the Hubble Space Telescope (HST). It was *Columbia's* first flight following an extensive two and a half year modification period (its most recent mission being STS-93). During the mission they installed a new science instrument, the Advanced Camera for Surveys (ACS), new rigid Solar Arrays (SA3), new Power Control Unit (PCU) and a new Cryocooler for the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). STS-109 also reboosted HST to a higher orbit.



Astronauts remove the FOC to make room for the ACS

The STS-109 astronauts performed a total of five spacewalks in five consecutive days to service and upgrade the Hubble Space Telescope. The spacewalkers received assistance from their crewmates inside *Columbia*. Currie operated the Shuttle's robot arm while Altman was her backup. Carey and Altman documented the EVA activities with video and still images.

Accomplishments of the spacewalks included the installation of new solar arrays, a new camera, a new Power Control Unit, a Reaction Wheel Assembly and an experimental cooling system for the NICMOS unit. STS-109 accumulated a total of 35 hours, 55 minutes of EVA time. Following STS-109, a total of 18 spacewalks had been conducted during four Space Shuttle missions to service Hubble (the others being STS-61, STS-82, STS-103 and STS-125) for a total of 129 hours, 10 minutes by 14 different astronauts.



Hubble on the payload bay just prior to being released by the STS-109 crew

It was also the last successful flight of the *Columbia* orbiter, as on its next mission, STS-107, it disintegrated on re-entry, killing all on board.

STS-109 is considered a night launch, as sunrise was at 6:47 AM, and *Columbia* launched at 6:22 AM EST, 25 minutes before sunrise.

Attempt	Planned	Result	Turnaround	Reason	Decision point	Weather go %	Notes
1	21 Feb 2002, 10:22:00 am	scrubbed	---				
2	28 Feb 2002, 6:48:00 am	scrubbed	6 days, 20 hours, 26 minutes	technical	21 Feb 2002, 10:00 am	60%	wrong bearings installed on shuttles main landing gear
3	1 Mar 2002, 6:22:02 am	success	0 days, 23 hours, 34 minutes				

STS-125

STS-125

Mission insignia

Mission statistics

Mission name	STS-125
Space shuttle	*Atlantis*
Launch pad	LC-39A
Launch date	May 11, 2009, 2:01:56 p.m. EDT (18:01:56 UTC)
Landing	May 24, 2009, 11:39:05 a.m. EDT (15:39:05 UTC)

	Runway 22 - Edwards Air Force Base
Mission duration	12 days, 21 hours, 37 minutes, 9 seconds
Number of orbits	197
Apogee	578 kilometres (359 mi)
Perigee	486 kilometres (302 mi)
Orbital period	97 min
Orbital altitude	570 kilometres (310 nmi)
Orbital inclination	28.5° at 304 nautical miles
Distance traveled	5.3 million miles

Crew photo

From left to right: Massimino, Good, Johnson, Altman, McArthur, Grunsfeld and Feustel

Related missions

Previous mission	**Subsequent mission**
STS-119	STS-127

STS-125, or **HST-SM4** (**Hubble Space Telescope Servicing Mission 4**), was the fifth and final space shuttle servicing mission to the Hubble Space Telescope (HST). Launch occurred on May 11, 2009 at 2:01 p.m. EDT. Landing occurred on May 24 at 11:39 a.m. EDT, with the mission lasting a total of just under 13 days.

Space Shuttle *Atlantis* carried two new instruments to the Hubble Space Telescope, the Cosmic Origins Spectrograph and the Wide Field Camera 3. The mission also replaced a Fine Guidance Sensor, six gyroscopes, and two battery unit modules to allow the telescope to continue to function at least through 2014. The crew also installed new thermal blanket insulating panels to provide improved thermal protection, and a soft-capture mechanism that would aid in the safe de-orbiting of the telescope by an unmanned spacecraft at the end of its operational lifespan. The mission also carried an IMAX camera and the crew documented the progress of the mission for an upcoming IMAX movie.

The crew of STS-125 included three astronauts who had previous experience servicing Hubble. Scott Altman visited Hubble in 2002 as commander of STS-109, the fourth Hubble servicing mission. John Grunsfeld, an astronomer, has serviced Hubble twice, performing a total of five spacewalks on STS-103 in 1999 and STS-109. Michael Massimino served with both Altman and Grunsfeld on STS-109, and performed two spacewalks to service the telescope.

NASA managers and engineers declared the mission a complete success. The completion of all the major objectives, as well as some that were not considered vital, upgraded the Hubble telescope to its most technologically advanced state since its launch nineteen years before and made it more powerful than ever. The upgrades will help Hubble to see deeper into the universe and farther into the past, closer to the time of the Big Bang.

STS-125 was the first visit to the Hubble Space Telescope for *Atlantis*; the telescope had been previously serviced twice by *Discovery* and once each by *Columbia* and *Endeavour*. The mission was the thirtieth flight of Space Shuttle *Atlantis* and the first flight of *Atlantis* in over 14 years (since STS-66) not to visit a space station.

Crew

Prince Philip of the United Kingdom visited Goddard Space Flight Center in May of 2007 and met with the crew of STS-125

Position	Astronaut
Commander	Scott Altman Fourth spaceflight
Pilot	Gregory C. Johnson First spaceflight
Mission Specialist 1	Michael T. Good First spaceflight EV4
Mission Specialist 2	Megan McArthur First spaceflight Flight Engineer, Lead robotics
Mission Specialist 3	John M. Grunsfeld Fifth spaceflight Lead spacewalker, EV1
Mission Specialist 4	Michael J. Massimino Second spaceflight

	EV3
Mission Specialist 5	Andrew J. Feustel First spaceflight EV2

Mission history

The fifth servicing mission to Hubble, HST-SM4, was originally scheduled to launch in late 2005 or early 2006. On January 16, 2004, then-NASA Administrator Sean O'Keefe canceled the mission, as well as any future missions to Hubble, citing safety constraints imposed by the *Columbia* Accident Investigation Board. During the announcement, O'Keefe stated that it was his decision alone, and not a recommendation from any other departments. The decision was widely criticized by the media, the science community, and those in NASA. Maryland Senator Barbara Mikulski, a member of the Senate subcommittee that oversees NASA's budget, publicly accused O'Keefe of making a decision outside the transparency process against the wishes of the science community, and stated she would work to reverse the decision. In March 2004, Representative Mark Udall introduced a bill to the House of Representatives that requested an independent panel of experts review O'Keefe's decision to cancel the servicing mission. Also in March 2004, Space Telescope Science Institute (STScI) Director Stephen Beckwith released the results of the Hubble Ultra-Deep Field survey to the entire science community, which helped show the public how important Hubble was to science. The data showed the deepest images ever taken by a telescope and revealed approximately 10,000 galaxies, some of which most likely dated back to when the universe was just five hundred million years old. With Beckwith when he released the data to the scientific community was Mikulski, who said of the results, "I think it's just amazing... this is why I will continue to stand up for Hubble."

Joining Mikulski as an advocate for servicing Hubble was NASA's Chief Scientist, physicist John Grunsfeld, who was present at the meeting when O'Keefe announced the cancellation of the mission. A veteran astronaut of four shuttle missions, including two Hubble servicing missions, Grunsfeld had devoted years to Hubble, and was very disappointed when O'Keefe canceled the mission. He briefly considered retiring from NASA, but realized if he stayed, he could continue to advance physics in other ways. Instead, Grunsfeld dedicated himself to finding alternate ways to service the telescope, possibly by sending a robot into orbit to do the job. When O'Keefe announced his resignation as Administrator in December 2004, five days after a National Academy of Sciences committee opposed O'Keefe's position regarding servicing Hubble, the media and science community saw hope for the telescope's servicing mission to be reinstated.

O'Keefe's replacement, former NASA Administrator Michael D. Griffin took just two months after his appointment to announce that he disagreed with O'Keefe's decision, and would consider sending a shuttle to repair Hubble. As an engineer, Griffin had previously worked on Hubble's construction, and respected the discoveries the telescope brought to the science community. He agreed with the National Academy of Sciences that a robotic mission was not feasible, and said that in light of the Return to Flight changes made following the *Columbia* accident, a shuttle mission to repair Hubble should be reassessed. After the successes of the Return to Flight STS-114 and STS-121 missions, and the lessons learned and improvements made following those missions, managers and engineers worked to formulate a plan that would allow the shuttle to service Hubble, while still adhering to the post-*Columbia* safety requirements.

On October 31, 2006, Griffin announced that the Hubble servicing mission was reinstated, scheduled for 2008, and announced the crew that would fly the mission, which included Grunsfeld. Senator Mikulski expressed her delight at the news, stating "The Hubble telescope has been the greatest telescope since Galileo invented the first one. It has gone to look at places in the universe that we didn't know existed before."

Mission payload

Location	Cargo	Mass
Bays 1-2	Orbiter Docking System EMUs 3006, 3004, 3015, 3017	1,800 kilograms (4,000 lb) ~480 kilograms (1,100 lb)
Bay 3P	Shuttle Power Distribution Unit (SPDU)	~17 kilograms (37 lb)
Bay 4-5	SLIC /COPE with Wide Field Camera 3	2,990 kilograms (6,600 lb)
Bay 7-8	ORUC COS/RSU/FGS Cosmic Origins Spectrograph Fine Guidance Sensor, Gyros	3,339 kilograms (7,360 lb)
Bay 10P	GABA/MFR	~50 kilograms (110 lb)
Bay 10P	GABA/PFR	~50 kilograms (110 lb)
Bay 11	HST-FSS/BAPS/SCM Berthing and Positioning Sys Soft Capture Mechanism	2,177 kilograms (4,800 lb)
Bay 12	MULE RNS, NOBL blankets	1,409 kilograms (3,110 lb)
Starboard Sill	Orbiter Boom Sensor System	~382 kilograms (840 lb)
Port Sill	Canadarm 301	410 kilograms (900 lb)
	Total:	**13,104 kilograms (28,890 lb)**

The Cosmic Origins Spectrograph in the cleanroom

The mission added two new instruments to Hubble. The first instrument, the Cosmic Origins Spectrograph, is now the most sensitive ultraviolet spectrograph installed on the telescope. Its far-UV channel is 30 times more sensitive than previous instruments and the near-UV is twice as sensitive. The second instrument, the Wide Field Camera 3, is a panchromatic wide-field camera that can record a wide range of wavelengths, including infrared, visible, and ultraviolet light. *Atlantis* also carried the Soft-Capture Mechanism, which was installed onto the telescope. This will enable a spacecraft to be sent to the telescope to assist in its safe de-orbit at the end of its life. It is a circular mechanism containing structures and targets to aid docking.

The Wide Field Camera 3 being prepared for launch

The infrastructure of the telescope was upgraded by replacing a "Fine Guidance Sensor" that controls the telescope's directional system, installing a set of six new gyroscopes, replacing batteries, and installing a new outer blanket layer to provide improved insulation.

The payload bay elements were the Super Lightweight Interchangeable Carrier (SLIC) which held the Wide Field Camera 3, new batteries, and a radiator; the ORU Carrier which stored the Cosmic Origins Spectrograph and FGS-3R instruments; the Flight Support Structure (FSS) which held onto the Hubble during repairs; the Multi-Use Lightweight Equipment Carrier (MULE) which held support equipment and the Relative Navigation Sensor (RNS) Experiment.

Along with the collectible items that are flown on shuttle missions, such as mission patches, flags, and other personal items for the crew, were an official Harlem Globetrotters basketball and a basketball that Edwin Hubble used in 1909 when he played for the University of Chicago. After being returned to Earth, the Harlem Globetrotters basketball would be placed in the Naismith Memorial Basketball Hall of Fame, and Hubble's ball would be returned to the University of Chicago.

IMAX movie

At the end of September 2007, Warner Bros. Pictures and IMAX Corporation announced that in cooperation with NASA, an IMAX 3D camera would travel to the Hubble telescope in the payload bay of Atlantis for production of a new film that will chronicle the story of the Hubble telescope. IMAX has made a number of movies centered around space, including *Destiny in Space*, *The Dream Is Alive*, *Mission to Mir*, *Blue Planet*, *Magnificent Desolation: Walking on the Moon 3D*, and *Space Station 3D*, made in 2001 on the first trip of IMAX to the ISS. The movie was released in March 2010, with the name *IMAX: Hubble 3D*.

Media

Astronaut Michael J. Massimino used Twitter to document the training and preparations for the mission. He mentioned that he would like to try sending Twitter updates from space during his off-duty time. Massimino's first update read, "From orbit: Launch was awesome!! I am feeling great, working hard, & enjoying the magnificent views, the adventure of a lifetime has begun!" Massimino was the first person to use Twitter in space.

Mission background

The mission marked:

- 157th American manned space flight
- 126th shuttle mission since STS-1
- 30th flight of *Atlantis*
- 53rd shuttle landing at Edwards Air Force Base
- 101st post-*Challenger* mission
- 13th post-*Columbia* mission

Shuttle processing

Atlantis and *Endeavour* were launch pad neighbors for the last time, in preparation for STS-125

Atlantis at LC-39A prior to launch, after the RSS was retracted

STS-125 was first assigned to *Discovery* with a launch date no earlier than May 2008. This originally moved the mission ahead of STS-119, ISS Assembly flight 15. Delays to several shuttle missions resulted in a change in mission ordering, and the orbiter was changed to *Atlantis* on January 8, 2007. The crew of *Atlantis* went to the Kennedy Space Center for the Crew Equipment Interface Test in early July 2008. This allowed the STS-125 crew to get familiar with the orbiter and the hardware they would be using during the flight.

Launch delays

On August 22, 2008, after a delay following Tropical Storm Fay, *Atlantis* was rolled from the Orbiter Processing Facility to the Vehicle Assembly Building, where it was mated to the external fuel tank and solid rocket booster stack. Problems were encountered during the mating process, and poor weather due to Hurricane Hanna caused a delay in the rollout of *Atlantis* to the launch pad, which is normally done seven days after rollover.

STS-125 was further pushed back to October 2008 due to manufacturing delays on external tanks for future space shuttle missions. Lockheed Martin experienced delays during the production changes to make new external tanks with all the enhancements recommended by the Columbia Accident Investigation Board, making it impossible for them to produce two tanks for the STS-125 mission—one for *Atlantis*, and one for *Endeavour* for an emergency rescue mission, if necessary—in time for the original August launch date.

The first rollout to Launch Pad 39A occurred on September 4, 2008. On September 27, the Science Instrument Command and Data Handling (SIC&DH) Unit on the Hubble Space Telescope failed. Because of its importance to the telescope, NASA postponed the launch of STS-125 on September 29 until 2009 so the failed unit could be replaced as well. *Atlantis* was rolled back to the Vehicle Assembly Building on October 20.

On October 30, 2008, NASA announced that *Atlantis* would be removed from its solid rocket boosters and external tank stack and sent back to the Orbiter Processing Facility to await a targeted launch time at 1:11 p.m. EDT on May 12, 2009. The stack was turned over to be used on the STS-119 mission instead. On March 23, *Atlantis* was mated to its new stack in the Vehicle Assembly Building, and rolled out to Launch Pad 39A on March 31. On April 24, 2009, NASA managers issued a request to move the STS-125 launch up one day to May 11 at 2:01 p.m. EDT. The change was made official at the flight readiness review on April 30. The reason cited for the change was to add one more day to the launch window, from two to three days.

Mission timeline

May 11 (Flight day 1, launch)

Space Shuttle *Atlantis* lifts off on STS-125 from Kennedy Space Center

Following a smooth countdown, *Atlantis* launched on time at 2:01 p.m. EDT. Almost immediately after launch and during the ascent, flight systems reported problems with a hydrogen tank transducer and a circuit breaker; the crew was immediately advised to disregard the resultant alarms and continue to orbit. During the post-launch news conference, NASA managers said the initial early review of the launch video showed no obvious debris events, but a thorough analysis would be performed to ensure the orbiter sustained no significant damage during ascent. After working through their post launch checklists, the crew opened the payload bay doors, deployed the Ku band antenna, and moved into the robotic activities portion of the day, which included a survey of the payload bay and crew cabin survey with the orbiter's robotic arm.

During the post-launch inspection of Launch Pad 39A, a twenty-five foot area on the north side of the flame deflector was found to have damage where some of the heat resistant coating came off. Following the launch of STS-124, severe damage was seen at the pad where bricks were blasted from the walls, but NASA officials stated the damage from the STS-125 launch was not nearly as severe and should not impact the launch of STS-127 in June.

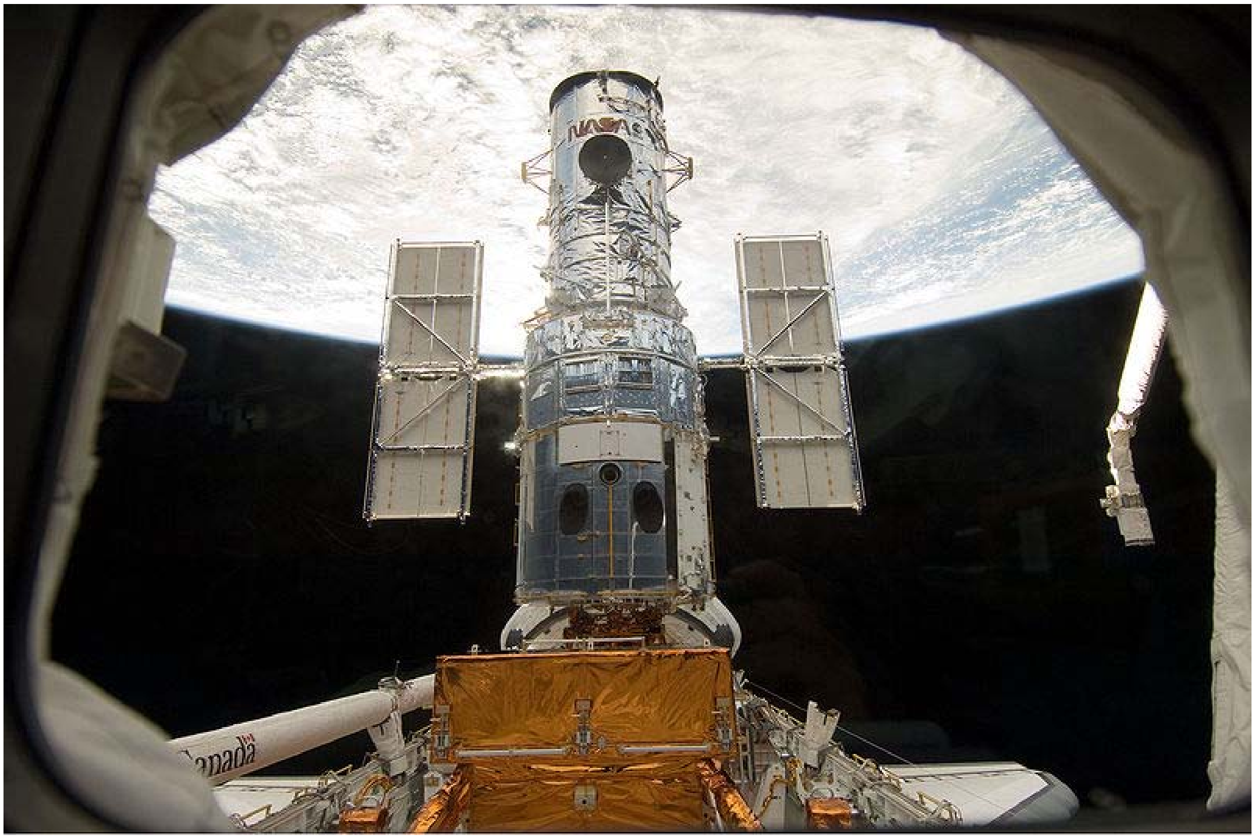
May 12 (Flight day 2)

Following the morning wake up call, the crew set right to work on the day's tasks, which were centered on inspection of the orbiter's heat shield. Using the shuttle robotic arm and the Orbiter Boom Sensor System (OBSS), the crew went through a detailed inspection of the orbiter's thermal protection system (TPS) tile and Reinforced carbon-carbon (RCC) surfaces. During the inspection, engineers on the ground noticed a small area of tile on the forward area of the shuttle's right wing that appeared to have suffered some damage during ascent. Mission managers called up to the crew to alert them of the find, advising Altman ("Scooter") that one of the orbiter's wing leading edge sensors recorded a debris event during ascent, around 104 – 106 seconds following liftoff, which may have been the cause of the damage seen in that area. CAPCOM Dan Burbank advised the crew that the damage did not initially appear to be serious, but assured the crew that the image analysis team would be reviewing the imagery further, and engineers on the ground would be analyzing it to determine if a focused inspection would be required.

As part of the Flight Day 2 Execute Package, ground engineers also provided further information on the circuit breaker failure seen at launch. The breaker (Channel 1 Aerosurfaces, ASA 1) is part of the shuttle's Flight Control Systems (FCS), a subsystem of the Guidance, Navigation and Control (GNC) systems. The failure would have no impact to the mission due to redundant systems.

In addition to the survey of the orbiter's heat shield, the crew gathered and inspected the EVA tools and spacesuits that would be used for the mission's spacewalks and prepared the Flight Support System (FSS) for berthing with Hubble on flight day three.

May 13 (Flight day 3)



Hubble docked in the cargo bay of *Atlantis*

John Grunsfeld uses a still camera with telephoto lens at an overhead window on the aft flight deck during flight day three activities.

Following the crew's post-sleep activities, they went to work performing the rendezvous operations that included burning the orbiter's engines to refine the approach to the Hubble telescope. Following some delays due to communications issues, Altman and Johnson ("Ray-J") guided the orbiter within fifty feet of the telescope. McArthur successfully grappled Hubble at 17:14 UTC, and at 18:12 the telescope was safely berthed in the payload bay of *Atlantis*. Later in the day, Grunsfeld and Feustel (Drew), along with Good ("Bueno") and Massimino ("Mass") worked on preparing for the next day's spacewalk, gathering tools and checking out the suits and equipment that would be used during the EVA.

At the Mission Management Team (MMT) briefing, MMT Chairman LeRoy Cain reported that the damage assessment team had cleared all of the orbiter's TPS tiles and blankets, and were expected to clear the RCC portion of the orbiter by flight day four. He stated that no focused inspection would be required. Cain also noted that a debris event was recorded on the orbiter's wing leading edge sensors, but it was far below the force that would indicate a problem, and would not impact the mission. The late inspection that is routinely performed prior to re-entry would give any additional information, but Cain stated "We're not concerned that it's done any kind of damage that would be any concern to us, certainly not critical damage."

During the Mission Status briefing, Lead Flight Director Tony Ceccacci noted that during the camera survey of the equipment in the payload bay, the team noticed some fine particulate matter around the box containing the Wide Field Camera 3 and asked the crew to take additional images using a higher resolution camera for the ground teams to assess. Cain later confirmed that the dust was not present prior to launch, and was most likely particulate shaken loose from the thick insulation blankets inside the payload bay during launch. The team advised the crew to avoid the particulate as much as possible during the spacewalks, and use caution when working around the container to avoid the debris, but it was not a significant concern.

May 14 (Flight day 4)

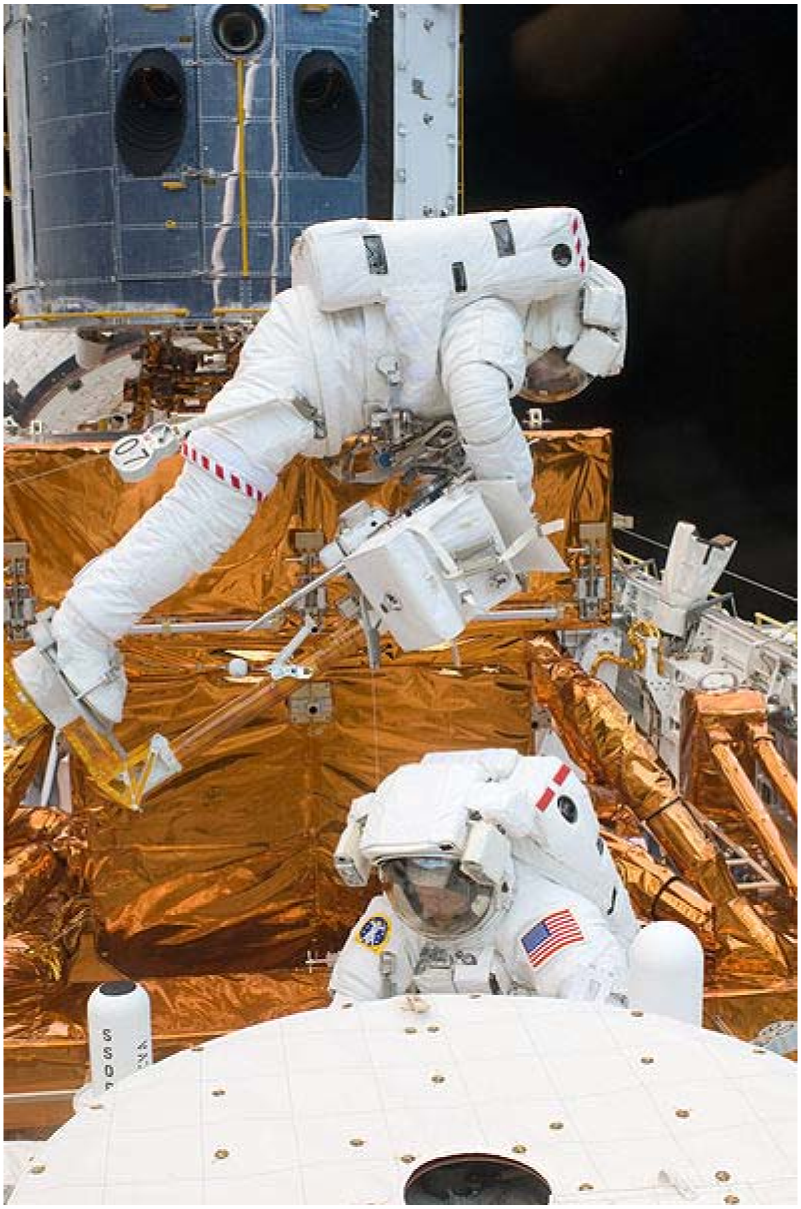
Mission Specialist John Grunsfeld, performing his sixth spacewalk, is reflected in the Hubble telescope's coating as he works during the mission's first EVA.

Following the crew's wake up, they set to work preparing for the mission's first spacewalk. Grunsfeld and Feustel suited up with the assistance of their EVA counterparts, Massimino and Good, and the spacewalk officially began when the two switched their suits to battery power at 12:52 UTC. At the start of the spacewalk, Feustel provided managers on the ground with a visual inspection report on the particulate matter seen earlier around the WFC3 box, reporting to the ground team that "I don't really see any of those particles...It's almost imperceivable. I can see some few particles on the front of the W-SIPE, little, whitish, grey looking, real small. It's low density, too." After getting their tools and equipment for the EVA set up, Grunsfeld and Feustel removed the old Wide Field and Planetary Camera 2, which was installed in 1993 during the telescope's first servicing mission, and replaced it with the new Wide Field Camera 3 (WFC3). Feustel initially had trouble removing the bolts from the old camera, which after over fifteen years in space required more torque to remove than expected. After multiple attempts, managers on the ground decided to have Grunsfeld get a contingency torque limiter from the airlock, which would allow Feustel to apply more force without exceeding a specific point, but the bolt would still not release. The concern was that the bolt would shear, and the camera would be unable to be removed should that happened. Finally, managers approved Feustel to remove the limiter, and apply as much force as he safely thought it would take to release the bolt, which was successful.

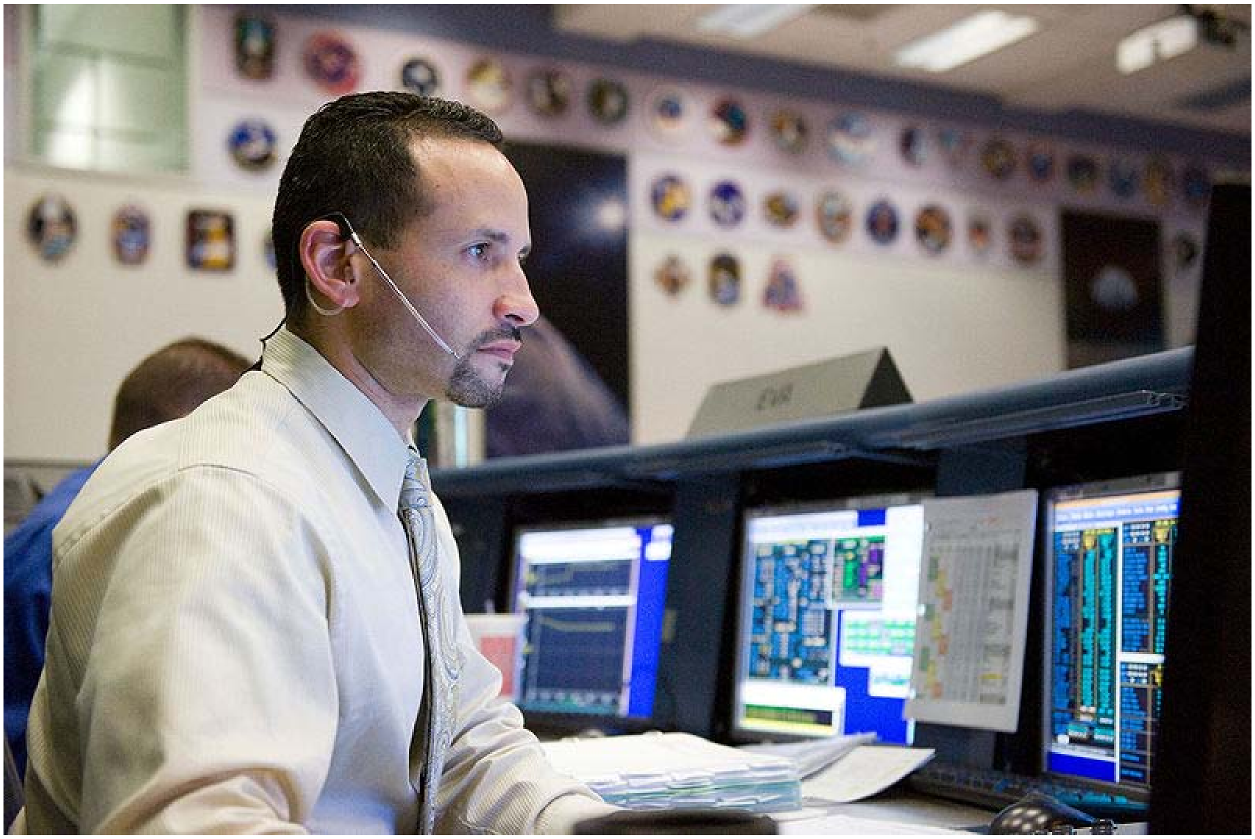
The new camera will allow Hubble to take large-scale, extremely clear and detailed photos over a wider range of colors than the old camera did. After the installation, controllers at the Space Telescope Operations Control Center at Goddard Space Flight Center sent commands to the camera to perform an aliveness test, which passed, indicating the camera was installed correctly.

The next task was to remove and replace the telescope's Science Instrument Command and Data Handling Unit, or SIC&DH, a computer that sends commands to Hubble's science instruments, and formats science data for transmission to the ground. This was the item that failed in September 2008, delaying STS-125 while engineers prepared a replacement part for the mission, and the crew trained for the new task. While the failure of the SIC&DH did not disable the telescope, replacing the unit restores the redundancies. The final major task was to install the Soft-Capture Mechanism (SCM), which includes the 72-inch-wide (1,800 mm) Low Impact Docking System (LIDS) that will allow spacecraft in the future to dock with the telescope, and to safely de-orbit the telescope at the end of its life. Feustel also installed two of four Latch Over Center Kits, or LOCKs, that make opening and closing Hubble's large access doors easier for the remaining spacewalks. The spacewalk officially ended at 20:12 UTC, for a time of seven hours and twenty minutes. It was the nineteenth spacewalk devoted to servicing the telescope, and brought the total time in servicing Hubble to one hundred thirty-six hours, thirty minutes. Due to the length of the spacewalk, and the delay in beginning, the crew was over an hour behind their scheduled timeline for the day, but worked through the post-EVA activities and evening activities without problems, and got to sleep only slightly behind their scheduled time. During the mission status briefing, David Leckrone, Hubble Project Senior Scientist, noted he was very relieved that the camera was replaced successfully, and noted that the problems with the bolt caused some concern, "I don't normally reveal my age and I'm not going to here, but I can tell you I'm five years older now than I was when I came to work this morning, we can sleep pretty well tonight, knowing that's been accomplished."

May 15 (Flight day 5)



Mission Specialists Michael Good (right) and Michael Massimino (lower left) work in the payload bay of *Atlantis* during the mission's second spacewalk.



Tomas Gonzalez-Torres, STS-125 Lead Spacewalk Officer, monitors the progress of the mission.

Following their wake up, the *Atlantis* crew set right to work preparing for the second spacewalk of the mission, with Massimino and Good suiting up with assistance from Grunsfeld and Feustel. As they were preparing for the EVA, the team on the ground informed the crew that the WFC3 had passed all the overnight functional tests, indicating it was in good working order.

While the spacewalk preparations were underway, Altman and McArthur completed a robotic survey of a small row of heat shield tiles that had not been sufficiently imaged during the day two inspection. Following the analysis of the survey, the managers cleared all of the TPS systems until the pre-landing inspection.

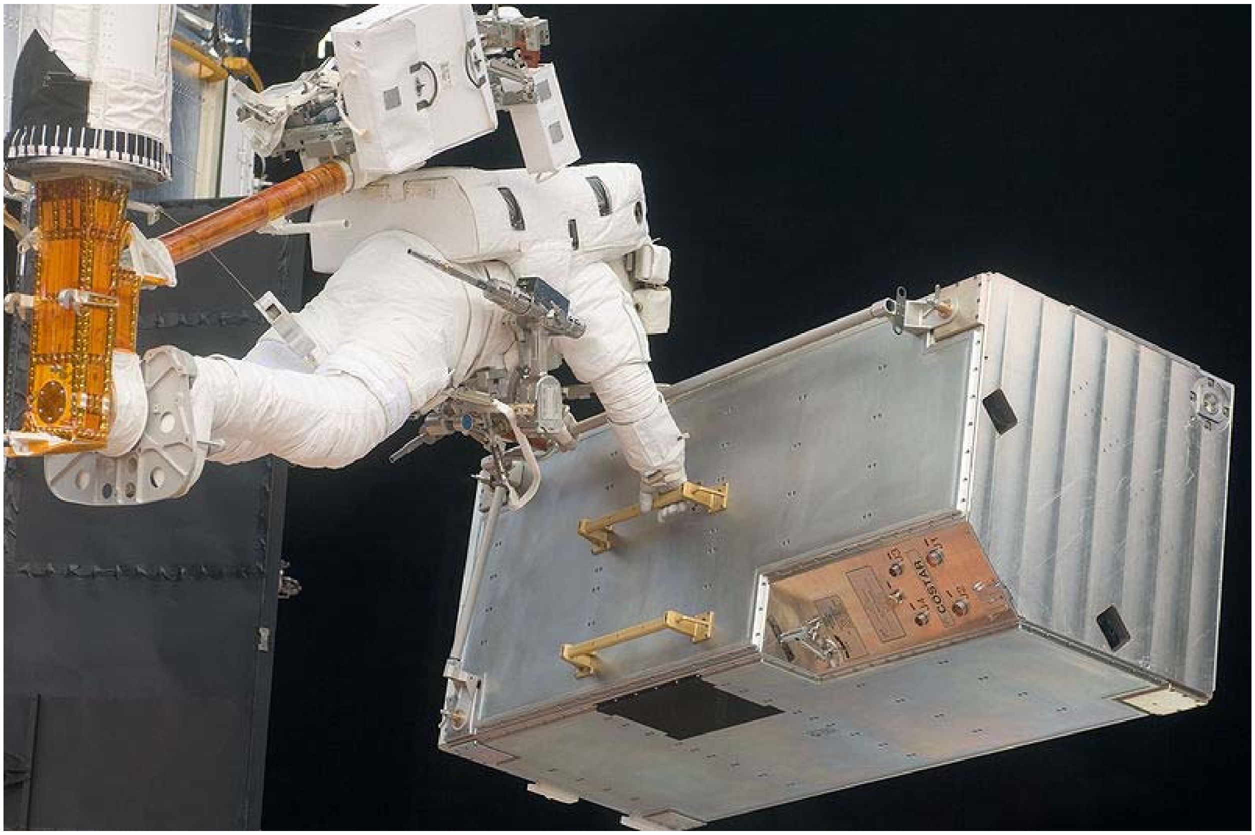
The mission's second spacewalk officially began at 12:49 UTC, and the pair set to work removing and replacing the telescope's three gyroscope rate sensing units (RSUs). Each unit contains two gyroscopes that allow the telescope to point itself. The first unit, RSU 2, was replaced without problems, but when they attempted to replace the second unit, RSU 3, the unit would not align onto the guide pins, and they could not seat it into the equipment bay. Managers decided to put the unit originally intended for the RSU 1 bay into the RSU 3 bay, and it was installed without problems. The pair then attempted to install the second unit into the third and final bay, but the unit again would not seat properly, and they were unable to install it. Instead, it was decided that an additional unit carried as a spare would be placed into the final bay. The spare unit was one that was removed during the STS-103 mission, and had been refurbished on the ground. The installation of all three gyro units was a critical objective of the servicing mission, as three had failed, one was offline due to electrical issues, and the other two had also been experiencing issues with performance. Ground controllers at Goddard Space Flight Center confirmed that all six gyroscopes and the new battery passed preliminary tests.

The problems with seating the second RSU set the spacewalkers back in the timeline by approximately two hours, but after Altman asked Massimino and Good how they felt, they replied they were doing well and felt fine to continue. Flight controllers on the ground evaluated the consumables for the two spacesuits, and decided that if Massimino recharged his suit's oxygen in the airlock, the pair could safely continue with the battery installation. After moving to the battery unit site, Good and Massimino removed one of the original battery modules from Bay 2 of the telescope, and replaced it with a new unit. The batteries provide power to the telescope when it passes into the Earth's shadow and its solar arrays are not exposed to the sun. The spacewalk officially ended at 20:45 UTC, for a time of seven hours, fifty-six minutes. It was the twentieth spacewalk to service Hubble, bringing the total time in EVA servicing the telescope to one hundred forty-four hours and twenty-six minutes.

During the mission status briefing, Tomas Gonzalez-Torres, the Lead EVA Officer, and Hubble Program Manager Preston Burch both explained that the spare RSU would not impact the life of the telescope, as it had been fully refurbished on the ground with two of the three improvements incorporated in newer models. "I would say the difference in the projected longevity of the observatory in the out years is very small. We don't see this is a significant detriment at all to the observatory. This was a tremendous accomplishment for us." Burch noted. Lead Flight Director Tony Ceccacci noted that due to the length of the spacewalk, and the resulting slip in the timeline, the crew's sleep shift would have to be moved an hour later, to allow them to get the proper amount of rest, and the rest of the docked timeline would also be shifted forward an hour.

May 16 (Flight day 6)

Grunsfeld and Feustel pose for a picture in the airlock of *Atlantis* prior to the mission's third spacewalk



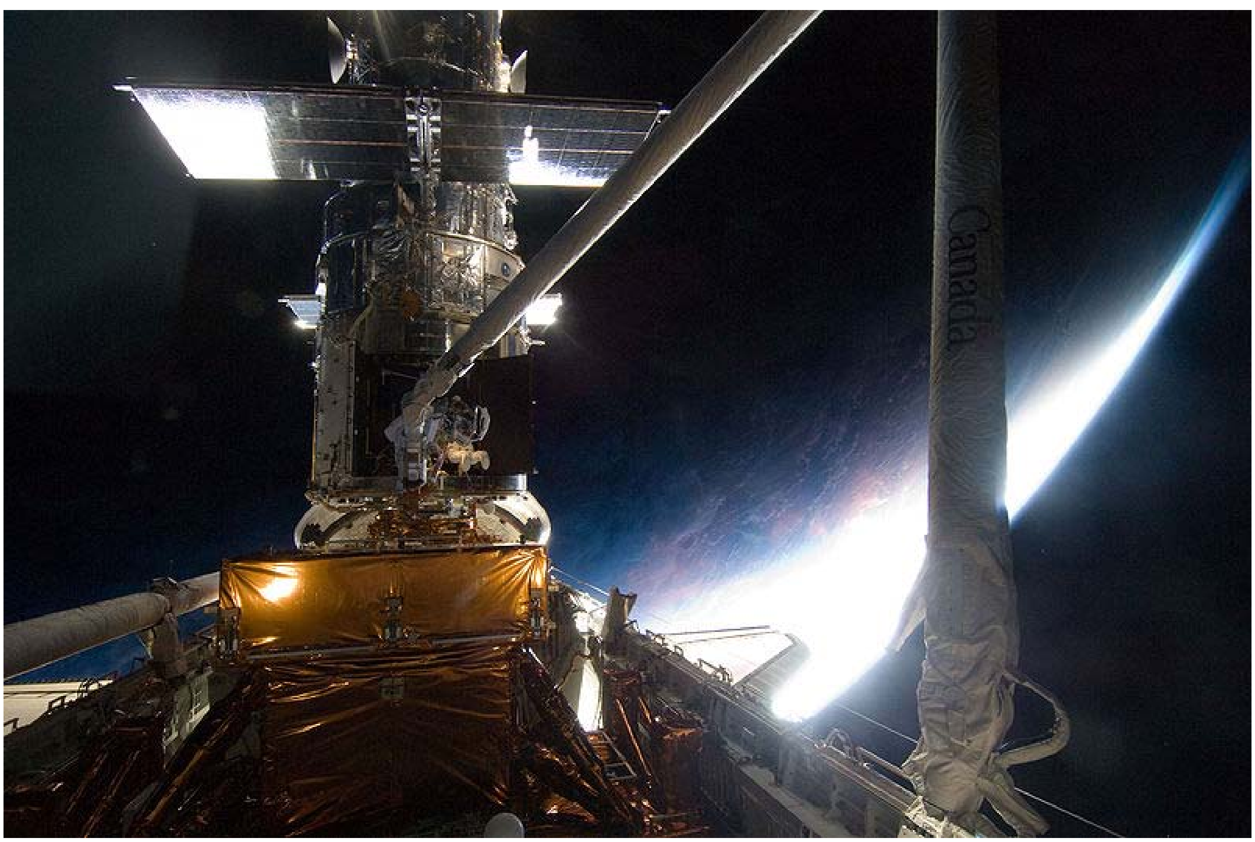
Feustel moves the COSTAR instrument from Hubble to the payload bay of *Atlantis*

After awakening, the crew set to work preparing for the mission's third spacewalk, one that was considered the most challenging and uncertain, yet had some of the highest priority items scheduled. The tasks were to remove the obsolete Corrective Optics Space Telescope Axial Replacement (COSTAR), originally installed during STS-61 to correct the spherical aberration of Hubble's mirror, and install the Cosmic Origins Spectrograph (COS), and to repair the Advanced Camera for Surveys (ACS). The ACS failed in June 2006 due to an electrical issue, and after being restored partially, failed again in 2007 due to an electrical short. The ACS was not designed to be serviced or repaired in space, so the task was considered one of the most challenging of the mission. After running into various snags in the first two spacewalks, managers on the ground were prepared to see unexpected issues arise during the complicated repair work. The spacewalk began at 13:35 UTC, and Grunsfeld and Feustel had no problems. The pair worked through their timeline so efficiently that they were over an hour ahead at one point. After removing COSTAR and stowing it in the orbiter's payload bay, they installed COS, and then moved on to the ACS repair. Using specially designed tools, they removed an access panel, replaced the camera's four circuit boards, and installed a new power supply.

The spacewalk was completed in six hours and thirty-six minutes, and the ACS passed the initial aliveness tests. It was the twenty-first Hubble servicing spacewalk, and Grunsfeld's seventh EVA, moving him up to fourth in the record book of spacewalking time. During the previous day's mission status briefing, Dave Leckrone, Hubble Space Telescope Senior Project Scientist, made a prediction, joking that since the first two spacewalks, which were considered to be straightforward, had run into issues, the most difficult EVA —- to repair the ACS, would be the smoothest one of the mission. "I have a prediction, We've always said EVA 3 was going to be the most difficult and the most challenging, and I predict it's going to go more smoothly than any other EVA on this mission. I just think that's some version of Murphy's Law that's going to lead us in that direction."

After the initial aliveness testing, the ACS was put through its functional tests. Managers and engineers had noted that the repairs were designed for only one of the three photo channels, the wide-field channel, and that the issues with the high-resolution channel may not be resolved by the designed fix. During the functional testing, the wide-field channel passed, but issues were seen with the high-resolution channel, indicating that the power issue may be farther upstream in the electronic circuits than the spacewalk repair addressed. Additional testing would be performed, but Hubble Program Manager Preston Burch noted that the fix was designed to "back power" the high-resolution channel through the paths connected to the wide-field channel, and while feasible, it was a possibility that the short circuit damage was in an area not corrected with the planned repair. Even if the high-resolution channel is unable to be restored, it was considered to be less important, since the bulk of the ACS science output is undertaken by the wide-field channel. The third channel, the solar-blind channel, passed overnight functional testing without issues.

May 17 (Flight day 7)



Mike Good working in an open panel of Hubble during the fourth spacewalk of the mission

Good and Massimino at work in the interior of Hubble, while repairing the Space Telescope Imaging Spectrograph

Mission Specialist Michael Massimino peers into the orbiter's aft flight deck window during the fourth spacewalk of the mission.

Beginning the mission's fourth spacewalk at 13:45 UTC, Massimino and Good went to work repairing the Space Telescope Imaging Spectrograph (STIS). The spectrograph failed in 2004 due to a blown power supply. As with the ACS, the STIS was not designed with the intention of servicing it while in space, and one of the major challenges was to remove a cover plate held tight with over 100 screws using a specially designed tool called a fastener-capture plate, designed to trap the screws and washers and prevent them from floating into space when removed. While preparing the fastener-capture plate, Massimino encountered issues with a handrail that had to be removed to accommodate the fastener-capture plate. The handrail had a stripped bolt on the bottom, preventing it from being released. After trying multiple options without success, managers on the ground advised Massimino to use brute force to remove the handrail, so he could proceed with the removal of the cover plate. The procedure was tested at Goddard Space Flight Center prior to approving it, and showed that the stripped bolt could be broken off safely using force. Working inside the orbiter, Grunsfeld walked Massimino through the procedure slowly, advising him to tape the handrail with Kapton tape to prevent any parts from breaking off or flying loose, to be aware of the reaction the force would have, as well as to watch for sharp edges on the handrail after removal.

Once the handrail was removed, Massimino went to work attaching the capture plate, but ran into additional problems when the battery in one of his power tools failed. Massimino was instructed to return to the orbiter's airlock to retrieve a spare tool and to recharge his suit's oxygen reserves, to allow for completion of the STIS repair. The rest of the STIS repair work was completed without any problems, but the spacewalkers were nearly two hours behind the scheduled timeline, so managers on the ground decided to postpone the task of installing a New Outer Blanket Layers (NOBLs) onto the telescope's outer shell. The spacewalk, originally scheduled to last six hours and thirty minutes, ended at 21:02 UTC, for a time of eight hours and two minutes. At the time, it became the sixth longest spacewalk in history. It was the twenty-second spacewalk devoted to servicing the Hubble telescope, and Massimino's fourth spacewalk, bringing his total EVA time to thirty hours, forty-four minutes.

During the mission status briefing, Jennifer Wiseman, Chief of Exoplanet and Stellar Astrophysics for Goddard Space Flight Center, noted that the repair of STIS was a major victory for both the mission and the science community, as that part of the telescope performed unique functions, helping scientists understand the materials planets are composed of, and looking at things like the motion of stars around black holes.

After initial aliveness testing that showed no issues, STIS was taken into functional testing, and issues were seen when the telescope put itself into safe mode due to a low thermal limit sensor. Ground controllers at Goddard would restart the testing once the thermal limit sensor was back in normal sensor range, but it is believed the component is in good shape.

May 18 (Flight day 8)

“

As Arthur C. Clarke says, the only way of finding the limits on the possible, is by going beyond them into the impossible. And on this mission, we tried some things that many people said were impossible - fixing STIS, repairing ACS, achieving all the content that we have in this mission. But we've achieved that and we wish Hubble the very best. It's really a sign of the great country that we live in that we're able to do things like this on a marvelous spaceship like the space shuttle *Atlantis*. And I'm convinced that if we can solve problems like repairing Hubble, getting to space, doing the servicing we do traveling 17,500 miles an hour around the Earth, that we can achieve other great things, like solving our energy problems and our climate problems, all things that are in the middle of NASA's prime and core values. —- John L. Grunsfeld

”

Completing the fifth of the five planned spacewalks, Grunsfeld and Feustel successfully installed the second battery, removed and replaced the Fine Guidance Sensor number three, and worked so efficiently that they were over an hour ahead of the timeline, giving them time to remove degraded insulation panels from three bays of the telescope, and install three New Outer Blanket Layers (NOBLs). Beginning the spacewalk at 12:20 UTC, the pair first worked on removing an aging battery module, and replaced it with a new pack, which combined with the battery replacement performed during the second spacewalk, gave the telescope all new nickel-hydrogen batteries. They then moved on to the removal and replacement of the Fine Guidance Sensor unit number three, improving Hubble's focus and stability when imaging. NASA engineers liken the new FGS to being able to keep a laser beam focused on a U.S. dime coin that is 320 km away. Both the new batteries, and the FGS passed both aliveness and functional testing. The mission's final EVA concluded at 19:22 UTC, after seven hours and two minutes. The total time spent during the mission in extra-vehicular activity was thirty-six hours, fifty-six minutes. The twenty-third and final spacewalk to service Hubble brought the total time spent in EVA working on the telescope to one hundred and sixty-six hours, six minutes. Lead Flight Director Tony Ceccacci noted that the final EVA was also the last planned spacewalk from a shuttle airlock. In what was likely his last EVA, Grunsfeld's has accumulated fifty-eight hours and thirty minutes spacewalking, just two minutes less than Jerry L. Ross, who is third on the list of spacewalking time.

The completion of all the major objectives, as well as some that were not considered vital, upgrade the telescope to its most technologically advanced state since its launch nineteen years ago, and make it more powerful than ever. The upgrades will also help Hubble to see deeper into the universe, and farther into the past, closer to the time of the Big Bang. Hubble's importance to science is not just seen in the dramatic images it provides, but also in the volume of work it has generated — an average of fourteen scientific articles are published each week based on data gathered from the telescope. Officially, the upgrades should extend Hubble's life through the year 2014, but Hubble Space Telescope Senior Scientist David Leckrone noted prior to the mission that if all of the mission's objectives were successful, the telescope could easily last longer than that. The next large telescope scheduled to be launched is the James Webb Space Telescope in 2014, which is infrared-only, so to have Hubble, which has ultraviolet, visible, and near-infrared capabilities, still operational after 2014 would be of great benefit to the scientific community.

May 19 (Flight day 9)

The Hubble Space Telescope being lifted out of the payload bay of *Atlantis* before being released back into space.

After awakening at 8:31 UTC, the crew set to work preparing to release Hubble from the payload bay of *Atlantis*. Using the shuttle's robotic arm, McArthur grappled Hubble at 10:45 UTC, and lifted it out of the orbiter's payload bay to prepare for the release. Good and Massimino were standing by ready to perform a spacewalk in the event that something went wrong during the telescope's deployment. After working through the checklist to prepare the telescope for release, managers on the ground gave the go to Altman to release Hubble, and at 12:57 UTC, McArthur successfully released the telescope as the vehicles flew over Africa. Performing a small separation burn, Johnson backed the orbiter away from the telescope, and Altman called down to managers on the ground confirming the deployment of Hubble. Commending the crew, Altman said "And Houston, Hubble has been released, it's safely back on its journey of exploration as we begin steps to conclude ours. Not everything went as we planned, but we planned a way to work around everything and with the whole team pulling together... we've been able to do some incredible things. And now Hubble can continue on its own, exploring the cosmos, and bringing it home to us as we head for home in a few days. Thank you." Hubble's new equipment and upgraded systems would be tested for several months prior to resuming operation, but if all tests are successful, operation of the telescope would resume in early September.

Following the separation burn, the crew set to work performing the standard late inspection of the thermal protection system of the orbiter. Using the robotic arm, McArthur, Altman, and Johnson worked through the procedures to inspect the wing leading-edge panels, reinforced carbon-carbon nose cap, and heat shield tiles. After evaluating the weather reports, managers on the ground slightly refined the schedule for landing, opting to bring the shuttle home one orbit early to try to avoid the possibility of showers that would prevent a landing on Friday. The new landing opportunity would bring the crew home at 10:01 a.m. EDT.

May 20 (Flight day 10)

Hubble floats free from *Atlantis*

After a busy week servicing Hubble, the crew of *Atlantis* had the majority of the day off, giving them time to rest and prepare for landing. They took their traditional on-orbit crew portrait, and spoke with reporters from around the world in a news conference. The crew also had the opportunity to speak with the Expedition 19 crew on board the International Space Station, in a conference call routed through satellites. The station crew congratulated them on a very successful mission, and the crew of *Atlantis* expressed their gratitude to the station crew for all the work they do during their long duration stays on the station.

The Spaceflight Meteorology Group at Johnson Space Center was predicting less than favorable weather for Friday's landing, so managers asked the crew to power down some non-critical systems to help conserve power, in the event that the orbiter is not able to land until Saturday.

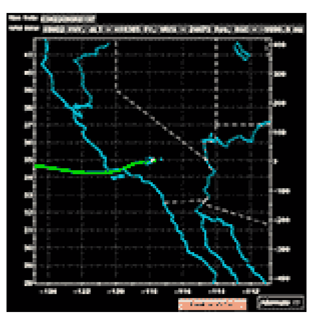
The STS-125 crew poses for the traditional in-flight portrait on the middeck of *Atlantis*

After evaluating the imagery sent down from the late inspection, the ground team officially cleared the orbiter's thermal protection system for re-entry. Initially, NASA had planned on releasing *Endeavour* from its stand-by status following the late inspection, but managers on the ground decided to wait until *Atlantis* had performed the de-orbit burn before standing down the STS-400 rescue mission officially.

Before going to sleep, the crew took a phone call from President Barack Obama, who congratulated them on their successful mission, joked with them, asking if they could see his house in Chicago, and expressed his pride in the crew. Obama told the crew, "Like a lot of Americans, I've been watching with amazement the gorgeous images you've been sending back, and the incredible repair mission you've been making in space," he said. "I think you're providing a wonderful example of the kind of dedication and commitment to exploration that represents America and the space program generally. These are traits that have always made this country strong, and all of you personify them."

May 21 (Flight day 11)

Pilot Gregory Johnson works through a landing simulation using the orbiter's Portable In-Flight Landing Operations Trainer (PILOT) program on flight day eleven.



Mid range tracking image for Edwards Air Force Base landing

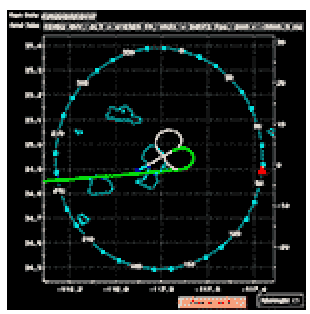
The crew spent the day in preparations for Friday's landing. After working through their post-sleep activities, Altman, Johnson and McArthur performed a check-out of the flight control surfaces, performed a reaction control system hot-fire, and went through communications checks with managers on the ground. The rest of the crew worked to stow away items that were used during the mission. The crew held a deorbit preparations briefing with the ground teams, and Altman and Johnson worked with the simulator on board to run through a series of landing simulations.

In the afternoon, the crew became the first shuttle crew to ever testify live from orbit in a United States Senate hearing. Barbara Mikulski, Chairman of the Senate Appropriations Committee, Subcommittee on Commerce, Justice, Science and Related Agencies, and former astronaut Senator Bill Nelson of Florida, spoke with the crew about the importance of spaceflight and the repair of Hubble. The first person to give testimony from space was John L. Phillips, who testified before the House Science Committee, Subcommittee on Space and Aeronautics in June 2005 while a member of Expedition 11 on board the International Space Station. The crew of *Atlantis* later spoke with reporters from the major networks CNN, ABC, NBC, CBS, and FOX before going to sleep.

While the weather in Florida continued to look grim for a landing Friday, managers on the ground advised the crew that they would proceed with deorbit preparations as planned, and see if the weather cleared up in the morning. NASA managers stated that for Friday, they would focus on a KSC landing for Friday, not activating any of the backup sites, but if the weather was not favorable for a Friday landing, Edwards Air Force Base could be activated on Saturday. *Atlantis* has enough consumables to stay in orbit until Monday.

Also late on Thursday, managers officially released *Endeavour* from its stand-by state, as *Atlantis* was cleared of any damage to its heat shield and was in good shape to return to Earth.

May 22 (Flight day 12)



Close range landing tracking image

As the crew worked through the procedures and checklists for entry on Friday, the managers on the ground closely examined the weather patterns around Florida, which were less than favorable. The crew was advised that there were low clouds and thunderstorms, both conditions that violated landing criteria, so managers waived the first opportunity. A second opportunity was also not taken, as the weather had not improved. Entry Flight Director Norm Knight called up Edwards Air Force Base shortly after the decision to delay to Saturday was made, which would give the crew a total of six Saturday landing opportunities, three at each location.

May 23 (Flight day 13)

Space Shuttle *Atlantis* lands at Edwards Air Force Base after a successful STS-125 mission

The crew of *Atlantis* had six possible landing opportunities on Saturday. Managers evaluated the best three opportunities of the day to try bring the orbiter home. Saturday's first landing opportunity at Kennedy Space Center was waived due to poor weather forecasts, and observed weather violations for the landing criteria. After further evaluating weather patterns around Florida, managers on the ground chose to waive the second opportunity as well, and wait one more day to attempt to get the orbiter into Florida on Sunday. Weather in California had excellent forecasts, so if the attempts on Sunday to land in Florida were not successful, the shuttle would be able to land at Edwards Air Force Base without weather being an issue.

May 24 (Flight day 14, landing)

The *Atlantis* crew had two Florida return opportunities for the day, as well as two for a California landing, giving the managers time to evaluate the weather and use California if necessary. After choosing to pass on the first opportunity for KSC and evaluate the second, managers on the ground decided that the weather in Florida was too dynamic to risk bringing the orbiter in, and opted to land at Edwards Air Force Base instead. The de-orbit burn was initiated at 14:24 UTC, a burn of the shuttle's engines that brought it out of orbit to begin the orbiter's reentry into the Earth's atmosphere. *Atlantis* successfully landed at Edwards Air Force Base on Runway 22 at 8:39 a.m. PDT after 197 orbits in space and a distance of approximately 5.2 million miles.

After working through the checklists to safely power down the orbiter, the crew performed the traditional walk-around of the shuttle and met with employees from NASA. Speaking briefly to the press following the walk around, Altman joked, "I didn't realize it was going to be so hard to get back to the Earth! We're all thrilled to have the mission complete."

During the post-landing briefing, Associate Administrator for Space Sciences Ed Weiler declared the mission a total success, and after noting the rocky road that it took to get the mission completed, said he considered the mission to be Hubble's Great American Comeback story, chapter two.

"This mission...was canceled January 16, 2004, if you'd have told me on that day I'd be sitting here five years later with a totally successful five-EVA mission, with a brand new Hubble once again that will probably operate well into the third decade of its life, I wouldn't have bet you a penny. But Hubble is the great American comeback story, chapter two." - Ed Weiler

Post landing

A unique view of *Atlantis* perched atop the modified Boeing 747 during its return ferry flight to Florida.

Following standard post-landing processing at Edwards Air Force Base, *Atlantis* was lifted into the air using the Mate-DeMate device, and attached to the top of a modified Boeing 747, called a Shuttle Carrier Aircraft (SCA) for its return flight to Florida. After departing California on June 1, the flight made an overnight stop at Biggs Army Airfield in El Paso, Texas, and on June 2 made stops in San Antonio, Texas, and Columbus, Mississippi to refuel. After performing a flyby of the coast, the SCA landed at Kennedy Space Center at 6:53 p.m EDT on June 2, 2009. One of the heavier return flights, *Atlantis* was still carrying the cargo from the mission in the payload bay, and weighed approximately one quarter of a million pounds. Combined with the 747, the total weight of the vehicle was approximately six hundred thousand pounds. *Atlantis* was removed from the SCA and towed to the Orbiter Processing Facility late June 2.

Extra-vehicular activity

Five back-to-back EVAs were planned for the mission. Spacewalks one through four were originally scheduled to last six hours, thirty minutes, while the fifth spacewalk was scheduled to last five hours, forty-five minutes. All five EVAs were conducted successfully, for a total time in EVA activity of thirty-six hours, fifty-six minutes.

EVA #	Spacewalkers	Start (UTC)	End (UTC)	Duration
EVA 1	John M. Grunsfeld Andrew J. Feustel	May 14 12:52	May 14 20:12	7 hours, 20 minutes
	Replaced the Wide Field and Planetary Camera 2 (WFPC2) with Wide Field Camera 3 (WFC3), replaced the Science Instrument Command and Data Handling Unit, lubricated three of the shroud doors, and installed a mechanism for spacecraft to capture Hubble for de-orbit at the end of the telescope's life (Soft Capture Mechanism).			
EVA 2	Michael J. Massimino Michael T. Good	May 15 12:49	May 15 20:45	7 hours, 56 minutes
	Removed and replaced all three of Hubble's gyroscope rate sensing units (RSUs). Removed and replaced the first of two battery unit modules.			
EVA 3	Grunsfeld Feustel	May 16 13:35	May 16 20:11	6 hours, 36 minutes
	Removed COSTAR, stowed it for return; installed the Cosmic Origins Spectrograph in its place; removed four faulty electronics cards from the Advanced Camera for Surveys and replaced them with a new electronics box and cable.			
EVA 4	Massimino Good	May 17 13:45	May 17 21:47	8 hours, 2 minutes
	Removed and replaced an electronics card for the Space Telescope Imaging Spectrograph (STIS). The spacewalk was extended due to problems removing a handrail as well as problems with a power tool, causing the spacewalk to end as the sixth longest EVA to that time.			
EVA 5	Grunsfeld Feustel	May 18 12:20	May 18 19:22	7 hours, 2 minutes

The twenty-third and final spacewalk to service Hubble, and last planned EVA from a shuttle airlock replaced the final battery module, installed Fine Guidance Sensor No. 3, removed degraded insulation panels from bays 5, 7 and 8, and installed three New Outer Blanket Layers (NOBLs) in their place, and removed and reinstalled a protective cover around Hubble's low-gain antenna.

Wake-up calls

NASA began a tradition of playing music to astronauts during the Gemini program, which was first used to wake up a flight crew during Apollo 15. Each track is specially chosen, often by their families, and usually has a special meaning to an individual member of the crew, or is applicable to their daily activities.

Flight Day	Song	Artist/Composer	Played for	
Day 2	"Kryptonite"	3 Doors Down	Pilot Gregory Johnson	
Day 3	"Upside Down"	Jack Johnson	Mission Specialist Megan McArthur	
Day 4	"Stickshifts and Safetybelts"	CAKE	Mission Specialist Andrew Feustel	
Day 5	"God of Wonders"	Third Day	Mission Specialist Michael Good	
Day 6	"Hotel Cepollina" (Parody of Hotel California in honor of Frank Cepollina)	Fuzzbox Piranha	Mission Specialist John Grunsfeld	
Day 7	"New York State of Mind"	Billy Joel	Mission Specialist Michael Massimino	
Day 8	"Sound of Your Voice"	Barenaked Ladies	Commander Scott Altman	
Day 9	"Lie in Our Graves"	Dave Matthews Band	McArthur	
Day 10	"Theme from Star Trek"	Alexander Courage	STS-125 Crew	
Day 11	"Cantina Band"	John Williams	STS-125 Crew	
Day 12	"Galaxy Song"	From the movie Monty Python's The Meaning of Life	STS-125 Crew	
Day 13	"Where My Heart Will Take Me" (Theme from *Star Trek: Enterprise*)	Russell Watson	STS-125 Crew	
Day 14	"Ride of the Valkyries"	Richard Wagner	STS-125 Crew	

In an end-of-mission twist, following the final wake up call, the *Atlantis* crew played "Take Me Home" by Phil Collins for the Mission Control Orbit Three team as a thank you for their hard work during the mission, and their work to bring the orbiter home.

Contingency mission

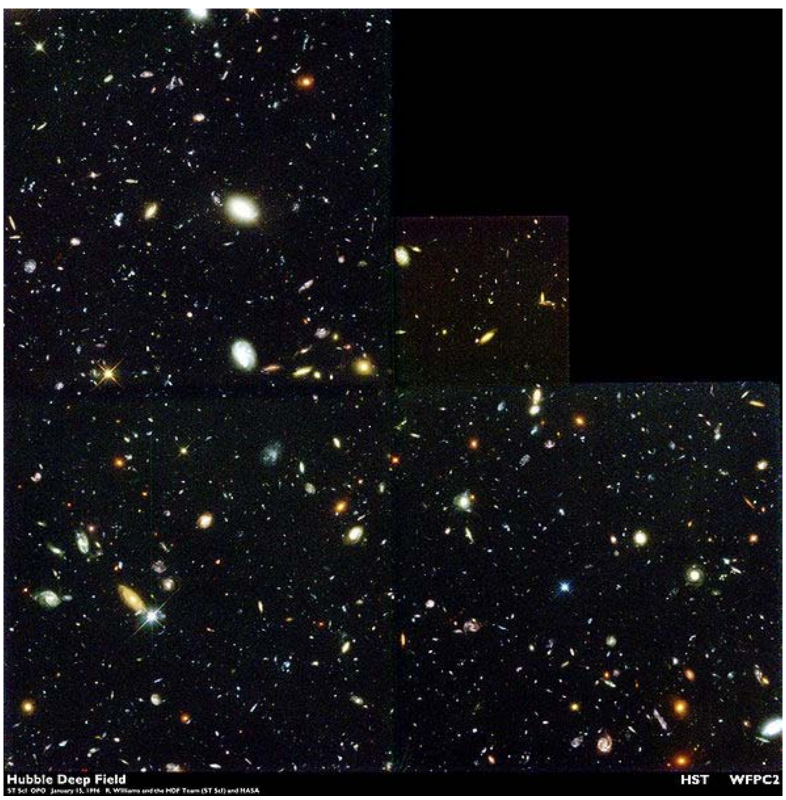
STS-125 was the only planned shuttle mission after the *Columbia* accident to be launched into a low-inclination orbit that did not allow rendezvous with the International Space Station. Due to the inclination and other orbit parameters of Hubble, *Atlantis* would have been unable to use the International Space Station as a safe haven in the event of structural or mechanical failure. To preserve NASA's post-*Columbia* requirement of having shuttle Launch On Need (LON) rescue capability, STS-400 was the flight designation given to the Contingency Shuttle Crew Support (CSCS) mission which would have been flown by *Endeavour* in the event *Atlantis* became disabled during STS-125. After *Atlantis* performed the late inspection and was cleared for re-entry, *Endeavour* was officially released from stand-by status on Thursday, May 21.

Chapter- 4

Important Discoveries by the Hubble Space Telescope

Hubble Deep Field

Coordinates: $12^{h}\ 36^{m}\ 49.4^{s}$, +62° 12′ 58″



The Hubble Deep Field

The **Hubble Deep Field** (HDF) is an image of a small region in the constellation Ursa Major, constructed from a series of observations by the Hubble Space Telescope. It covers an area 2.5 arcminutes across, two parts in a million of the whole sky, which is equivalent in angular size to a 65 mm tennis ball at a distance of 100 metres. The image was assembled from 342 separate exposures taken with the Space Telescope's Wide Field and Planetary Camera 2 over ten consecutive days between December 18 and December 28, 1995.

The field is so small that only a few foreground stars in the Milky Way lie within it; thus, almost all of the 3,000 objects in the image are galaxies, some of which are among the youngest and most distant known. By revealing such large numbers of very young galaxies, the HDF has become a landmark image in the study of the early universe, with the associated scientific paper having received over 800 citations by the end of 2008.

Three years after the HDF observations were taken, a region in the south celestial hemisphere was imaged in a similar way and named the Hubble Deep Field South. The similarities between the two regions strengthened the belief that the universe is uniform over large scales and that the Earth occupies a typical region in the universe (the cosmological principle). A wider but shallower survey was also made as part of the Great Observatories Origins Deep Survey. In 2004 a deeper image, known as the Hubble Ultra Deep Field (HUDF), was constructed from a total of eleven days of observations. The HUDF image is the deepest (most sensitive) astronomical image ever made at visible wavelengths.

Conception

The dramatic improvement in Hubble's imaging capabilities after corrective optics were installed encouraged attempts to obtain very deep images of distant galaxies.

One of the key aims of the astronomers who designed the Hubble Space Telescope was to use its high optical resolution to study distant galaxies to a level of detail that was not possible from the ground. Positioned above the atmosphere, Hubble avoids atmospheric airglow allowing it to take more sensitive visible and ultraviolet light images than can be obtained with seeing-limited ground-based telescopes (when good adaptive optics correction at visible wavelengths becomes possible, 10 m ground-based telescopes may become competitive). Although the telescope's mirror suffered from spherical aberration when the telescope was launched in 1990, it could still be used to take images of more distant galaxies than had previously been obtainable. Because light takes billions of years to reach Earth from very distant galaxies, we see them as they were billions of years ago; thus, extending the scope of such research to increasingly distant galaxies allows a better understanding of how they evolve.

After the spherical aberration was corrected during Space Shuttle mission STS-61 in 1993, the improved imaging capabilities of the telescope were used to study increasingly distant and faint galaxies. The Medium Deep Survey (MDS) used the Wide Field and Planetary Camera 2 (WFPC2) to take deep images of random fields while other instruments were being used for scheduled observations. At the same time, other dedicated programs focused on galaxies that were already known through ground-based observation. All of these studies revealed substantial differences between the properties of galaxies today and those that existed several billion years ago.

Up to 10% of the HST's observation time is designated as Director's Discretionary (DD) Time, and is typically awarded to astronomers who wish to study unexpected transient phenomena, such as supernovae. Once Hubble's corrective optics were shown to be performing well, Robert Williams, the then director of the Space Telescope Science Institute, decided to devote a substantial fraction of his DD time during 1995 to the study of distant galaxies. A special Institute Advisory Committee recommended that the WFPC2 be used to image a "typical" patch of sky at a high galactic latitude, using several optical filters. A working group was set up to develop and implement the project.

Target selection

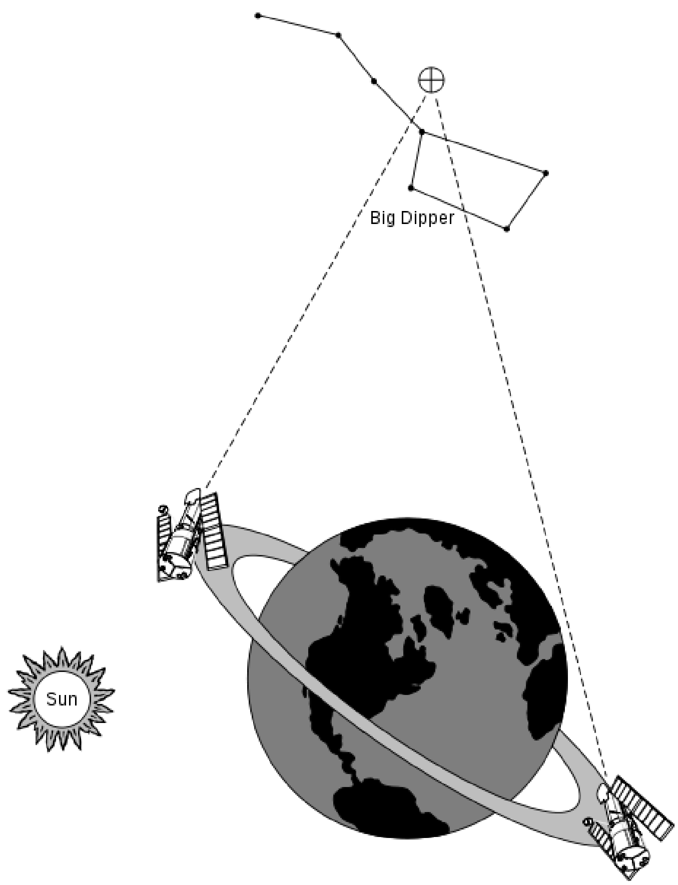
The HDF is at the centre of this image of one degree of sky. The Moon as seen from Earth would fill roughly one quarter of this image.

The field selected for the observations needed to fulfill several criteria. It had to be at a high galactic latitude, because dust and obscuring matter in the plane of the Milky Way's disc prevents observations of distant galaxies at low galactic latitudes. The target field had to avoid known bright sources of visible light (such as foreground stars), and infrared, ultraviolet and X-ray emissions, to facilitate later studies at many wavelengths of the objects in the deep field, and also needed to be in a region with a low background infrared 'cirrus', the diffuse, wispy infrared emission believed to be caused by warm dust grains in cool clouds of hydrogen gas (H I regions).

These criteria restricted the field of potential target areas. It was decided that the target should be in Hubble's 'continuous viewing zones' (CVZs)—the areas of sky which are not occulted by the Earth or the moon during Hubble's orbit. The working group decided to concentrate on the northern CVZ, so that northern-hemisphere telescopes such as the Keck telescopes, the Kitt Peak National Observatory telescopes and the Very Large Array (VLA) could conduct follow-up observations.

Twenty fields satisfying these criteria were initially identified, from which three optimal candidate fields were selected, all within the constellation of Ursa Major. Radio snapshot observations with the VLA ruled out one of these fields because it contained a bright radio source, and the final decision between the other two was made on the basis of the availability of guide stars near the field: Hubble observations normally require a pair of nearby stars on which the telescope's Fine Guidance Sensors can lock during an exposure, but given the importance of the HDF observations, the working group required a second set of back-up guide stars. The field that was eventually selected is located at a right ascension of $12^h\ 36^m\ 49.4^s$ and a declination of +62° 12′ 58″; in area it is a mere 5.3 square arcminutes. This is approximately 1/28,000,000 of the total area of the sky.

Observations



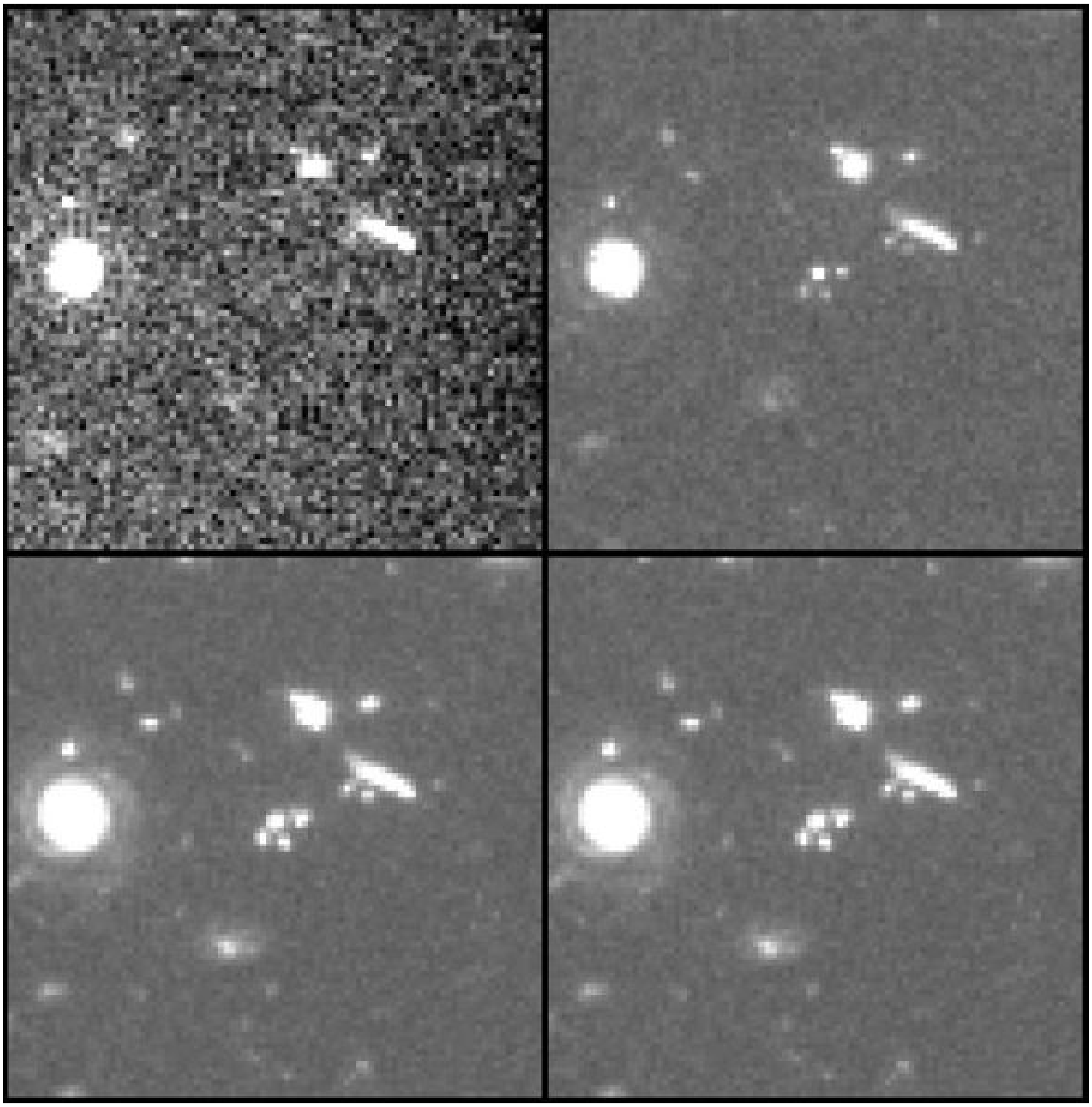
The HDF was located in Hubble's northern Continuous Viewing Zone, as shown by this diagram

Once a field had been selected, an observing strategy had to be developed. An important decision was to determine which filters the observations would use; WFPC2 is equipped with forty-eight filters, including narrowband filters isolating particular emission lines of astrophysical interest, and broadband filters useful for the study of the colours of stars and galaxies. The choice of filters to be used for the HDF depended on the 'throughput' of each filter—the total proportion of light that it allows through—and the spectral coverage available. Filters with bandpasses overlapping as little as possible were desirable.

In the end, four broadband filters were chosen, centred at wavelengths of 300 nm (near-ultraviolet), 450 nm (blue light), 606 nm (red light) and 814 nm (near-infrared). Because the quantum efficiency of Hubble's detectors is quite low at 300 nm, the noise in observations at this wavelength is primarily due to CCD noise rather than sky background; thus, these observations could be conducted at times when high background noise would have harmed the efficiency of observations in other passbands.

Between December 18 and December 28, 1995—during which time Hubble orbited the Earth about 150 times—342 images of the target area in the chosen filters were taken. The total exposure times at each wavelength were 42.7 hours (300 nm), 33.5 hours (450 nm), 30.3 hours (606 nm) and 34.3 hours (814 nm), divided into 342 individual exposures to prevent significant damage to individual images by cosmic rays, which cause bright streaks to appear when they strike CCD detectors. A further 10 Hubble orbits were used to make short exposures of flanking fields to aid follow-up observations by other instruments.

Data processing



A section of the HDF about 14 arcseconds across in each of the four wavelengths used to construct the final version: 300 nm (top left), 450 nm (top right), 606 nm (bottom left) and 814 nm (bottom right)

The production of a final combined image at each wavelength was a complex process. Bright pixels caused by cosmic ray impacts during exposures were removed by comparing exposures of equal length taken one after the other, and identifying pixels that were affected by cosmic rays in one exposure but not the other. Trails of space debris and artificial satellites were present in the original images, and were carefully removed.

Scattered light from the Earth was evident in about a quarter of the data frames, creating a visible "X" pattern on the images. This was removed by taking an image affected by scattered light, aligning it with an unaffected image, and subtracting the unaffected image from the affected one. The resulting image was smoothed, and could then be subtracted from the bright frame. This procedure removed almost all of the scattered light from the affected images.

Once the 342 individual images were cleaned of cosmic-ray hits and corrected for scattered light, they had to be combined. Scientists involved in the HDF observations pioneered a technique called 'drizzling', in which the pointing of the telescope was varied minutely between sets of exposures. Each pixel on the WFPC2 CCD chips recorded an area of sky 0.09 arcseconds across, but by changing the direction in which the telescope was pointing by less than that between exposures, the resulting images were combined using sophisticated image-processing techniques to yield a final angular resolution better than this value. The HDF images produced at each wavelength had final pixel sizes of 0.03985 arcseconds.

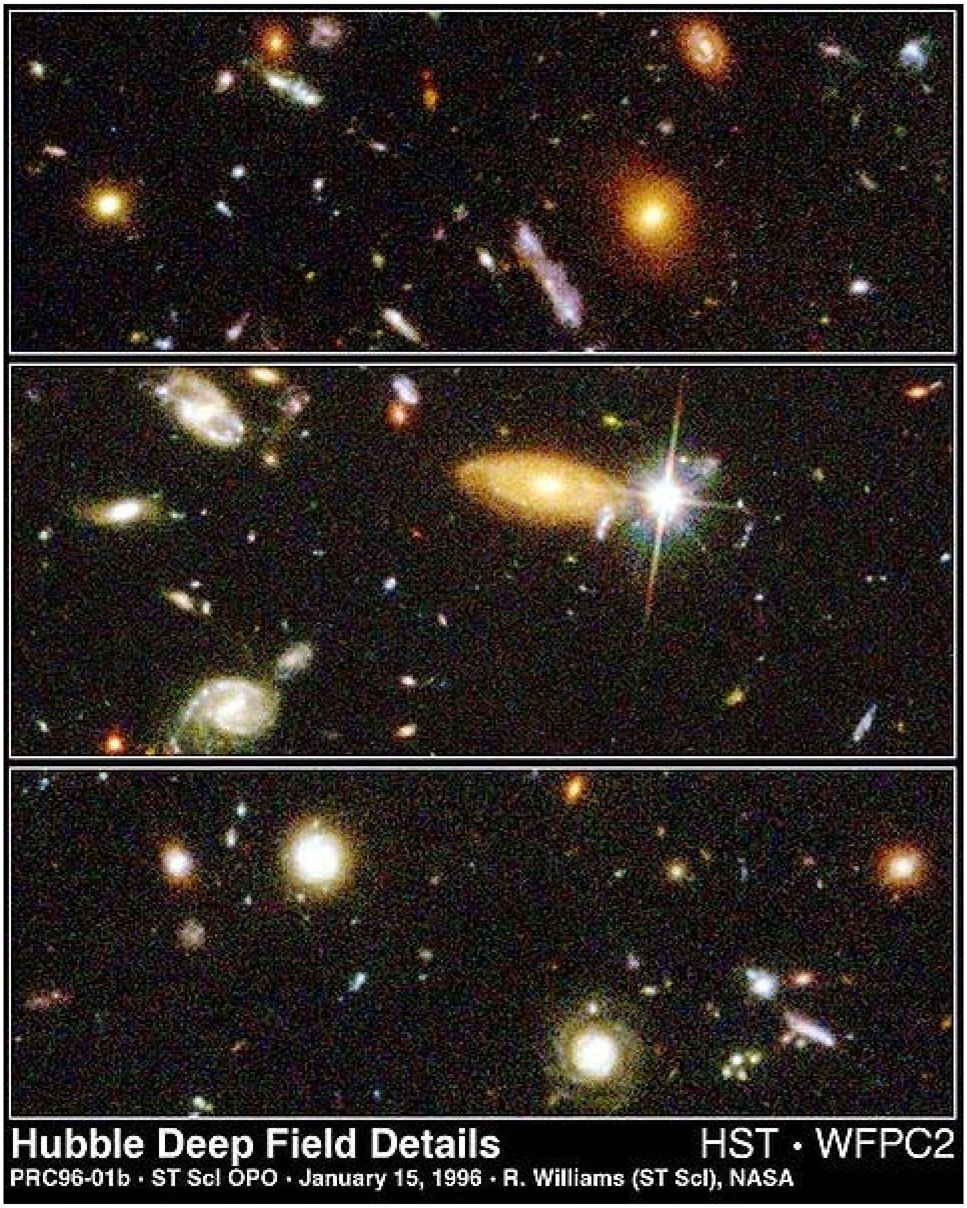
The data processing yielded four monochrome images (at 300 nm, 450 nm, 606 nm and 814 nm), one at each wavelength. One image was designated as red (814 nm), the second as green (606 nm) and the third as blue (450 nm), and the three images were combined to give a colour image. Because the wavelengths at which the images were taken do not correspond to the wavelengths of red, green and blue light, the colours in the final image only give an approximate representation of the actual colours of the galaxies in the image; the choice of filters for the HDF (and the majority of Hubble images) was primarily designed to maximize the scientific utility of the observations rather than to create colours corresponding to what the human eye would actually perceive.

Contents of the Deep Field

The final images were released at a meeting of the American Astronomical Society in January 1996, and revealed a plethora of distant, faint galaxies. About 3,000 distinct galaxies could be identified in the images, with both irregular and spiral galaxies clearly visible, although some galaxies in the field are only a few pixels across. In all, the HDF is thought to contain fewer than twenty galactic foreground stars; by far the majority of objects in the field are distant galaxies.

There are about fifty blue point-like objects in the HDF. Many seem to be associated with nearby galaxies, which together form chains and arcs: these are likely to be regions of intense star formation. Others may be distant quasars. Astronomers initially ruled out the possibility that some of the point-like objects are white dwarfs, because they are too blue to be consistent with theories of white dwarf evolution prevalent at the time. However, more recent work has found that many white dwarfs become bluer as they age, lending support to the idea that the HDF might contain white dwarfs.

Scientific results



Details from the HDF illustrate the wide variety of galaxy shapes, sizes and colours found in the distant universe.

The HDF data provided extremely rich material for cosmologists to analyse and as of late 2008, the associated scientific paper for the image has received over 800 citations. One of the most fundamental findings was the discovery of large numbers of galaxies with high redshift values.

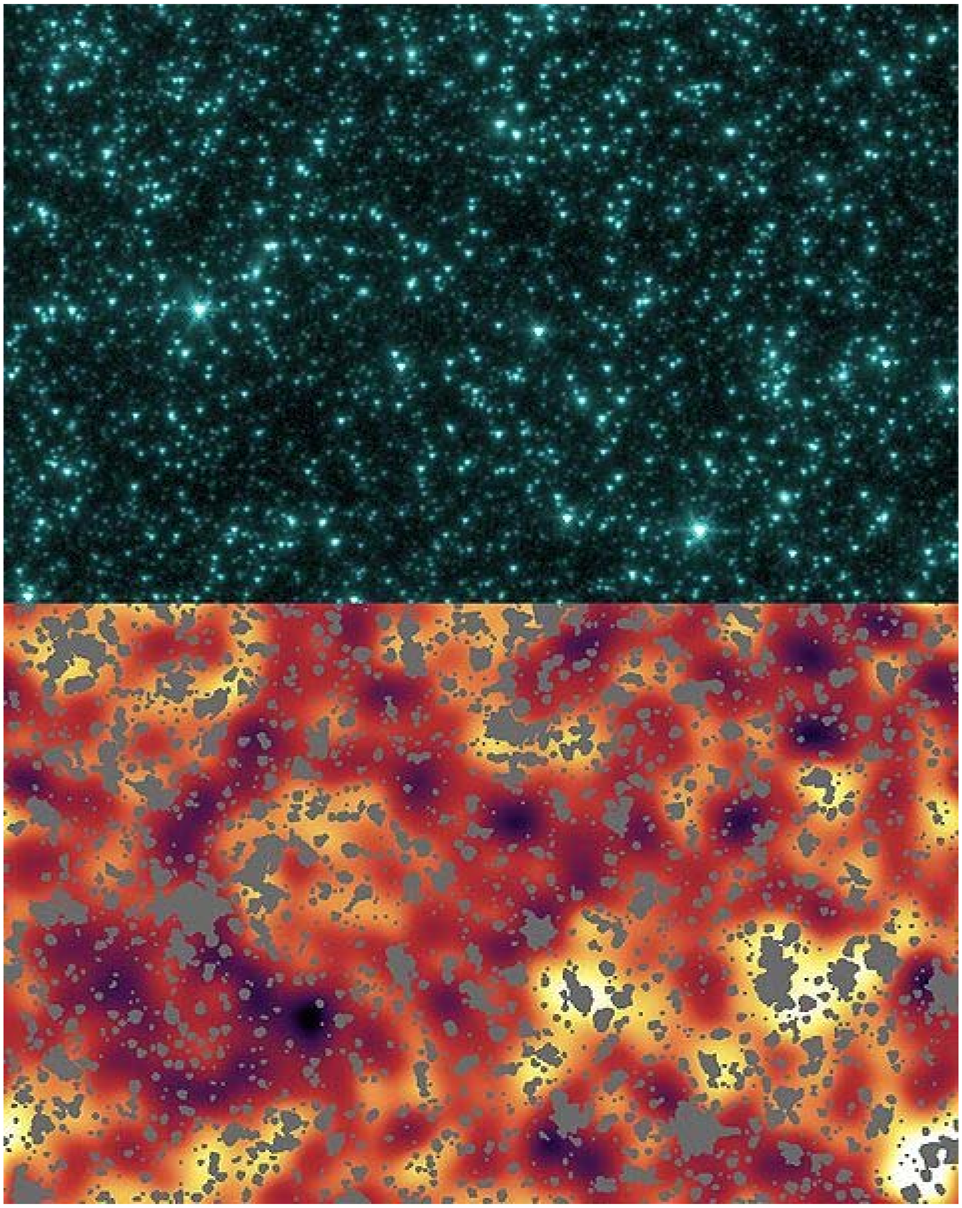
As the universe expands, more distant objects recede from the Earth faster, in what is called the Hubble Flow. The light from very distant galaxies is significantly affected by the cosmological redshift. While quasars with high redshifts were known, very few galaxies with redshifts greater than one were known before the HDF images were produced. The HDF, however, contained many galaxies with redshifts as high as six, corresponding to distances of about 12 billion light-years. Due to redshift the most distant objects in the HDF (Lyman-break galaxies) are not actually visible in the Hubble images; they can only be detected in images of the HDF taken at longer wavelengths by ground-based telescopes.

The HDF galaxies contained a considerably larger proportion of disturbed and irregular galaxies than the local universe; galaxy collisions and mergers were more common in the young universe as it was much smaller than today. It is believed that giant elliptical galaxies form when spirals and irregular galaxies collide.

The wealth of galaxies at different stages of their evolution also allowed astronomers to estimate the variation in the rate of star formation over the lifetime of the universe. While estimates of the redshifts of HDF galaxies are somewhat crude, astronomers believe that star formation was occurring at its maximum rate 8–10 billion years ago, and has decreased by a factor of about 10 since then.

Another important result from the HDF was the very small number of foreground stars present. For years astronomers had been puzzling over the nature of dark matter, mass which seems to be undetectable but which observations implied made up about 90% of the mass of the universe. One theory was that dark matter might consist of Massive Astrophysical Compact Halo Objects (MACHOs)—faint but massive objects such as red dwarfs and planets in the outer regions of galaxies. The HDF showed, however, that there were not significant numbers of red dwarfs in the outer parts of our galaxy.

Multifrequency followup



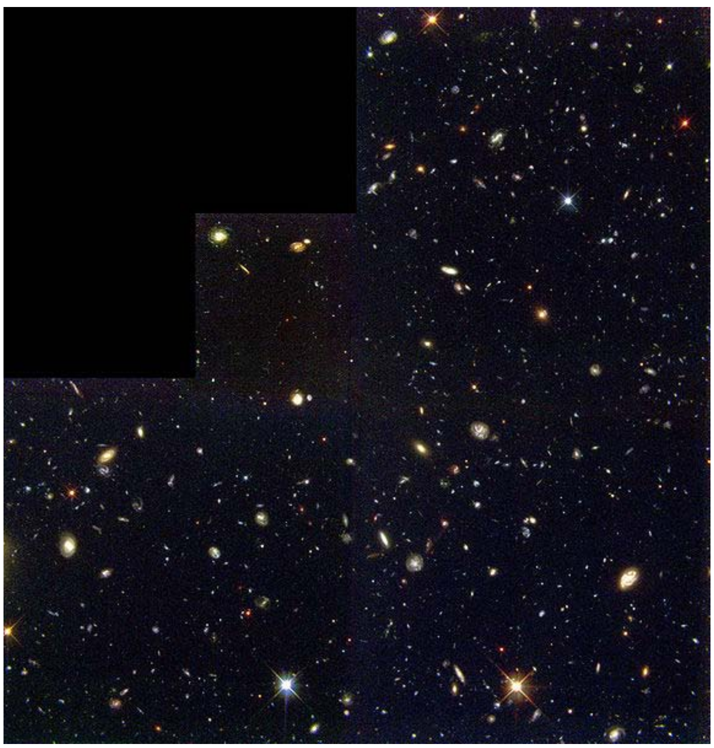
The HDF imaged by the Spitzer Space Telescope. The top segment shows the foreground objects in the field; the bottom shows the background with the foreground objects removed.

Very-high redshift objects (Lyman-break galaxies) cannot be seen in visible light and generally are detected in infrared or submillimetre wavelength surveys of the HDF instead. Observations with the Infrared Space Observatory (ISO) indicated infrared emission from 13 galaxies visible in the optical images, attributed to large quantities of dust associated with intense star formation. Infrared observations have also been made with the Spitzer Space Telescope. Submillimeter observations of the field have been made with SCUBA on the James Clerk Maxwell Telescope, initially detecting 5 sources, although with very low resolution. Observations have also been made with the Subaru telescope in Hawaii.

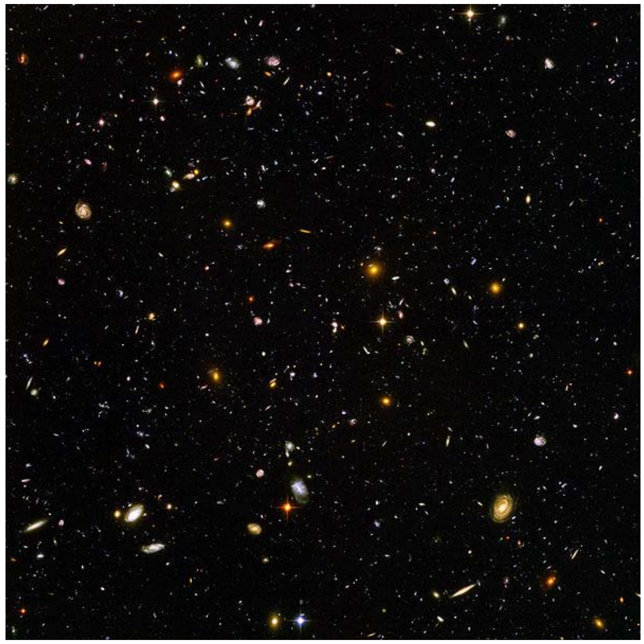
X-ray observations by the Chandra X-ray Observatory revealed six sources in the HDF, which were found to correspond to three elliptical galaxies: one spiral galaxy, one active galactic nucleus and one extremely red object, thought to be a distant galaxy containing a large amount of dust absorbing its blue light emissions.

Ground-based radio images taken using the VLA revealed seven radio sources in the HDF, all of which correspond to galaxies visible in the optical images. The field has also been surveyed with the Westerbork Synthesis Radio Telescope and the MERLIN array of radio telescopes at 1.4 GHz; the combination of VLA and MERLIN maps made at wavelengths of 3.5 and 20 cm have located 16 radio sources in the HDF-N field, with many more in the flanking fields. Radio images of some individual sources in the field have been made with the European VLBI Network at 1.6 GHz with a higher resolution than the Hubble maps.

Subsequent HST observations



The Hubble Deep Field South looks very similar to the original HDF, demonstrating the cosmological principle.



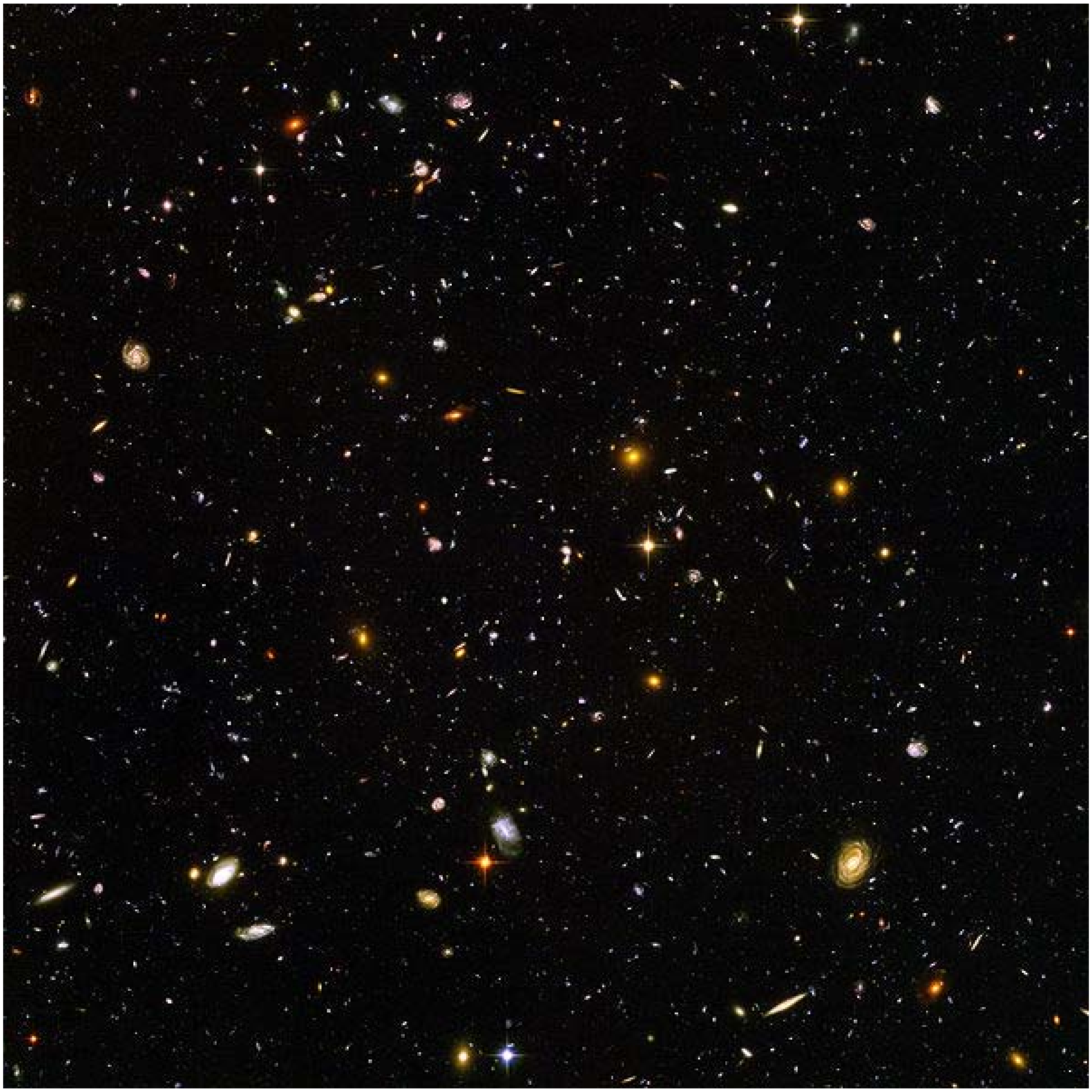
The Hubble Ultra Deep Field further corroborates this

An HDF counterpart in the southern celestial hemisphere was created in 1998: the HDF-South. Created using a similar observing strategy, the HDF-S was very similar in appearance to the original HDF. This supports the cosmological principle that at its largest scale the universe is homogeneous. The HDF-S survey used the Space Telescope Imaging Spectrograph (STIS) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instruments installed on the HST in 1997; the Hubble Deep Field has since been re-observed several times using WFPC2, as well as by the NICMOS and STIS instruments. Several supernova events were detected by comparing the first and second epoch observations of the HDF-N.

A wider survey, but less sensitive, was carried out as part of the Great Observatories Origins Deep Survey; a section of this was then observed for longer to create the Hubble Ultra Deep Field, which is the most sensitive optical deep field image to date.

Hubble Ultra Deep Field

Coordinates: $3^h\ 32^m\ 39.0^s$, −27° 47′ 29.1″

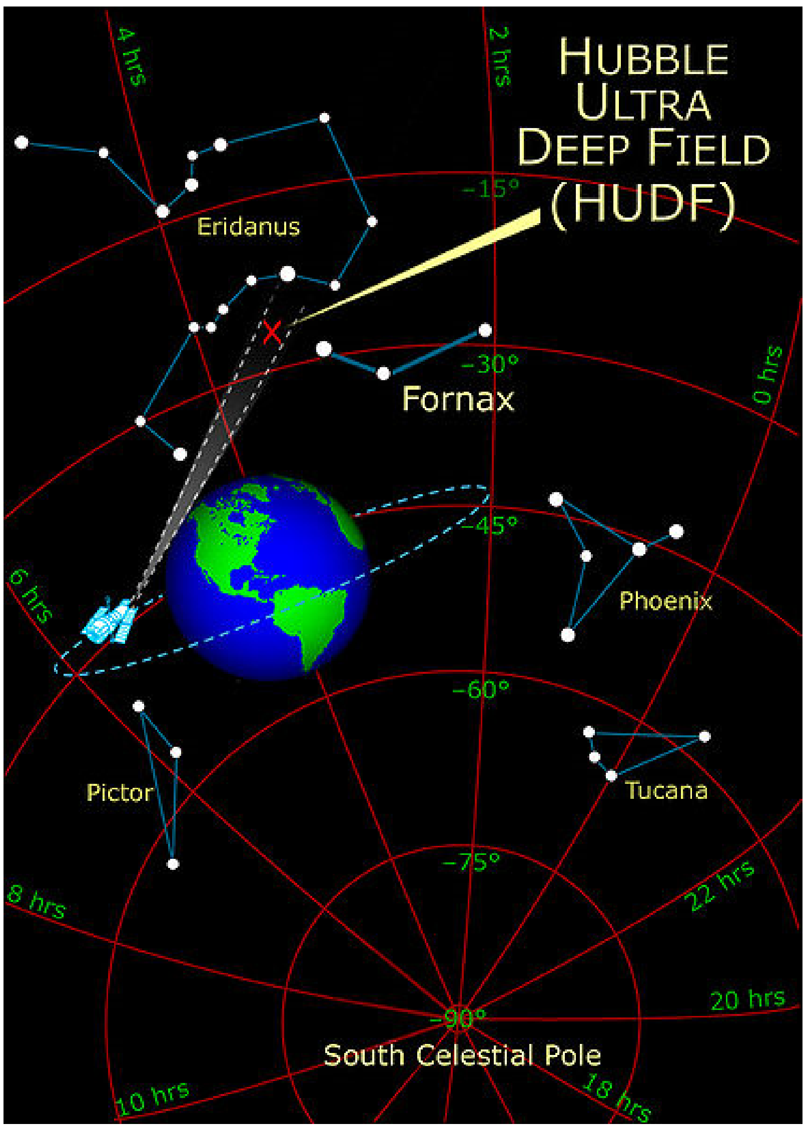


This high-resolution image of the HUDF includes galaxies of various ages, sizes, shapes, and colors. The smallest, reddest galaxies, of which there are approximately 10000, are some of the most distant galaxies to have been taken by an optical telescope, existing at the time shortly after the big bang.

The **Hubble Ultra Deep Field** (**HUDF**) is an image of a small region of space in the constellation Fornax, composited from Hubble Space Telescope data accumulated over a period from September 24, 2003 through to January 16, 2004. It is the deepest image of the universe ever taken, looking back approximately 13 billion years (between 400 and 800 million years after the Big Bang), and it will be used to search for galaxies that existed at that time. The HUDF image was taken in a section of the sky with a low density of bright stars in the near-field, allowing much better viewing of dimmer, more distant objects. The image contains an estimated 10,000 galaxies.

Located southwest of Orion in the southern-hemisphere constellation Fornax, the image covers 11.0 square arcminutes. This is just one-tenth the solid angle subtended by the full moon as viewed from Earth, smaller than a 1 mm-by-1 mm square of paper held 1 meter away, and equal to roughly one thirteen-millionth of the total area of the sky. The image is oriented so that the upper left corner points toward north (−46.4°) on the celestial sphere.

Planning



Location of the Hubble Ultra Deep Field on the sky

In the years since the original Hubble Deep Field, the Hubble Deep Field South and the GOODS sample were analyzed, providing increased statistics at the high redshifts probed by the HDF. When the Advanced Camera for Surveys (ACS) detector was installed on the HST, it was realized that an ultra deep field could observe galaxy formation out to even higher redshifts than had currently been observed, as well as providing more information about galaxy formation at intermediate redshifts (z~2).

Unlike the Deep Fields, the HUDF does not lie in Hubble's Continuous Viewing Zone (CVZ). The earlier observations, using the Wide Field and Planetary Camera 2 (WFPC2) camera, were able to take advantage of the increased observing time on these zones by using wavelengths with higher noise to observe at times when earthshine contaminated the observations; however ACS does not observe at these wavelengths, so the advantage was reduced.

As with the earlier fields, this one was required to contain very little emission from our galaxy, with little Zodiacal dust. The field was also required to be in a range of declinations such that it could be observed both by southern hemisphere instruments, such as the Atacama Large Millimeter Array, and northern hemisphere ones, such as those located on Hawaii. It was ultimately decided to observe a section of the Chandra Deep Field South, due to existing deep X-ray observations from Chandra X-ray Observatory and two interesting objects already observed in the GOODS sample at the same location: a redshift 5.8 galaxy and a supernova. The coordinates of the field are right ascension $3^h\ 32^m\ 39.0^s$, declination -27° 47′ 29.1″ (J2000). The field is 200 arcseconds to a side, with a total area of 11 square arcminutes, and lies in the constellation of Fornax.

Observations

Four filters were used on the ACS, centered on 435, 606, 775 and 850 nm, with exposure times set to give equal sensitivity in all filters. These wavelength ranges match those used by the GOODS sample, allowing direct comparison between the two. As with the Deep Fields, the HUDF used Directors Discretionary Time. In order to get the best resolution possible, the observations were dithered by pointing the telescope at slightly different positions for each exposure—a process trialled with the Hubble Deep Field—so that the final image has a higher resolution than the pixels on their own would normally allow.

The observations were done in two epochs, between September 23 and October 28, 2003, and December 4, 2003, to January 15, 2004. The total exposure time is just under 1 million seconds, from 400 orbits, with a typical exposure time of 1200 seconds. In total, 800 ACS exposures were taken over the course of 11.3 days, 2 every orbit, and NICMOS observed for 4.5 days. To observe the whole sky to the same sensitivity, the HST would need to observe continuously for a million years.

Observations made of the HUDF with the HST.

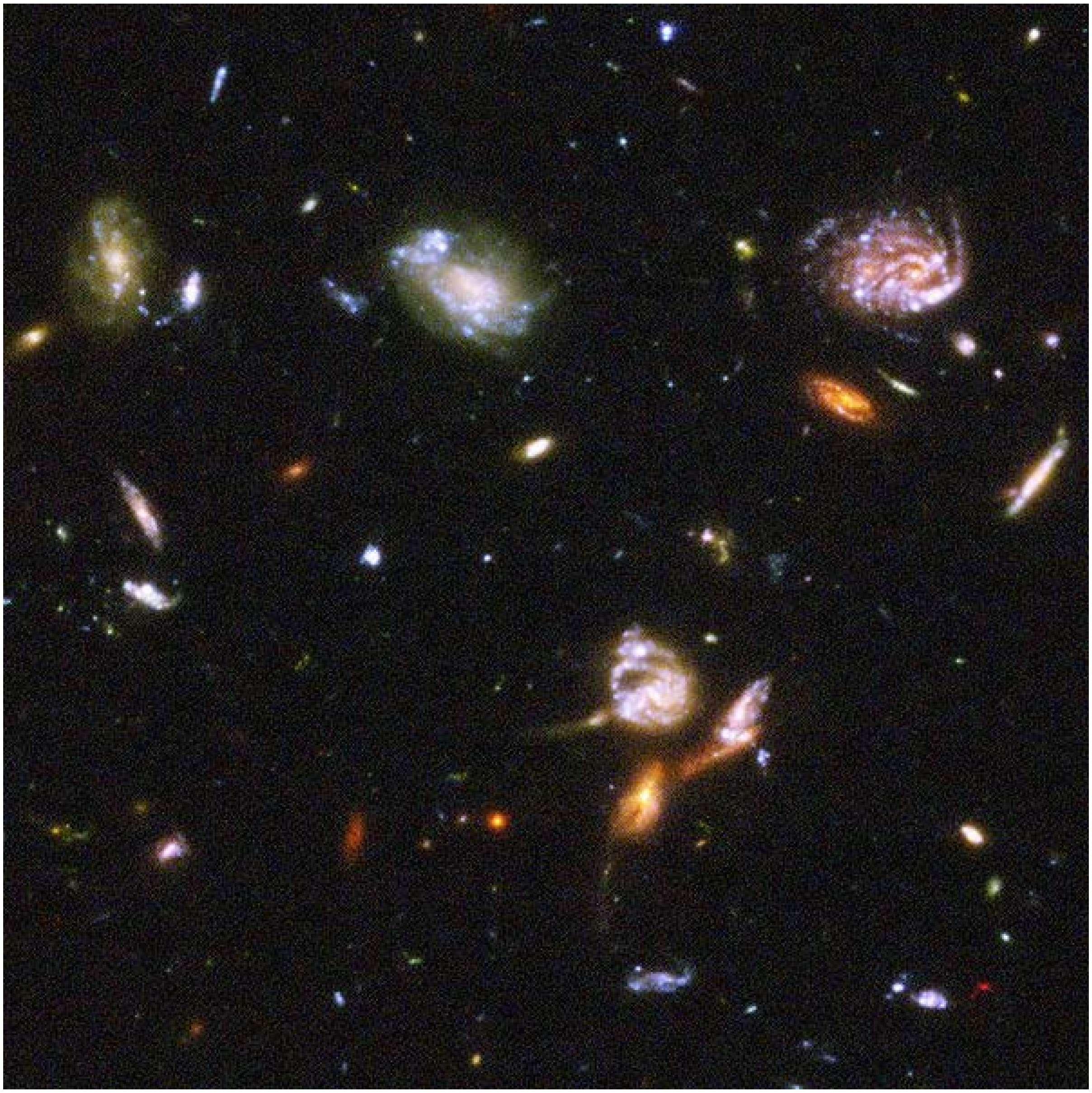
Camera	Filter	Wavelength	Total exposure time	Exposures
ACS	F435W	435 nm	134,900 s (56 orbits)	~116
ACS	F606W	606 nm	135,300 s (56 orbits)	~116

ACS	F775W	775 nm	347,100 s (144 orbits) ~288
ACS	F850LP	850 nm	346,600 s (144 orbits) ~288

After the installation of WFC3 on Hubble in 2009, the HUDF09 programme (GO-11563) devoted 192 orbits to observations of three fields, including HUDF, using the newly available F105W, F125W and F160W infra-red filters (which correspond to the I, J and H bands):

Observations made of the HUDF with WFC3

Camera	**Filter**	**Wavelength**	**Exposure time**
WFC3	F105W	1050 nm ± 150	16 orbits, 14 usable
WFC3	F125W	1250 nm ± 150	16 orbits
WFC3	F160W	1600 nm ± 150	28 orbits



Part of the Hubble Ultra Deep Field

The HUDF is the deepest image of the universe ever taken and it will be used to search for galaxies that existed between 400 and 800 million years after the Big Bang (redshifts between 7 and 12). The star near the center of the field is USNO-A2.0 0600-01400432 with apparent magnitude of 18.95.

The field imaged by the ACS contains over 10,000 objects, the majority of which are galaxies, many at redshifts greater than 3, and some that probably have redshifts between 6 and 7. The NICMOS measurements may have discovered galaxies at redshifts up to 12.

Scientific results

- High rates of star formation during the very early stages of galaxy formation, under a billion years after the Big Bang.
- Improved characterization of the distribution of galaxies, their numbers, sizes and luminosities at different epochs, allowing investigation into the evolution of galaxies.
- Confirmation that galaxies at high redshifts are smaller and less symmetrical than ones at lower redshifts, showing the rapid evolution of galaxies in the first couple of billion years after the Big Bang.

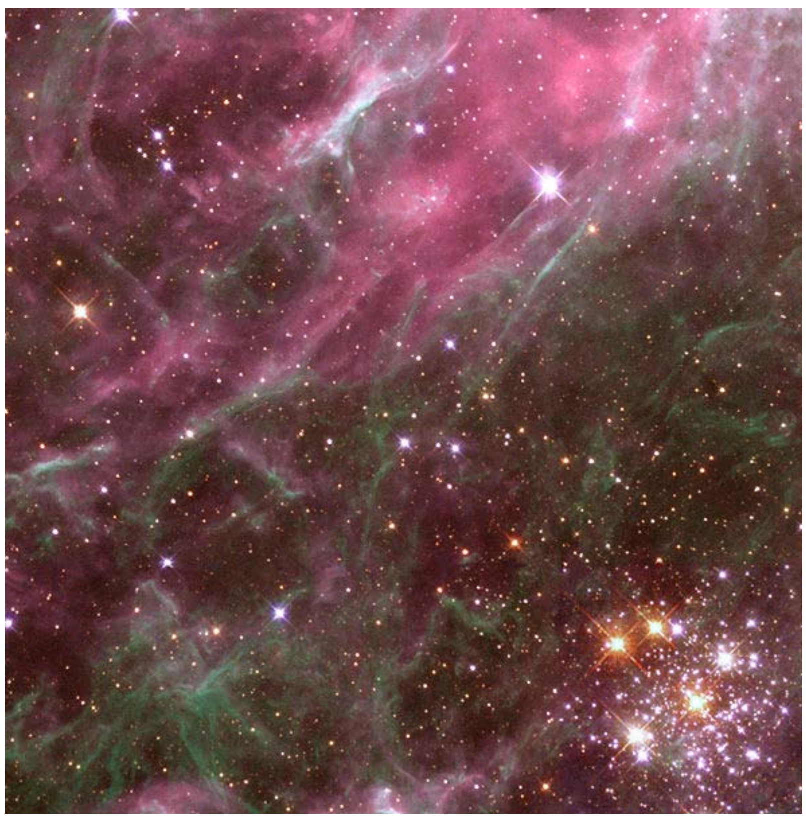
Follow-up observations

The HUDF remains the deepest view of the universe until the release of data from the Deep Field observation underway by the Hubble Space Telescope after its 2009 refurbishing. Deep Field observations are also planned for the James Webb Space Telescope in 2014.

Chapter- 5

Future and Successors for the Hubble Space Telescope

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. 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. 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. 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. There are further contingency plans for science with just one gyro, 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. One more gyro failed in 2007. 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.

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. 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). 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. 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.

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.

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. 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.

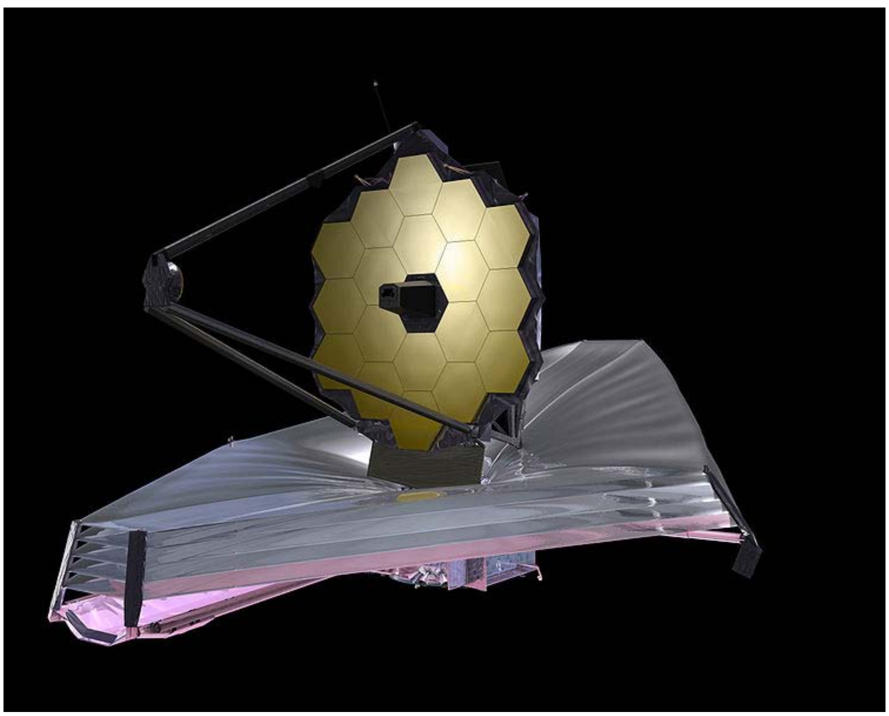
In January 2004, O'Keefe said he would review his decision to cancel the final shuttle servicing mission to HST due to public outcry and requests from Congress for NASA to look for a way to save it. On 13 July 2004 an official panel from the National Academy of Sciences made the recommendation that the HST should be preserved despite the apparent risks. Their report urged "NASA should take no actions that would preclude a space shuttle 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". 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.

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. 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. 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 and completed all the long planned replacements as well as additional repairs, including replacing the main data-handling unit.

James Webb Space Telescope

James Webb Space Telescope



Artist's impression of JWST. In normal working mode the mirror will not be lit, as it will be in complete and permanent sun-shade from the radiation shield below.

General information

Organization	NASA / ESA / CSA
Major contractors	Northrop Grumman

	Ball Aerospace
Launch date	2014 or in 2015
Launched from	Guiana Space Centre ELA-3 Kourou, French Guiana
Launch vehicle	Ariane 5
Mission length	5 years (design) 10 years (goal)
Mass	6,200 kg (14,000 lb)
Orbit period	1 year
Location	1.5×10^6 km (Lagrangian point L2)
Telescope style	Three Mirror Anastigmat
Wavelength	0.6 to 28 µm (infrared)
Diameter	~6.5 m (21 ft)
Collecting area	25 m^2 (270 sq ft)
Focal length	131.4 m (431 ft)
	Instruments
NIRCam	Near IR Camera
NIRSpec	Near IR Spectrograph
MIRI	Mid IR Instrument
FGS	Fine Guidance Sensor

The **James Webb Space Telescope** (**JWST**) is a planned infrared space observatory and is the scientific successor to the Hubble Space Telescope. The JWST or Webb Telescope's main scientific goal is to observe the most distant objects in the universe beyond the reach of either ground based instruments or the Hubble. The JWST is a project of the United States space agency (NASA) with international collaboration from the European Space Agency and the Canadian Space Agency, including contributions from fifteen nations.

Originally called the **Next Generation Space Telescope (NGST)**, it was renamed in 2002 after NASA's second administrator James E. Webb (1906–1992). Webb had headed NASA from the beginning of the Kennedy administration through the Johnson administration (1961–68), thus overseeing all the manned launches in the Mercury through Gemini programs, until just before the first manned Apollo flight.

Current plans call for the telescope to be launched on an Ariane 5 rocket in June 2014 (or mid 2015) on a five-year mission (10 year goal). The JWST will orbit the Sun in Earth's partial shadow, approximately 1,500,000 km (930,000 mi) on the far side of Earth at the L2 Lagrange point. Objects at the L2 point orbit the Sun in synchrony with the Earth, which allows JWST to use one radiation shield, positioned between the telescope and the Earth, to protect it from both the Sun's and the Earth's heat and light. It's also possible for the same shield to block moonlight, because the telescope is much further from Earth than the Moon is.

Mission

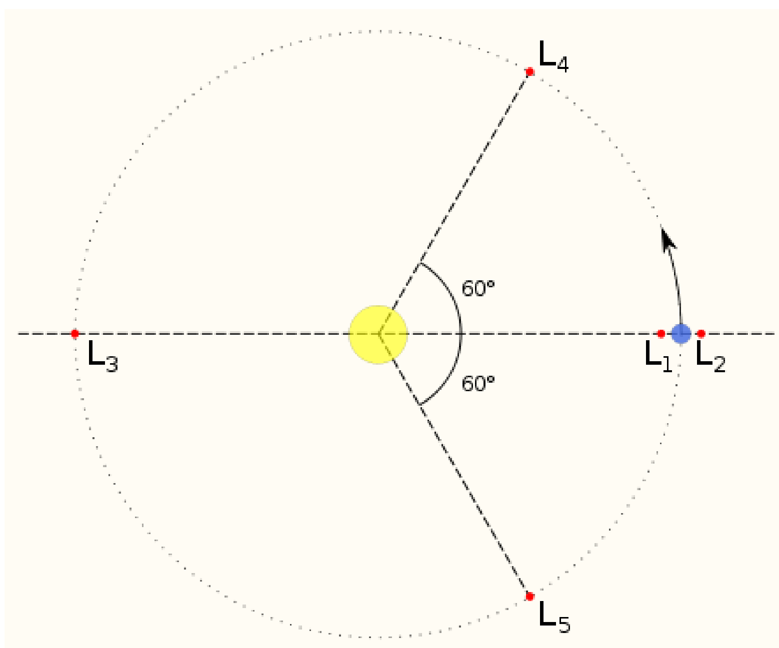
Full scale model on display at NASA Goddard

The JWST's primary scientific mission has four main components: to search for light from the first stars and galaxies which formed in the Universe after the Big Bang, to study the formation and evolution of galaxies, to understand the formation of stars and planetary systems and to study planetary systems and the origins of life. All of these jobs are more effectively done in the near-infrared than the visible. For this reason the JWST will lose the Hubble Telescope's visible light and ultraviolet capability but will be able to see much further into the infrared.

Due to a combination of redshift, dust obscuration, and the low temperatures of many of the sources to be studied, the JWST must operate at infrared wavelengths to see deeply into dust or distance. Its present design spans the wavelength range from 0.6 (near the cutoff between red and near-infrared) to 28 micrometers (deep infrared which corresponds to temperatures of about 100 kelvin). To ensure that the observations are not hampered by infrared emission from the telescope and instruments themselves the entire observatory must be cold. It must be well-shielded from the Sun so that it can radiatively cool to roughly 40 K (−230 °C, −390 °F). To do this JWST will incorporate a large metalized fan-fold sunshield which will unfurl to block infrared radiation from the Sun, Earth and Moon. The telescope's location at the Sun-Earth L_2 Lagrange point ensures that the Earth and Sun occupy roughly the same relative position in the telescope's view and thus make the operation of this shield possible.

The observatory is due to be launched no earlier than June 2014 and is currently scheduled to be launched by an Ariane 5 from Guiana Space Centre Kourou, French Guiana into an L_2 orbit with a launch mass of approximately 6.2 tons. After a commissioning period of approximately six months the observatory will begin the science mission which is expected to last a minimum of five years. The potential for extension of the science mission beyond this period exists and the observatory is being designed accordingly.

Orbit



A diagram showing the five Lagrangian points of the Sun-Earth system. JWST will be located at L2, where the Earth and sun are directly behind it at all times.

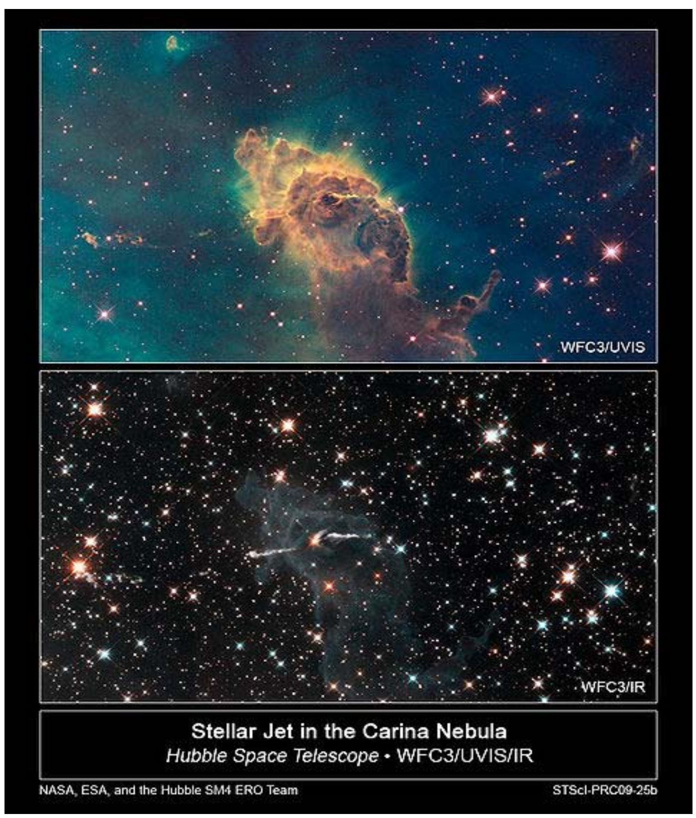
An idealized view from L2. A human observer at L2 would only be able to see the blinding white annulus of the Sun. The Sun disk is about 10% wider than the Earth disk.

To avoid swamping the faint astronomical signals with radiation from the telescope, the telescope and its instruments must be very cold. JWST has a large shield that blocks the light from the Sun, Earth, and Moon, which otherwise would heat the telescope and interfere with the observations. To have such a shield work, JWST must be in an orbit where all three of these objects are in about the same direction. The answer was to put JWST in an (relatively small) orbit around the Earth-Sun L2 point, or L_2. At the L_2 point, the Sun and Earth are in exactly the same direction at all times, and the moon swings laterally in orbit by only a relatively small amount.

The telescope's L_2 orbit will be an elliptical orbit about the semi-stable second Lagrange point. The Earth-Sun L_2 point, about which the Webb telescope will orbit, is 1,500,000 km (930,000 mi) from the Earth, which is about 3.92 times farther away from Earth than is the moon. (This distance underscores how much more difficult the Webb telescope would be to service than the Hubble telescope after launch; no plan contemplates doing so). The large distance of L_2 from Earth compared with the distance of the moon from the Earth, means that the diameter of the moon's orbit is less than 30 degrees as seen from the view of JWST. This allows the telescope's radiation shield (which is not symmetrical) to block all moonlight from the telescope, even as the moon moves to the extremes of its orbital excursion away from the Sun-Earth line. The shield extends farther laterally on one axis for this reason.

Normally, an object circling the Sun further out than the Earth would take more than one year to complete its orbit. However, the balance of gravitational pull at the L_2 point (in particular, the extra pull from Earth as well as the Sun) means that JWST will keep up with the Earth as it goes around the Sun. The combined gravitational forces of the Sun and the Earth can hold a spacecraft at this point, so that in theory it takes no rocket thrust to keep a spacecraft in orbit around L_2. In reality, the stable point is comparable to that of a ball balanced upon a saddle shape. Along one direction any perturbation will drive the ball toward the stable point, while in the crossing direction the ball, if disturbed, will fall away from the stable point. Thus some station-keeping is required but with little energy expended.

Optics



Two alternate Hubble Space Telescope views, comparing visible (top) and infrared (bottom) astronomy: Carina Nebula. Credit: NASA/ESA.

Infrared reveals more stars

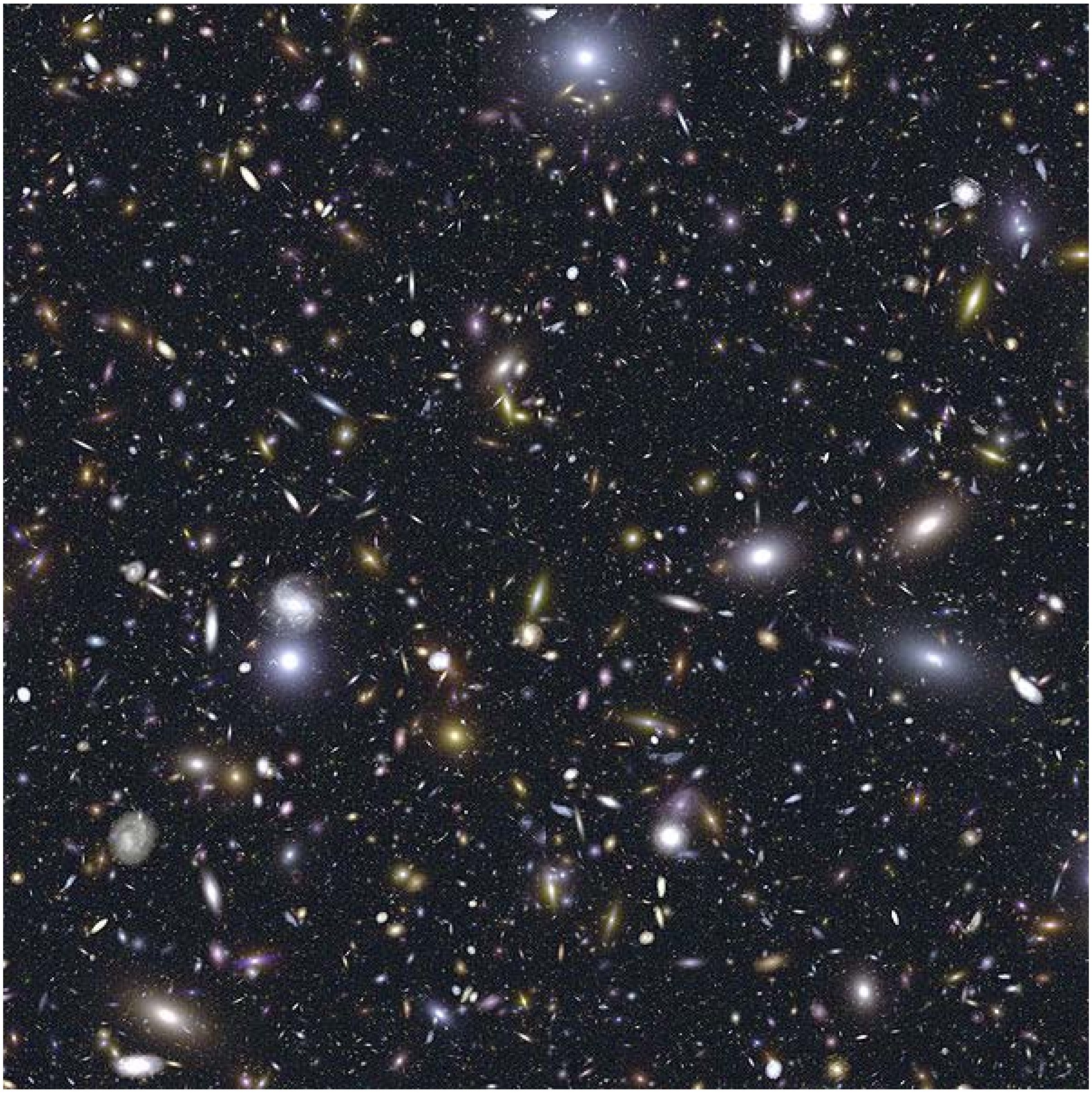
JWST is a true successor to the Hubble Space Telescope (HST), because JWST will be able to see many more and much older stars. Compare the two images taken utilizing the HST of the Carina Nebula. Though both images are of the same astronomical object taken by HST, the top image was photographed utilizing the visible spectrum, whereas the bottom image was taken in the infrared. Notice how more stars can be counted almost anywhere in the bottom (infrared spectrum) image than in the same corresponding location of the top (visible spectrum) image.

Visible spectrum views cannot peer through much of the gas and dust that may obscure an image like infrared views can. Almost all of the gas and dust obscuring images in visible spectrum views may entirely disappear if viewed in the infrared, so that the stars lying behind the gas and dust become easier to see. Infrared astronomy can penetrate dusty regions of space (such as molecular clouds), detect objects such as planets, and also view highly red-shifted objects from the early days of the universe.

The most distant stars in view are also the "youngest," that is, they were formed during a time period closer in time to that of the Big Bang than those stars less distant to us, such as our Sun. Because the universe is expanding, the light reaching us from those younger stars becomes red-shifted and are therefore easier to see if viewed in the infrared.

Infrared light is also useful for observing the cores of active galaxies which are often cloaked in gas and dust.

JWST optical design



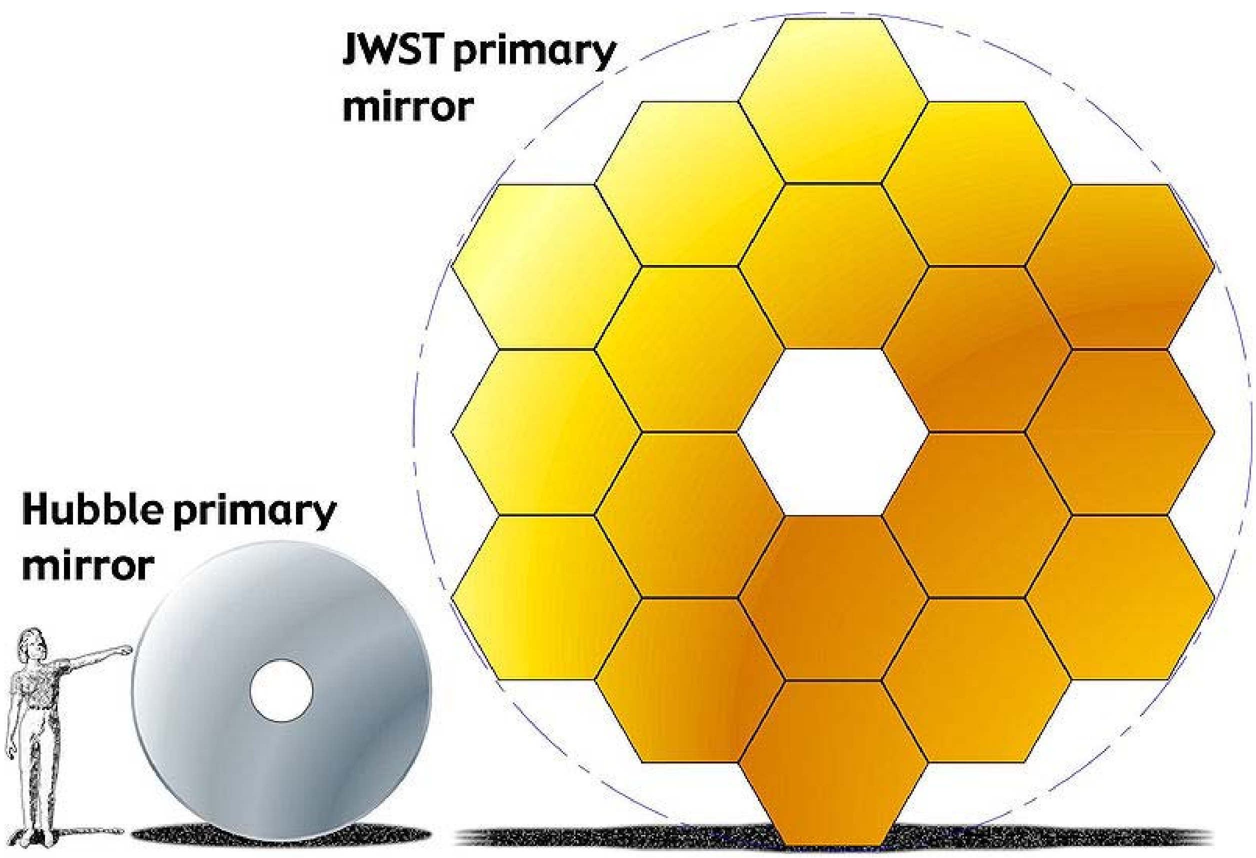
A Simulation of JWST's performance. This shows a "typical" JWST image, based on the expected density of sources of different types, and the predicted JWST performance. It is a false color image, since the JWST observes in the infrared. Credit: JWST/NASA/ESA.

Although JWST has a planned mass half that of the Hubble, its primary mirror (a 6.5 meter diameter gold-coated beryllium reflector) has a collecting area which is almost six times larger. As this diameter is much larger than any current launch vehicle, the mirror is composed of 18 hexagonal segments, which will unfold after the telescope is launched. These mirrors are currently being developed by Axsys Technologies in Cullman, Alabama. Sensitive micromotors and a wavefront sensor will position the mirror segments in the correct location, but subsequent to this initial configuration they will only rarely be moved. This process is much like an initial calibration, unlike terrestrial telescopes like the Keck which continually adjust their mirror segments using active optics to overcome the effects of gravitational and wind loading.

Ball Aerospace & Technologies Corp. is the principal optical subcontractor for the JWST program, led by prime contractor Northrop Grumman Aerospace Systems, under a contract from the NASA Goddard Space Flight Center, in Greenbelt, Maryland. Seventeen additional primary mirror segments, secondary, and tertiary mirrors, plus flight spares, will be delivered to Ball Aerospace from its beryllium mirror manufacturing team that includes Axsys, Brush Wellman, and Tinsley Laboratories. As each additional mirror is delivered to Ball Aerospace over the next year (to 2010), it will be mounted onto a lightweight, actuated strong-back assembly and undergo functional and environmental testing.

NASA has indicated that they will be incorporating microshutters, each about 100 by 200 micrometers, into the optics of the James Webb Space Telescope's Near InfraRed Spectrograph. An array of 62,000 of the shutters will sit in front of the spectrograph's 8-megapixel infrared detector. The microshutters will create an effect similar to a human eye squinting. When one squints, one's eyelashes block light; in the same way, the microshutters allow the telescope to focus on the faint light of stars and galaxies even if they are adjacent to brighter objects.

Program status



Comparison with Hubble primary mirror

The JWST program is in the final design and fabrication phase (Phase C). As is typical for a complex design that cannot be changed once launched, there are detailed reviews of every portion of design, construction, and proposed operation.

In April 2006 the program was independently reviewed following a replanning phase begun in August 2005. The review concluded the program was technically sound, but that funding phasing at NASA needed to be changed. NASA has rephased its JWST budgets accordingly. The August 2005 replanning was necessitated by the cost growth revealed in Spring 2005. The primary technical outcomes of the replanning are significant changes in the integration and test plans, a 22-month launch delay (from 2011 to 2013), and elimination of system level testing for observatory modes at wavelength shorter than 1.7 micrometers. Other major features of the observatory are unchanged following the replanning efforts.

As of the 2005 re-plan, the life-cycle cost of the project was estimated at about US$4.5 billion. This comprises approximately US$3.5 billion for design, development, launch and commissioning, and approximately US$1.0 billion for ten years of operations. ESA is contributing about €300million, including the launch, and the Canadian Space Agency about $39M Canadian. As of May 2007 costs were still on target, but by 2010 cost over-runs were impacting other programs, though JWST itself remains on schedule.

In January 2007 nine of the ten technology development items in the program successfully passed a non-advocate review. These technologies were deemed sufficiently mature to retire significant risks in the program. The remaining technology development item (the MIRI cryocooler) completed its technology maturation milestone in April 2007. This technology review represented the beginning step in the process that ultimately moved the program into its detailed design phase (Phase C).

In March 2008, the project successfully completed its Preliminary Design Review (PDR). In April 2008, the project passed the Non-Advocate Review. Other passed reviews include the Integrated Science Instrument Module review in March 2009, the Optical Telescope Element review completed in October 2009, and the Sunshield review completed in January 2010.

In April 2010, the telescope passed the overall Mission Critical Design Review (MCDR). Passing the MCDR signified the integrated observatory will meet all science and engineering requirements for its mission. The MCDR encompassed all previous design reviews. The project schedule will undergo a review during the months following the MCDR. The spacecraft design, which passed a preliminary review in 2009, will continue toward final approval in 2011.

Construction and engineering

Six of the James Webb Space Telescope beryllium mirror segments undergoing a series of cryogenic tests at the X-ray & Cryogenic Facility at NASA's Marshall Space Flight Center in Huntsville, Alabama.

NASA's Goddard Space Flight Center in Greenbelt, Maryland is leading the management of the observatory project. The project scientist for the James Webb Space Telescope is John C. Mather. Northrop Grumman Aerospace Systems serves as the primary contractor for the development and integration of the observatory. They are responsible for developing and building the spacecraft element, which includes both the spacecraft bus and sunshield. Ball Aerospace has been subcontracted to develop and build the Optical Telescope Element (OTE). Goddard Space Flight Center is also responsible for providing the Integrated Science Instrument Module (ISIM).

The ISIM contains four science instruments. NIRCam (Near InfraRed Camera) is an infrared imager which will have a spectral coverage ranging from the edge of the visible (0.6 micrometers) through the Near Infrared (5 micrometers). The NIRCam will also serve as the observatory's wavefront sensor, which is required for wavefront sensing and control activities. The NIRCam is being built by a team led by the University of Arizona, with Principal Investigator Marcia Rieke. The industrial partner is Lockheed-Martin's Advanced Technology Center located in Palo Alto, California.

The James Webb Space Telescope's Engineering Design Unit (EDU) primary mirror segment, coated with gold.

In addition to the Near Infrared (NIR) imaging capabilities of the NIRCam, the observatory will also perform spectrography over this range with the NIRSpec (Near InfraRed Spectrograph). NIRSpec is being built by the European Space Agency at ESTEC in Noordwijk, the Netherlands, leading a team involving EADS Astrium, Ottobrunn, and Friedrichshafen, Germany, and the Goddard Space Flight Center: the NIRSpec project scientist is Peter Jakobsen. The NIRSpec design provides 3 observing modes: a low resolution mode using a prism, an R~1000 multi-object mode and an R~2700 integral field unit or long-slit spectroscopy mode. Switching of the modes is done by operating a wavelength preselection mechanism called Filter Wheel Assembly and selecting a correspondent dispersive element (prism or grating) using the Grating Wheel Assembly mechanism. Both mechanisms are based on the successful ISOPHOT wheel mechanisms of the Infrared Space Observatory. The mechanisms and their optical elements are being designed, integrated and tested by Carl Zeiss Optronics GmbH of Oberkochen, Germany, under contract from Astrium.

The mid-IR wavelength range will be measured by the MIRI (Mid InfraRed Instrument), which contains both a mid-IR camera and spectrometer that has a spectral range extending from 5 to 27 micrometers. MIRI is being developed as a collaboration between NASA and a consortium of European countries, and is led by George Rieke (University of Arizona) and Gillian Wright (UK Astronomy Technology Centre, Edinburgh, part of the Science and Technology Facilities Council (STFC)). MIRI features similar wheel mechanisms as NIRSpec which are also developed and built by Carl Zeiss Optronics GmbH under contract from the Max Planck Institute for Astronomy, Heidelberg.

The FGS (Fine Guidance Sensor), led by the Canadian Space Agency under project scientist John Hutchings (Herzberg Institute of Astrophysics, National Research Council of Canada), is used to stabilize the line-of-sight of the observatory during science observations and also includes a Tunable Filter module for astronomical narrow-band imaging in the 1.5 to 5 micrometer wavelength range. The infrared detectors for both the NIRCam and NIRSpec modules are being provided by Teledyne Imaging Sensors (formerly Rockwell Scientific Company).

NASA is considering plans to add a grapple feature so future spacecraft might visit the observatory to fix gross deployment problems, such as a stuck solar panel or antenna. However, the telescope itself would not be serviceable, so that astronauts would not be able to perform tasks such as swapping instruments, as with the Hubble Telescope. Final approval for such an addition was to be considered as part of the Preliminary Design Review in March 2008.

Most of the data processing on the telescope is done by conventional single board computers. The conversion of the analog science data to digital form is performed by the custom-built SIDECAR ASIC (**S**ystem for **I**mage **D**igitization, **E**nhancement, **C**ontrol **A**nd **R**etrieval **A**pplication **S**pecific **I**ntegrated **C**ircuit). It is said that the SIDECAR ASIC will include all the functions of a 20-pound instrument box in a package the size of a half-dollar, and consume only 11 milliwatts of power. Since this conversion must be done close to the detectors, on the cool side of the telescope, the low power use of this IC will be important for maintaining the low temperature required for optimal operation of the JWST.

Ground support

The Space Telescope Science Institute (STScI) in Baltimore, Maryland has been selected as the Science and Operations Center (S&OC) for JWST. In this capacity, STScI will be responsible for the scientific operation of the telescope and delivery of data products to the astronomical community.

Public displays

In May 2007 a full-scale model of the telescope was assembled for display at the Smithsonian's National Air and Space Museum on the National Mall, Washington DC. The model was intended to give the viewing public a better understanding of the size, scale and complexity of the satellite. The model is significantly different from the telescope, as the model must withstand gravity and weather, so is constructed mainly of aluminum and steel measuring approximately 24 m (79 ft) x 12 m (39 ft) x 12 m (39 ft) and weighs 5.5 tonnes (12,000 lb).

The model has been on display at various places since 2005: Seattle, Washington; Colorado Springs, Colorado; Paris, France; Greenbelt, Maryland; Rochester, New York; Orlando, Florida; Dublin, Ireland; Montreal, Canada; Hatfield, United Kingdom; Munich, Germany, and Manhattan, New York. The model was built by the main contractor, Northrop Grumman Aerospace Systems.

Most recently, the model was on ongoing display in New York City's Battery Park during the 2010 World Science Festival. It served as the backdrop for a panel discussion featuring Nobel Prize laureate John C. Mather, astronaut John Grunsfeld and astronomer Heidi Hammel, which was followed by a star party hosted by Neil deGrasse Tyson, the director of the city's Hayden Planetarium.

Advanced Technology Large-Aperture Space Telescope

The **Advanced Technology Large-Aperture Space Telescope (ATLAST)** is a 8 to 16.8-meter (320 to 660-inch) UV-optical-NIR space telescope proposed by Space Telescope Science Institute, the science operations center for the Hubble Space Telescope (HST). If approved, built, and launched, ATLAST would be a true replacement and successor for the HST, with the ability to obtain spectroscopic and imaging observations of astronomical objects in the ultraviolet, optical, and Infrared wavelengths, but with substantially better resolution than either HST or the planned James Webb Space Telescope (JWST). Like JWST, ATLAST will be launched to the Sun-Earth L_2 Lagrange point.

ATLAST is envisioned as a flagship mission of the 2025 - 2035 period, designed to address one of the most compelling questions of our time: Is there life elsewhere in our Galaxy? It will accomplish this by detecting "biosignatures" (such as molecular oxygen, ozone, water, and methane) in the spectra of terrestrial exoplanets. But ATLAST is more than just a "life-finder." ATLAST will have the performance required to reveal the underlying physics that drives star formation and to trace the complex interactions between dark matter, galaxies, and the intergalactic medium. Because of the large leap in observing capabilities that ATLAST will provide, we cannot fully anticipate the diversity or direction of the investigations that will dominate its use – just as the creators of HST did not foresee its pioneering roles in characterizing the atmospheres of Jupiter-mass exoplanets or measuring the acceleration of cosmic expansion using distant supernovae. ATLAST will have the versatility to outlast the scientific vision of current-day astronomers.

Design

ATLAST will have a primary mirror diameter in the 8-m to 16.8-m range. Two different telescope architectures have been identified for ATLAST, but with similar optical designs, that span the range in viable technologies. The architectures are a telescope with a monolithic primary mirror and two variations of a telescope with a large segmented primary mirror. The concepts invoke heritage from the HST and JWST designs, but also take significant departures from these designs to minimize complexity, mass, or both. ATLAST will have an angular resolution that is 5 - 10 times better than JWST and a sensitivity limit that is up to 2,000 times better than HST.

Two of the concepts, the 8-m monolithic mirror telescope and the 16.8-m segmented mirror telescope, span the range of UVOIR observatories that are enabled by NASA's proposed Ares V launch vehicle, which is part of Project Constellation. The 8-m ATLAST offers the inherent advantages of a monolithic aperture telescope in terms of high-contrast imaging and superb wavefront control. The 16-m ATLAST represents a pathway to truly large apertures in space and uses the largest extrapolation of a JWST-like chord-fold primary mirror packaging. However, the ATLAST mission is not solely dependent on Ares V. The third concept, a 9.2-m segmented telescope, is compatible with an Evolved Expendable Launch Vehicle (EELV) and also adopts JWST design heritage. The ATLAST technology development plan is supported with funding from NASA's Astrophysics Strategic Mission Concept Study program, the Goddard Space Flight Center, the Marshall Space Flight Center, the Jet Propulsion Laboratory (Caltech) and related programs at Northrop Grumman Aerospace Systems and Ball Aerospace and Technology Corp.

In both designs, ATLAST will be able to be serviced on a regular basis, much like the HST has been. Using either a robotic ferry (the currently proposed method), or an astronaut crew flying in an Orion spacecraft (which will allow NASA to gain experience for future manned Solar System missions), instruments such as cameras would be replaced and returned to Earth for analysis and future upgrades. Like the HST and proposed JWST, ATLAST would be powered by solar panels.

Mission

ATLAST would either be launched from the Kennedy Space Center's Launch Pad 39A atop of the Ares V rocket or, if the 9.2-meter design is adopted, from NASA facilities capable of launching EELVs. Much like the proposed Orion/Altair flights to the Moon, the Ares V will place ATLAST and the Earth Departure Stage (EDS) into a "parking" orbit, while engineers check out the systems of both the EDS and the ATLAST. Once cleared, the EDS will fire again and ATLAST will then begin a three-month journey to the Sun-Earth L_2 Point, entering a so-called "halo orbit" around the point once it is reached. While en route to the Sun-Earth L_2 Point, the segmented versions of the telescope would deploy their optics.

Servicing missions, launched every 5 to 7 years, would allow astronomers to upgrade the ATLAS Telescope with new instruments and technologies that will come online down the road, and like the HST, ATLAST should have a 20-year lifespan.

Extrasolar planets

"ATLAST, using an internal coronagraph or an external occulter, can characterize the atmosphere and surface of an Earth-sized exoplanet in the Habitable Zone of long-lived stars at distances up to ~45 pc, including its rotation rate, climate, and habitability. ATLAST will also allow us to glean information on the nature of the dominant surface features, changes in cloud cover and climate, and, potentially, seasonal variations in surface vegetation.