Hubble Space Telescope (HST)
Past, Present & Future

Development & Deployment

Past Servicing Missions

Science Highlights

Reference Information

Design

Future Mission
HST Development and Deployment

- National Academy of Sciences study group recommended the development of a large space telescope in 1962.

- The approval of the Space Shuttle program in 1972 made the space telescope feasible.

- Congress authorized funding for the project in 1977.

- Assembly of the HST spacecraft was completed in 1985 but launch was delayed due to the Space Shuttle redesign following the Challenger accident.

- The HST was launched and deployed during the STS-31 mission on the Space Shuttle Discovery on April 24, 1990.
HST Communications Network
February 19, 1997, STS-82, Space Shuttle Discovery - HST redeployed after the second servicing mission.

HST Design

February 19, 1997, STS-82, Space Shuttle Discovery - HST redeployed after the second servicing mission.
HST Optical Telescope Assembly

Schematic shows the principal optical elements of the Optical Telescope Assembly. For clarity, the length is compressed, focal plane is shown farther behind the primary mirror than is the actual case, and the pickoff mirrors of the Fine Guidance Sensors are omitted (the Wide Field/Planetary Camera would fit in the fourth FGS position).
HST Optical Telescope Assembly (OTA)
To the surprise of astronomers, HST observations along with those of ground-based observatories have shown the universe is not just expanding, but accelerating. Many scientists believe this acceleration is caused by a “dark energy” that pervades the universe. Dark energy can be thought of as a sort of “antigravity” that is pushing galaxies apart by stretching space at an increasing pace. The nature of this energy is a complete mystery, even though astronomers estimate that it makes up about 70 percent of the mass and energy in the entire universe.

In the above image, an arrow points to a Cepheid star in the Andromeda galaxy observed by Hubble (inset boxes) during four days. Cepheid stars are regular radial-pulsating stars, with a well-defined period-luminosity relationship. Astronomers use cyclical changes in the brightness of Cepheid stars to determine astronomical distances.
2) Tracing the Growth of Galaxies

Because the universe was smaller in the past, galaxies were more likely to interact with one another gravitationally. Some of the Hubble’s cosmic “snapshots” show fantastic stellar streamers pulled out and flung across space by colliding galaxies. They apparently settled over time into the more familiarly shaped galaxies seen closer to Earth and hence nearer to the present time. By carefully studying galaxies at different epochs, astronomers can see how galaxies changed and evolved over time. Among the things they investigate are the relative amounts of stars and gas in galaxies, the types and amounts of identifiable chemical elements present, and star-formation rates.

Astronomers have used the HST to capture the appearance of many developing galaxies throughout cosmic time. This is possible because of the mathematical relationship between cosmic distance and time: the deeper Hubble peers into space, the farther back it looks in time. The most distant and earliest galaxies spied by Hubble are smaller and more irregularly shaped than today’s grand spiral and elliptical galaxies. This is evidence that galaxies grew over time through mergers with other galaxies to become the giant systems we see today.

The HST’s Ultra Deep Field image (left) is one of the most distant looks into space ever. The cumulative exposure time needed to capture the image was about a million seconds or 11 days. This historic view is actually two separate images taken in 1995 and 1998.

Credits: NASA, ESA, STScI, HUDF
3) Recognizing Worlds Beyond Our Sun

The imaged planet circles the star Fomalhaut, located 25 light-years away. This unusual planet follows a highly elongated orbit near the inner edge of a ring-like disk around Fomalhaut, and is presently about 10 times farther from the star than Saturn is from the sun.

Astronomers also used Hubble to make the first measurements of the atmospheric composition of extrasolar planets. HST observations have identified atmospheres that contain sodium, oxygen, carbon, hydrogen, carbon dioxide, methane and water vapor. Most of the planetary bodies studied to date are too hot for life as we know it. But the Hubble observations demonstrate that the basic organic components for life can be detected and measured on planets orbiting other stars.

At the time of the HST’s launch in 1990, astronomers had not found any planets outside our solar system. As of early 2017, scientists have now confirmed the existence of more than 3,000 extrasolar planets, most of them discovered by NASA’s Kepler Space Observatory and by ground-based telescopes. Hubble, however, has made some unique contributions to the planet hunt. 

Astronomers used the HST to take one of the first-ever visible-light pictures (left) of an extrasolar planet, named Fomalhaut b in 2004.

Credits: NASA, ESA, UCB, LLNL, JPL
Large galaxy clusters contain both dark matter and normal matter. The immense gravity of all this material warps the space around the cluster, causing the light from objects located behind the cluster to be distorted and magnified demonstrating gravitational lensing. The above illustration shows paths of light from a distant galaxy that is being gravitationally lensed by a foreground cluster. The HST’s uniquely sharp vision allows astronomers to map the distribution of dark matter in space using gravitational lensing. The universe appears to have about five times more dark matter than regular matter and seems to be organized around an immense network of dark matter filaments that have grown over time.

Dark matter is an invisible form of matter that makes up most of the universe’s mass and creates its underlying structure. Dark matter’s gravity drives normal matter (gas and dust) to collect and build up into stars and galaxies. Although astronomers cannot see dark matter, they can detect its influence by observing how the gravity of massive galaxy clusters, which contain dark matter, bend and distort the light of more distant galaxies located behind the cluster. This phenomenon is called “gravitational lensing.”
5) Realizing Monster Black Holes Are Everywhere

The HST provided decisive evidence that the hubs of most galaxies contain enormous black holes, which have the mass of millions or even billions of stars. Not only are black holes resident in almost every galaxy, but somehow their sizes correspond. A Hubble census of galaxies showed that a black hole’s mass is dependent on the mass of its host galaxy’s central bulge of stars; the larger the galaxy, the larger the black hole. This close relationship may be evidence that black holes grew along with their galaxies, devouring a fraction of the galaxy’s mass. Hubble also provided astronomers with the first-ever views of material encircling black holes in large, flat disks.

Combining images (above) with data from the HST’s spectrographs, researchers have peered into the center of many galaxies and established the existence of large black holes. These massive black holes surround themselves with luminous stars and gas, which are visible as bright knots. In a census performed by Hubble in the late 1990s, galaxies New General Catalogue (NGC) 3379 and NGC 3377 were found to have black holes that weighed 50 million and over 100 million solar masses, respectively, and NGC 4486B was revealed to have a double nucleus at its core.
HST Science Highlights

6) Uncovering Icy Objects in the Kuiper Belt

While probing the dwarf planet Pluto on the outskirts of our solar system, the HST spied four previously unknown moons orbiting the icy world. The tiny moons Nix and Hydra were the first to be spotted, followed by the even tinier Kerberos and Styx. Astronomers discovered that Nix and Hydra are rotating chaotically, that is, unpredictably, as they orbit the dwarf planet.

A composite of two images of the Pluto system (left) was taken by Hubble in July 2012. The blue areas are from a long exposure used to capture the tiny outer moons, which greatly oversaturated Pluto and Charon. The dark central vertical band is from a shorter exposure designed to show Pluto and Charon more clearly. The diameters of Pluto and its moons are not to scale.

Hubble also played a critical role in helping astronomers prepare for the New Horizons spacecraft flyby of Pluto in July 2015. With frequent observations of Pluto from the early 1990s to 2010, scientists refined maps of the dwarf planet’s surface. New Horizons personnel used these maps to prepare for the spacecraft’s brief rendezvous with Pluto and its moons. Peering out even farther, to the dim outer reaches of the solar system, Hubble uncovered Kuiper Belt objects that the New Horizons spacecraft could potentially visit on its continual outward journey.
7) Studying the Outer Planets and Moons

The HST has witnessed impacts on Jupiter that were produced by minor bodies in the solar system. The latest collision observed by Hubble occurred in 2009 when a suspected asteroid plunged into Jupiter’s atmosphere, leaving a temporary dark feature the size of the Pacific Ocean.

In 1994, Hubble watched 21 fragments of Comet Shoemaker-Levy 9 bombard the giant planet sequentially, the first time astronomers witnessed such an event. Each impact left a temporary black, sooty scar within Jupiter’s clouds.

Shown above, beginning at the lower right and ending in the upper left, is a series of four images documenting the blackened impact sites as they rotated into view from behind the planet.

Jupiter’s moons also have yielded important clues in the search for life beyond Earth. Hubble provided the best evidence yet for an underground saltwater ocean on Ganymede, the largest moon in the solar system, by detecting related activity in Ganymede’s own auroras. A subterranean ocean is thought to have more water than all the water on Earth’s surface. Hubble also recorded evidence of transient changes in the atmosphere above the surface of Jupiter’s moon Europa. Astronomers suspect that these disturbances are caused by gas plumes expelled from a subsurface ocean. Identifying liquid water is crucial in the search for habitable worlds beyond Earth and in the quest to find life as we know it.

Credits: NASA, HST Comet Science Team
Another Hubble observation of the asteroid belt revealed images of asteroid P/2013 P5 (right) showing it to be like none other, with various dust trails radiating in multiple directions and changing in appearance with time. Astronomers were surprised by the asteroid's unusual appearance. Unlike all other known asteroids, which appear simply as tiny points of light, this asteroid resembles a rotating lawn sprinkler. Computer models of the object suggest that the tails could have been formed by a series of dust-ejection events.

Asteroids do not just slam into planets like Jupiter or Earth, they also collide with each other. Astronomers using the HST witnessed one such impact in the asteroid belt between Mars and Jupiter, a reservoir of leftover rubble from the construction of our solar system. The Hubble observations in 2010 (left) showed a bizarre, X-shaped pattern of filamentary structures near the point-like core of an object with trailing streamers of dust. This complex structure suggested the small body was the product of a head-on collision between two asteroids traveling five times faster than a rifle bullet.
Astronomers used the HST to confirm that planets form in dust disks around stars. The telescope first resolved protoplanetary disks around nearly 200 stars in the bright Orion Nebula. Looking at nearby stars elsewhere in the sky, Hubble completed the largest and most sensitive visible-light imaging survey of dusty debris disks, which were probably created by collisions between leftover objects from planet formation. Using a mask to block the star’s bright light, Hubble scientists spotted a mysterious gap in a vast protoplanetary disk of gas and dust swirling around the star TW Hydrae. This 2005 Hubble image (left) and graphic (right) show a gap that is most likely caused by a growing, unseen planet that is gravitationally sweeping up material and carving out a lane in the disk like a snowplow. The gap is 1.9 billion miles wide and not yet completely cleared of material.
10) Exploring the Birth of Stars

Observed in 2010, “Mystic Mountain” (above) is from the much more extensive Carina Nebula. Towers of cool hydrogen gas laced with dust are seen to rise along the nebula’s wall. At the top, a three-light-year-tall pillar of gas and dust is being eaten away by the brilliant light and winds from nearby stars. The pillar is also being pushed apart from within, as infant stars buried inside it fire off jets of gas that can be seen streaming left and right from the tips of the peaks. The colors correspond to the glow of oxygen (blue), hydrogen and nitrogen (green), and sulfur (red).

The HST’s infrared detectors have penetrated gigantic, turbulent clouds of gas and dust where tens of thousands of stars are bursting to life. Hubble views of these nebulas reveal a bizarre landscape sculpted by radiation from young, exceptionally bright stars. The observations show that star birth is a violent process, producing intense ultraviolet radiation and shock fronts. The radiation clears out cavities in stellar nursery clouds and erodes material from giant gas pillars that are incubators for fledgling stars. Hubble has also captured energetic jets of glowing gas from young stars in unprecedented detail. These jets are a byproduct of gas swirling into newly forming stars.

Credits: NASA, ESA, STScI
The colors in the image were assigned to distinguish various chemical elements, which are now all racing into space to enrich new generations of stars. The colors indicate the different elements that were expelled during the explosion. The orange filaments are the tattered remains of the star and consist mostly of hydrogen. Blue in the filaments in the outer part of the nebula represents neutral oxygen, green is singly-ionized sulfur, and red indicates doubly-ionized oxygen.

Hubble’s 1999 and 2000 composite view of M1, the Crab Nebula (left), showed details never before seen about this mighty blast and the rapidly spinning pulsar that remains at its core. M1 is the remnant of a stellar explosion that was seen in the year 1054 AD by Chinese astronomers.

The HST has revealed unprecedented details in the appearance of sun-like stars that have entered the death throes of their lives. Hubble has shown that their shapes are varied and complex. Some look like pinwheels, others like butterflies, and still others like hourglasses. Such images yield insights into the complex dynamics that accompany a star’s release of its outer gaseous layers before it collapses to form a white dwarf.
In January 2002, an unexplained flash of light from a red supergiant star left what looked like an expanding bubble of debris. The light illuminated clouds that were already in place around the star. Since light travels at a finite speed, the flash took years to reach the most distant clouds and expose them. The phenomenon is called a “light echo,” as it is reminiscent of sound waves echoing down a canyon and revealing its walls.

The HST image of the star V838 Monocerotis (left) reveals a light echo unveiling never-before-seen dust patterns when the star suddenly brightened for several months in 2002.

V838 Monocerotis is located about 20,000 light-years away from Earth in the direction of the constellation Monoceros, placing the star at the outer edge of our Milky Way galaxy. The star presumably ejected the illuminated dust shells in previous outbursts. Light from the latest outburst travels to the dust and then is reflected to Earth. Monocerotis grew enormously in size. This behavior of ballooning to an immense size, but not losing its outer layers, is very unusual. The outburst may represent a transitory stage in a star’s evolution that is rarely seen.
When Edwin Hubble discovered that the universe was a vast frontier of innumerable galaxies beyond our Milky Way, he categorized them according to three basic shapes: spiral, elliptical and irregular. The HST’s images uncovered a plethora of oddball, peculiarly shaped galaxies that are more numerous the farther back into time the telescope looks. The expanding universe was smaller long ago, and galaxies were both younger and more likely to interact since they were closer to one another. Hubble’s images capture snapshots of galaxies at various stages of interaction. These observed mergers form a preview of the coming collision between our own Milky Way and the neighboring Andromeda galaxy 4 billion years from now.

The above composite image of the Antennae galaxies shows the merging of a pair of galaxies. It was observed in 2004 and 2005. The two spiral galaxies started to interact a few hundred million years ago. The orange blobs to the left and right of image center are the two cores of the original galaxies and consist mainly of old stars criss-crossed by filaments of dust, which appears brown in the image. The two galaxies are dotted with brilliant blue star-forming regions surrounded by glowing hydrogen gas, appearing in the image in pink. During the course of the collision, billions of stars will be formed. The brightest and most compact of these star birth regions are called super star clusters.
December 9, 1993, STS-61, Space Shuttle Endeavour - Astronaut F. Story Musgrave, anchored on the end of the shuttle Remote Manipulator System (RMS) arm, prepares to be elevated to the top of the HST to install protective covers on the magnetometers. Astronaut Jeffrey A. Hoffman, inside the payload bay, assisted Musgrave with final servicing tasks on the telescope, wrapping up five days of space walks. The Flight Support Station served as the berthing platform for Hubble.

HST Servicing Mission 1
December 8, 1993, STS-061, Space Shuttle, Endeavour, Astronaut Kathryn C. Thornton lifts the Corrective Optics Space Telescope Axial Replacement (COSTAR) prior to its installation on the HST. Thornton is anchored to a foot restraint on the end of the RMS arm. Astronaut Thomas D. Akers, who assisted in the COSTAR installation, is at lower left.
This comparison of the core of the galaxy M100 shows the dramatic improvement in the HST after SM 1 in December 1993. The new image, taken with the second generation WFPC2 installed, beautifully demonstrates how the camera’s corrective optics compensate fully for the optical aberration in Hubble's primary mirror. The HST could now explore the universe with unprecedented clarity and sensitivity, and fulfill its most important scientific objectives. M100 is a majestic face-on spiral galaxy located in the constellation Coma Berenices about 56 million light years from Earth.
HST Servicing Mission 2

February 19, 1997, STS-82, Space Shuttle Discovery - Attached to the "robot arm" the HST is unberthed and lifted up into the sunlight.
December 23, 1999, STS-103, Space Shuttle Discovery - Astronauts C. Michael Foale (left) and Claude Nicollier work on the HST. Nicollier replaces one of the three Fine Guidance Sensors. He is standing on a foot restraint connected to the end of Discovery's RMS robot arm.
March 7, 2002, STS-109, Space Shuttle Columbia - Astronauts Jim Newman (right) and Mike Massimino installed the new Advanced Camera for Surveys (ACS) in the HST. The astronauts stepped inside Hubble through the starboard side of the axial bay. Here they removed the Faint Object Camera to make room for the ACS. Newman, on Columbia's RMS robotic arm, removed the Faint Object Camera to make room for the new ACS.
HST Servicing Mission 4

May 13, 2009, STS-125, Space Shuttle Atlantis - The astronauts view the HST in the cargo bay following its capture and lock-down in Earth orbit to begin the last servicing mission.
May 14, 2009, STS-125, Space Shuttle Atlantis - Astronaut Andrew Feustel, supported by the RMS arm, prepares to install the Wide Field Camera 3 (WFC3) during the first of five spacewalks.
May 16, 2009, STS-125, Space Shuttle Atlantis - Astronaut Andrew Feustel, positioned on a foot restraint on the end of the RMS arm, removes the Corrective Optics Space Telescope Axial Replacement (COSTAR) from the HST during the third EVA. The Cosmic Origins Spectrograph replaced COSTAR.
May 18, 2009, STS-125, Space Shuttle Atlantis - Astronaut John Grunsfeld, positioned on a foot restraint attached to the RMS arm, is shown installing a battery group replacement during the last EVA.
May 19, 2009, STS-125, Space Shuttle Atlantis - A crewmember captured this image of the HST as the two spacecraft continue their separation following the last servicing mission.
May 19, 2009, STS-125, Space Shuttle Atlantis - A crew member captured this image as the two spacecrafts begin their separation. During the first SM4 spacewalk, the Soft Capture Mechanism was installed to enable a future crew or robotic vehicle to safely de-orbit Hubble at the end of its life.
Reference Information

Images:
All images are from NASA except as noted

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HST Development and Deployment

- Long before mankind had the ability to go into space, astronomers dreamed of placing a telescope above Earth's obscuring atmosphere. An observatory in space was proposed in 1923 by the German scientist Hermann Oberth, who inspired rocket pioneer Dr. Wernher von Braun's interest in space travel. Scientific instruments installed on early rockets, balloons, and satellites in the late 1940s through the early 1960s produced enough exciting scientific revelations to hint at how much remained to be discovered.

- In 1962, just four years after NASA was established, a National Academy of Sciences study group recommended the development of a large space telescope as a long-range goal of the fledgling space program. The first two successful NASA satellites (Orbiting Astronomical Observatory 2 and 3) designed for observing the stars were launched in 1968 and in 1972. These orbiting astronomical observatories produced a wealth of information, and support for an even larger, more powerful optical space telescope grew.

- The approval of the Space Shuttle, with its capacity for manned delivery, retrieval and servicing of large payloads, made the space telescope concept feasible. NASA selected a team of scientists in 1973 to establish the basic design of such a telescope and its instruments. Congress authorized funding for the project in 1977.

- NASA assigned responsibility for design, development, and construction of the space telescope to the Marshall Space Flight Center in Huntsville, Alabama. The European Space Agency became involved with the project in 1975 and agreed to furnish the solar arrays and one of the scientific instruments. Construction and assembly of the space telescope was a painstaking process which spanned almost a decade. The precision-ground primary mirror was completed in 1981, and the optical assembly was delivered for integration into the satellite in 1984. The science instruments were delivered to NASA for testing in 1983. Assembly of the entire spacecraft was completed in 1985.

- Launch of the HST was originally scheduled for 1986. It was delayed during the Space Shuttle redesign following the Challenger accident. Engineers used the interim period to subject the telescope to intensive testing and evaluation, assuring the greatest possible reliability. The telescope was shipped from Lockheed in Sunnyvale, California to the Kennedy Space Center in Florida in October 1989. The HST was launched aboard the STS-31 mission on the Space Shuttle Discovery on April 24, 1990.
HST Communications Network

The HST performs only in response to detailed instructions from controllers on the ground. Four antennae send and receive information between the telescope and the Flight Operations Team at the Space Telescope Science Institute. Scientists communicate with the telescope via the Tracking and Data Relay Satellite (TDRS) system. There are currently five TDRS satellites located at various locations in geostationary orbit. At least one of the five satellites must have line-of-sight visibility from the spacecraft. Scientists can interact directly with the telescope during times of satellite visibility, allowing them to make small changes in the telescope pointing to fine-tune observations. TDRS visibility does not affect a planned observation because the commanding is done well in advance. When none of the satellites are visible from the HST, a special data recorder stores the observation. The data is stored and then transmitted during periods of TDRS visibility.

HST Scientific Data Communication

- The light (1) from a star or an object travels through the HST (2) aperture into the Optical Telescope Assembly to the focal plane where the light is turned into a focused image. Parts of the image enter the apertures of the scientific instruments.
- These images, as well as other scientific data are converted to electronic digitized signals and transmitted by the HST High Gain Antennas to the TDRS (3) system.
- From the TDRS system, the HST data is transmitted to the Ground Station (4) at White Sands, NM.
- The data is then transmitted to the Space Telescope Operations Control Center (5) at the Goddard Space Flight Center via a commercial satellite. The Operations Center is the ground control facility for the telescope. The observation data is received at the center and translated into a format usable by the Science Institute. In turn, the HST observing agenda from the Science Institute is translated into computer commands by the control center and relayed to the telescope. The control center also monitors the health and safety of the spacecraft.
- The Space Telescope Science Institute (6), on the campus of Johns Hopkins University in Baltimore, Maryland, performs the science planning for the telescope. Scientists at the institute select observing proposals from astronomers, coordinate research, and generate the HST observing agenda for the telescope. They also archive and distribute results of the investigations. The institute is operated by the Association of Universities for Research in Astronomy and directed by Goddard Space Flight Center.
HST Design

HST Characteristics

Orbit: 370 statute miles (590 km) altitude, 28.5 degrees inclination relative to the equator
Orbital Speed: 17,500 miles per hour (28,000 km per hour)
Length: 43.5 ft. (13.3 m); Width: 14 ft. (4.3 m) diameter; Weight: 24,500 lbs or 12.25 tons (11,111 kgs)
Life: approximately 20 years with on-orbit servicing; Cost: $2.2 billion at launch

The general design is a high-quality, mid-size reflector telescope, encircled by a satellite bus, designed to let astronomers and astrophysicists see the universe without the view being distorted or filtered by passage through the Earth's atmosphere. The HST spacecraft is divided into three major areas: the Support Systems Module (SSM), the Optical Telescope Assembly (OTA), and the Science Instruments (SIs):

Support Systems Module (SSM)

The SSM encloses the OTA and provides all services necessary to operate and protect the OTA in space. The SSM was designed and built by Lockheed Missiles & Space Co. Principal sections of the SSM are:

- Equipment Section - a ring of equipment bays encircling the OTA Primary Mirror Assembly. The Equipment Section contains most of the systems that operate the HST and has doors similar to those on the OTA Equipment Section.
- Forward light shield and aperture door - shields the OTA from bright light sources and closes to completely protect the OTA.
- Forward shroud - encloses the Metering Truss Structure of the OTA.
- Aft shroud - encloses the radial and axial instrument bays and the Focal Plane Structure. The space shuttle maintenance platform interface equipment (alignment target, berthing pins, electrical power umbilical) are located on the aft bulkhead.
- The SSM has two pairs of deployable appendages: solar arrays - convert sunlight to electricity to power the HST; and high gain antennas - provide communications with the Tracking and Data Relay Satellite system.

SSM Servicing Provisions - the Space Shuttle captures the HST by attaching the shuttle remote manipulator system arm to a grapple fixture, mounted to the SSM. The arm berths the HST in the shuttle cargo bay to a maintenance platform, the Flight Support System, using three latches that attach to pins mounted to the SSM aft shroud bulkhead. Umbilical connectors, also mounted to the aft shroud bulkhead, can provide shuttle power to the berthed HST. Astronauts then perform servicing operations in the shuttle cargo bay.
HST Design

Optical Telescope Assembly (OTA)
The OTA is the core of the HST. The light from a star or an object travels through the aperture, down the OTA, and past the secondary mirror. The light then strikes the primary mirror where the beam is narrowed and reflected to the secondary mirror where it is intensified into a small diameter beam. A meteoroid shield sun shade protects these optics. The beam passes through a hole in the primary mirror to the focal plane almost five feet behind it. The focal plane is where the light is turned into a focused image. Parts of the image enter the apertures of the SIs. These images, as well as other scientific data are converted to electronic digitized signals and transmitted by the high gain antennas. The OTA is divided into four main areas:

- Primary Mirror Assembly - Primary Mirror, Main Ring, Reaction Plate, and the Central Baffle.
- Secondary Mirror Assembly - Metering Truss Structure, Secondary Mirror Subassembly, and the Main Baffle.

The OTA was developed by the Perkin-Elmer Corp. in Danbury, CT under contract to Marshall Space Flight Center in Huntsville, AL.

Science Instruments (SIs)
The HST design provides space for five science instruments in the focal plane of the OTA. The five instruments launched April 24, 1990 were:

- Faint Object Camera (FOC) - images stars about the same brightness as the background glow of space. Developed by the European Space Agency.
- Faint Object Spectrograph (FOS) - analyzes the spectra of extremely faint objects in space. Developed by the University of California at San Diego.
- Goddard High Resolution Spectrometer (HRS) - can distinguish between almost identical wavelengths of UV light. Developed by Goddard Space Flight Center.
- High Speed Photometer (HSP) - measures changes in the brightness of objects over short periods of time. Developed by the University of Wisconsin.
- Wide Field/Planetary Camera (WF/PC) - images stars and planets. Developed by Jet Propulsion Laboratory.
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Servicing Mission 1 (SM1)
SM1, launched December 2, 1993, was the first opportunity to conduct planned maintenance on the telescope. The flaw in the primary mirror was corrected; new instruments were installed; and the spacecraft hardware was installed and replaced.

Primary Mirror Corrected
After the HST deployment, scientists realized the primary mirror had a flaw called spherical aberration. The outer edge of the mirror was ground too flat by a depth of 2.2 microns (roughly equal to one-fiftieth the thickness of a human hair). This aberration resulted in an inability to focus the light. Corrective Optics Space Telescope Axial Replacement (COSTAR) was developed as an effective means of countering the effects of the flawed shape of the mirror. COSTAR was a telephone booth-sized instrument that placed five pairs of corrective mirrors in front of the FOC, FOS and HRS. COSTAR, built by Ball Aerospace located in Boulder, CO, replaced the High Speed Photometer instrument. All of the instruments installed during Servicing Missions 2, 3A and 3B have internal corrections for spherical aberration.

New Science Instrument
Added Wide Field Planetary Camera 2 (WFPC2) - significantly improved ultraviolet performance over WFPC1, the original instrument. In addition to having more advanced detectors and more stringent contamination control, WFPC2 incorporated built-in corrective optics.

Spacecraft Hardware
• Replaced Solar Arrays - converts sunlight to electricity to power the HST.
• Replaced Solar Array Drive Electronics - controls the positioning of the solar arrays.
• Replaced Magnetometers - senses the Earth’s magnetic field with respect to the HST attitude.
• Replaced Coprocessors for the flight computer - upgraded the computer memory and processing speed.
• Replaced two Rate Sensor Units - the gyroscopes are the heart of the HST pointing system.
• Replaced two Electronics Control Units - provides the gyroscope control electronics.
• Installed the Goddard High Resolution Spectrograph Redundancy Kit - a device that provides an alternate power supply.
Servicing Mission 2 (SM2)

SM2, launched February 11, 1997, greatly improved HST productivity. The installation of two new instruments, replacing the FOS and GHRS, extended the wavelength range of the HST into the near infrared for imaging and spectroscopy. This allowed the HST to probe the most distant reaches of the universe. The replacement of failed or degraded spacecraft components increased efficiency and performance.

New Science Instruments

- **Added Space Telescope Imaging Spectrograph (STIS)** - provides the HST with unique and powerful spectroscopic capabilities. A spectrograph separates the light gathered by the telescope into its spectral components so that the composition, temperature, motion, and other chemical and physical properties can be analyzed. STIS searches for massive black holes by studying the star and gas dynamics around galactic centers. It also uses its high sensitivity and spatial resolution to study star formation.
- **Added Near Infrared Camera and Multi-Object Spectrometer (NICMOS)** - capable of both infrared imaging and spectroscopic observations of astronomical targets. NICMOS gave astronomers their first clear view of the universe at near-infrared wavelengths (longer wavelengths than the human eye can see). NICMOS's near infrared capabilities provides views of objects too distant for research by previous HST optical and ultraviolet instruments.

Spacecraft Hardware

- **Replaced one Fine Guidance Sensor** - provides pointing information for the spacecraft and a scientific instrument for astrometric science.
- **Added Optical Control Electronics Enhancement Kit** - provides the electronic pathway for commanding the alignment mechanisms.
- **Replaced Solid State Recorder** - replaced one of the three Engineering/Science Tape Recorders.
- **Replaced one Reaction Wheel Assembly** - momentum wheels move the telescope to a target and maintains the HST in a stable position.
- **Replaced one Data Interface Unit** - provides a common command and data interface between the data management system and the other HST equipment.
- **Replaced one Solar Array Drive Electronics** - controls the positioning of the solar arrays.
Servicing Mission 3A (SM3A)

What was originally conceived as a mission of preventive maintenance turned more urgent on November 13, 1999, when the fourth of six gyros failed. Unable to conduct science without three working gyroscopes, the HST was put in a safe-hold mode and the science program was suspended. In accordance with NASA's flight rules, a "call-up" mission was quickly approved, developed and executed in a record 7 months!

SM3A, launched December 19, 1999, successfully replaced six gyroscopes and other equipment, and performed maintenance upgrades to the HST. Although no new scientific instruments were installed, many activities took place over 3 EVA days. The originally planned 4 days of EVA were changed to 3 days because of the weather-delayed launch. The space shuttle de-orbit time was fixed for this mission in order to avoid any possible Y2K problems.

Spacecraft Hardware

- Installed Advanced Computer - 20 times faster with six times more memory than its predecessor. This computer dramatically increased capabilities, reduced maintenance, and significantly lowered operational costs. It was successfully tested aboard STS-95 in 1998 on the HOST mission.
- Replaced one Fine Guidance Sensor - used for steady pointing and measurement.
- Installed Handrail Covers - fit like sleeves around the handrails above the bay for the Fine Guidance Sensor. The covers prevent possible contamination in the Aft Shroud area from flaking handrail paint.
- Installed New Outer Blanket Layer - stainless steel panels covered with a protective thermal coating fit over the existing, degraded insulation on Hubble's exterior surface, to control Hubble's internal temperature.
- Replaced Rate Sensor Units - the gyroscopes are part of the HST pointing system. The HST has a total of six gyroscopes grouped in pairs inside three Rate Sensor Units. They are arranged in such a way that any three gyroscopes can keep HST operating with full accuracy.
- Replaced S-Band Single Access Transmitter - uses radio waves to send data to the ground.
- Replaced one Solid State Recorder - can store 10 times as much data as the replaced mechanical recorder. The new recorder replaces one of the two remaining tape recorders aboard the spacecraft.
- Installed Voltage/Temperature Improvement Kits - protects the batteries from overcharging and overheating when in a safe mode.
Servicing Mission 3B (SM3B)

SM3B, launched March 1, 2002, was actually the fourth visit to service the HST. NASA split the original Servicing Mission 3 into two parts and conducted 3A in December of 1999. During SM 3B, a new science instrument was installed, and several other activities were accomplished over a 12 day mission with 5 space walks.

New Science Instrument Installed and NICMOS Instrument Repaired

- Added the Advanced Camera for Surveys (ACS) having 10 times more discovery power than the camera (FOC) it replaced. ASC sees in wavelengths ranging from visible to far ultraviolet. It is a team of three different cameras with specialized capabilities. The high resolution camera takes extremely detailed pictures of the inner regions of galaxies and searches neighboring stars for planets and planets-to-be. The solar blind camera blocks visible light to enhance ultraviolet sensitivity. It is also used to study weather on our own solar system planets. With a field of view twice the size of the current HST surveyor, the ACS wide field camera can conduct new surveys of the universe. Astronomers can use it to study the nature and distribution of galaxies in order to understand how our universe evolved.

- Added Near Infrared Camera and Multi-Object Spectrometer (NICMOS) Cryocooler - By fitting NICMOS with the experimental cryogenic system, NASA hopes to re-cool the detectors to revive its infrared vision, and extend its life by several years. NICMOS was placed on the HST in 1997 but became inactive two years later, after depleting the ice needed to cool its infrared detectors. The HST engineering team successfully demonstrated this technology in 1998 aboard the STS-95 mission.

Spacecraft Hardware

- Replaced Solar Arrays - During SM1, the original solar arrays were replaced by Solar Array 2 and have powered the HST for over 8 years. The new Solar Array 3 are rigid arrays, which do not roll up and therefore are more robust. Although one-third smaller than the first two solar array pairs, they will produce 30 percent more power.

- Replaced Power Control Unit - controls and distributes electricity from the solar arrays and batteries to other parts of the telescope. Replacing the original unit, which had been on the job for 11 years, required the HST to be completely powered down for the first time since its launch in 1990. The new unit allows astronomers to take full advantage of extra power generated by the new solar arrays.
Servicing Mission 4 (SM4)
SM4, launched on May 11, 2009, was originally scheduled for 2004. SM4 was postponed and then cancelled after the loss of the Space Shuttle Columbia. Following the successful recovery of the shuttle program and a re-examination of SM4 risks, NASA approved the mission. SM4 was perhaps Hubble’s most challenging and intense servicing mission, with a multitude of tasks to be completed over the course of five spacewalks.

Two New Science Instruments Installed and Two Instruments Repaired
- Astronauts installed two new instruments on the HST during SM4: Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS).
  - WFC3 sees three different kinds of light: near-ultraviolet, visible and near-infrared, though not simultaneously. The camera’s resolution and field-of-view is much greater than that of previous instruments. Astronauts removed Hubble’s Wide Field and Planetary Camera 2 (WFPC2) to make room for WFC3.
  - COS, a spectrograph that breaks light into its component colors, revealing information about the object emitting the light, sees exclusively in ultraviolet light. COS improves Hubble’s ultraviolet sensitivity at least 10 times, and up to 70 times when observing extremely faint objects. COS took the place of the device installed in Hubble during the first servicing mission to correct Hubble’s flawed mirror, the Corrective Optics Space Telescope Axial Replacement (COSTAR). Since the first servicing mission, all of Hubble’s replacement instruments have had technology built into them to correct Hubble’s marred vision, making COSTAR no longer necessary.
- During SM4, astronauts accomplished a feat never envisioned by the telescope creators, on-site repairs for two instruments: the Advanced Camera for Surveys (ACS) and the Space Telescope Imaging Spectrograph (STIS). Both had stopped working; ACS after an electrical short in 2007 and STIS after a power failure in 2004. To perform the repairs, astronauts had to access the interior of the instruments, switch out components, and re-route power.
  - The successful completion of the repair of the two instruments, along with the addition of the two new instruments, gave Hubble a full complement of five functioning instruments for its future observations.
Servicing Mission 4 (SM4)

Spacecraft Hardware

- In late September 2008, only two weeks before the mission was to launch, a malfunction occurred in one of the systems that commands the science instruments and directs the flow of data within the telescope. The problem was fixed by switching to a backup system, but NASA was unwilling to leave the telescope without a spare. The mission was delayed until May 2009 while engineers and scientists tested and prepared an existing and nearly identical system. Astronauts were able to install the spare Science Instrument Command and Data Handling unit in addition to all previously scheduled tasks.

- Since SM4 was expected to be the last astronaut mission to the HST, one of the goals was to reinforce and reinvigorate the telescope’s basic spaceflight systems. Astronauts replaced all of Hubble’s batteries, which were 18 years old, with new, improved units. Astronauts installed six new gyroscopes, which are used to point the telescope, and a Fine Guidance Sensor, which locks onto stars as part of the pointing system. They covered key Hubble equipment bays with insulating panels called New Outer Blanket Layers, to replace protective blankets that had broken down over the course of their long exposure to the harsh conditions of space. They also installed a new device, the Soft Capture Mechanism. This simple device will allow a robotic spacecraft to attach itself to Hubble someday, once the telescope is at the end of its life, and guide it through its descent into Earth's atmosphere.
How will the Hubble Space Telescope’s Life End?

As of April 2015, the HST was in excellent condition. Hubble is a robust machine with many built-in redundancies, and its operators have drawn up a number of contingency plans over the telescope’s long life. The HST program has contingency plans in place for: power, communications, attitude control, gyroscopes, instruments, computers, and just about everything else.

- However, serious problems could conceivably crop up in a number of different Hubble systems, such as a problem with the observatory’s orientation-maintaining reaction wheels.
- There are four reaction wheels, all of which are working well; Hubble needs at least three of them to work. If one were to fail, the HST would be only one failure away from halting operations.

Preparing for the Future

When the HST reaches the end of its life, NASA will de-orbit the spacecraft safely using a next-generation space vehicle. Originally planned for Earth return on the Space Shuttle, HST’s scientific life has extended beyond the 2011 retirement of the Shuttle. As part of Servicing Mission 4 (SM4) in 2009, astronauts installed the Soft Capture and Rendezvous System (SCRS) that will enable the future rendezvous, capture, and safe disposal of Hubble by either a crew or a robotic mission. The SCRS is comprised of the Soft Capture Mechanism (SCM) system and the Relative Navigation System (RNS).

- **Soft Capture Mechanism**
  - The SCM was launched on the Flight Support System (FSS) within the cargo bay of the Space Shuttle Atlantis. The SCM is about 72 inches in diameter and 2 feet high.
  - The SCM uses a Low Impact Docking System (LIDS) interface and associated relative navigation targets for future rendezvous, capture, and docking operations. The system’s LIDS interface is designed to be compatible with the rendezvous and docking systems to be used on the next-generation space transportation vehicle.
  - During SM4, astronauts attached the SCM to the bottom of the HST, inside the FSS berthing and positioning ring, without affecting the normal FSS-to-Hubble interfaces. It was attached to the telescope using three sets of jaws that clamp onto the existing berthing pins on the telescope’s aft bulkhead. The astronauts actuated a gearbox, and the jaws released the SCM from the FSS and clamped it onto Hubble’s berthing pins.
Preparing for the Future (Continued)

- Relative Navigation System
  - The RNS is an imaging system consisting of optical and navigation sensors and supporting avionics. It collects data on Hubble during capture and deployment.
  - The RNS system acquired valuable information about Hubble from images and video of the telescope’s aft bulkhead as Atlantis released the HST at the end of SM4. This information will enable NASA to pursue numerous options for the safe de-orbit of Hubble.

HST Successor

- The HST team members aim to keep Hubble operating through at least 2020, so that its operations will overlap those of NASA’s James Webb Space Telescope (JWST), which is scheduled to launch in 2018.
  - JWST is optimized to view the cosmos in infrared light, while Hubble sees more in the visible and ultraviolet wavelengths.
  - Using both space telescopes in tandem gives a more panchromatic view of the universe than just Hubble alone, or just from JWST alone.