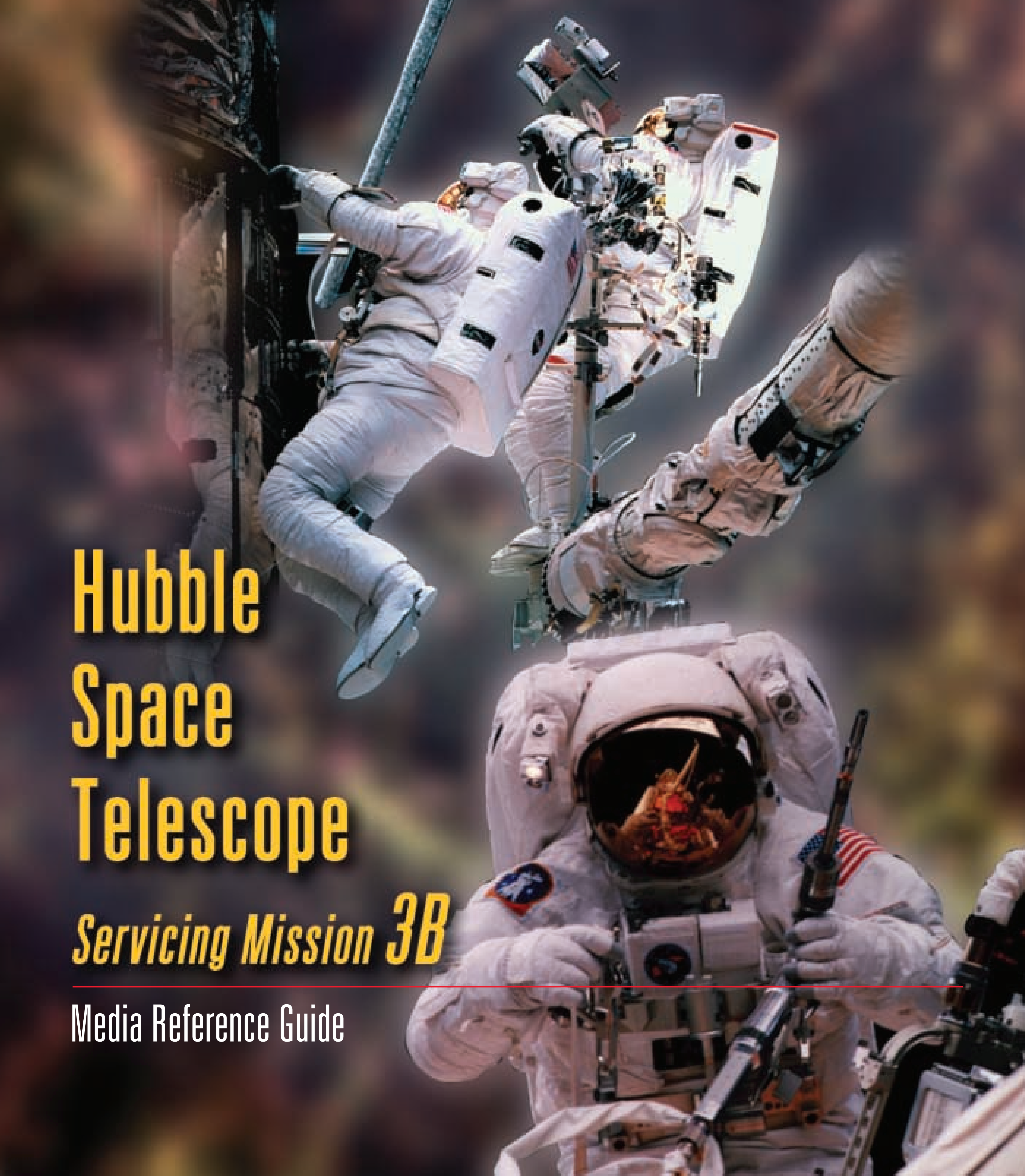
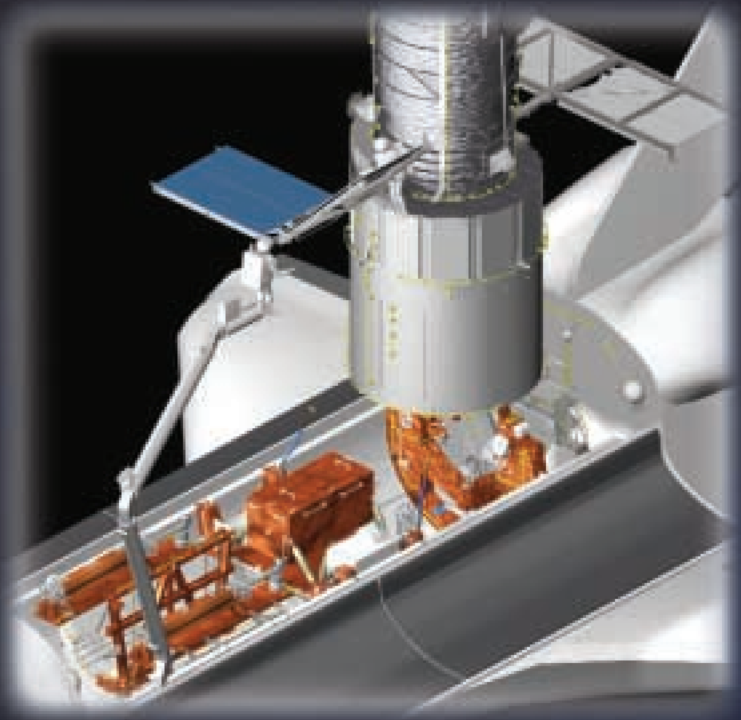


Hubble Space Telescope

Servicing Mission 3B

Media Reference Guide



Solar Arrays

Spacewalking astronauts unfold one of Hubble's new highly efficient solar arrays that will provide 20 percent more power to the orbiting observatory.

Power Control Unit

SM3B astronaut installs replacement for Telescope's aging Power Control Unit.

Hubble Space Telescope
Servicing Mission 3B
Media Reference Guide

Special thanks to everyone who
helped pull this book together.

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the National Aeronautics and Space Administration

Who Was Edwin P. Hubble?

Photo courtesy of the Carnegie Institution of Washington

Edwin Hubble (1889–1953) at the 48-inch Schmidt telescope on Palomar Mountain

One of the great pioneers of modern astronomy, the American astronomer Edwin Powell Hubble (1889–1953), started out by getting a law degree and serving in World War I. However, after practicing law for one year, he decided to "chuck law for astronomy and I knew that, even if I were second rate or third rate, it was astronomy that mattered."

He completed a Ph.D. thesis on the Photographic Investigation of Faint Nebulae at the University of Chicago and then continued his work at Mount Wilson Observatory, studying the faint patches of luminous "fog" or nebulae in the night sky.

Using the largest telescope of its day, a 2.5-m reflector, he studied Andromeda and a number of other nebulae and proved that they were other star systems (galaxies) similar to our own Milky Way.

He devised the classification scheme for galaxies that is still in use today, and obtained extensive evidence that the laws of physics outside the Galaxy are the same as on Earth—in his own words: "verifying the principle of the uniformity of nature."

In 1929, Hubble analyzed the speeds of recession of a number of galaxies and showed that the speed at which a galaxy moves away from us is proportional to its distance (Hubble's Law). This discovery of the expanding universe marked the birth of the "Big Bang Theory" and is one of the greatest triumphs of 20th-century astronomy.

In fact, Hubble's remarkable discovery could have been predicted some 10 years earlier by none other than Albert Einstein. In 1917, Einstein applied his newly developed General Theory of Relativity to the problem of the universe as a whole. Einstein was very disturbed to discover that his theory predicted that the universe could not be static, but had to either expand or contract. Einstein found this prediction so unbelievable that he went back and modified his original theory in order to avoid this problem. Upon learning of Hubble's discoveries, Einstein later referred to this as "the biggest blunder of my life."

— ESA Bulletin 58

CONTENTS

ILLUSTRATIONS

Figure **Page**

Another Step in Our Journey to the Stars

Throughout history, humankind has expanded its knowledge of the universe by studying the stars. Great scientists such as Nicholaus Copernicus, Galileo Galilei, Johannes Kepler, Issac Newton, Edwin Hubble and Albert Einstein contributed significantly to our understanding of the universe.

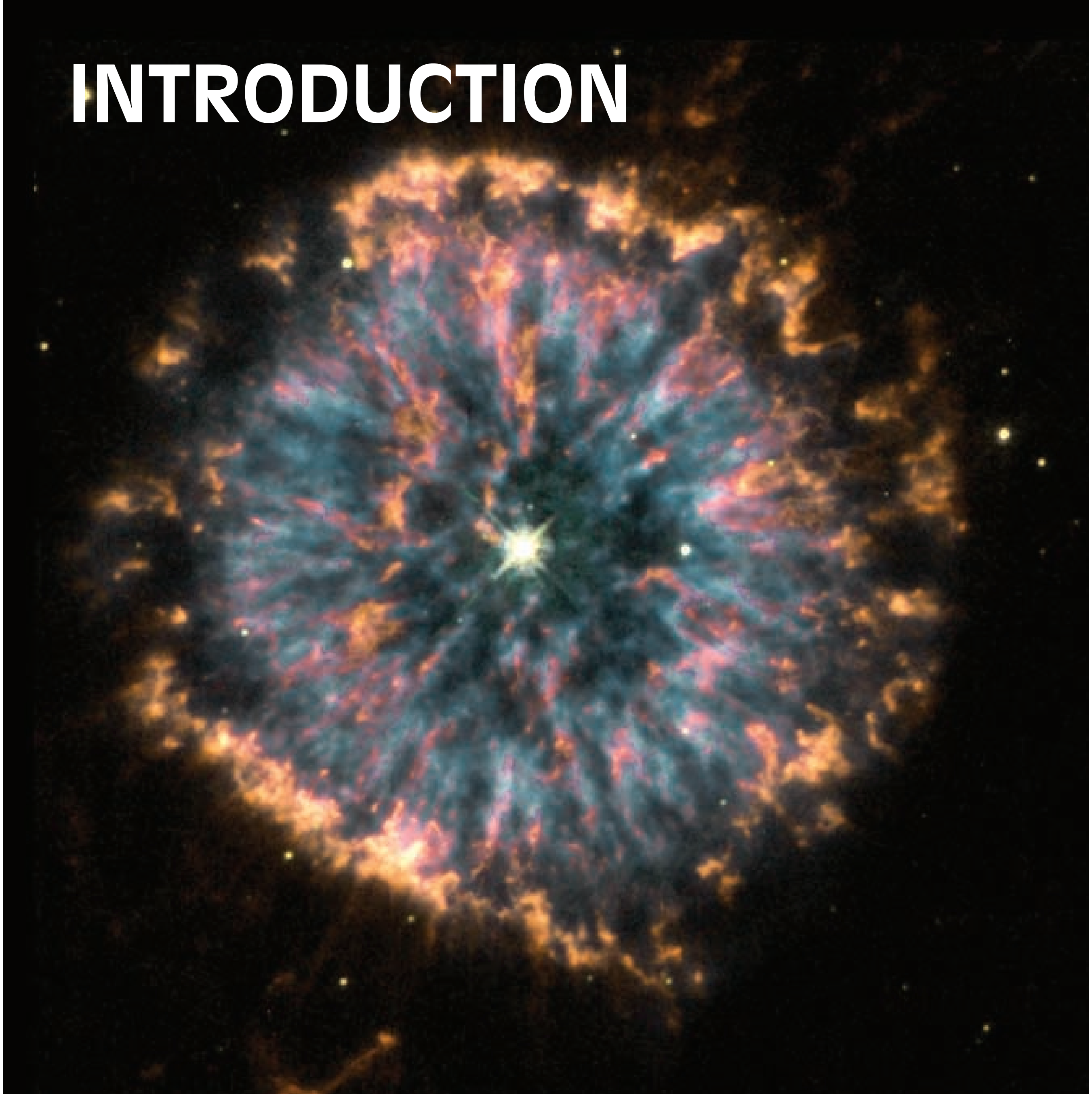
The launch of the Hubble Space Telescope in 1990 signified another great step toward unraveling the mysteries of space. Spectacular discoveries such as massive black holes at the center of galaxies, the existence of precursor planetary systems like our own, and the quantity and distribution of cold dark matter are just a few examples of the Telescope's findings.

With NASA's Servicing Mission 3B, we continue to carry the quest for knowledge in the 21st century.

About the Inside Covers

Three-dimensional computer models illustrate tasks that the STS-109 crew will perform in orbit during Servicing Mission 3B. The models enable engineers to study task feasibility and to confirm that astronauts can safely reach and service components and locations on the spacecraft. These dimensionally accurate, visually correct images help the extravehicular activity servicing team prepare to install new components and upgrade functional systems on the Telescope.

INTRODUCTION



Gazing through his first crude telescope in the 17th century, Galileo discovered the craters of the Moon, the satellites of Jupiter and the rings of Saturn. These observations led the way to today's quest for in-depth knowledge and understanding of the cosmos. And for nearly 12 years NASA's Hubble Space Telescope (HST) has continued this historic quest.

Since its launch in April 1990, Hubble has provided scientific data and images of unprecedented resolution from which many new and exciting discoveries have been made. Even when reduced to raw numbers, the accomplishments of the 12.5-ton orbiting observatory are impressive:

- Hubble has taken about 420,000 exposures.
- Hubble has observed nearly 17,000 astronomical targets.
- Astronomers using Hubble data have published over 3,200 scientific papers.
- Circling Earth every 90 minutes, Hubble has traveled about 1.7 billion miles.

This unique observatory operates around the clock above the Earth's atmosphere gathering information for teams of scientists who study the origin, evolution and contents of the universe. The Telescope is an invaluable tool for examining planets, stars, star-forming regions of the Milky Way, distant galaxies and quasars, and the tenuous hydrogen gas lying between the galaxies.

The HST can produce images of the outer planets in our solar system that approach the clarity of those from planetary flybys. Astronomers have resolved previously unsuspected details of numerous star-forming regions of the Orion Nebula in the Milky Way and have detected expanding gas shells blown off by exploding stars.

Using the Telescope's high-resolution and light-gathering power, scientists have calibrated the distances to remote galaxies to precisely measure the expansion of the universe and thereby calculate its age. They have detected and measured the rotation of dust, gas and stars trapped in the gravitational field at the cores of galaxies that portend the presence of massive black holes.

Hubble's deepest views of the universe, unveiling a sea of galaxies stretching back nearly to the beginning of time, have forced scientists to rethink some of their earlier theories about galactic evolution. (Section 3 of this guide contains additional information on the Telescope's scientific discoveries.)

The Telescope's mission is to spend 20 years probing the farthest and faintest reaches of the cosmos. Crucial to fulfilling this objective is a series of on-orbit manned servicing missions. During these missions astronauts perform planned repairs and maintenance activities to restore and upgrade the observatory's capabilities. To facilitate this process, the Telescope's designers configured science instruments and several vital engineering subsystems as Orbital Replacement Units (ORU)—modular packages with standardized fittings accessible to astronauts in pressurized suits (see Fig. 1-1).

The First Servicing Mission (SM1) took place in December 1993 and the Second Servicing Mission (SM2) in February 1997. Hubble's Third Servicing Mission was separated into two parts: Servicing Mission 3A (SM3A) flew in December 1999 and Servicing Mission 3B (SM3B) is scheduled for an early 2002 launch.

SM3B astronauts will:
- Install a new science instrument, the Advanced Camera for Surveys (ACS).
- Fit Hubble with a new pair of rigid solar arrays.
- Replace the Power Control Unit (PCU).
- Replace a Reaction Wheel Assembly (RWA).
- Retrofit the Near Infrared Camera and Multi-Object Spectrometer (NICMOS).
- Install New Outer Blanket Layer (NOBL) insulation panels.

The ACS consists of three electronic channels and a complement of filters and dispersers that detect light from the ultraviolet to the near infrared (1200 to 10,000 angstroms). This camera will be able to survey a field with 2.3 times the area of the Wide Field and Planetary Camera 2 (WFPC2) currently on Hubble. It will provide four times as much spatial information and up to five times the sensitivity of WFPC2. The ACS will not replace WFPC2, however. WFPC2 will continue with its spectacular observations on the Telescope.

Designed and built by Goddard Space Flight Center (GSFC), the European Space Agency (ESA) and Lockheed Martin Space Systems Company, the new solar arrays will produce 20 percent more power than the current arrays. In addition, they are less susceptible to damage and the extreme temperature swings induced by Hubble's orbit.

The PCU controls and distributes electricity from the solar arrays and batteries to other parts of the Telescope. Although it is still functioning, this PCU has been on the Telescope since 1990 and some of its relays have failed. Replacement will ensure proper operation over the long term.

One of four RWAs will be replaced. The reaction wheels are part of an actuator system that moves the spacecraft into commanded positions. Using spin momentum, the wheels move HST into position and then keep the spacecraft stable. The wheel axes are oriented so that Hubble can operate with only three wheels.

The NICMOS, a dormant instrument, will be retrofitted with a new, experimental NICMOS Cooling System (NCS) to return it to active duty.

If time permits, NOBL insulation panels will be installed to prevent damage to Hubble from sunlight and extreme temperature changes and to maintain the Telescope's normal operating temperature.

Hubble Space Telescope Configuration

Figures 1-2 and 1-3 show the overall Telescope configuration. Figure 1-4 lists specifications for the Telescope. The major elements are:
- Optical Telescope Assembly (OTA)—two mirrors and associated structures that collect light from celestial objects
- Science instruments—devices used to analyze the images produced by the OTA
- Support Systems Module (SSM)—spacecraft structure that encloses the OTA and science instruments
- Solar Arrays (SA).

Optical Telescope Assembly

The OTA consists of two mirrors, support trusses and the focal plane structure. The optical system is a Ritchey-Chretien design, in which two special aspheric mirrors form focused images over the largest possible field of view. Incoming light travels down a tubular baffle that absorbs stray light. The concave primary mirror—94.5 in. (2.4 m) in diameter—collects the light and converges it toward the convex secondary mirror, which is only 12.2 in. (0.3 m) in diameter. The secondary mirror directs the still-converging light back toward the primary mirror and through a 24-in. hole in its center into the Focal Plane Structure, where the science instruments are located.

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Fig. 1-1
The Hubble Space Telescope (HST)—shown in a clean room at Lockheed Martin Space Systems Company – Missiles & Space Operations in Sunnyvale, California, before shipment to Kennedy Space Center—is equipped with science instruments and engineering subsystems designed as Orbital Replacement Units.

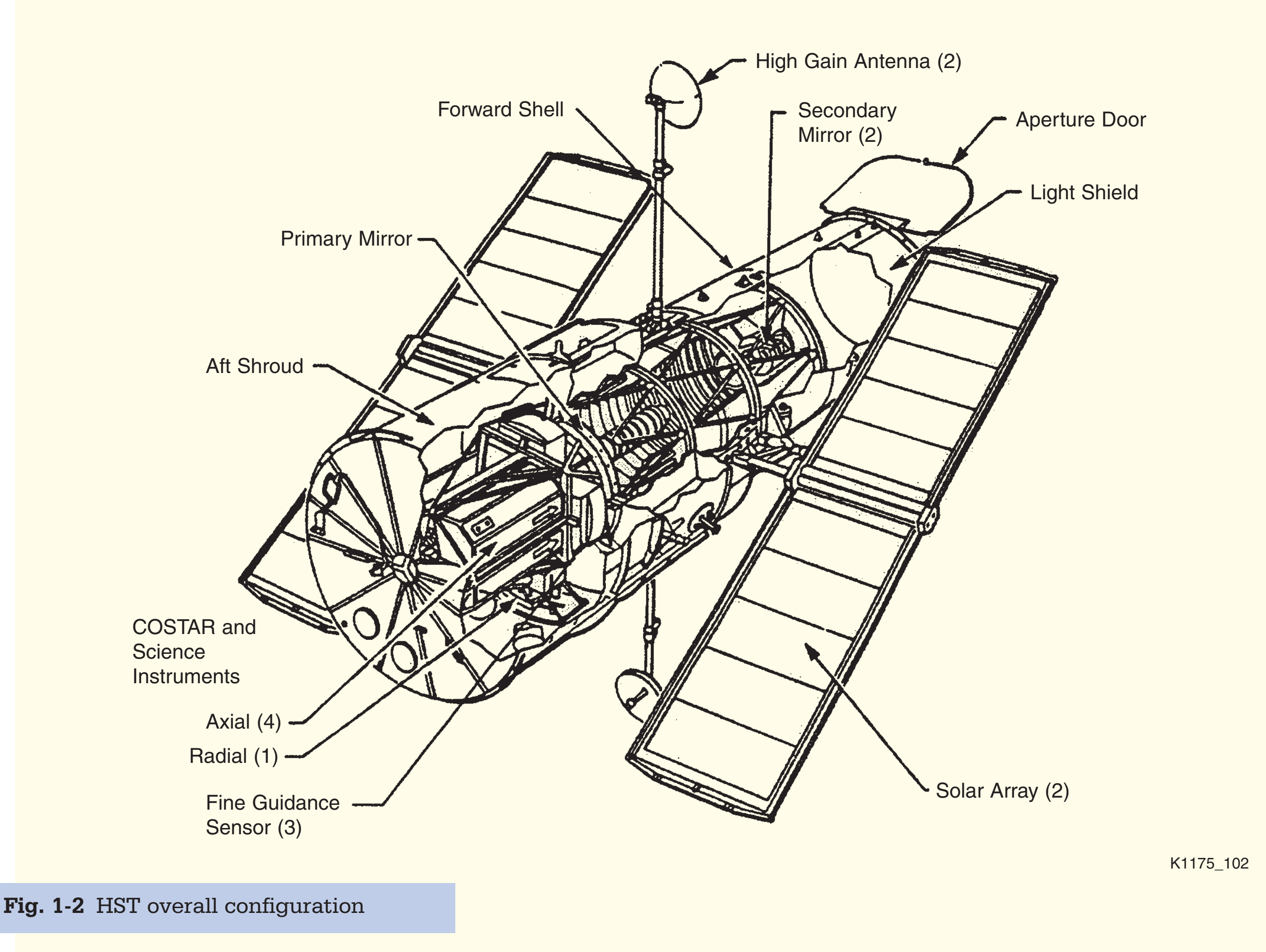

Fig. 1-2 HST overall configuration

Science Instruments

Hubble can accommodate eight science instruments. Four are aligned with the Telescope's main optical axis and are mounted immediately behind the primary mirror. These axial science instruments are:

- Space Telescope Imaging Spectrograph (STIS)
- Faint Object Camera (FOC)
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS)
- Corrective Optics Space Telescope Axial Replacement (COSTAR).

In addition to the four axial instruments, four other instruments are mounted radially (perpendicular to the main optical axis). These radial science instruments are:

- Wide Field and Planetary Camera 2 (WFPC2)
- Three Fine Guidance Sensors (FGS).

Space Telescope Imaging Spectrograph. STIS separates incoming light into its component wavelengths, revealing information about the atomic composition of the light source. It can detect a broader range of wavelengths than is possible from Earth because there is no atmosphere to absorb certain wavelengths. Scientists can determine the chemical composition, temperature, pressure and turbulence of the target producing the light—all from spectral data.

Faint Object Camera. The FOC was decommissioned in 1997 to better allocate existing resources. However, the camera remains turned on and available to scientists if needed. The FOC will be returned to Earth after the ACS is installed in its place during SM3B.

Near Infrared Camera and Multi-Object Spectrometer. Use of this now-dormant instrument will resume after successful installation of NCS during SM3B.

Corrective Optics Space Telescope Axial Replacement. COSTAR was installed on HST in 1993 to fix a flaw in the shape of the primary mirror (a common mirror fabrication defect called spherical aberration) that was detected shortly after Hubble's launch in 1990. Because all the instruments now on the Telescope are equipped with corrective optics, COSTAR no longer is needed, but it will remain on the Telescope until its slot is filled by a new science instrument on SM4.

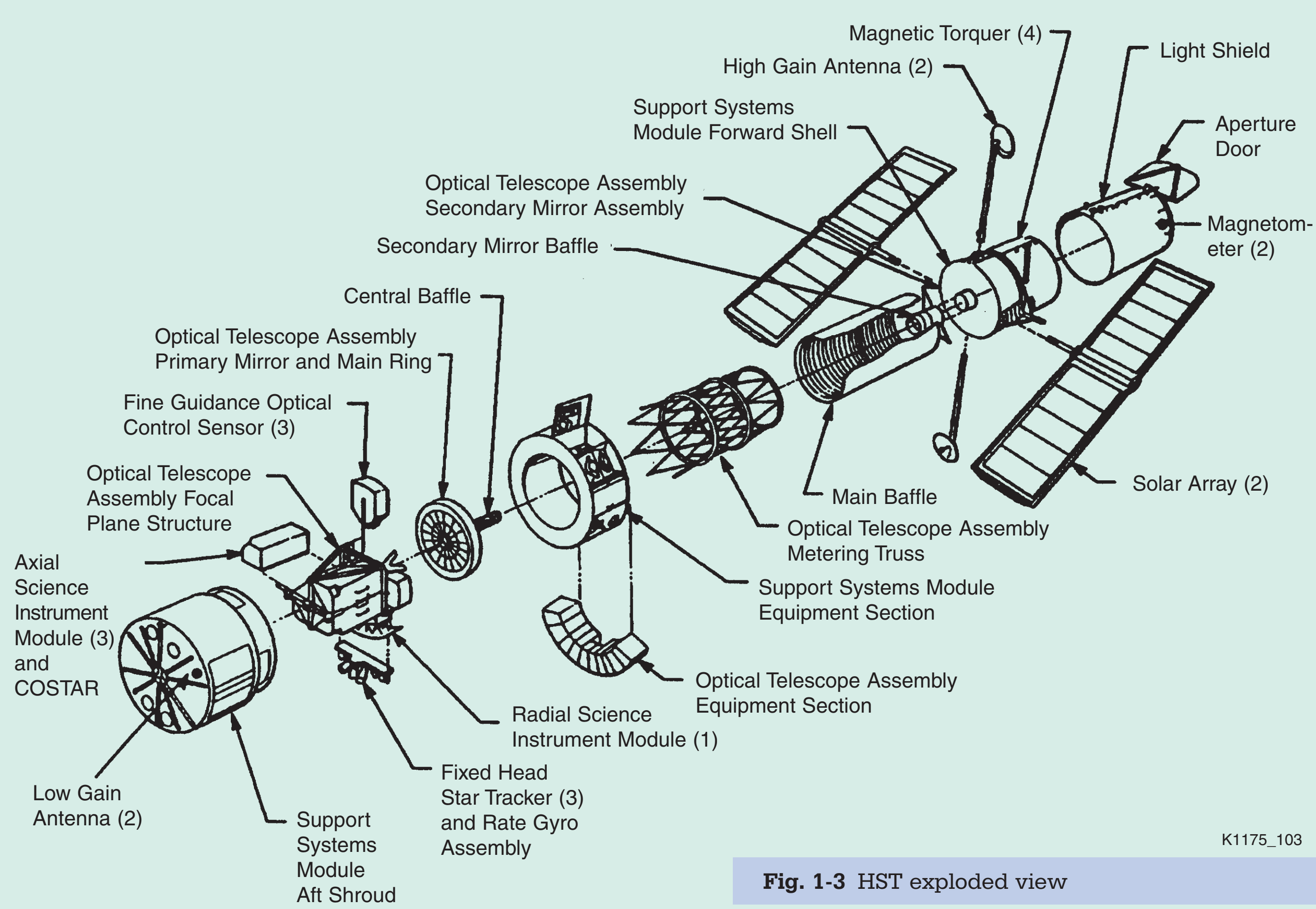

Fig. 1-3 HST exploded view

Hubble Space Telescope (HST)	
Weight	24,500 lb (11,110 kg)
Length	43.5 ft (15.9 m)
	10 ft (3.1 m) Light Shield and Forward Shell
Diameter	14 ft (4.2 m) Equipment Section and Aft Shroud
Optical system	Ritchey-Chretien design Cassegrain telescope
Focal length	189 ft (56.7 m) folded to 21 ft (6.3 m)
Primary mirror	94.5 in. (2.4 m) in diameter
Secondary mirror	12.2 in. (0.3 m) in diameter
Field of view	See instruments/sensors
Pointing accuracy	0.007 arcsec for 24 hours
Magnitude range	5 m_v to 30 m_v (visual magnitude)
Wavelength range	1100 to 24,000 Å
Angular resolution	0.1 arcsec at 6328 Å
Orbit	320 nmi (593 km), inclined 28.5 degrees from equator
Orbit time	97 minutes per orbit
Mission	20 years

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Fig. 1-4 HST specifications

Wide Field and Planetary Camera 2. WFPC2 is an electronic camera that records images at two magnifications. A team at the Jet Propulsion Laboratory (JPL) in Pasadena, California, built the first WFPC and developed the WFPC2. The team incorporated an optical correction by refiguring relay mirrors in the optical train of the cameras. Each relay mirror is polished to a prescription that compensates for the incorrect figure on HST's primary mirror. Small actuators fine-tune the positioning of these mirrors on orbit.

Fine Guidance Sensors. The three FGSs have two functions: (1) provide data to the spacecraft's pointing system to keep HST pointed accurately at a target when one or more of the science instruments is being used to take data and (2) act as a science instrument. When functioning as a science instrument, two of the sensors lock onto guide stars and the third measures the brightness and relative positions of stars in its field of view. These measurements, referred to as astrometry, are helping to advance knowledge of the distances and motions of stars and may be useful in detecting planetary-sized companions of other stars.

Support Systems Module

The SSM encloses the OTA and the science instruments like the dome of an Earth-based observatory. It also contains all of the structures, mechanisms, communications devices, electronics and electrical power subsystems needed to operate the Telescope.

This module supports the light shield and an aperture door that, when opened, admits light. The shield connects to the forward shell on which the SAs and High Gain Antennas (HGA) are mounted. Electrical energy from the SAs charges the spacecraft batteries to power all HST systems. Four antennas, two high-gain and two low-gain, send and receive information between the Telescope and the Space Telescope Operations Control Center (STOCC). All commanding occurs through the Low Gain Antennas (LGA).

Behind the OTA is the Equipment Section, a ring of bays that house the batteries and most of the electronics, including the computer and communications equipment. At the rear of the Telescope, the aft shroud contains the science instruments.

Solar Arrays

The SAs provide power to the spacecraft. They are mounted like wings on opposite sides of the Telescope, on the forward shell of the SSM. The SAs are rotated so each wing's solar cells face the Sun. The cells absorb the Sun's light energy and convert it into electrical energy to power the Telescope and charge the spacecraft's batteries, which are part of the Electrical Power Subsystem (EPS). Batteries are used when the Telescope moves into Earth's shadow during each orbit.

Computers

Hubble's Data Management Subsystem (DMS) contains two computers: the Advanced Computer, installed during SM3A, and the Science Instrument Control and Data Handling (SI C&DH) unit. The Advanced Computer performs onboard computations and handles data and command transmissions between the Telescope systems and the ground system. The SI C&DH unit controls commands received by the science instruments, formats science data and sends data to the communications system for transmission to Earth.

The Hubble Space Telescope Program

Hubble Space Telescope represents the fulfillment of a 50-year dream and 25 years of dedicated scientific effort and political vision to advance humankind's knowledge of the universe. The HST program comprises an international community of engineers, scientists, contractors and institutions. It is managed by GSFC for the Office of Space Science (OSS) at NASA Headquarters.

The program falls under the Search for Origins and Planetary Systems scientific theme. Within GSFC, the program is in the Flight Programs and Projects Directorate, under the supervision of the Associate Director/ Program Manager for HST. It is organized as two flight projects: (1) the HST Operations Project and (2) the HST Development Project.

Responsibilities for scientific oversight on HST are divided among the members of the Project Science Office (PSO). The PSO is designed to interact effectively and efficiently with the HST Program and the wide range of external organizations involved with the HST. The senior scientist for the HST and supporting staff work in the Office of the Associate Director/ Program Manager for HST. This group is concerned with the highest level of scientific management for the project. Figure 1-5 summarizes the major organizations that oversee the program.

The roles of NASA centers and contractors for on-orbit servicing of the HST are:

- Goddard Space Flight Center (GSFC)—Overall management of daily on-orbit operations of HST and the development, integration and test of replacement hardware, space support equipment and crew aids and tools
- Johnson Space Center (JSC)—Overall servicing mission management, flight crew training, and crew aids and tools
- Kennedy Space Center (KSC)—Overall management of launch and post-landing operations for mission hardware
- Ball Aerospace—Design, development and provision of axial science instruments
- JPL—Design, development and provision of WFPC1 and WFPC2
- Lockheed Martin—Personnel support for GSFC to accomplish (1) development, integration and test of replacement hardware and space support equipment; (2) system integration with the Space Transportation System (STS); (3) launch and post-landing operations and (4) daily HST operations.

Major subcontractors for SM3B include Goodrich Corporation, Honeywell, Jackson and Tull, Orbital Sciences Corporation, Computer Sciences Corporation, Association of Universities for Research in Astronomy (AURA), Swales Aerospace, QSS, Creare and L-3 Communications.

The HST program requires a complex network of communications among GSFC, the Telescope, Space Telescope Ground System and the Space Telescope Science Institute. Figure 1-6 shows communication links.

The Value of Servicing

Hubble's visionary modular design allows NASA to equip it with new, state-of-the-art instruments every few years. These servicing missions enhance the Telescope's science capabilities, leading to fascinating new discoveries about the universe. Periodic service calls also permit astronauts to "tune up" the Telescope and replace limited-life components.

Organization	Function
NASA Headquarters Office of Space Science Directorate of Astronomy and Physics	• Overall responsibility for the program
Goddard Space Flight Center – Office of the Associate Director/ Program Manager for HST – HST Operations Project – HST Development Project	• Overall HST program management • HST project management • Responsible for overseeing all HST operations
Space Telescope Operations Control Center	• Provides minute-to-minute spacecraft control • Schedules, plans and supports all science operations when required • Monitors telemetry communications data to the HST
Space Telescope Science Institute	• Selects observing programs from numerous proposals • Analyzes astronomical data
Goddard Space Flight Center – HST Flight Systems and Servicing Project	• Responsible for implementing HST Servicing Program • Manages development of new HST spacecraft hardware and service instruments • Manages HST Servicing Payload Integration and Test Program • Primary interface with the Space Shuttle Program at JSC

Fig. 1-5 Organization summary for HST program operational phase

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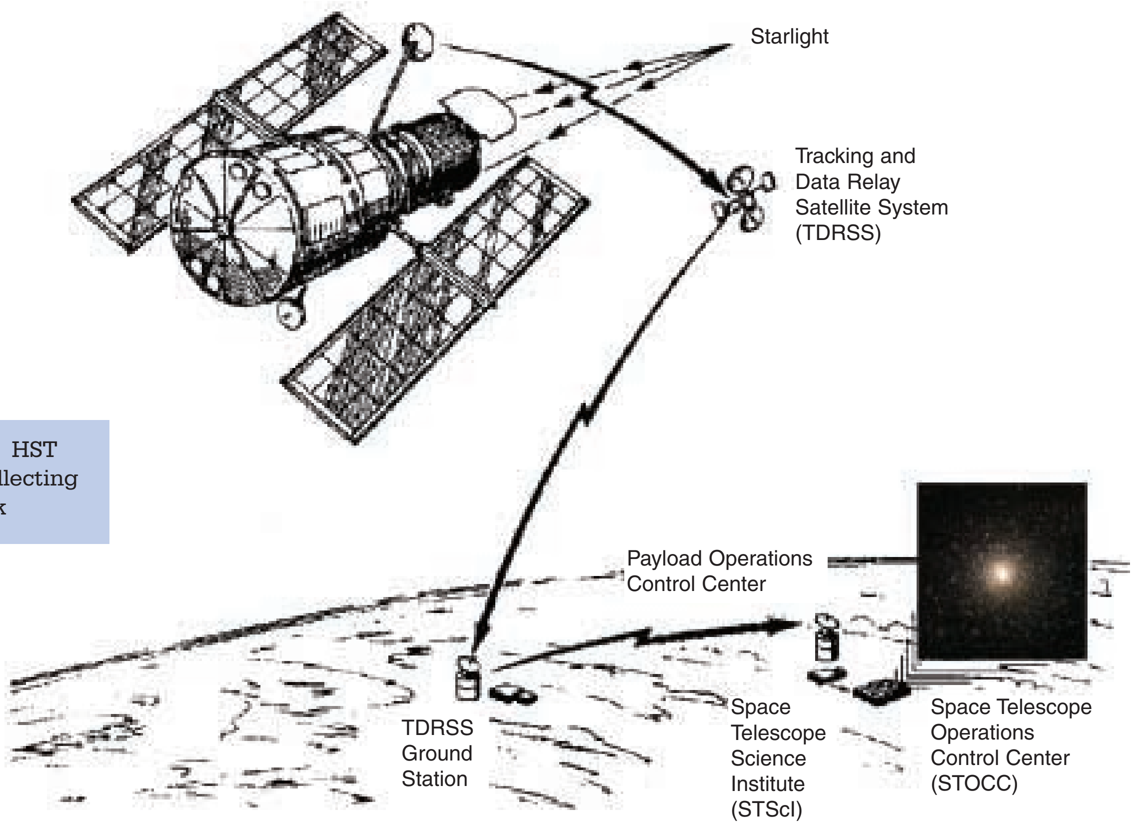

Fig. 1-6 HST data collecting network

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HST SERVICING MISSION 3B

The Hubble Space Telescope (HST) is the first observatory designed for extensive maintenance and refurbishment in orbit. Its science instruments and many other components were planned as Orbital Replacement Units (ORU)—modular in construction with standardized fittings and accessible to astronauts. Handrails, foot restraints and other built-in features help astronauts perform servicing tasks in the Shuttle cargo bay as they orbit Earth at 17,500 mph.

NASA plans to launch HST Servicing Mission 3B (SM3B) in early 2002. The third servicing mission (SM3), originally planned for June 2000, had six scheduled extravehicular activity (EVA) days, followed by a reboost of the Telescope. However, when the progressive failure of several Rate Sensor Unit gyros left the spacecraft unable to perform science operations, NASA split SM3 into two separate flights. The first flight, designated SM3A and manifested as STS-103, was launched in December 1999 and included four scheduled EVA days. After the flight was delayed until late December, NASA reduced the number of scheduled EVAs to three to ensure that the Shuttle would be on the ground before the year 2000 rollover.

SM3A accomplishments include replacement of all three Rate Sensor Units (six gyros), NICMOS valve reconfiguration, installation of six Voltage/Temperature Improvement Kits, replacement of the DF-224 Computer with the Advanced Computer, change-out of the Fine Guidance Sensor Unit-2 and mate of the associated Optical Control Electronics Enhancement Kit connectors, change-out of the S-Band Single Access Transmitter-2, replacement of the Engineering/Science Tape Recorder-3 with a Solid

State Recorder and installation of New Outer Blanket Layers (NOBLs) over Bays 1, 9 and 10.

SM3B is manifested as STS-109 aboard the Space Shuttle *Columbia* (OV-102) to be launched to a rendezvous altitude of approximately 315 nautical miles. During the planned 11-day mission, the Shuttle will rendezvous with, capture and berth the HST to the Flight Support System (FSS). Following servicing, the Shuttle will unberth Hubble and redeploy it to its mission orbit.

Five EVA days are scheduled during the SM3B mission. *Columbia's* cargo bay is equipped with several devices to help the astronauts:

- The FSS will berth and rotate the Telescope.
- Large, specially designed equipment containers will house the ORUs.
- Astronauts will work and be maneuvered as needed from the Shuttle robot arm.

SM3B will benefit from lessons learned on NASA's previous on-orbit servicing missions: the 1984 Solar Maximum repair mission, the 1993 HST First Servicing Mission (SM1), the 1997 HST Second Servicing Mission (SM2) and the 1999 HST Third Servicing Mission (SM3A). NASA has incorporated these lessons in detailed planning and training sessions for *Columbia* crewmembers Scott Altman, Duane Carey, Nancy Currie, John Grunsfeld, James Newman, Michael Massimino and Richard Linnehan.

Reasons for Orbital Servicing

HST is a national asset and an invaluable international scientific resource that has revolutionized modern astronomy. To achieve its full potential, the Telescope will continue to conduct extensive, integrated scientific observations, including follow-up work on its many discoveries.

Although the Telescope has numerous redundant parts and safemode systems, such a complex spacecraft cannot be designed with sufficient backups to handle every contingency likely to occur during a 20-year mission. Orbital servicing is the key to keeping Hubble in operating condition. NASA's orbital servicing plans address three primary maintenance scenarios:

- Incorporating technological advances into the science instruments and ORUs
- Normal degradation of components
- Random equipment failure or malfunction.

Technological Advances. Throughout the Telescope's life, scientists and engineers have upgraded its science instruments and spacecraft systems. For example, when Hubble was launched in 1990, it was equipped with the Goddard High Resolution Spectrograph and the Faint Object Spectrograph. A second-generation instrument, the Space Telescope Imaging Spectrograph, took over the function of those two instruments—adding considerable new capabilities—when it was installed during SM2 in 1997. A slot was then available for the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), which expanded the Telescope's vision into the infrared region of the spectrum. In addition, on both SM2 and SM3A a new state-of-the-art Solid State Recorder (SSR) replaced an Engineering/Science Tape Recorder (E/STR). Similarly, during SM3A the original DF-224 Computer was replaced with a faster, more powerful Advanced Computer based on the Intel 80486 microchip.

Component Degradation. Servicing plans take into account the need for routine replacements, for example, restoring HST system redundancy and limited-life items such as spacecraft thermal insulation and gyroscopes.

Equipment Failure. Given the enormous scientific potential of the Telescope—and the investment in designing, developing, building and putting it into orbit—NASA must be able to correct unforeseen problems that arise from random equipment failures or malfunctions. The Space Shuttle program provides a proven system for transporting astronauts fully trained for on-orbit servicing of the Telescope.

Originally, planners considered using the Shuttle to return the Telescope to Earth approximately every 5 years for maintenance. However, the idea was rejected for both technical and economic reasons. Returning Hubble to Earth would entail a significantly higher risk of contaminating or damaging delicate components. Ground servicing would require an expensive clean room and support facilities, including a large engineering staff, and the Telescope would be out of action for a year or more—a long time to suspend scientific observations.

Shuttle astronauts can accomplish most maintenance and refurbishment within a 10-day on-orbit mission with only a brief interruption to scientific operations and without the additional facilities and staff needed for ground servicing.

Orbital Replacement Units

Advantages of ORUs include modularity, standardization and accessibility.

Modularity. Engineers studied various technical and human factors criteria to simplify Telescope maintenance. Considering the limited time available for repairs and the astronauts' limited visibility, mobility and dexterity in the EVA environment, designers simplified the maintenance tasks by planning entire components for replacement.

ORUs are self-contained boxes installed and removed using fasteners and connectors. They range from small fuses to phone-booth-sized science instruments weighing more than 700 pounds (318 kg). Figure 2-1 shows the ORUs for SM3B.

Standardization. Standardized bolts and connectors also simplify on-orbit repairs. Captive bolts with 7/16-inch, double-height hex heads hold many ORU components in place. To remove or install the bolts, astronauts need only a 7/16-inch socket fitted to a power tool or manual wrench. Some ORUs do not contain these fasteners. When the maintenance philosophy changed from Earth-return to on-orbit servicing, other components were selected as replaceable units after their design had matured. This added a greater variety of fasteners to the servicing requirements, including non-captive 5/16-inch hex head bolts and connectors without wing tabs. Despite these exceptions, the high level of standardization among units reduces the number of tools needed for the servicing mission and simplifies astronaut training.

Accessibility. To be serviced in space, Telescope components must be seen and reached by an astronaut in a bulky pressure suit, or they must be within range of an appropriate tool. Therefore, most ORUs are mounted in equipment bays around the perimeter of the spacecraft. To access these units, astronauts simply open a large door that covers the appropriate bay.

Handrails, foot restraint sockets, tether attachments and other crew aids are essential to safe, efficient on-orbit servicing. In anticipation of such missions,

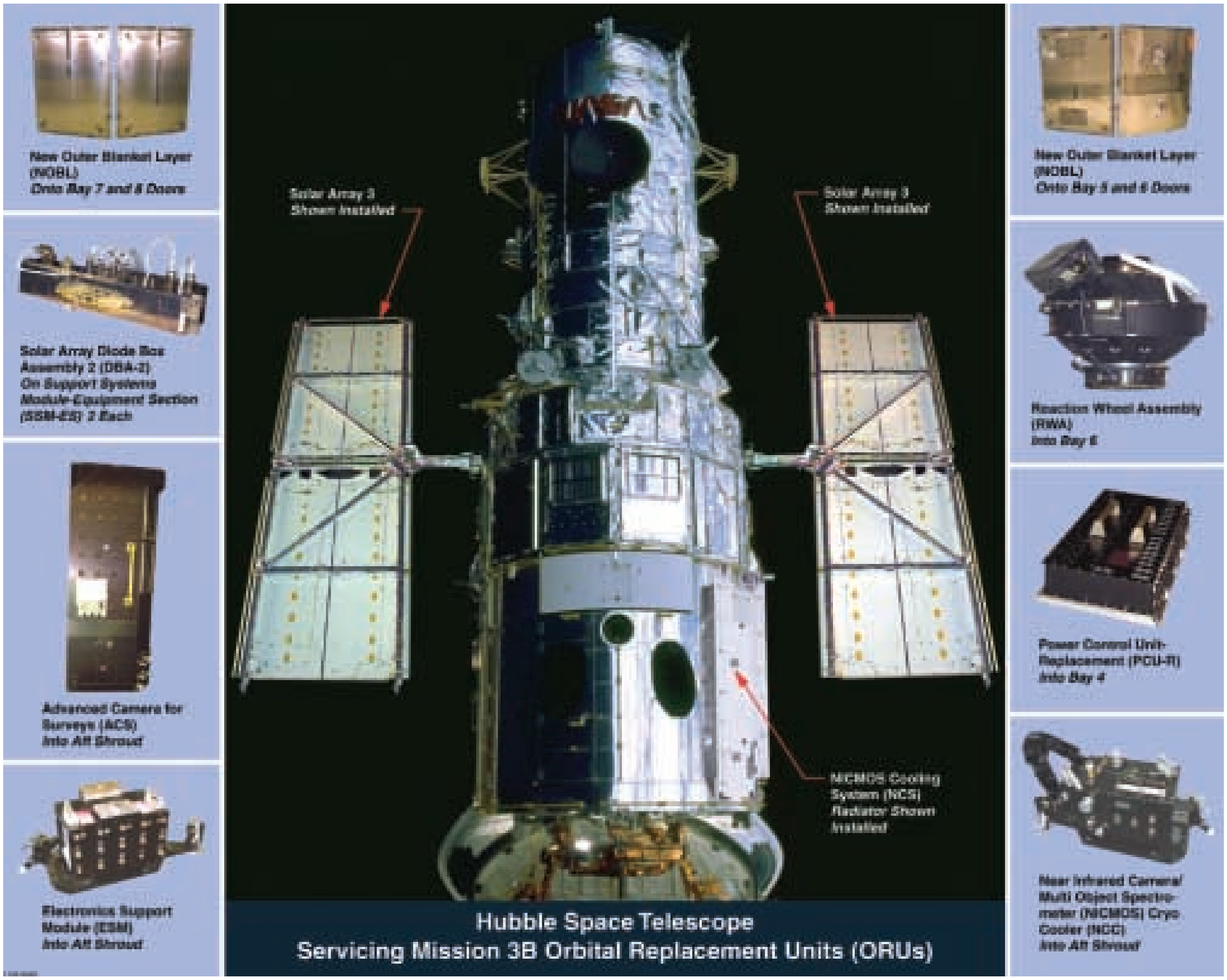

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Fig. 2-1 Hubble Space Telescope Servicing Mission 3B Orbital Replacement Units

31 foot-restraint sockets and 225 feet of handrails were designed into the Telescope. Foot restraint sockets and handrails greatly increase astronauts' mobility and stability, affording them safe worksites conveniently located near ORUs.

Crew aids such as portable lights, special tools, installation guiderails, handholds and portable foot restraints (PFR) also ease servicing of Hubble components. Additionally, foot restraints, translation aids and handrails are built into various equipment and instrument carriers specific to each servicing mission.

Shuttle Support Equipment

To assist astronauts in servicing the Telescope, *Columbia* will carry into orbit several thousand pounds of hardware and Space Support Equipment (SSE), including the Remote Manipulator System (RMS), FSS, Rigid Array Carrier (RAC), Second Axial Carrier (SAC) and Multi-Use Lightweight Equipment (MULE) carrier.

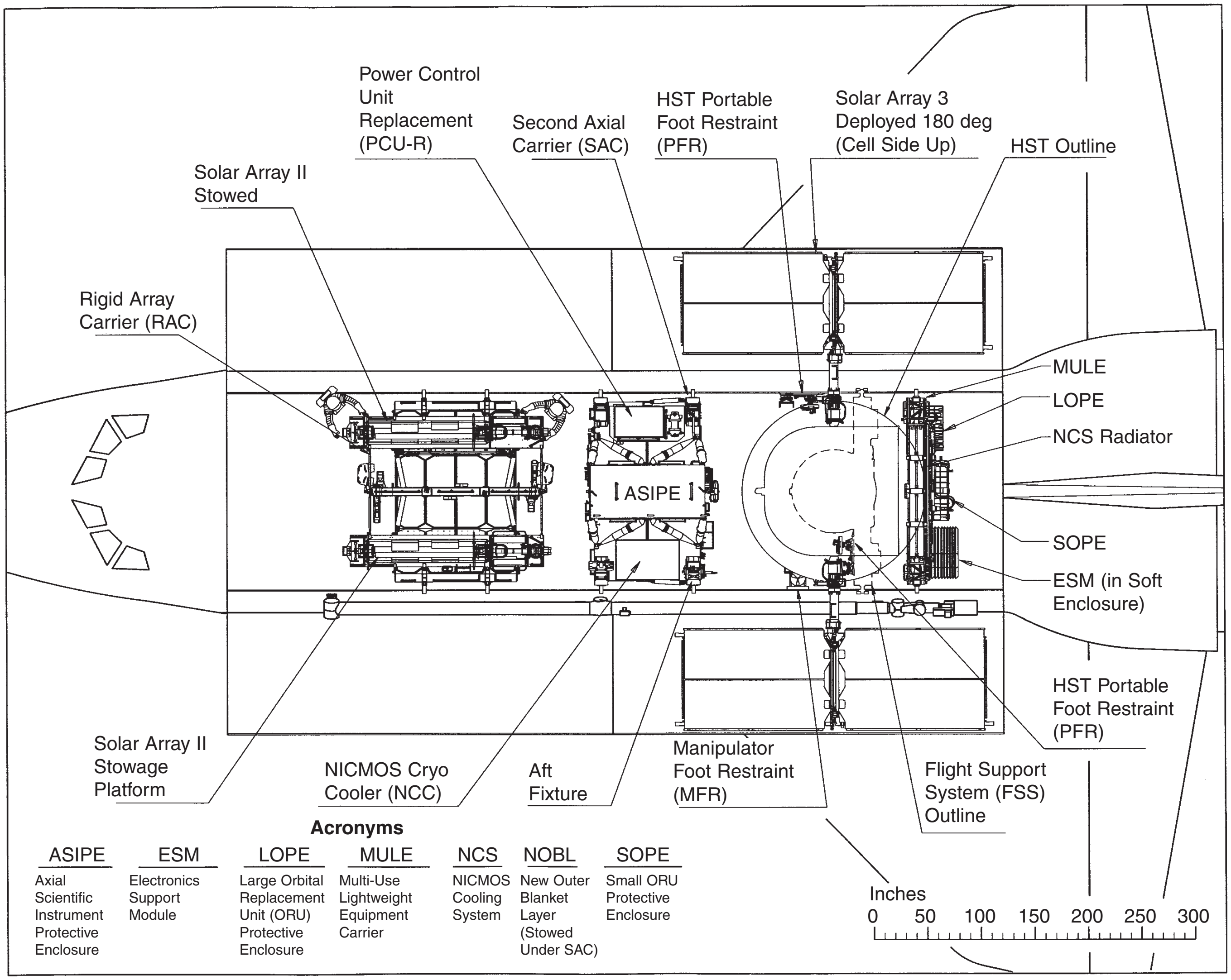
Remote Manipulator System

The *Columbia* RMS, also known as the robotic arm, will be used extensively during SM3B. The astronaut operating this device from inside the cabin is designated the intravehicular activity (IVA) crewmember. The RMS will be used to:

- Capture, berth and release the Telescope
- Transport new components, instruments and EVA astronauts between worksites
- Provide a temporary work platform for one or both EVA astronauts.

Space Support Equipment

Ground crews will install four major assemblies essential for SM3B—the FSS, RAC, SAC and MULE—in *Columbia's* cargo bay (see Fig. 2-2).



Acronyms

ASIPE	ESM	LOPE	MULE	NCS	NOBL	SOPE
Axial Scientific Instrument Protective Enclosure	Electronics Support Module	Large Orbital Replacement Unit (ORU) Protective Enclosure	Multi-Use Lightweight Equipment Carrier	NICMOS Cooling System	New Outer Blanket Layer (Stowed Under SAC)	Small ORU Protective Enclosure

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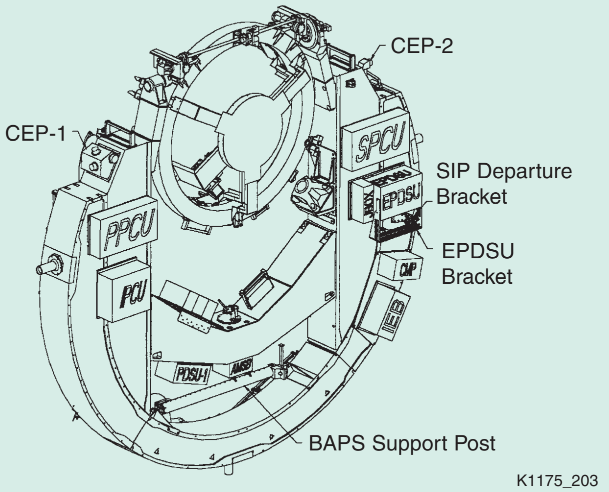
Fig. 2-2 Servicing Mission 3B Payload Bay configuration

Flight Support System

The FSS is a maintenance platform used to berth the HST in the cargo bay after the *Columbia* crew has rendezvoused with and captured the Telescope (see Fig. 2-3). The platform was adapted from the FSS first used during the 1984 Solar Maximum repair mission. It has a U-shaped cradle that spans the rear of the cargo bay. A circular berthing ring with three latches secures the Telescope to the cradle. The berthing ring can rotate the Telescope almost 360 degrees (176 degrees clockwise or counterclockwise from its null position) to give EVA astronauts access to every side of the Telescope.

The FSS also pivots to lower or raise the Telescope as required for servicing or reboosting. The FSS's umbilical cable provides power from *Columbia* to maintain thermal control of the Telescope during the servicing mission.



Acronyms

AMSB	Advanced Mechanism Selection Box
CEP	Contamination Environment Package
CMP	Contamination Monitoring Package
EPDSU	Enhanced Power Distribution and Switching Unit
IPCU	Interface Power Control Unit
PDSU	Power Distribution and Switching Unit
PPCU	Port Power Conditioning Unit
SIP	Standard Interface Panel
SPCU	Starboard Power Conditioning Unit

Fig. 2-3 Flight Support System configuration – aft view

Rigid Array Carrier

The RAC is located in *Columbia's* forward cargo bay. It has provisions for safe transport to orbit of the third-generation Solar Arrays (SA3) and associated second-generation Diode Box Assemblies (DBA2), and for return from orbit of the second-generation Solar Arrays (SA2) and their associated Diode Box Assemblies (DBA). The RAC also includes the MLI Repair Tool, two SA2 Spines, spare PIP pins, a spare DBA2, two portable connector trays, two spare SADA Clamps, the MLI Tent, Large and Small MLI Patches, four SA2 Bistem Braces, a Jettison Handle and two Auxiliary Transport Modules (ATM) to house miscellaneous smaller hardware (see Fig. 2-4).

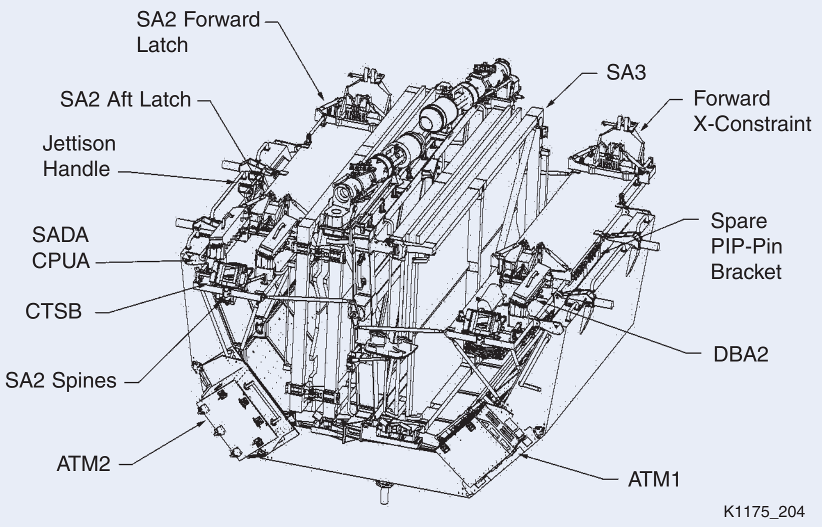


Fig. 2-4 Rigid Array Carrier configuration

Note: For clarity, MLI covers are not shown

Second Axial Carrier

The SAC is centered in *Columbia's* cargo bay. It has provisions for safe transport of ORUs to and from orbit (see Fig. 2-5). In the SM3B configuration:

- The Advanced Camera for Surveys (ACS) is stored in the Axial Scientific Instrument Protective Enclosure (ASIPE).
- The Power Control Unit (PCU) and PCU Transport Handle are stored on the starboard side.
- The NICMOS Cryo Cooler (NCC), WFPC Thermal Cover and Fixed Head Star Tracker (FHST) Covers are stored on the port side.
- The NOBL Transporter (NT) contains the new protective coverings to be installed on the Telescope equipment bay doors.
- The SAC houses other hardware, including the MLI Recovery Bag, eight Aft Shroud Latch Repair Kits, Handrail Covers and Caddies, PCU Harness Retention Device, Scientific Instrument Safety Bar, Cross Aft Shroud Harness (CASH), an Aft Fixture, two STS PFRs and an Extender, two Translation

Aids (TA), one ASIPE mini-TA and the Bays 5, 10 and DBA Thermal Covers.

The protective enclosure, its heaters and thermal insulation control the temperature of the new ORUs, providing an environment with normal operating temperatures. Struts between the ASIPE enclosure and the pallet protect Science Instruments from loads generated at liftoff and during Earth return.

Multi-Use Lightweight Equipment Carrier

The MULE is located in *Columbia's* aft cargo bay (see Fig. 2-6). It has provisions for safe transport of the NCS Radiator, Electronics Support Module (ESM), Large ORU Protective Enclosure (LOPE) and Small ORU Protective Enclosure (SOPE).

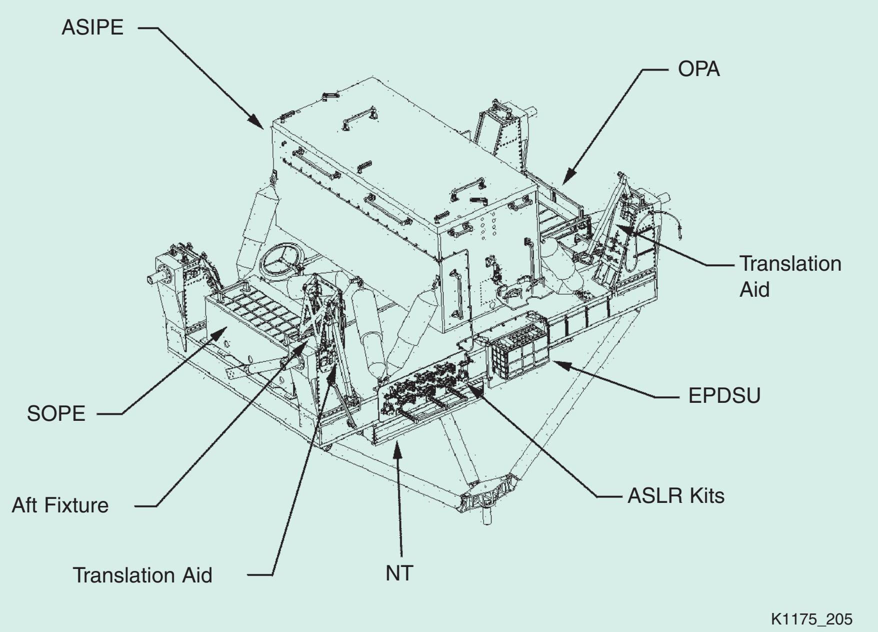


Fig. 2-5 Second Axial Carrier configuration

Astronaut Roles and Training

To prepare for SM3B, the seven-member *Columbia* crew trained extensively at NASA's Johnson Space Center (JSC) in Houston, Texas, and Goddard Space Flight Center (GSFC) in Greenbelt, Maryland.

Although there has been extensive cross training, each crewmember also has trained for specific tasks. Training for Mission Commander Scott Altman and Pilot Duane Carey focused on rendezvous and proximity operations, such as retrieval and deployment of the Telescope. The two astronauts rehearsed these operations using JSC's Shuttle Mission Simulator, a computer-supported training system. In addition, they received IVA training: helping the EVA astronauts into suits and monitoring their activities outside the *Columbia* cabin.

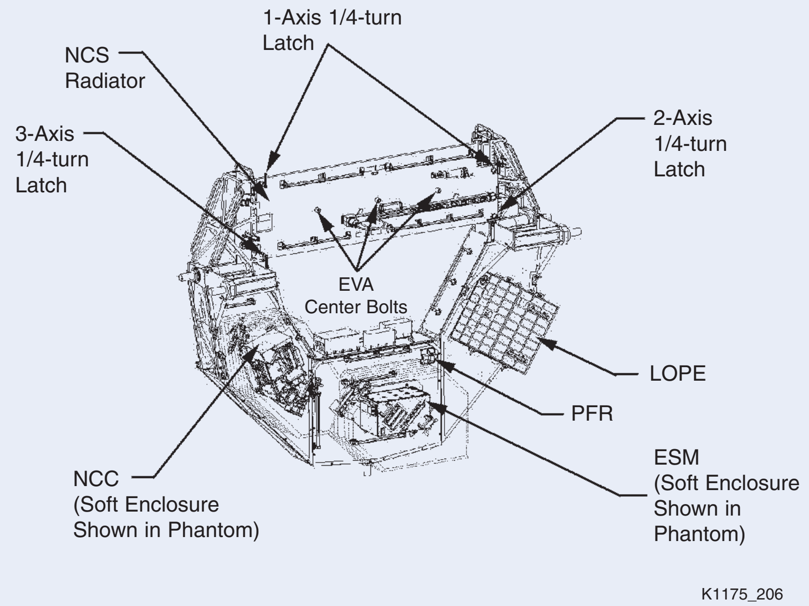


Fig. 2-6 Multi-Use Lightweight Equipment Carrier configuration

The five Mission Specialists also received specific training, starting with classroom instruction on the various ORUs, tools and crew aids, SSE such as the RMS (the robotic arm) and the FSS. Principal operator of the robotic arm is Mission Specialist Nancy Currie, who also performs IVA duties. The alternate RMS operator is Commander Altman.

Currie trained specifically for capture and redeployment of the Telescope, rotating and pivoting the Telescope on the FSS and related contingencies. These operations were simulated with JSC's Manipulator Development Facility, which includes a mockup of the robotic arm and a suspended helium balloon with dimensions and grapple fixtures similar to those on the Telescope. RMS training also took place at JSC's Neutral Buoyancy Laboratory (NBL), enabling the RMS operator and alternates to work with individual team members. For hands-on HST servicing, EVA crewmembers work in teams of two in the cargo bay. Astronauts John Grunsfeld, Richard Linnehan, James Newman and Michael Massimino logged many days of training for this important role in the NBL, a 40-foot (12-m)-deep water tank (see Fig. 2-7).

In the NBL, pressure-suited astronauts and their equipment are made neutrally buoyant, a condition that simulates weightlessness. Underwater mockups of the Telescope, FSS, RAC, SAC, MULE, RMS and the Shuttle cargo bay enabled the astronauts to practice the entire SM3B EVA servicing. Such training activities help the astronauts efficiently use the limited number of days (5) and duration (6 hours) of each EVA period.

Other training aids at JSC helped recreate orbital conditions for the *Columbia* crew. In the weightlessness of space, the tiniest movement can set instruments weighing several hundred pounds, such as ACS, into motion. To simulate the delicate on-orbit conditions, models of the instruments are placed on pads above a stainless steel floor and floated on a thin layer of pressurized gas. This allows crewmembers to practice carefully nudging the instruments into their proper locations.

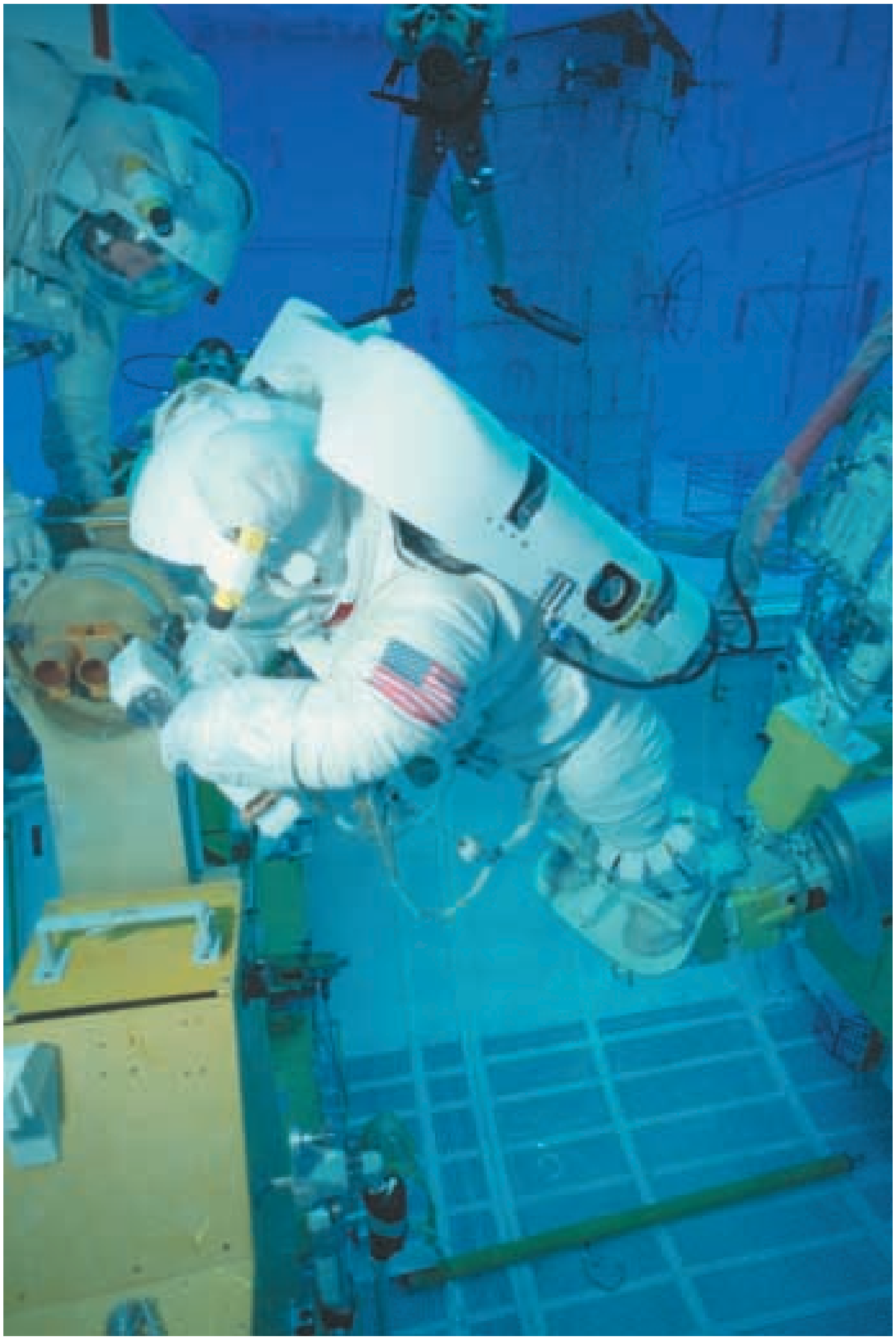


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Fig. 2-7 Neutral Buoyancy Laboratory at Johnson Space Center

Astronauts also used virtual reality technologies in their training. This kind of ultrarealistic simulation enabled the astronauts to "see" themselves next to the Telescope as their partners maneuver them into position with the robotic arm.

Extravehicular Crew Aids and Tools

Astronauts servicing HST use three different kinds of foot restraints to counteract the weightless environment. When anchored in a Manipulator Foot Restraint (MFR), an astronaut can be transported from one worksite to the next with the RMS. Using either the STS or HST PFR, an astronaut establishes a stable worksite by mounting the restraint to any of

31 different receptacles placed strategically around the Telescope or 17 receptacles on the RAC, SAC, FSS and MULE.

In addition to foot restraints, EVA astronauts have more than 150 tools and crew aids at their disposal. Some of these are standard items from the Shuttle's toolbox while others are unique to SM3B. All tools are designed for use in a weightless environment by astronauts wearing pressurized gloves.

The most commonly used ORU fasteners are those with 7/16-inch, double-height hex heads. These bolts are used with three different kinds of fittings: J-hooks, captive fasteners and keyhole fasteners. To replace a unit, an astronaut uses a 7/16-inch extension socket on a powered or manual ratchet wrench. Extensions up to 2 feet long are available to extend his or her reach. Multi-setting torque limiters prevent over-tightening of fasteners or latch systems.

For units with bolts or screws that are not captive in the ORU frame, astronauts use tools fitted with socket capture fittings and specially designed capture tools so that nothing floats away in the weightless space environment. To grip fasteners in hard-to-reach areas, they can use wobble sockets.

Some ORU electrical connectors require special devices, such as a connector tool, to loosen circular connectors. If connectors have no wing tabs, astronauts use a special tool to get a firm hold on the connector's rotating ring.

Portable handles have been attached to many larger ORUs to facilitate removal or installation. Other tools and crew aids include tool caddies (carrying aids), tethers, transfer bags and a protective cover for the Low Gain Antenna (LGA).

When working within the Telescope's aft shroud area, astronauts must guard against optics contamination by using special tools that will not outgas or shed particulate matter. All tools are certified to meet this requirement.

Astronauts of Servicing Mission 3B

NASA carefully selected and trained the SM3B STS-109 crew (see Fig. 2-8). Their unique set of experiences and capabilities makes them ideally qualified for this challenging assignment. Brief biographies of the astronauts follow.

Scott D. Altman, NASA Astronaut (Commander, USN)

Scott Altman of Pekin, Illinois, is commander of SM3B. He received a bachelor of science degree in aeronautical and astronautical engineering from the University of Illinois in 1981 and a master of science degree in aeronautical engineering from the Naval Postgraduate School in 1990. Altman has logged over 4000 flight hours in more than 40 types of aircraft, and over 664 hours in space. He was the pilot on STS-90 in 1998, a 16-day Spacelab flight. He also was the pilot on STS-106 in 2000, a 12-day mission to prepare the International Space Station for the arrival of its first permanent crew. Altman was one of two operators of the robot arm transporting the EVA crew during the STS-106 space walk. Altman will command the crew of STS-109 for SM3B and serve as the alternate RMS operator.

Duane G. "Digger" Carey, NASA Astronaut (Lieutenant Colonel, USAF)

Duane Carey, *Columbia* pilot on SM3B, is from St. Paul, Minnesota. He received a bachelor of science degree in aerospace engineering and mechanics and a master of science degree in aerospace engineering from the University of Minnesota-Minneapolis in 1981 and 1982, respectively. Carey flew the A10A during tours in England, Louisiana and the Republic of Korea and the F-16 in Spain. He worked as an F-16 experimental test pilot and System Safety Officer at Edwards Air Force Base. He has logged over 3700 hours in more than 35 types of aircraft. Carey was selected as an astronaut candidate by NASA in 1996 and, having completed 2 years of training and evaluation, has qualified for flight assignment as a pilot on STS-109.

Nancy Jane Currie, Ph.D., NASA Astronaut (Lieutenant Colonel, USA)

Nancy Currie, the RMS operator on SM3B, is from Troy, Ohio. Currie received her bachelor of arts degree in biological science from Ohio State University in 1980, a master of science degree in safety from the University of Southern California in 1985 and a doctorate in industrial engineering from the University of Houston in 1997. A Master Army Aviator, she has logged 3900 flying hours in a variety of rotary and fixed wing aircraft. She was selected by NASA in 1990 and became an astronaut after completion of her training in 1991. Currie has logged over 737 hours in space. She was a mission specialist on STS-57 in 1993, STS-70 in 1995 and STS-88 in 1998.

John M. Grunsfeld, Ph.D., NASA Astronaut

John Grunsfeld is an astronomer and an EVA crewmember (EV1 on EVA Days 1, 3 and 5) on the SM3B mission. He was born in Chicago, Illinois. Grunsfeld received a bachelor of science degree in physics from the Massachusetts Institute of Technology in 1980 and a master of science degree and a doctor of philosophy degree in physics from

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Fig. 2-8 The STS-109 mission has seven crewmembers: (clockwise from top) Commander Scott D. Altman, Pilot Duane G. "Digger" Carey, Mission Specialist Nancy Jane Currie, Mission Specialist John M. Grunsfeld, Mission Specialist Richard M. Linnehan, Mission Specialist James H. Newman and Mission Specialist Michael J. Massimino.

the University of Chicago in 1984 and 1988, respectively. Grunsfeld reported to the Johnson Space Center in 1992 for a year of training and became qualified for flight selection as a mission specialist. He has logged over 835 hours in space. On his first mission, STS-67 in 1995, Grunsfeld and the crew conducted observations to study the far ultraviolet spectra of faint astronomical objects and the polarization of ultraviolet light coming from hot stars and distant galaxies. Grunsfeld flew on STS-81 in 1997 on the fifth mission to dock with Russia's Space Station Mir and the second to exchange U.S. astronauts. Grunsfeld's latest flight was aboard STS-103 in 1999 where he performed two space walks to service Hubble on SM3A.

Richard M. Linnehan, DVM, NASA Astronaut

Rick Linnehan is a doctor of veterinary medicine and an EVA crewmember (EV2 on EVA Days 1, 3 and 5) on SM3B. He was born in Lowell, Massachusetts. Linnehan received a bachelor of science degree in Animal Sciences from the University of New Hampshire in 1980 and his DVM degree from the Ohio State University College of Veterinary Medicine in 1985. Linnehan reported to the Johnson Space Center in 1992 for a year of training and became qualified for flight selection as a mission specialist. He has logged 786 hours in space. His first mission was aboard the STS-78 Life and Microgravity Spacelab, the longest Space Shuttle mission to date (17 days). This mission combined both microgravity studies and a life sciences payload. STS-90 was his second Spacelab mission. During the 16-day flight, Linnehan and the crew served as both experimental subjects and operators for 26 individual life science experiments focusing on the effects of microgravity on the brain and nervous system.

James H. Newman, Ph.D., NASA Astronaut

Jim Newman is an EVA crewmember (EV1 on EVA Days 2 and 4) on SM3B. He was born in the Trust Territory of the Pacific Islands (now the Federated States of Micronesia), but considers San Diego, California, to be his hometown. Newman received a bachelor of arts degree in physics (graduating cum laude) from Dartmouth College in 1978, and a master of arts degree and a doctorate in physics from Rice University in 1982 and 1984, respectively. Selected by NASA in 1990, Newman flew as a mission specialist on STS-51 in 1993, STS-69 in 1995 and STS-88 in 1998. He has logged over 32 days in space, including four space walks. On STS-51, Newman and the crew deployed the Advanced Communications Technology Satellite and the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer on the Shuttle Pallet Satellite. On STS-69, Newman and the crew deployed and retrieved a SPARTAN satellite and the Wake Shield Facility. On STS-88, the first International Space Station assembly mission, Newman performed three space walks to connect external power and data umbilicals between Zarya and Unity.

Michael J. Massimino, Ph.D., NASA Astronaut

Mike Massimino is an EVA crewmember (EV2 on EVA Days 2 and 4) on the SM3B mission. He was born in Oceanside, New York. He attended Columbia University, receiving a bachelor of science degree in industrial engineering with honors in 1984. He also received master of science degrees in mechanical engineering and in technology and policy, a mechanical engineering degree and a doctorate in mechanical engineering from the Massachusetts Institute of Technology (MIT) in 1988, 1990 and 1992, respectively. Massimino was selected as an astronaut candidate by NASA in 1996 and, having completed 2 years of training and evaluation, is qualified for flight assignment as a mission specialist. STS-109 will be Massimino's first space flight, where he will perform two space walks to service the HST.

Servicing Mission Activities

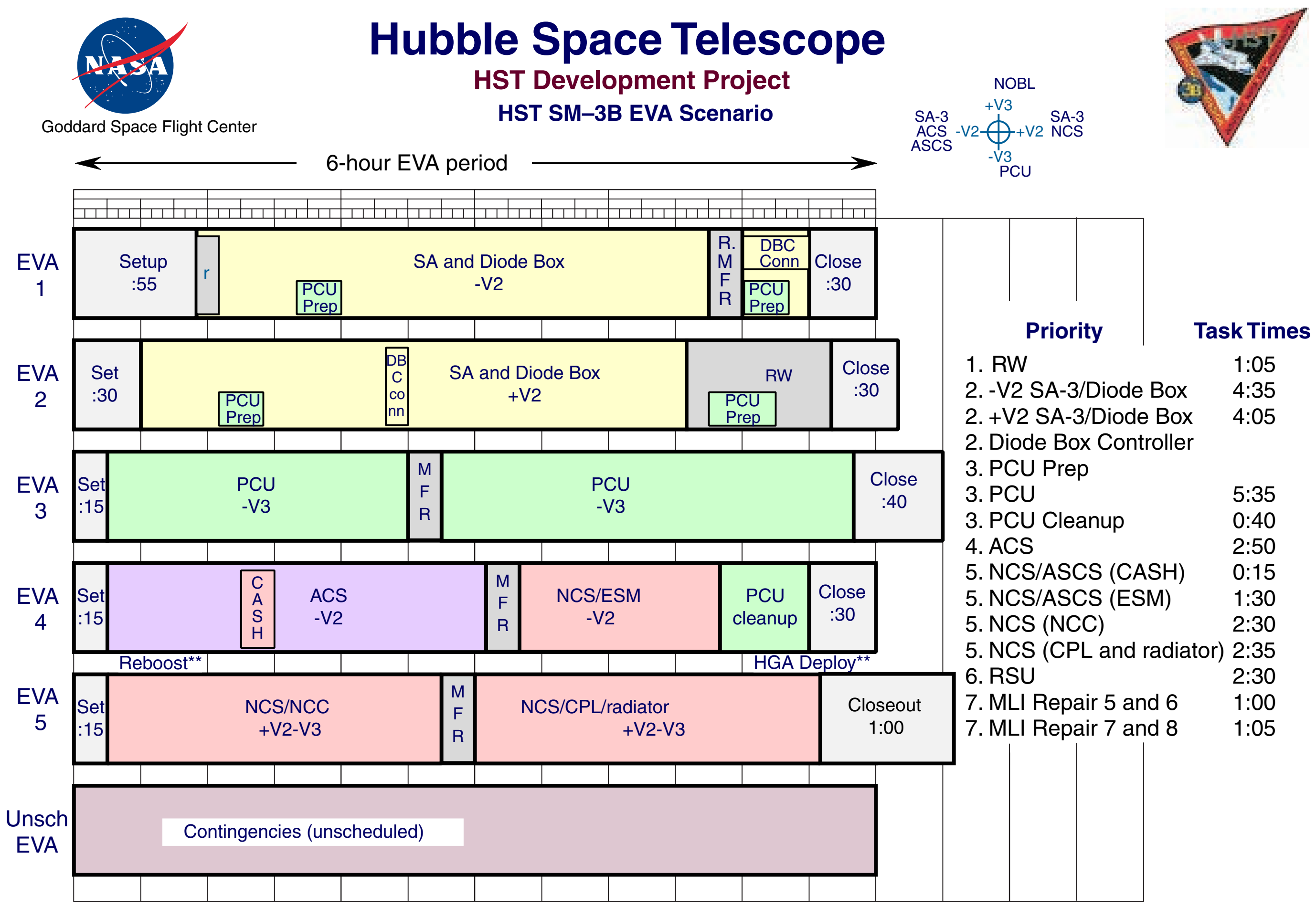
After berthing the Telescope on Flight Day 3 of SM3B, the seven-person *Columbia* crew will begin an ambitious servicing mission. Five days of EVA tasks are scheduled. Each EVA session is scheduled for 6 hours (see Fig. 2-9).

Rendezvous With Hubble

Columbia will rendezvous with Hubble in orbit 315 nautical miles (504 km) above the Earth. Prior to approach, in concert with the Space Telescope Operations Control Center (STOCC) at GSFC, Mission Control at JSC will command HST to stow the High Gain Antennas (HGA) and close the aperture door. As *Columbia* approaches the Telescope, Commander Altman will control the thrusters to avoid contaminating HST with propulsion residue. During the approach the Shuttle crew will remain in close contact with Mission Control.

As the distance between *Columbia* and HST decreases to approximately 200 feet (60 m), the STOCC ground crew will command the Telescope to perform a final roll maneuver to position itself for grappling. The Solar Arrays (SA) will remain fully deployed parallel to Hubble's optical axis.

When *Columbia* and HST achieve the proper position, Mission Specialist Currie will operate the robotic arm to grapple the Telescope. Using a camera mounted at the berthing ring of the FSS platform in the cargo bay,



Priority	Task Times
1. RW	1:05
2. -V2 SA-3/Diode Box	4:35
2. +V2 SA-3/Diode Box	4:05
2. Diode Box Controller	
3. PCU Prep	
3. PCU	5:35
3. PCU Cleanup	0:40
4. ACS	2:50
5. NCS/ASCS (CASH)	0:15
5. NCS/ASCS (ESM)	1:30
5. NCS (NCC)	2:30
5. NCS (CPL and radiator)	2:35
6. RSU	2:30
7. MLI Repair 5 and 6	1:00
7. MLI Repair 7 and 8	1:05

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Fig. 2-9 Detailed schedule of extravehicular activities during SM3B

she will maneuver it to the FSS, where the Telescope will be berthed and latched.

Once the Telescope is secured, the crew will remotely engage the electrical umbilical and switch Hubble from internal power to external power from *Columbia.* Pilot Carey will then maneuver the Shuttle so that the HST SAs face the Sun, recharging the Telescope's six onboard nickel-hydrogen (NiH_2) batteries.

Extravehicular Servicing Activities—Day by Day

Each EVA servicing period shown in Fig. 2-9 is a planning estimate; the schedule will be modified as needed as the mission progresses. During the EVAs, HST will be vertical relative to *Columbia's* cargo bay. Four EVA mission specialists will work in two-person teams on alternate days. John Grunsfeld and Rick Linnehan comprise one team, and Jim Newman and Mike Massimino the other.

One astronaut, designated EV1, accomplishes primarily the free-floating portions of the EVA tasks. He can operate from a PFR or while free floating. The other astronaut, EV2, works primarily from an MFR mounted on *Columbia's* robotic arm (RMS), removing and installing the ORUs on the Hubble. EV1 assists EV2 in removal of the ORUs and installation of the replaced units in the SM3B carriers.

To reduce crew fatigue, EVA crewmembers swap places once during each EVA day: the free floater goes to the RMS MFR and vice versa. Inside *Columbia's* aft flight deck, the off-shift EVA crewmembers and the designated RMS operator assist the EVA team by reading out procedures and operating the RMS.

EVA Day 1: Replace –V2 Solar Array and Diode Box Assembly and install Diode Box Controller cross-strap harness.

At the beginning of EVA Day 1 (the fourth day of the mission), the first team of EVA astronauts, Grunsfeld and Linnehan, suit up, pass through the *Columbia* airlock into the cargo bay and perform the initial setup. To prevent themselves from accidentally floating off, they attach safety tethers to a cable running along the cargo bay sills.

Grunsfeld (EV1) does various tasks to prepare for that day's EVA servicing activities. These include deploying the ASIPE mini-Translation Aid (TA), deploying the port and starboard TAs as required, removing the MFR from its stowage location and installing it on the RMS grapple fixture, installing the Low Gain Antenna Protective Cover (LGAPC), removing the Berthing and Positioning System (BAPS) Support Post (BSP) from its stowage location and installing it on the FSS, and inspecting the P105 and P106 umbilical covers. Meanwhile, Linnehan (EV2) brings out of the airlock the Crew Aids and Tools (CATs) and installs the MFR handrail to the MFR on the RMS.

The BSP is required to dampen the vibration that the servicing activities will induce into the deployed SAs. Prior to the BSP installation, the IVA team commands the HST to an 85-degree pivot angle. The two center push-in-pull-out (PIP) pins are installed each day and removed each night in case the Shuttle must make an emergency return to Earth. EV1 removes the BSP from its stowage position in the FSS cradle, and then installs one end to the BAPS ring with a PIP pin and the aft end to the FSS cradle with another PIP pin. Finally the BSP is commanded to its 90-degree limit and the two center PIP pins are installed.

After the initial setup, the EVA crew will replace the –V2 Solar Array and Diode Box Assembly on the Telescope. They will also install the Diode Box Controller (DBC) cross-strap harness. First EV1, who is free floating, retrieves the HST PFR and APE and transfers them to EV2 in the MFR. EV2 moves to the HST and installs the PFR on HST foot restraint receptacle 8 for the free floater's use. EV1 translates to the RAC to retrieve the DBC cross-strap harness and a Portable Connector Tray, and temporarily stows them on the Telescope. Then he ingresses the PFR. Together the astronauts retract the –V2 SA2 Primary Deployment Mechanism (PDM). EV1 then engages the PDM lock and installs the Portable Connector Tray. While still in the PFR, EV1 demates the SA2 connectors from the DBA while EV2 retrieves the WFPC Cover and installs it on the –V3 Aft Shroud in support of the PCU change-out on EVA Day 3.

Next the astronauts remove the –V2 SA2 from the Telescope. They disengage the SADA Clamp, remove SA2, translate it to the RAC and install it on the starboard shelf via the SADA Clamp and forward constraint PIP pin mechanical attachments.

EV1 translates back to the Telescope and removes the –V2 DBA by disengaging the remaining X-connector drive mechanism and releasing the four J-hook bolts while EV2 retrieves the DBA2 from the RAC and translates it to EV1 at the Telescope worksite. The astronauts swap hardware and EV1 installs the DBA2 on the Telescope while EV2 translates to the RAC with the DBA and installs it and closes its thermal cover. EV1 installs the DBC cross-strap harness onto the Telescope and mates it to the –V2 DBA2.

With the DBA2 now installed on the Telescope, the astronauts begin the installation work for the replacement Solar Array. Both translate to the RAC. EV2 disengages Latch 5, deploys the mast and engages the two mast bolts. EV1 ingresses the aft PFR, releases and pivots Latch 3 to clear the tang, disengages the two tang bolts, stows the tang and engages the two tang bolts. EV2 disengages Latch 2. EV1 pivots Latch 3 to the stowed position and installs the PIP pin, deploys the MLI flap over the tang interface and releases Latch 4. EV1 stabilizes SA3 while EV2 releases Latch 1. The astronauts then remove SA3 from the RAC.

Both crewmembers install SA3 onto the Telescope by properly orienting SA3 and inserting the SADA into the SADA Clamp until the three soft dock tangs engage. EV1 engages the SADA Clamp closed and mates the SA3 electrical interfaces. EV2 translates back to the RAC and performs the SA2 close-out work: engaging the aft latch, the forward latch and the two forward constraint bolts.

Then the astronauts deploy the SA3 panel, engage the panel locking bolts and release the SA3 brake. EV1 routes the DBC cross-strap harness to the +V2 side, removes the HST PFR and temporarily stows it on the ASIPE, and removes and stows a Portable Connector Tray on the RAC. Meanwhile, EV2 maneuvers to the –V3 aft shroud and installs the two FHST covers in preparation for the PCU change-out on EVA Day 3.

At this time, the astronauts perform the MFR swap: Grunsfeld ingresses the MFR and Linnehan becomes the free floater. EV1 (the free floater) translates to the ASIPE, retrieves the PFR from temporary stowage and transfers it to EV2, who installs it in foot restraint receptacle 19 in preparation for EVA Day 2. EV1 retrieves the Bay 10 Thermal Cover and installs it over Bay 10 of the Telescope while EV2 disengages and removes the Telescope's +V2 trunnion EPS panel, mates the DBC cross-strap harness and installs an MLI tent over the EPS panel cavity.

For the daily close-out, EV1 inspects the FSS main umbilical mechanism, disengages the two center PIP pins on the BSP, retracts the mini-TA, retracts the port and starboard TAs if required, and takes a tool inventory. Meanwhile EV2 prepares the CATs installed on the MFR handrail for return into the airlock and egresses the MFR. EV1 releases the MFR safety tether from the grapple fixture for contingency Earth return. After completing the EVA Day 1 tasks, both astronauts return to the airlock and perform the airlock ingress procedure.

EVA Day 2: Replace +V2 Solar Array and Diode Box Assembly and Reaction Wheel Assembly – 1 (RWA-1)

During EVA Day 2, Newman (EV1) and Massimino (EV2) will replace the +V2 Solar Array and Diode Box Assembly on the Telescope and complete the DBC installation by mating it to the +V2 SA3. They also will replace the RWA-1.

Fewer daily setup tasks are required for EVA Day 2 than for EVA Day 1. After completing the airlock egress procedure, EV1 reconnects the safety strap on the MFR, installs the two BSP center PIP pins and deploys the mini-TA. EV2 exits the airlock with the EVA Day 2 required CATs installed on the MFR handrail and installs the MFR handrail.

After completing the daily setup tasks, the astronauts begin the tasks for the +V2 Solar Array and Diode Box Assembly change-outs, which are similar to the –V2 Solar Array and Diode Box Assembly change-outs performed during EVA Day 1. First EV1 and EV2 retrieve the HST PFR and APE and install them on HST foot restraint receptacle 19. EV1 translates to the RAC to retrieve a Portable Connector Tray and temporarily stows it on the Telescope. Then he ingresses the PFR.

Together the astronauts retract the +V2 SA2 PDM. EV1 then engages the PDM lock and installs the Portable Connector Tray. Still in the PFR, EV1 demates the SA2 connectors from the DBA while EV2 disengages five of six bolts on each door of Telescope Bays 2, 3 and 4 in support of the PCU change-out on EVA Day 3.

Next the astronauts remove the +V2 SA2 from the Telescope. They disengage the SADA Clamp, remove SA2, translate it to the RAC and install it on the port shelf via the SADA Clamp and forward constraint PIP pin mechanical attachments.

EV1 translates back to the Telescope and removes the +V2 DBA by disengaging the remaining X-connector drive mechanism and releasing the four J-hook bolts while EV2 retrieves the DBA2 from the RAC and translates it to EV1 at the Telescope worksite. The astronauts swap hardware and EV1 installs the DBA2 on the Telescope while EV2 translates to the RAC with the DBA and installs it and closes its thermal cover.

With the +V2 DBA2 now installed on the Telescope, they begin installation work for the replacement Solar Array. Both astronauts translate to the RAC. EV2 disengages Latch 5, deploys the mast and engages the two mast bolts. EV1 ingresses the forward PFR, releases and pivots Latch 3 to clear the tang, disengages the two tang bolts, stows the tang and engages the two tang bolts. EV2 disengages Latch 2. EV1 pivots Latch 3 to the stowed position and installs the PIP pin, deploys the MLI flap over the tang interface and releases Latch 4. EV1 stabilizes SA3 while EV2 releases Latch 1. Both remove SA3 from the RAC.

Working together, the astronauts install SA3 onto the Telescope by properly orienting SA3 and inserting the SADA into the SADA Clamp until the three soft dock tangs engage. EV1 engages the SADA Clamp closed and mates the SA3 electrical interfaces, then mates the DBC cross-strap harness to the +V2 DBA2. EV2 translates back to the RAC and performs the SA2 close-out work: engaging the aft latch, the forward latch and the two forward constraint bolts.

Both astronauts work together again to deploy the SA3 panel, engage the panel locking bolts and release the SA3 brake (see Fig. 2-10). EV1 removes the HST PFR and APE and stows them on the FSS, and removes and stows the Portable Connector Tray on the RAC.

Upon completion of the SA changeout task, the EVA crew will replace the RWA-1. EV1 translates to the LOPE on the aft starboard side of the MULE, opens the lid, removes the two RWA1-R wing tab connectors from the LOPE pouch and secures them to the RWA1-R handle Velcro, disengages the three keyway bolts, removes the replacement RWA-1 (RWA1-R) and translates to the top of the starboard MULE.

EV2 maneuvers to Bay 6 and opens the Bay 6 door, demates the two RWA-1 wing tab heater connectors from the heater bracket, demates the two RWA-1 wing tab connectors from RWA-1, disengages the three RWA-1 keyway bolts and removes RWA-1 from HST Bay 6. Then he maneuvers to the starboard MULE location and performs an RWA swap with EV2.

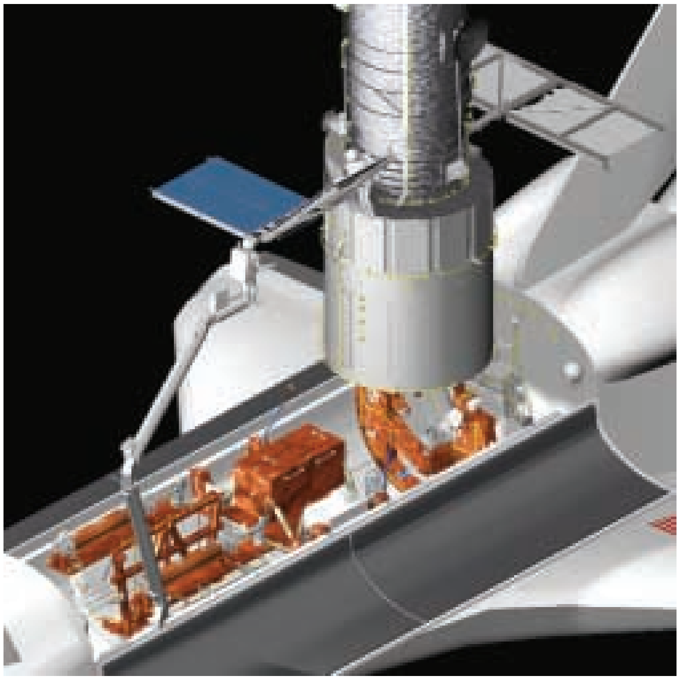

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Fig. 2-10 Deployment of new rigid solar array

EV1 maneuvers with RWA1-R to the Bay 6 worksite, installs it on HST, engages the three keyway bolts and mates the four wing tab electrical connectors. Then he closes the Bay 6 door.

After transferring the RWA1-R to EV2 and receiving RWA-1 from EV2, EV1 translates back to the LOPE, installs the RWA-1 in the LOPE, engages the three keyway bolts, stows the two wing tab connectors in the LOPE pouch and closes the LOPE lid.

EV1 retrieves the Bay 5 Thermal Cover and installs it in the retracted position on the Telescope Bay 5 in preparation for the PCU change-out on EVA Day 3. EV1 also retrieves the doorstop extensions and installs them on the +V2 aft shroud doorstops in preparation for the NCS Radiator installation on EVA Day 5.

For the daily close-out, EV1 inspects the FSS main umbilical mechanism, disengages the two center PIP pins on the BSP, retracts the mini-TA, retracts the port and starboard TAs if required and takes a tool inventory. Meanwhile EV2 prepares the CATs installed on the MFR handrail for return into the airlock and egresses the MFR. EV1 releases the MFR safety tether from the grapple fixture for contingency Earth return. After completing the EVA Day 2 tasks, both astronauts return to the airlock and perform the airlock ingress procedure.

EVA Day 3: Replace PCU.

During EVA Day 3, Grunsfeld (EV1) and Linnehan (EV2) will replace the PCU in the Telescope Bay 4. After the airlock egress procedure, EV1 reconnects the safety strap on the MFR, installs the two BSP center PIP pins and deploys the mini-TA. EV2 exits the airlock with the EVA Day 3 required CATs installed on the MFR handrail and installs the MFR handrail.

Both astronauts complete the daily setup tasks, then begin the PCU change-out. EV1 translates to the RAC to retrieve the Power Distribution Unit (PDU) fuse plug caddy and battery stringers and transfers them to EV2. EV2 translates to the Telescope Bay 3, opens the bay door, demates the three battery connectors, installs caps to deadface the battery power and temporarily closes the door. He then translates to Bay 2 and performs the same procedure for the Bay 2 battery.

Meanwhile EV1 translates to Bay 5 and deploys the thermal cover, retrieves the DBA thermal cover, translates to the +V2 DBA2 and installs its thermal cover. Then he translates to Bay 10 and deploys the thermal cover, retrieves the DBA thermal cover, translates to the -V2 DBA2 and installs its thermal cover. EV1 deploys the FHST covers on the Telescope, then translates to the SAC, retrieves the Harness Retention Device and transfers it to EV2 at the Bay 4 worksite.

EV2 opens the Bay 4 door and installs the Harness Retention Device and door stay. EV2 removes the six inboard PDU Fuse Plugs to gain sufficient access to the PCU connectors on the left side. EV1 retrieves the PCU handhold from the SAC and temporarily stows it by the +V2 trunnion. Then he translates to the airlock and recharges his suit with oxygen, enabling him to extend his EVA time. EV2 disengages seven of 10 PCU keyway bolts and demates all but the last six connectors (30).

At this point, EV1 and EV2 perform the MFR swap. EV2 completes demating the remaining PCU connectors, installs the PCU handhold, disengages the three remaining bolts, disengages the PCU groundstrap and removes the PCU from the Telescope.

EV1 translates to the starboard SAC where the replacement PCU (PCU-R) is located, ingresses the PFR, opens the thermal cover, disengages the six keyway bolts and removes the PCU-R from the SAC.

EV1 and EV2 swap boxes at the SAC worksite. EV2 translates with the PCU-R back to the Telescope worksite, installs it, engages seven keyway bolts and engages the groundstrap (see Fig. 2-11). EV1 stows the PCU on the SAC, engages the six keyway bolts, retightens the two PCU handhold wing bolts, egresses the PFR and reinstalls the PCU thermal cover. He then translates to the airlock and recharges his suit with oxygen. EV2 mates the 36 connectors on the PCR-R, a difficult and time-consuming task.

EV1 inspects the Telescope exterior handrails to be used for the ACS and NCS tasks on EVA Days 4 and 5 and, if required, installs handrail covers. EV2 reinstalls the PDU fuse plugs, removes the Harness Retention Device, removes the door stay and closes the Bay 4 door with one J-bolt. He re-opens the Bay 3 door, remates the battery connectors and closes the door with one J-bolt. Then he performs the same procedure for the Bay 2 battery. After the PDU fuse plugs are reinstalled, EV1 translates to the +V2 DBA2, retrieves the thermal cover, stows it on its Bay 5 thermal cover stowage pouch and retracts the Bay 5 thermal cover. He translates to the -V2 DBA2, retrieves the thermal cover, stows it on its Bay 10 thermal cover stowage pouch and retracts the Bay 10 thermal cover. Next EV1 retrieves the Harness Retention Device and stows it on the SAC. Then he retracts the FHST covers, receives the PDU fuse plug caddy and battery stringers from EV2, and stows them on the RAC. If time allows, EV2 removes the WFPC thermal cover and stows it on the SAC.


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Fig. 2-11 Change-out of Power Control Unit

For the daily close-out, EV1 inspects the FSS main umbilical mechanism, disengages the two center PIP pins on the BSP, retracts the mini-TA, retracts the port and starboard TAs if required and takes a tool inventory. Meanwhile EV2 prepares the CATs installed on the MFR handrail for return into the airlock and egresses the MFR. EV1 releases the MFR safety tether from the grapple fixture for contingency Earth return. After the completion of the EVA Day 3 tasks, both astronauts return to the airlock and perform the airlock ingress procedure.

EVA Day 4: Replace FOC with ACS, install ESM and perform PCU cleanup tasks.

During EVA Day 4, Newman (EV1) and Massimino (EV2) will replace the Faint Object Camera (FOC) with the ACS, install the ESM in the Telescope aft shroud and do the remaining PCU cleanup tasks. After the airlock egress procedure, EV1 reconnects the safety strap on the MFR, installs the two BSP center PIP pins and deploys the mini-TA. EV2 exits the airlock with the EVA Day 4 required CATs installed on the MFR handrail and installs the MFR handrail.

The astronauts complete the daily setup tasks, then begin the FOC/ACS change-out. EV1 deploys the aft fixture, retrieves the COSTAR Y-harness from the RAC port ATM and stows it on the Telescope aft shroud. EV2 opens the –V2 aft shroud doors. EV1 and EV2 work together to remove the FOC from the Telescope. EV1 demates the four FOC connectors, disconnects the FOC purge line and disconnects the groundstrap. EV2 disengages the FOC A-Latch and EV1 disengages the FOC B-Latch. Then EV2 removes the FOC from the Telescope and stows it on the aft fixture.

EV1 and EV2 now work together to install the CASH. Even though the CASH is part of the NCS installation, it is installed now to maximize EVA timeline efficiencies and eliminate the need to open the –V2 aft shroud doors a second time on EVA Day 5. EV1 and EV2 retrieve the CASH from the SAC and install it on handrails inside the aft shroud.

EV1 and EV2 retrieve the ACS from the ASIPE. EV1 configures the aft ASIPE PFR, opens the ASIPE lid, disconnects the ACS groundstrap and deploys the B-Latch alignment aid. EV2 disengages the A-Latch and EV1 disengages the B-Latch. They both remove the ACS from the ASIPE. EV1 closes the ASIPE lid and engages one lid latch to maintain thermal stability inside the ASIPE. The astronauts continue to work together to install the ACS into the Telescope aft shroud (see Fig. 2-12). They insert the ACS along the guiderails, deploy the B-Latch alignment aid arm,

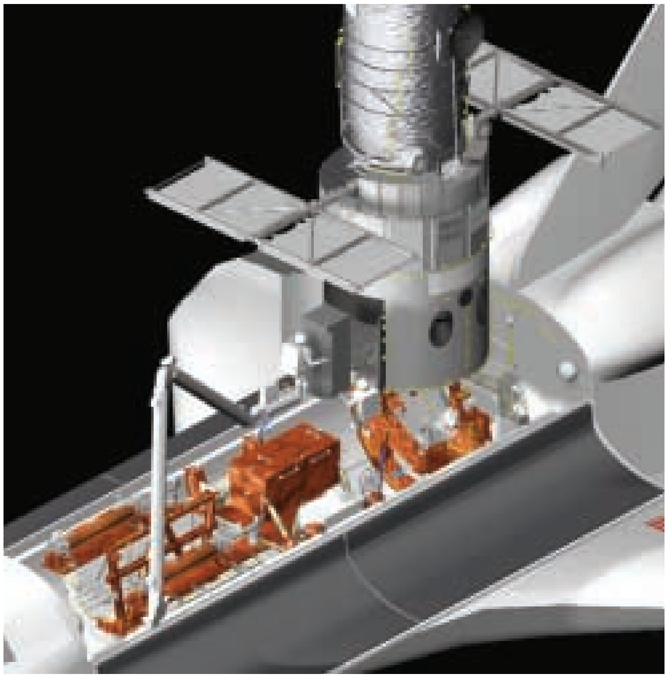

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Fig. 2-12 Installation of the Advanced Camera for Surveys

engage the B-Latch and A-Latch, stow the alignment aid, tether the ESM groundstrap to the ACS handrail, reinstall the HST groundstrap and mate the four ACS connectors.

Next the astronauts install the FOC into the ASIPE. EV2 retrieves the FOC from the aft fixture while EV1 re-opens the ASIPE lid. EV2 inserts the FOC into the ASIPE guiderails while EV1 stows the aft fixture and engages the FOC B-Latch. EV2 engages the A-Latch. EV1 disengages the FOC groundstrap bolt and installs the groundstrap on FOC, then closes the ASIPE lid and engages the five lid latches.

After completing the FOC installation into the ASIPE, the astronauts perform the MFR swap. They retrieve the ESM from the MULE and install it in the –V2 aft shroud. Then they install the ACS ESM groundstrap on the ESM, retrieve the Y-harness from temporary stowage, demate the four COSTAR connectors, mate four Y-harness connectors to the COSTAR harnesses, mate four Y-harness connectors to COSTAR and mate four Y-harness connectors to the ESM. EV2 mates the four CASH connectors to the ESM. Now they are ready to close the –V2 aft shroud doors.

The PCU cleanup task follows the FOC/ACS change-out and the ESM installation. EV1 removes the Bay 10 thermal cover and stows it on the ASIPE, then removes the Bay 5 thermal cover and stows it on the ASIPE. He also articulates the aft ASIPE PFR to its landing configuration. Meanwhile, EV2 engages the remaining five J-bolts on each door of Bays 2, 3 and 4. Then the astronauts remove the FHST and WFPC covers from the Telescope and stow them on the SAC.

For the daily close-out, EV1 inspects the FSS main umbilical mechanism, disengages the two center PIP pins on the BSP, retracts the mini-TA, retracts the port and starboard TAs if required and takes a tool inventory. Meanwhile EV2 prepares the CATs installed on the MFR handrail for return into the airlock and egresses the MFR. EV1 releases the MFR safety tether from the grapple fixture for contingency Earth return. After completing the EVA Day 4 tasks, both astronauts return to the airlock and perform the airlock ingress procedure.

EVA Day 5: Install the NCC and NCS Radiator.

During EVA Day 5, Grunsfeld (EV1) and Linnehan (EV2) will install the remaining NCS hardware. After the airlock egress procedure, EV1 reconnects the safety strap on the MFR, installs the two BSP center PIP pins and deploys the mini-TA. EV2 exits the airlock with the EVA Day 5 CATs installed on the MFR handrail and installs the MFR handrail.

Both astronauts complete the daily setup tasks, then begin the NCS installation. EV2 opens the Telescope +V2 aft shroud doors while EV1 retrieves the Cryo Vent Line (CVL) bag and NCS sock bag from the RAC port ATM and the NCC groundstrap and cryo vent insert from the RAC starboard ATM. Together the astronauts prepare the NICMOS for the NCS installation. They remove the NICMOS CVL and stow it in the CVL bag, close the NICMOS vent line valve, disengage the NICMOS groundstrap from NICMOS, install the NCC groundstrap adapter on NICMOS and install the cryo vent insert. EV1 retrieves the P600 harness from the RAC starboard ATM. EV2 retrieves the NCC from the SAC and opens the neon bypass valve while EV1 closes the NCC contamination cover.

Both astronauts install the NCC into the Telescope aft shroud. EV2 installs the NCC groundstrap on NCC and mates the four CASH connectors. EV1 translates to the MULE and releases some of the NCS Radiator latches and shear ties. At this point, they perform the MFR swap.

Next comes retrieval of the NCS Radiator. EV1 closes the left aft shroud door and together with EV2 disengages the remaining latches, removes the NCS Radiator from the MULE and opens the NCS Radiator handrail latches. They install the NCS Radiator onto the exterior of the Telescope aft shroud.

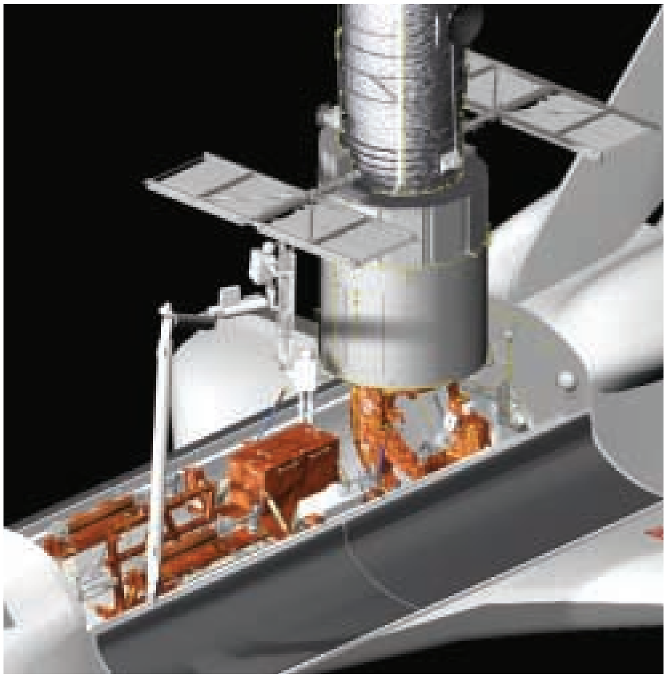
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Fig. 2-13 Installation of NICMOS Cooling System radiator

EV1 prepares the NCC by installing the coolant in and coolant out cryo valve heaters and neon lines while EV2 installs the NCC power cable to the EPS test panel and reinstalls the MLI tent. They install the NCS Radiator conduit through the cryo vent insert opening in the aft bulkhead and engage the cryo vent insert latches and locking bolts (see Fig. 2-13). Then the NCS Radiator harnesses are mated to the NCS, the NCC saddle thermal cover opened and the CPL evaporator removed from the sock and tethered to the bulkhead standoff by EV1. EV2 opens the NCS Radiator diode box, checks some LEDs and switches, and closes the diode box cover. He installs the CPL evaporator in the saddle, installs the saddle cover, engages its two bolts and closes the NCC saddle thermal cover. Together the astronauts close the aft shroud doors. The crew will then stow the CVL and NCS sock bags in the RAC port ATM.


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Fig. 2-14 Redeploying the Hubble Space Telescope

The final close-out procedure follows the NCS installation. EV1 inspects the FSS main umbilical mechanism and the P105/P106 covers, removes the LGA protective cover from the Telescope and reinstalls it on the FSS, disengages the two center PIP pins on the BSP, retracts the mini-TA, retracts the port and starboard TAs (if required) to their landing configurations and takes a tool inventory. Meanwhile EV2 prepares the CATs installed on the MFR handrail for return into the airlock, egresses the MFR and performs the MFR stow procedure. After completing the EVA Day 5 tasks, both astronauts return to the airlock and perform the airlock ingress procedure.

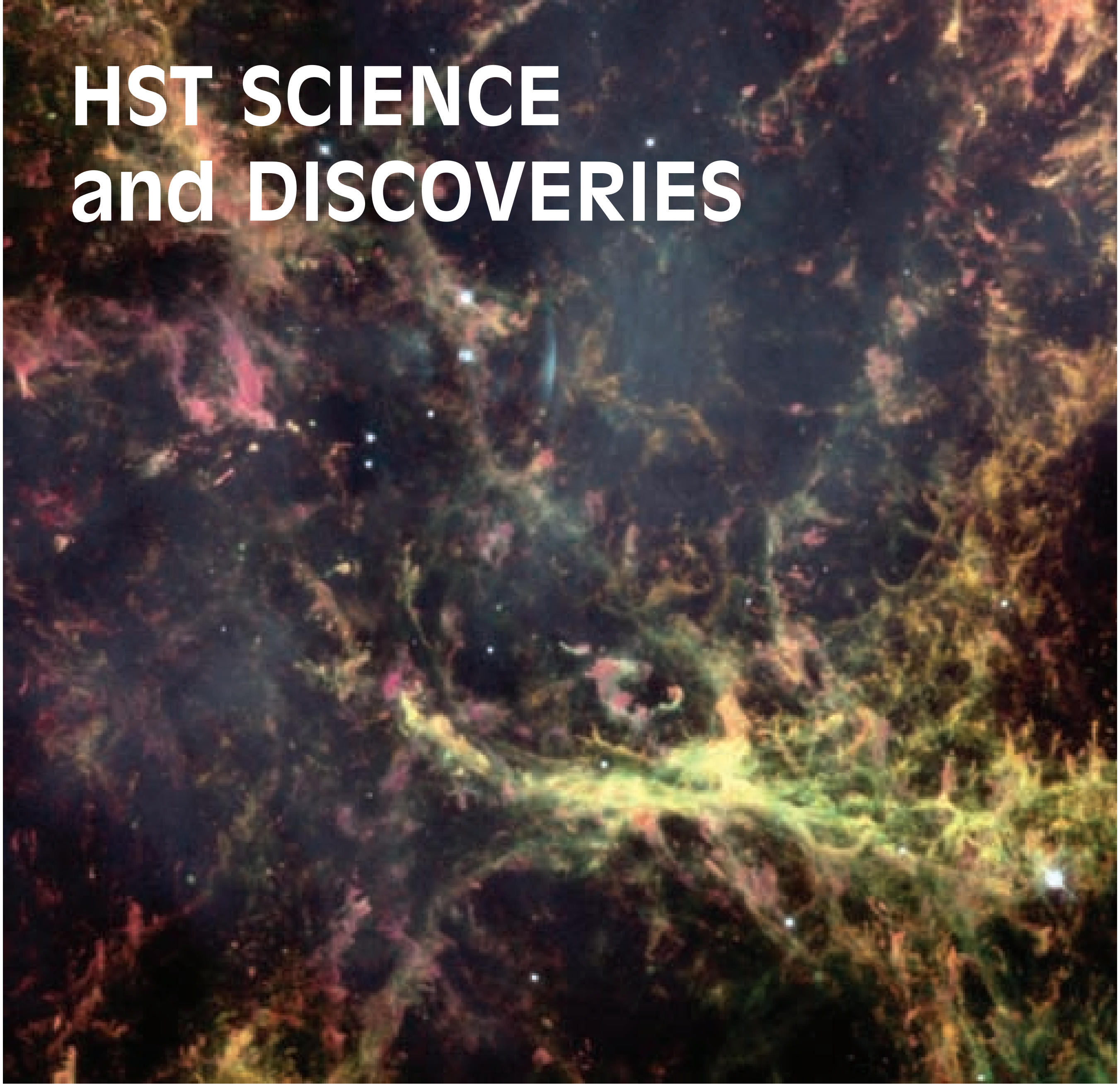
Possible EVA Day 6: Replace RSU, install NOBLs 5, 6, 7 and 8, and install ASLR kits if needed.

While there is no scheduled EVA Day 6 on the manifest, if all goes well during EVA Days 1 through 5 and the *Columbia* consumables are adequate, the astronauts may execute a sixth EVA day to change out an RSU, install the Bays 5, 6, 7 and 8 NOBLs, and install repair kits on the aft shroud doors, if any of the latches exhibited excessive running torque upon examination on EVA days 4 and 5.

EVA Contingency Day. An unscheduled EVA day has been allocated for enhancing payload mission success and for any payload requirements on the HST redeployment day.

Redeploying the Telescope. The day following EVA Day 5 will be devoted to any unscheduled EVA tasks and redeployment of the HST into Earth orbit (see Fig. 2-14). The SAs are slewed to the Sun to generate electrical power for the Telescope and to charge the batteries, and HGAs are commanded to their deployed position. When the battery charging is complete, the RMS operator guides the robotic arm to engage HST's grapple fixture. The ground crew commands Hubble to switch to internal power. This accomplished, crewmembers command *Columbia's* electrical umbilical to demate from Hubble and open the berthing latches on the FSS. If any Telescope appendages fail to deploy properly, two mission specialists can perform EVA tasks, manually overriding any faulty mechanisms.

HST SCIENCE and DISCOVERIES



The launch and deployment of NASA's Hubble Space Telescope (HST) ushered in a golden era of space exploration and discovery. For nearly 12 years, Hubble's rapid-fire rate of unprecedented discoveries has invigorated astronomy. Not since the invention of the telescope four centuries ago has our vision of the universe changed so radically in such a short stretch of time.

As the 12.5-ton Earth-orbiting observatory looks into space unburdened by atmospheric distortion, new details about planets, stars and galaxies come into crystal clear view. The Telescope has produced a vast amount of information and a steady stream of images that have astounded the world's astronomical and scientific communities. It has helped confirm some astronomical theories, challenged others and often come up with complete surprises for which theories do not yet exist.

Hubble was designed to provide three basic capabilities:

- High angular resolution—the ability to image fine detail
- Ultraviolet performance—the ability to produce ultraviolet images and spectra
- High sensitivity—the ability to detect very faint objects.

Each year NASA receives over a thousand new observing proposals from astronomers around the world. Observing cycles are routinely oversubscribed by a factor of six.

The Telescope is extremely popular because it allows scientists to get their clearest view ever of the cosmos and to obtain information on the temperature, composition and motion of celestial objects by analyzing the radiation they emit or absorb. Results of HST observations are being presented regularly in scientific papers at meetings of the American Astronomical Society and other major scientific conferences.

Although Hubble's dramatic findings to date are too numerous to be described fully in this Media Reference Guide, the following paragraphs highlight some of the significant astronomical discoveries and observations in three basic categories:

- Formation and evolution of stars and planets
- Earth's Solar System
- Galaxies and cosmology.

For further information, visit the Space Telescope Science Institute website at http://oposite.stsci.edu.

Evolution of Stars and Planets

It's a cruel world for some fledgling planets. Hubble found an inhospitable neighborhood for embryonic planets in the Orion Nebula, a stellar breeding ground peppered with hot, massive stars whose blistering radiation erodes material around them. The Telescope also hunted for planets in a nearby globular cluster and found none, although up to 50 detections were expected. But Hubble did find a vast stellar nursery in the Large Magellanic Cloud.

Probing the universe since April 24, 1990, Hubble has chased after planets, snapped pictures of the most luminous known star and chronicled the explosive death of a massive star.

Elusive Planets

Scanning 35,000 stars in the tightly packed globular star cluster 47 Tucanae, the Telescope was on the prowl for planets (see Fig. 3-1). Surprisingly, it found none. However, the results do not rule out the possibility that the cluster could contain normal solar systems like ours that the Telescope cannot detect.

Hubble can detect only Jupiter-sized planets orbiting close to their parent stars—closer than the scorched planet Mercury. These star-hugging planets complete an orbit and pass in front of their parent stars every few days. Nevertheless, the finding suggests that the conditions for planet formation and evolution may be fundamentally different in the cluster than in our galactic backyard.

Searching for planets in 47 Tucanae, 15,000 light-years away, was not easy. Planets at that distance are too dim to be seen directly. So astronomers used an indirect method to detect the planets, pushing the

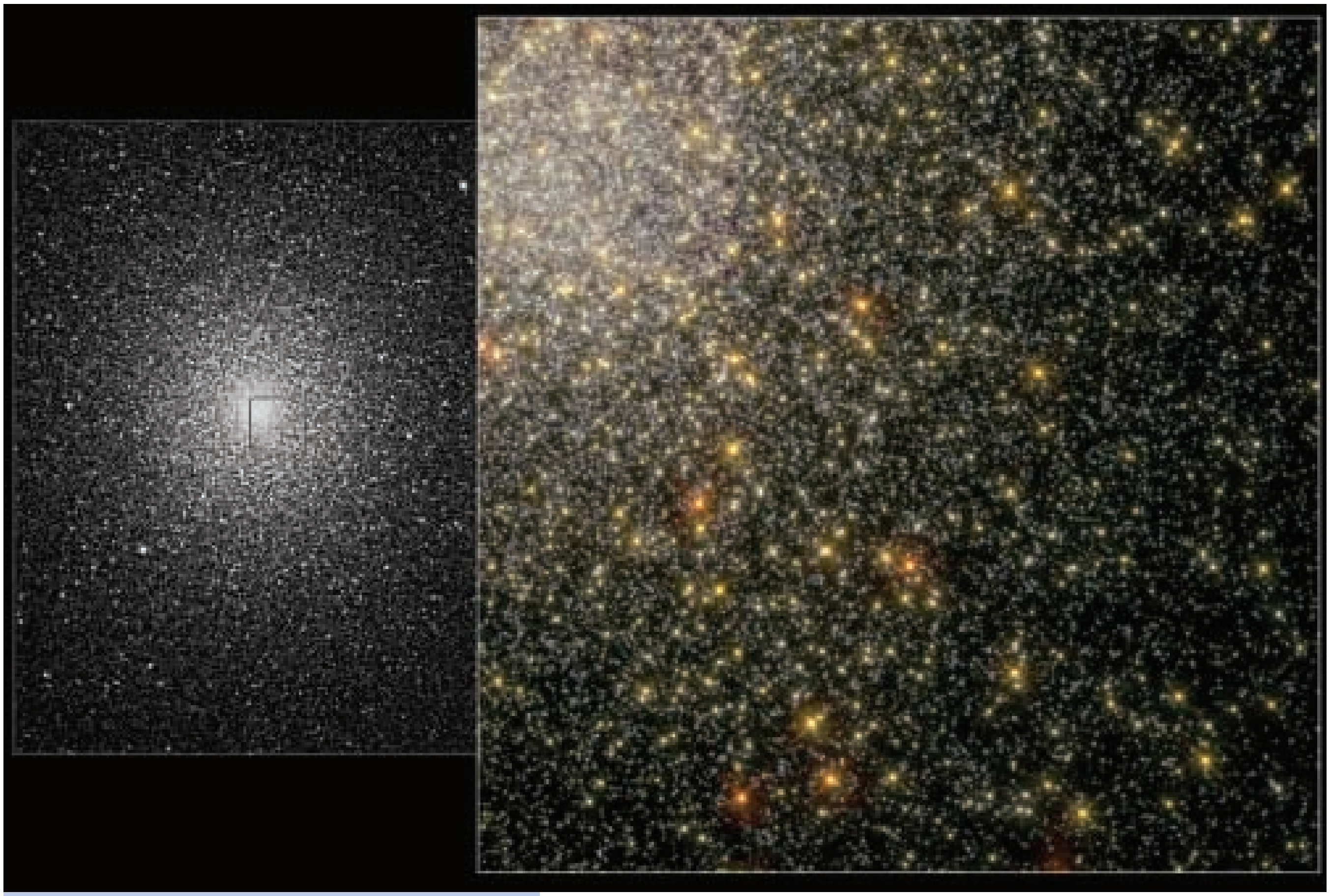


Fig. 3-1 A vast "city" of stars in 47 Tucanae

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Telescope to the limit of its capabilities. Among the 35,000 stars, astronomers looked for a slight dimming of a star due to a planet passing in front of it, an event called a transit. The planet had to be slightly larger than Jupiter, our solar system's largest planet, to block enough light for Hubble to detect it.

Why didn't the Telescope find any Jupiter-sized planets? One reason is that the stars are packed together so tightly that the gravity of nearby stars stripped nascent planets from their parent stars. Another possibility is that a torrent of ultraviolet radiation from the earliest and biggest stars may have boiled away fragile embryonic dust disks out of which planets would have formed.

In a star-forming region a few thousand light-years closer to Earth, planets are playing a life-and-death game of survival. Hubble produced the first direct visual evidence for the growth of planet "building blocks" inside dust disks around dozens of stars in the Orion Nebula (see Fig. 3-2).

Planetary building blocks are large grains, ranging in size from smoke particles to sand grains. To make planets, these grains stick together. Hubble observations show that it may be easy to begin building planets deep inside the star-forming cloud. Reaching adulthood, however, may be a hazardous process. Fledgling planets try to form quickly before they are destroyed by blistering ultraviolet radiation from the nebula's brightest star, Theta 1 Orionis C.

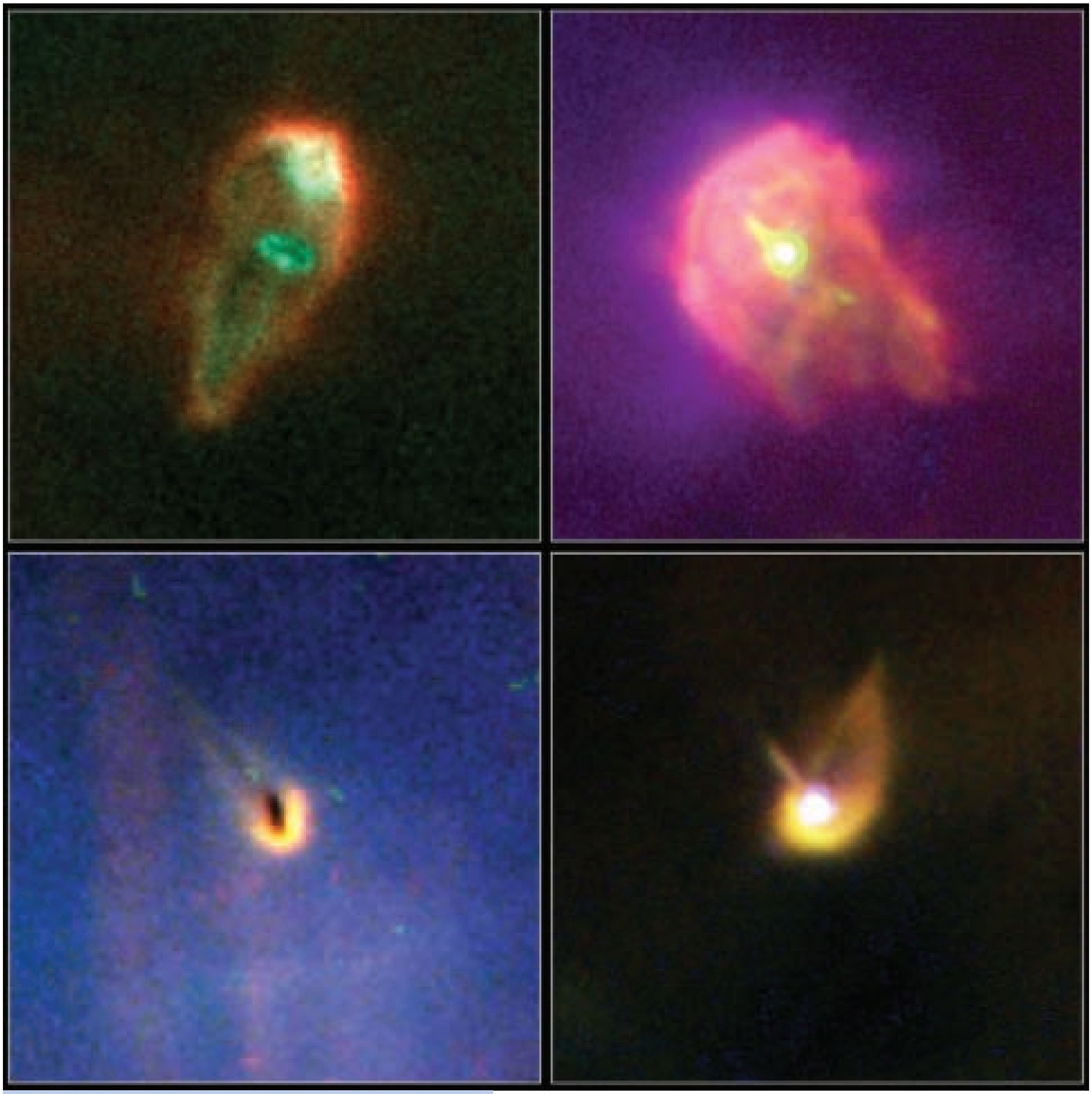

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Fig. 3-2 Planetary nurseries under fire in Orion

Astronomers predict that 90 percent of the youngest disks—which started out being billions of miles across—will be destroyed within 100,000 years. But planet formation will continue in the disks shielded from the deadly radiation. These stars probably will become the parents of a variety of planets.

Stars Under Construction

The telescope has snapped a panoramic portrait of a vast, sculpted landscape of gas and dust where thousands of stars are being born (see Fig. 3-3). This fertile star-forming region, called the 30 Doradus Nebula, has a sparkling stellar centerpiece: the most spectacular cluster of massive stars in our cosmic neighborhood of about 25 galaxies.

The mosaic picture shows that ultraviolet radiation and high-speed material unleashed by the stars in the cluster, called R136 (the large blue blob left of center), are weaving a tapestry of creation and destruction, triggering the collapse of looming gas and dust clouds and forming pillar-like structures that are incubators for nascent stars.

The view offers an unprecedented, detailed look at the entire inner region of 30 Doradus, measuring 200 light-years wide by 150 light-years high. The

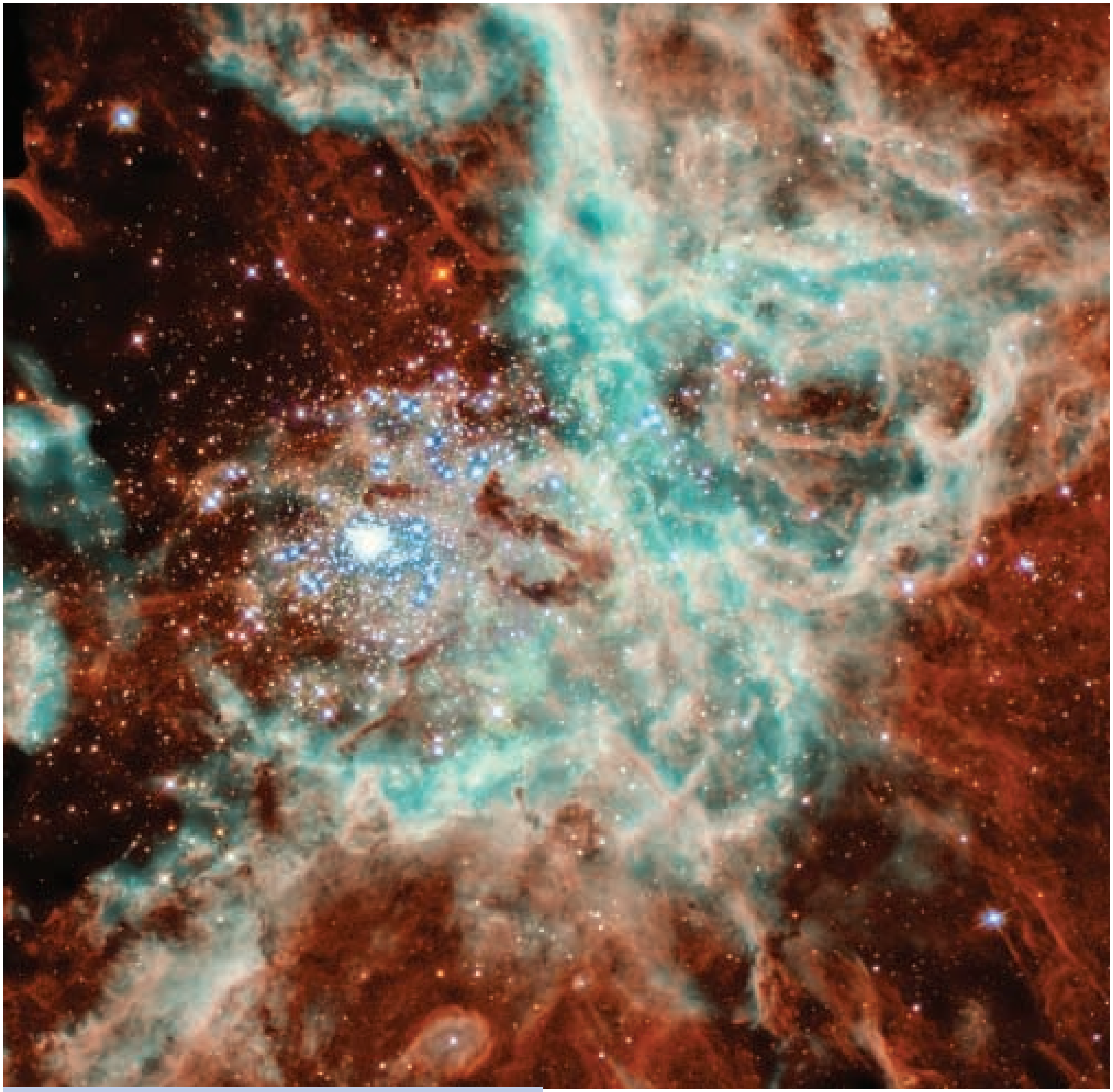

Fig. 3-3 Vast star-forming region in 30 Doradus Nebula

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nebula resides in the Large Magellanic Cloud (a satellite galaxy of the Milky Way), 170,000 light-years from Earth.

Nebulas like 30 Doradus are the "signposts" of recent star birth. High-energy ultraviolet radiation from the young, hot, massive stars in R136 causes the surrounding gaseous material to glow. Previous Hubble telescope observations showed that R136 contains several dozen of the most massive stars known, each about 100 times the mass of the Sun and about 10 times as hot. These stellar behemoths all formed at the same time about 2 million years ago.

Most Luminous Star

Astronomers used Hubble's probing "eye" to find what may be the most luminous known star—a celestial mammoth that releases up to 10 million times the power of the Sun and is big enough to fill the diameter of Earth's orbit. Called the Pistol Star, this stellar behemoth unleashes as much energy in 6 seconds as the Sun does in 1 year (see Fig. 3-4). The image, taken with the Telescope's infrared camera, also reveals a bright nebula, created by extremely massive stellar eruptions. The nebula is so big (4 light-years) it would nearly span the distance from the Sun to Alpha Centauri, the star nearest to Earth's solar system.

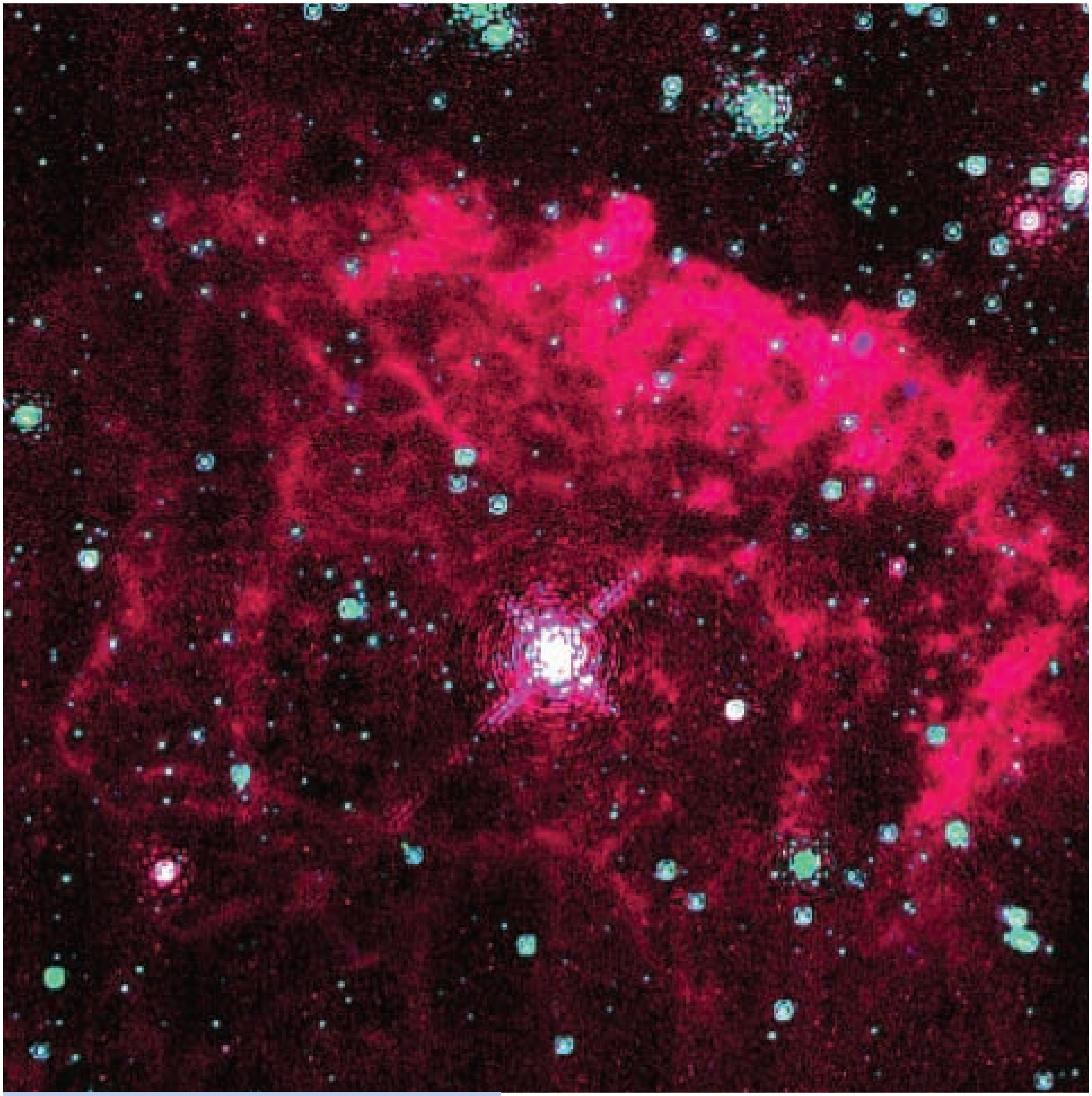

Fig. 3-4 A brilliant star at the Milky Way's core

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When the titanic star formed 1 to 3 million years ago, astronomers estimate that it may have weighed up to 200 times the mass of the Sun before shedding much of its bulk in violent eruptions. The star is approximately 25,000 light-years from Earth near the center of the Milky Way Galaxy.

When massive stars die, they don't go quietly. Instead, they end their lives with mammoth explosions. Hubble has been watching one of these explosions, supernova 1987A. A ground-based telescope first saw the star's self-destruction in February 1987.

In July 1997 Hubble's imaging spectrograph captured the first images of material ejected by the exploding star as they slammed into an inner ring around the dying object. A 100-billion-mile-wide knot of gas in a piece of the ring has already begun to "light up" as its temperature surges from a few thousand degrees to a million degrees Fahrenheit. By analyzing this glowing ring, astronomers may find clues to many of the supernova's unanswered mysteries: What was the progenitor star? Was it a single star or a binary system? The ring was formed 20,000 years ago before the star exploded. What process created it? The supernova is 167,000 light-years away in the Large Magellanic Cloud.

Earth's Solar System

A comet disintegrating as it looped around the Sun.
Another comet slamming into Jupiter.
Auroras on Jupiter and Saturn.
Wacky weather on Mars.

Hubble has kept an "eye" on our solar system.

Death of a Comet

From July to August 2000, the orbiting observatory provided unprecedented close-up views of the demise of Comet LINEAR as the icy body passed around the Sun (see Fig. 3-5). The mountain-sized object broke apart during the summer of 1999. Hubble pictures

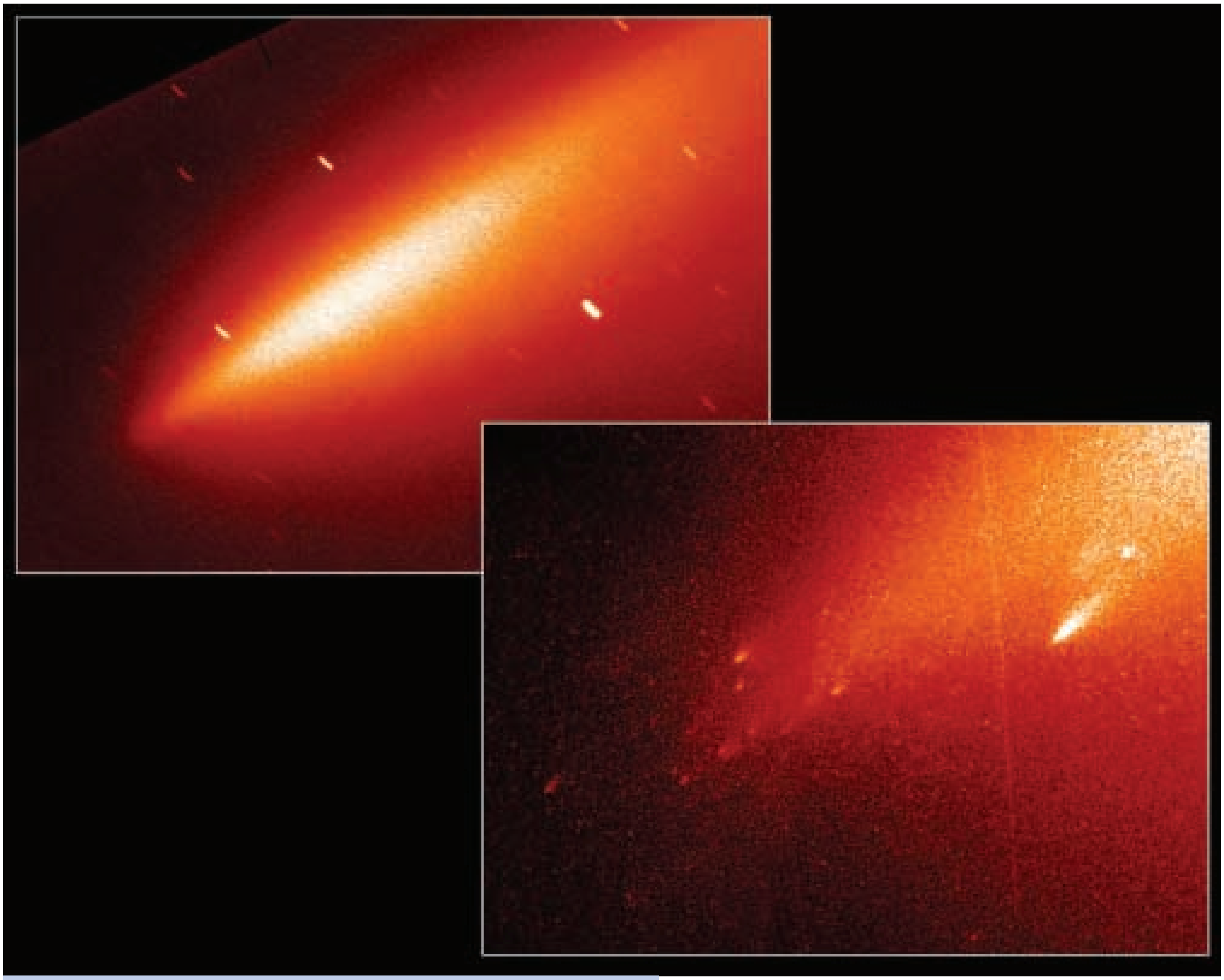

Fig. 3-5 Hubble discovers missing pieces of Comet LINEAR

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support the popular theory that comets are composed of clusters of small, icy bodies called "cometesimals," which date to the early solar system.

In July 2000 the Telescope first noticed the comet falling apart when it fortuitously saw a piece of the icy body blow off and sail along its wispy tail. Following the comet's closest approach to the Sun on July 26, astronomers using ground-based telescopes reported that the comet had vanished. But astronomers employing Hubble discovered that the comet had disintegrated into a cadre of "mini-comets" with tails, each perhaps tens of feet across. The group of objects resembled a shower of glowing balls from fireworks.

Astronomers believe that the Sun's heat caused the comet to distintegrate. By studying how the comet fell apart, astronomers hope to learn how it was put together about 4.6 billion years ago.

Crash on Jupiter

In 1994 the Telescope watched pieces of a comet invade Jupiter. It recorded 21 fragments of Comet Shoemaker-Levy 9 slamming into the giant planet. As each comet fragment crashed into Jupiter, Hubble caught mushroom-shaped plumes along the edge of the planet. The largest fragment impact created an Earth-sized bull's-eye pattern on Jupiter.

The Telescope's probe of the comet's bombardment, combined with results from other space-borne and Earth-based telescopes, sheds new light on Jupiter's atmospheric winds and its immense magnetic field. Hubble's sharp images show that the fragments, the largest of which were probably a few miles across, did not break up catastrophically before plunging into Jupiter's atmosphere. This reinforces the notion that solid, massive bodies produced the comet's atmospheric explosions.

Mars Close-up

In 2001 Hubble captured the best view of Mars ever obtained from Earth (see Fig. 3-6). Frosty white water ice clouds and swirling orange dust storms above a vivid rusty landscape reveal Mars as a dynamic planet.

The picture was taken on June 26 when Mars was approximately 43 million miles (68 million km) from Earth—the closest Mars has been to Earth since 1988. Details as small as 10 miles (16 km) across can be seen. The colors have been carefully balanced to give a realistic view of Mars' hues as they might appear through a ground-based telescope.

Especially striking is the large amount of seasonal dust storm activity seen in the image. One large storm system is churning high above the northern polar cap and a smaller dust storm cloud can be seen nearby. Another large dust storm is spilling out of the giant Hellas impact basin in the Southern Hemisphere.


Fig. 3-6 Mars at opposition in 2001

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Hubble has observed Mars before, but never in such detail. The biennial close approaches of Mars and Earth are not all the same. Because Mars' orbit around the Sun is markedly elliptical, the close approaches to Earth can range from 35 million to 63 million miles.

Astronomers study the changeable surface and weather conditions on Mars, in part, to help plan for two NASA missions to land rovers on the planet's surface in 2004. The Mars opposition of 2001 serves as a prelude for 2003 when Mars and Earth will come within 35 million miles of each other, the closest since 1924 and not to be matched until 2287.

Dances of Light

Hubble also studied auroras—curtains of light—that seem to dance above the north and south poles of Saturn and Jupiter. Astronomers used the Telescope's ultraviolet-light camera, the imaging spectrograph, to probe these auroras.

Saturn's auroras rise more than 1,000 miles above the cloud tops. Its auroral displays are caused by an energetic wind from the Sun that sweeps over the planet, much like Earth's aurora. But Saturn's auroras can be seen only in ultraviolet light, which is invisible from Earth. These auroras are primarily shaped and powered by a continual tug-of-war between Saturn's magnetic field and the flow of charged particles from the Sun.

The Telescope took many images of Jupiter's auroras, including some in ultraviolet light. Jovian auroral storms develop when electrically charged particles trapped in the magnetic field surrounding the planet spiral inward at high energies toward the north and south magnetic poles. When these particles hit the upper atmosphere, they excite atoms and molecules there, causing them to glow (the same process that makes streetlights shine). Jupiter's auroras are caused, in part, by particles spewed out by volcanoes on Io, one of Jupiter's moons (see Fig. 3-7).

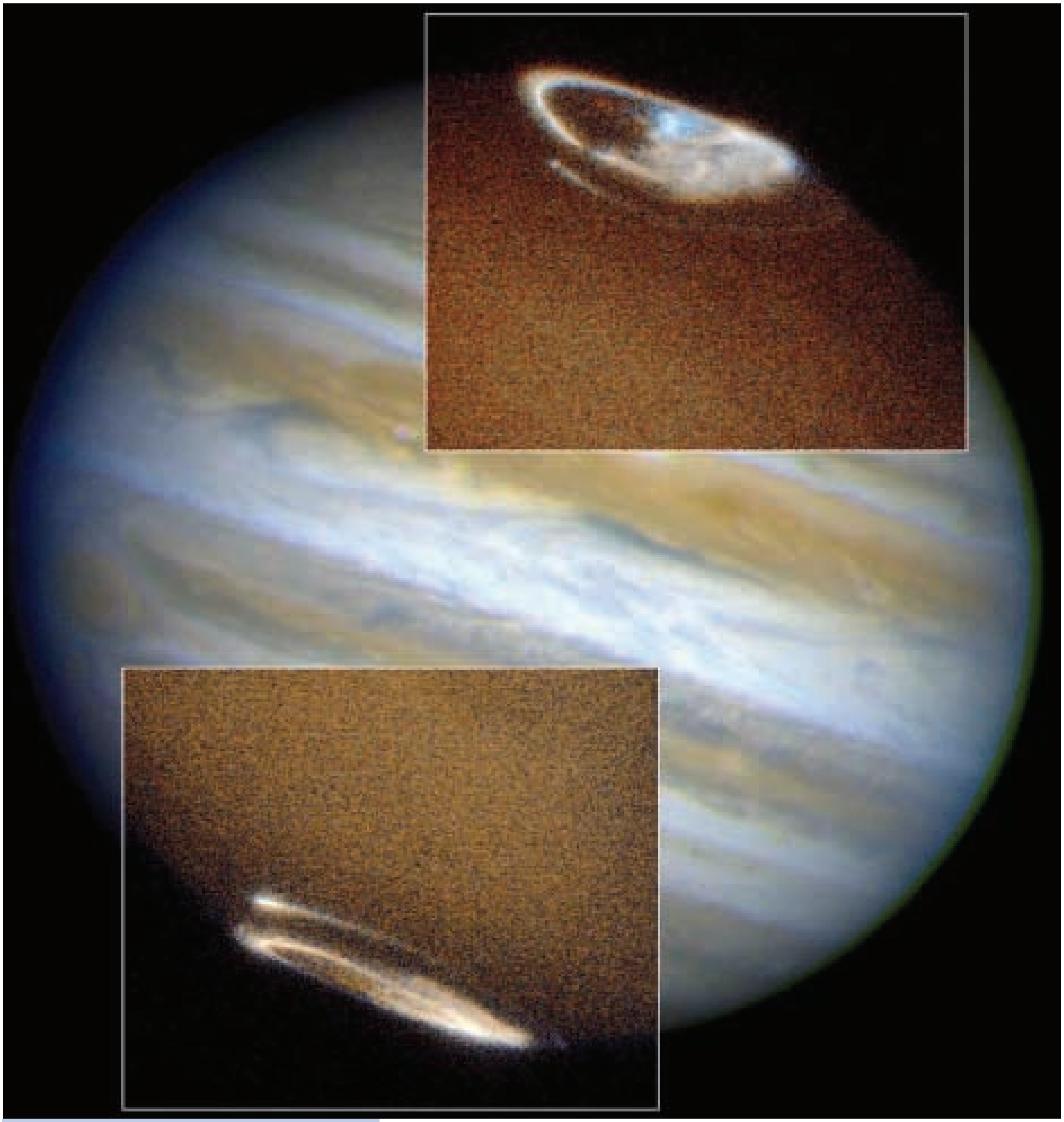

Fig. 3-7 Auroral storms on Jupiter

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Galaxies and Cosmology

To find the most distant exploding star ever seen, Hubble gazed far across the cosmos and discovered a bewildering zoo of galaxies that existed in the early universe. Looking closer to Earth, the Telescope snapped pictures of clusters of young stars born in the wreckage of colliding galaxies and helped astronomers measure the universe's expansion rate by taking pictures of a special class of pulsating star. Using Hubble, astronomers also conducted a census of more than 30 galaxies to study the relationship between galaxies and their black holes. These observations shed light on how the universe behaves and how galaxies were formed.

"Dark Energy"

In 2001 the Telescope's discovery of the farthest exploding star ever found bolstered the case for the existence of a mysterious form of "dark energy" in the universe. The exploding star is a supernova, which erupted in a faraway galaxy 10 billion years ago. The concept of dark energy, which shoves galaxies away from each other at an ever-increasing speed, was first proposed, and then discarded, by Albert Einstein in the early 1900s.

This Hubble discovery also reinforced the startling idea that the universe only recently began speeding up, a finding made in 1998 when the unusually dim light of several distant supernovas suggested the universe is expanding more quickly than in the past. The light from this 10-billion-year-old supernova offered the first tantalizing observational evidence that gravity began slowing down the universe's expansion after the Big Bang. Only later did the repulsive force of dark energy win out over gravity's attractive grip. Astronomers made the discovery by analyzing hundreds of images of ancient galaxies taken by Hubble in infrared and visible light.

Black Holes

Hubble also looked at scores of galaxies to study the relationship between galaxies and their black holes. Using Hubble's Space Telescope Imaging Spectrograph, astronomers conducted a census of more than 30 galaxies. Evidence suggests that monstrous black holes were not born big but instead grew on a measured diet of gas and stars controlled by the host galaxies. The finding supports the idea that a titanic black hole did not precede a galaxy's birth. Instead it co-evolved with the galaxy by trapping about 0.2 percent of the mass of the galaxy's bulbous hub of stars and gas.

This means that black holes in small galaxies went relatively undernourished, weighing in at a few million solar masses. Black holes in the centers of giant galaxies, some tipping the scale at over a billion solar masses, were so engorged with infalling gas that they once blazed as quasars, the brightest objects in the cosmos.

The bottom line is that the final mass of a black hole is not primordial; it is determined during the galaxy formation process. Galaxies are the largest assemblages of stars in the universe: billions of stars bound together by the mutual pull of gravity.

Starburst Galaxies

Most galaxies form new stars at a fairly slow rate, but members of a rare class known as starburst galaxies blaze with extremely active star formation. Scientists using Hubble's WFPC2 are perfecting a technique to determine the history of starburst activity in galaxies by using the colors of star clusters. Measuring the clusters' colors yields information about stellar temperatures. Since young stars are blue and older stars more red, the colors can be related to their ages, similar to counting the rings in a fallen tree trunk in order to determine the tree's age.

Galaxy NGC 3310 is forming clusters of new stars at a prodigious rate (see Fig. 3-8). NGC 3310 has several hundred star clusters, visible as bright blue diffuse objects that trace the galaxy's spiral arms. Each star cluster represents the formation of up to about a million stars, a process that takes less than 100,000 years. Hundreds of individual young, luminous stars also can be seen throughout the galaxy.

Once formed, the star clusters become redder with age as the most massive and bluest stars exhaust their fuel and burn out. Measurements of the wide variation in cluster colors show that they range in age from about 1 million up to more than 100 million years. This suggests that the starburst "turned on" over 100 million years ago, perhaps triggered when a companion galaxy collided with NGC 3310.

Hubble's observations may change astronomers' view of starbursts. They once thought starbursts to be brief episodes, resulting from catastrophic events like a galactic collision. However, the wide range of cluster ages in NGC 3310 suggests that once triggered the starbursting can continue for an extended interval.

Fig. 3-8 Galaxy NGC 3310 ablaze with active star formation

K1175_308

Stellar Kindergartens

NGC 4013 is a spiral galaxy, similar to the Milky Way, lying some 55 million light-years from Earth in the direction of the constellation Ursa Major. Viewed pole-on, NGC 4013 would look like a nearly circular pinwheel. From Earth, however, it happens to be seen edge-on. Even at 55 million light-years, the galaxy is larger than Hubble's field of view and the image shows only a little more than half of the object, albeit with unprecedented detail (see Fig. 3-9).

Dark clouds of interstellar dust stand out because they absorb the light of background stars. Most of the clouds lie in the plane of the galaxy, forming a dark band about 500 light-years thick, which appears to cut the galaxy in two from upper left to lower right. When light passes through a volume containing small particles (for example, molecules in the Earth's atmosphere or interstellar dust particles in galaxies), it becomes fainter and redder. By studying the color and the amount of light absorbed by these distant clouds in NGC 4013, astronomers can estimate the amount of matter in them. Individual clouds contain as much as 1 million times the amount of mass in the Sun.

Astronomers believe that new stars are formed in these dark interstellar clouds. Later, when the dust disperses, the young stars become visible as clusters of blue stars. NGC 4013 shows several examples of these stellar kindergartens near the center of the image in Fig. 3-9, lying in front of the dark band along the galaxy's equator. (The extremely bright star near the upper left corner is a nearby foreground star belonging to the Milky Way, which lies in the line of sight to NGC 4013.)

The Evolving Universe

Studying galaxies falls into the realm of cosmology, the study of the evolution of the universe on the largest scale. By looking at the distribution of galaxies in

Fig. 3-9 Spiral galaxy NGC 4013 viewed edge-on

K1175_309

space, Edwin P. Hubble discovered that the universe is expanding. He found that galaxies were rushing away from each other at a rate proportional to their distance: those farthest away were receding the fastest. The measured value for this expansion rate is called the Hubble constant.

Measuring the Hubble constant was one of the three major goals for the Telescope before it was launched in 1990. In May 1999 the Hubble Space Telescope Key Project team announced that it had completed its efforts to measure precise distances to far-flung galaxies, an ingredient needed to determine the age, size and fate of the universe. The team measured the Hubble constant at 70 km/sec/mpc with an uncertainty of 10 percent. This means that a galaxy appears to be moving 160,000 mph faster for every 3.3 million light-years away from Earth.

The team used the Telescope to observe 18 galaxies, some as far away as 65 million light-years. They were looking for Cepheid variable stars, a special class of pulsating star used for accurate distance measurements. Almost 800 were discovered. But the team could only pick out Cepheids in nearby and intermediate-distance galaxies. To calculate distances to far-flung galaxies, they used “secondary” distance measurements, such as a special class of exploding star called a Type Ia supernova.

Combining the Hubble constant measurement with estimates for the density of the cosmos, the team determined that the universe is approximately 12 billion years old if its expansion rate is constant or decelerating somewhat under the influence of gravity. But if the expansion rate is accelerating, as scientists now believe, the universe is older, perhaps 14 billion years. The team also determined that the universe does not have enough bulk to halt the expansion of space.

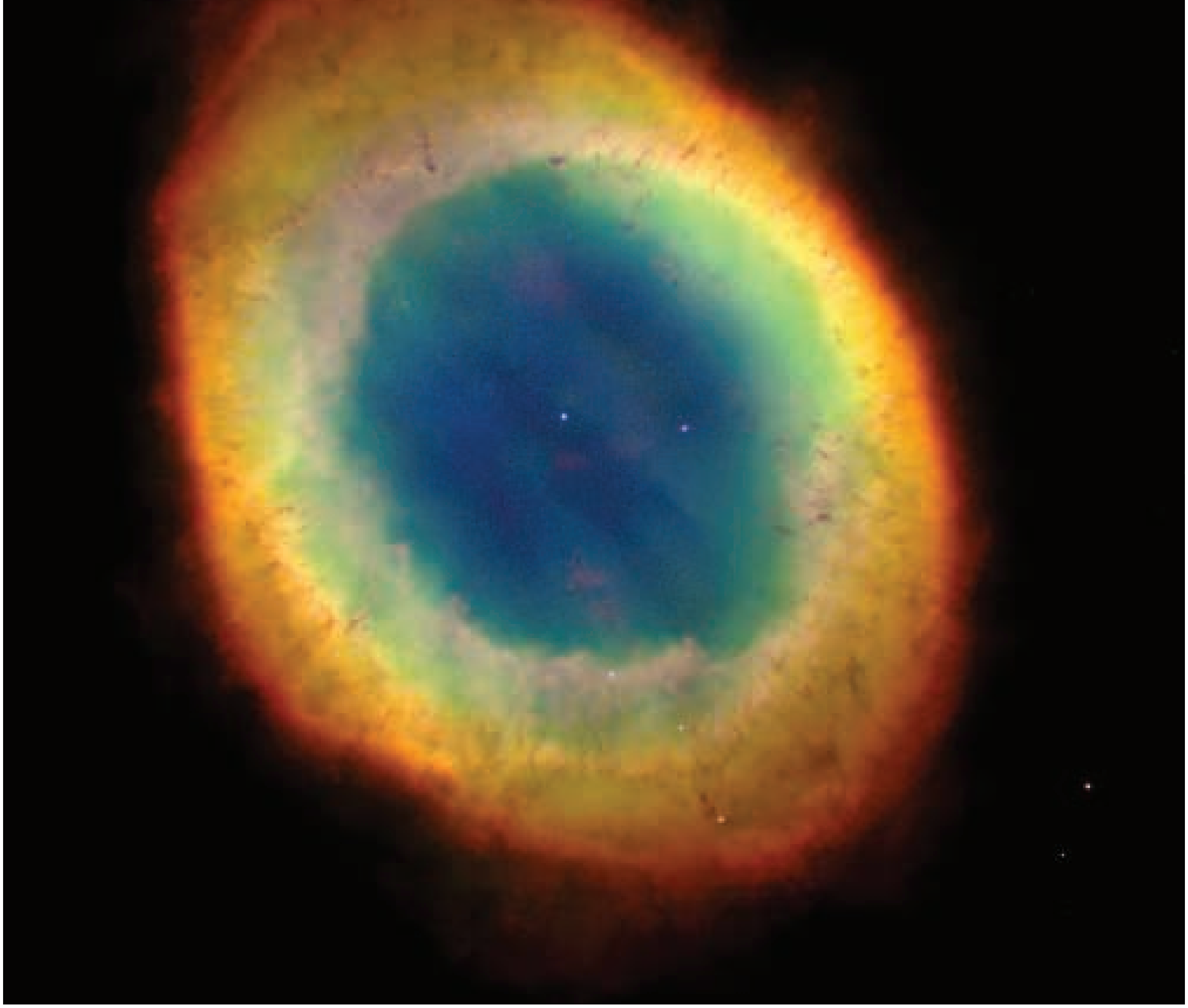
Summary

The Hubble Space Telescope has established itself as a premier astronomical observatory that continues to make dramatic observations and discoveries at the forefront of astronomy. Following the successful First and Second Servicing Missions, the Telescope has achieved all of its original objectives. Among a long list of achievements, Hubble has:

- Improved our knowledge of the size and age of the universe
- Provided decisive evidence of the existence of supermassive black holes at the centers of galaxies
- Clearly revealed the galactic environments in which quasars reside
- Detected objects with coherent structure (protogalaxies) close to the time of the origin of the universe
- Provided unprecedentedly clear images and spectra of the collision of Comet Shoemaker-Levy 9 with Jupiter
- Detected a large number of protoplanetary disks around stars
- Elucidated the various processes by which stars form
- Provided the first map of the surface of Pluto
- Routinely monitored the meteorology of planets beyond Earth’s orbit
- Made the first detection of an ultraviolet high-energy laser in Eta Carinae.

After Servicing Mission 3B, the Telescope will view the universe anew with significantly expanded scientific capabilities from the new ACS and a reactivated NICMOS. These additions, and the upgrades to Hubble’s operating hardware, promise other momentous discoveries in the years ahead.

SCIENCE INSTRUMENTS



Three instruments are in active scientific use on the Hubble Space Telescope:

- Wide Field and Planetary Camera 2 (WFPC2)
- Space Telescope Imaging Spectrograph (STIS)
- Fine Guidance Sensor 1R (FGS1R), designated as the prime FGS for astrometric science.

Other instrument bays are occupied by the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), now dormant due to the depletion of its solid nitrogen cryogen; the Faint Object Camera (FOC), an obsolete instrument that has been decommissioned; and COSTAR, a corrective optical device no longer needed.

During HST Servicing Mission 3B (SM3B), the FOC will be replaced by the Advanced Camera for Surveys (ACS). In addition, an experimental mechanical cooling system will be attached to NICMOS to determine if it can be brought back into operation. COSTAR will remain in place until HST Servicing Mission 4 (SM4) when it will be removed to make room for the Cosmic Origins Spectrograph (COS).

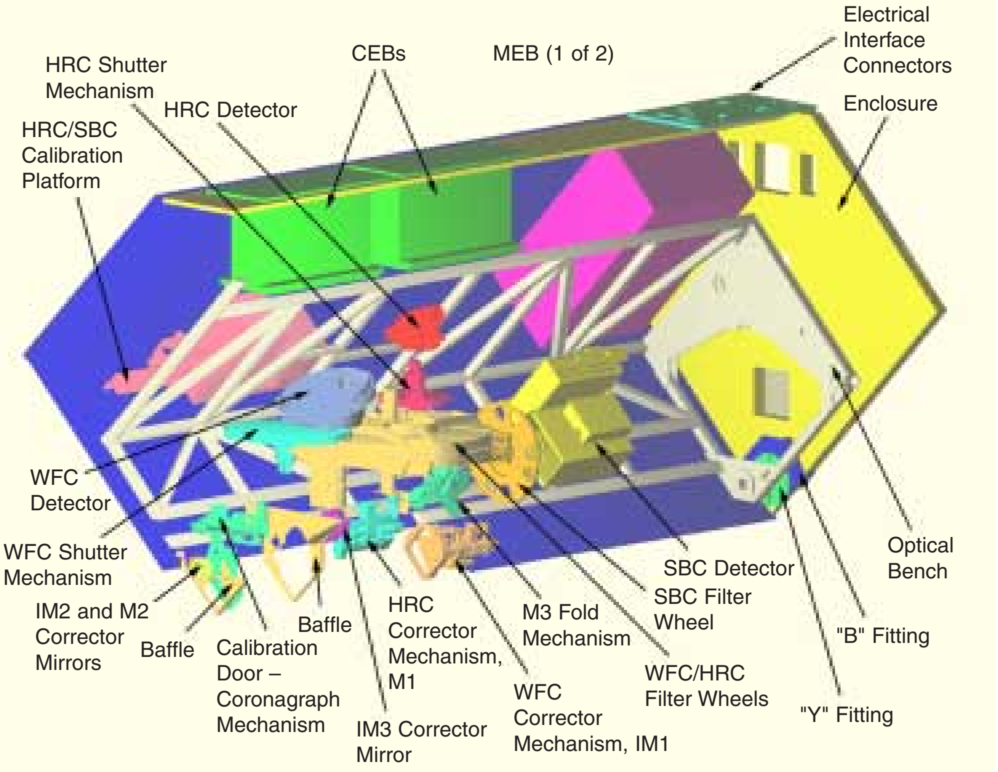
Hubble’s three FGSs are undergoing a systematic program of refurbishment and upgrading. On each servicing mission, one FGS is being replaced, returned to the ground, disassembled and refurbished, then taken back to HST to become the replacement unit for the next FGS to be serviced. The final refurbished FGS will be installed during SM4.

Advanced Camera for Surveys

Astronauts will install the Advanced Camera for Surveys (ACS), in the Telescope during SM3B. ACS is a collaborative effort of Johns Hopkins University, the NASA Goddard Space Flight Center, Ball Aerospace and the Space Telescope Science Institute.

The primary purpose of this third-generation instrument (see Fig. 4-1) is to increase the discovery efficiency of imaging with HST. ACS will provide a combination of detector area and quantum efficiency surpassing that available from current instruments by a factor of 10. It consists of three independent channels with wide-field, high-resolution and ultraviolet (UV) imaging capability and an assortment of filters designed for a broad range of scientific goals.

ACS will be five times more sensitive than the WFPC2 and will have more than twice its viewing field. The ACS's wide field of view (FOV), high throughput mirrors with higher reflectivity and larger, more sensitive detectors dramatically improve the Telescope's ability to deliver valuable science data.



Channel	Spectral Range (Nanometers)	Detector Array Size (Pixels)	Pixel Size (Microns)	Field of Vie (Arcsec)
Wide Field	350 – 1050	4096 x 4096	15 x 15	200 x 204
High Resolution	200 – 1050	1024 x 1024	21 x 21	26 x 29
Solar Blind	115 – 180	1024 x 1024	25 x 25	26 x 29

Weight	875 pounds (397 kg)
Dimensions	3 x 3 x 7 feet (0.9 x 0.9 x 2.2 m)
Principal investigator	Dr. Holland Ford, Johns Hopkins University
Prime contractor	Ball Aerospace
Wavelength range	115 – 1050 nanometers

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Fig. 4-1 Advanced Camera for Surveys (ACS) configuration

Wide Field Channel. The high sensitivity and wide field of the ACS Wide Field Channel (WFC) in visible and red wavelengths will make it the instrument of choice for imaging programs. Sky surveys with the WFC will study the nature and distribution of galaxies. Scientists should be able to set firm limits on the number of galaxies in the universe and determine precisely the epoch of galaxy formation. Its red-light sensitivity will allow the WFC to observe old and distant galaxies whose spectra are red-shifted due to the expansion of the universe.

High Resolution Channel. The ACS High Resolution Channel (HRC) will take extremely detailed pictures of the inner regions of galaxies and search neighboring stars for planets and protoplanetary disks. ACS has a coronograph that can suppress light from bright objects, enabling the HRC to observe fainter targets nearby, such as the galactic neighborhoods around bright quasars. The HRC will allow astronomers to view the light at the centers of galaxies containing massive black holes as well as more prosaic galaxies, star clusters and gaseous nebulas. With its excellent spatial resolution, the HRC also can be used for high-precision photometry in stellar population programs.

Solar Blind Channel. The ACS Solar Blind Channel (SBC) blocks visible light to enhance Hubble's vision in the UV portion of the spectrum. Some features—such as emission lines that indicate the presence of certain molecules—can be detected only in the UV. The SBC uses a highly sensitive photon-counting detector to enhance the visibility of these features. This channel will search for hot stars and quasars and study auroras and weather on planets in our solar system.

Physical Description

ACS will reside in an axial bay behind the HST main mirror. It is designed to provide HST with a deep, wide-field survey capability. The primary design goal of the ACS WFC is to achieve a factor of 10 improvement in discovery efficiency compared to WFPC2. Discovery efficiency is defined as the product of imaging area and instrument throughput.

In addition, ACS also provides:

- Grism spectroscopy: low resolution (R~100) wide-field spectroscopy from 5500 to 11,000 Å, available in both the WFC and the HRC.
- Objective prism spectroscopy: low resolution (R~100 at 2000 Å) near-UV spectroscopy from 2000 to 4000 Å, available in the HRC.
- Objective prism spectroscopy: low resolution (R~100 at 1216 Å) far-UV spectroscopy from 1150 to 1700 Å, available in the SBC.
- Coronography: aberrated beam coronography in the HRC from 2000 to 11,000 Å with 1.8 arcsecond- and 3.0 arcsecond-diameter occulting spots.
- Imaging polarimetry: polarimetric imaging in the HRC and WFC with relative polarization angles of 0, 60 and 120 degrees.

ACS Optical Design

The ACS design incorporates two main optical channels: one for the WFC and one shared by the HRC and SBC. Each channel has independent corrective optics to compensate for HST's spherical aberration. The WFC has three optical elements, coated with silver to optimize instrument throughput in visible light. The silver coatings cut off at wavelengths short of 3700 Å. The WFC has two filter wheels shared with the HRC, offering the possibility of internal WFC/HRC parallel observing for some filter combinations. Figure 4-2 shows the WFC optical design. Figure 4-3 shows the HRC/SBC optical chain, which comprises three aluminized mirrors overcoated with magnesium fluoride.

The HRC and SBC are selected by means of a plane fold mirror (M3 in Fig. 4-3). To select the HRC, the fold mirror is inserted into the optical chain so that the beam is imaged onto the HRC detector through the WFC/HRC filter wheels. To select the SBC, the fold mirror is moved out of the beam to yield a two-mirror optical chain that images through the SBC filter wheel onto the SBC detector. To access the aberrated beam coronograph, a mechanism is inserted into the HRC optical chain. This mechanism positions a substrate with two occulting spots at the aberrated telescope focal plane and an apodizer at the re-imaged exit pupil.

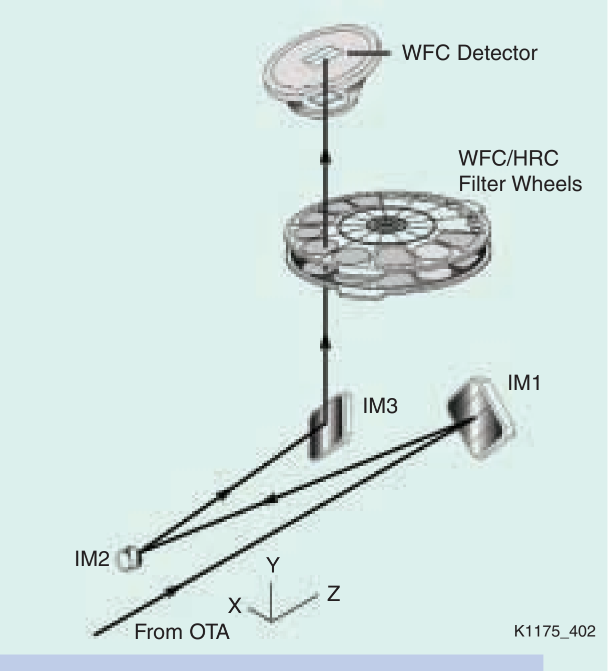

Fig. 4-2 ACS Wide Field Channel optical design

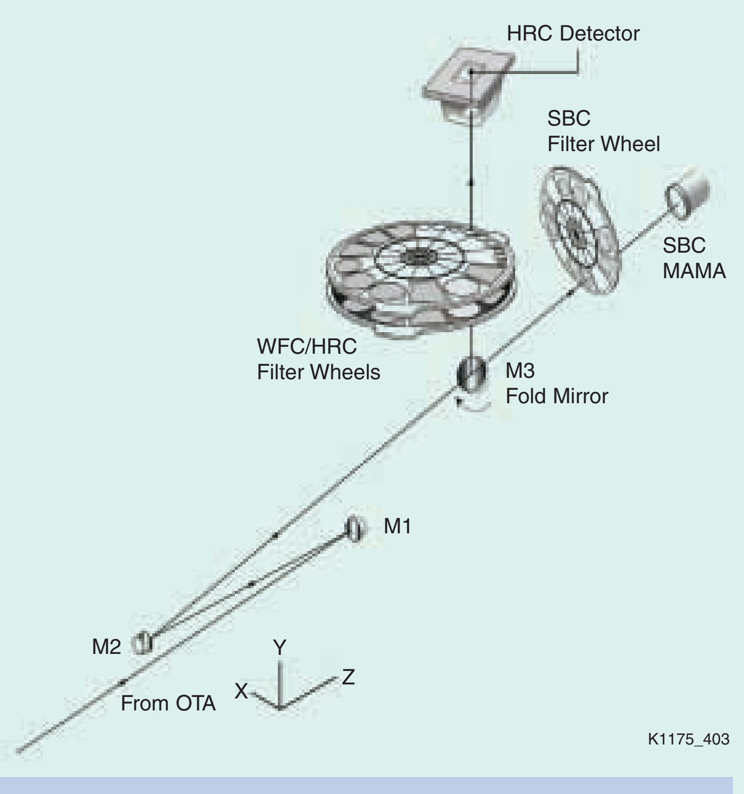

Fig. 4-3 ACS High Resolution/Solar Blind Channels optical design

Filter Wheels

ACS has three filter wheels: two shared by the WFC and HRC and one dedicated to the SBC. The WFC/HRC filter wheels contain the major filter sets summarized in Fig. 4-4. Each wheel also contains one clear WFC aperture and one clear HRC aperture. Parallel WFC and HRC observations are possible for some filter combinations, unless the user disables this option or the parallel observations cannot be added because of timing considerations. Note: Since the filter wheels are shared, it is not possible to independently select the filter for WFC and HRC parallel observations. Figure 4-5 shows the SBC filters.

Filter Type	Filter Description	Channel
Broadband	Sloan Digital Sky Survey (SDSS)	WFC/HRC
	B, V, Wide V, R, I	WFC/HRC
	Near-UV	HRC
Narrowband	H*a* (2%), [OIII] (2%), [NII] (1%)	WFC/HRC
	NeV (3440 Å)	HRC
	Methane (8920 Å)	HRC/[WFC*]
Ramp filters	2% bandpass (3700 – 10700 Å)	WFC/HRC
	9% bandpass (3700 – 10700 Å)	WFC/HRC
Spectroscopic	Grism	WFC/HRC
	Prism	WFC/HRC
Polarizers	Visible (0 deg, 60 deg, 120 deg)	HRC/[WFC*]
	Near-UV (0 deg, 60 deg, 120 deg)	HRC/[WFC*]

*Limited field of view for filters using WFC

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Fig. 4-4 ACS CCD filters

Filter Type	Description
Medium band	Lyman-Alpha
Long pass	MgF_2, CaF_2, BaF_2, quartz, fused silica
Objective prisms	LiF, CaF_2

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Fig. 4-5 SBC filters

Observations

With its wider field of view, superb image quality and exquisite sensitivity, ACS will take full advantage of Hubble's unique position as a space-based telescope. ACS sees in wavelengths ranging from ultraviolet to the far red (115 to 1050 nanometers). The new instrument is actually a set of three different, specialized channels. Each plays a unique imaging role, enabling ACS to contribute to many different areas of astronomy and cosmology.

Among the observations ACS will undertake are:
- Searching for extra-solar planets
- Observing weather and aurorae on planets in our own solar system
- Conducting vast sky surveys to study the nature and distribution of galaxies
- Searching for galaxies and clusters of galaxies in the early universe
- Searching for hot stars and quasars
- Examining the galactic neighborhoods around bright quasars.

Near Infrared Camera and Multi-Object Spectrometer

NICMOS is a second-generation instrument installed on the HST during SM2 in 1997. Its cryogen was depleted in 1998. During SM3B astronauts will install the NICMOS Cooling System (NCS), which uses a new technology called a Reverse Brayton-Cycle Cryocooler (see Fig. 4-6).

This type of mechanical cooler allows longer operational lifetimes than current expendable cryogenic systems. The attempt to revive NICMOS with NCS is viewed as an experimental application of a promising new technology. There is no guarantee that NICMOS will return to full, normal science operation. However, the importance of the science enabled by NICMOS makes the "experiment" well worth the effort.

NCS has three fluid loops:
- Circulator loop
- Primary cooling loop
- Capillary Pumped Loop (CPL).

Gas circulates first in the circulator loop between the cooling system and the inside of the NICMOS cryostat, carrying heat away from the cryostat and keeping the detectors at their operating temperature (73 Kelvin or -200°C).

The primary cooling loop is the heart of the NICMOS cryocooler. It contains a compressor, a turboalternator and two heat exchangers. This loop implements a reverse-Brayton thermodynamic cycle, providing the cooling power for the entire system. Generating this cooling power also produces a significant amount of heat (up to 500 watts). The CPL carries the heat away from the primary cooling loop. It connects the main heat-generating component, the compressor, with an external radiator that radiates the heat into space. The heat is removed by evaporating ammonia on the hot end of the CPL and recondensing it at the cold end.

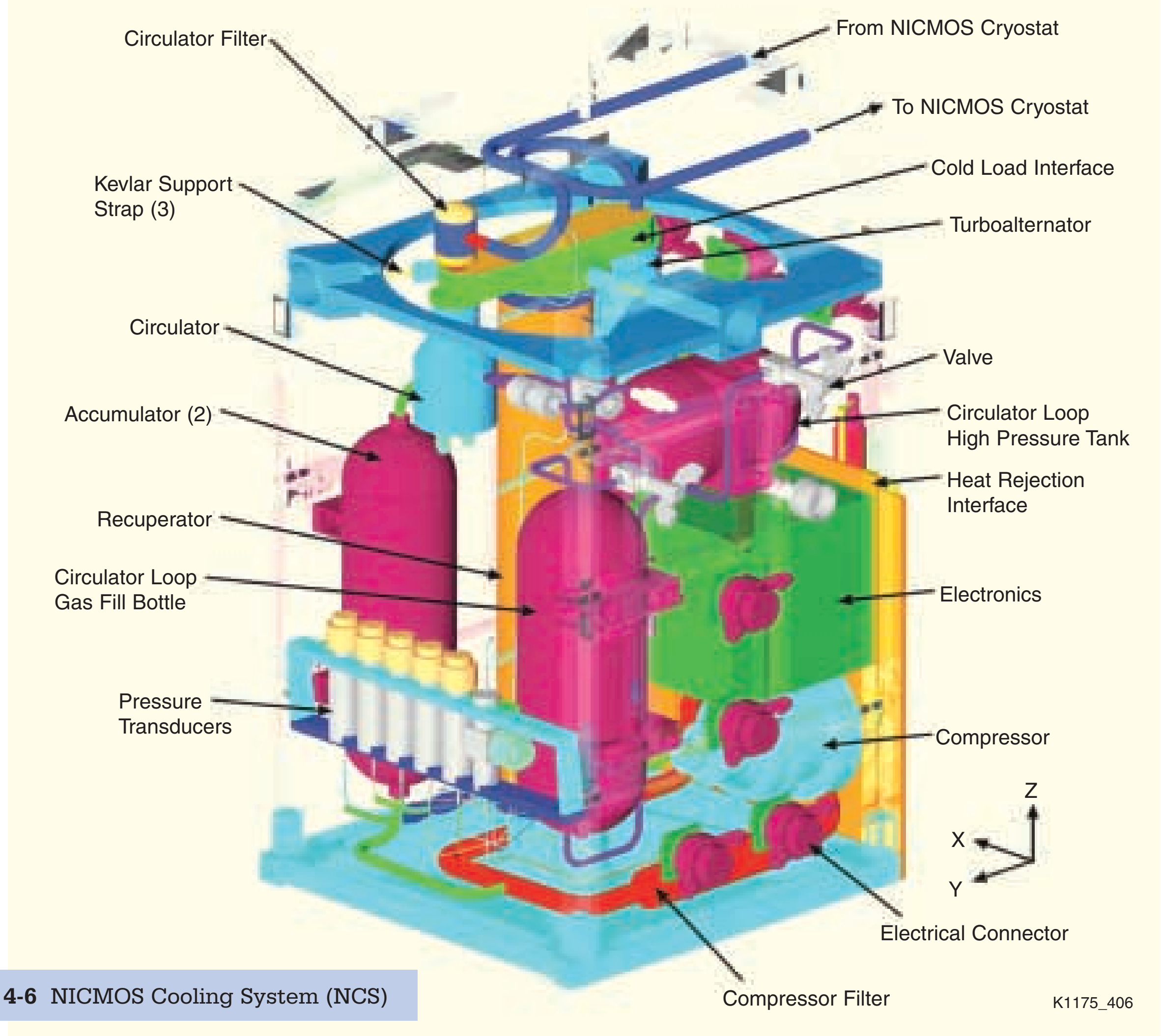

Fig. 4-6 NICMOS Cooling System (NCS)

The Electronics Support Module (ESM) controls the major functions of the NCS. It contains an 8051 microprocessor that implements control laws for cooler functions, including compressor, turboalternator and circulator speed. It also controls the CPL reservoir temperatures, regulating the quantity of heat transported to the radiator. In the background, the ESM collects and monitors critical NCS telemetry and general housekeeping telemetry, and relays commands to the NCS subsytems.

Instrument Description

NICMOS is an all-reflective imaging system: near–room-temperature foreoptics relay images to three focal plane cameras contained in a cryogenic dewar system (see Fig. 4-7). Each camera covers the same spectral band of 0.8 to 2.5 microns with a different magnification and an independent filter wheel. They look at different segments of the HST FOV simultaneously. Figure 4-8 lists the cameras and their optical characteristics.

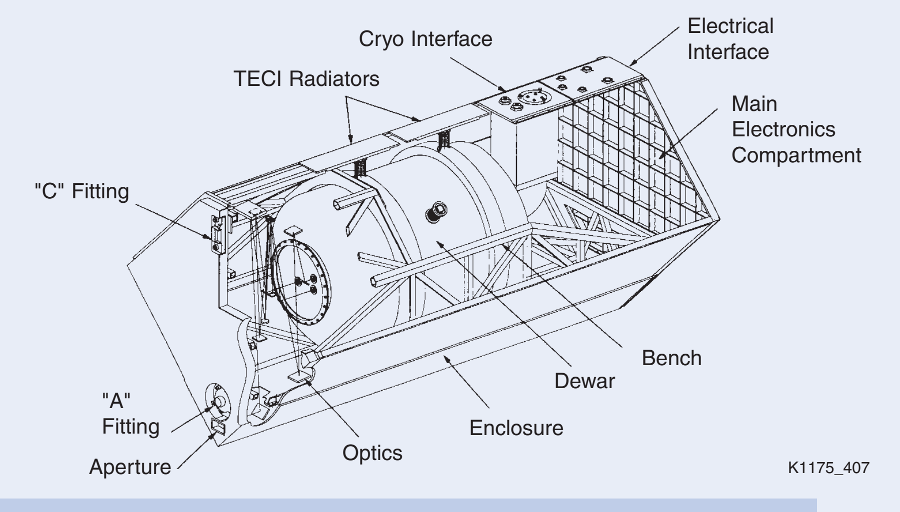

Fig. 4-7 Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

Parameter	Camera 1	Camera 2	Camera 3
Total field (arcsec)	11.0	19.2	51.2
Pixel size (arcsec)	0.043	0.075	0.20
Magnification	3.33	1.91	0.716
f number	80.0	45.7	17.2

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Fig. 4-8 NICMOS optical characteristics

Light entering the instrument entrance aperture falls on a flat folding mirror and is redirected to a spherical mirror. It is then re-imaged on the corrective mirror, which is mounted to an offset pointing mechanism. This mirror corrects the HST spherical aberration and also has a cylindrical deformation to correct for astigmatism in the optical path.

Next the corrected image is relayed to a three-mirror field-dividing assembly, which splits the light into three separate, second-stage optical paths. In addition to the field-dividing mirror, each second-stage optic uses a two-mirror relay set and a folding flat mirror.

The field-dividing mirrors are tipped to divide the light rays by almost 4.5 degrees. The tip allows physical separation for the two-mirror relay sets for each camera and its FOV. The curvature of each mirror allows the required degree of freedom to set the exit pupil at the cold mask placed in front of the filter wheel of each camera.

A corrected image is produced in the center of the Camera 1 field mirror. Its remaining mirrors are confocal parabolas with offset axes to relay the image into the dewar with the correct magnification and minimal aberration.

Cameras 2 and 3 have different amounts of astigmatism because their fields are at different off-axis points from Camera 1. To correct the residual astigmatism, one of the off-axis relay mirrors in Camera 3 is a hyperbola and one of the relay mirrors in Camera 2 is an oblate ellipsoid. Camera 2 also allows a coronagraphic mode by placing a dark spot on its field-dividing mirror. During this mode the HST is maneuvered so that the star of observation falls within the Camera 2 field-dividing mirror and becomes occulted for coronagraphic measurements.

All the detectors are 256 x 256-pixel arrays of mercury cadmium telluride (HgCdTe) with 40-micron pixel-to-pixel spacing. An independent, cold filter wheel is placed in front of each camera and is rotated by room-temperature motors placed on the external access port of the dewar.

A multilevel, flat-field illumination system corrects detector nonuniformities. The light source and associated electronics are located in the electronics section at the rear of the instrument. IR energy is routed to the optical system using a fiber bundle. The fiber bundle illuminates the rear of the corrector mirror, which is partially transparent and fits the aperture from the fiber bundle. The backside of the element is coarsely ground to produce a diffuse source.

The instrument structural enclosure houses all operating components in two individual compartments: optics and electronics. A graphite-epoxy optical bench, kinematically mounted within the enclosure, separates the two compartments. The foreoptics and the cryogenic dewar mount to the bench. The electronics control the thermal environment, partly through radiators mounted to the outboard enclosure panels. A combination of active proportional heaters, selective surface finishes and multilayer insulation (MLI) maintains the temperature.

Optical paths penetrate the dewar in three places. Each camera port consists of an external vacuum shell window, an internal heat-blocking window and a cold mask to prevent the detectors from seeing warm structure. Each camera has an independently controlled filter wheel. Warm stepper motors mounted on the vacuum shell turn the filter wheels, mounted on the vapor-cooled shell. Graphite-epoxy, thin-walled tubes are used for the drive shafts connecting the warm motors to the cold wheels. The drive shafts provide torsional rigidity for accurately positioning the filter in the optical path while maintaining low thermal conductivity.

NICMOS Specifications

Figure 4-9 shows the NICMOS specifications. Three detector cables and three detector clock cables route electrical signals from the cryogen tank to the hermetic connector at the vacuum shell. The cables consist of small-diameter, stainless-steel wire mounted to a polymeric carrier film. They are shielded to minimize noise and crosstalk between channels. (Shielding is an aluminized polyester film incorporated into drain wires.) The cables also have low thermal conductivity to minimize parasitic heat loads. In addition, two unshielded cables connect to thermal sensors used during fill and for on-orbit monitoring.

Near Infrared Camera and Multi-Object Spectrometer (NICMOS)	
Weight	861 lb (391 kg) in flight configuration
Dimensions	7.1 x 2.8 x 2.8 feet (2.2 x 0.88 x 0.88 m)
Principal investigator	Dr. Rodger I. Thompson, U. of Arizona
Contractor	Ball Aerospace
Field of view	51.2 x 51.2 arcsec 19.2 x 19.2 arcsec 11.0 x 11.0 arcsec
Detectors	3 HgCdTe arrays 256 x 256 pixels

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Fig. 4-9 NICMOS specifications

Besides processing signals from and controlling the detectors, the electronics prepare data for transmission to the HST computer, respond to ground commands through the HST and control operation of the instrument. NICMOS uses an onboard 80386 microprocessor with 16 megabytes of memory for instrument operation and data handling. Two systems are provided for redundancy. The detector control electronics subsystem includes a microprocessor dedicated to operation of the focal plane array assemblies. Two microprocessors are provided for redundancy.

Observations

A restored NICMOS will provide IR imaging and limited spectroscopic observations of astronomical targets between 1.0 and 2.5 microns. It will extend HST's capabilities into the near IR, generating high-resolution images for detailed analysis of:

- Prostellar clouds, young star clusters and brown dwarfs
- Obscured active galaxy nuclei
- Temporal changes in planetary atmospheres
- Young protogalaxies
- Supernovae at high redshift used to time the acceleration of the expansion of the universe.

Space Telescope Imaging Spectrograph

STIS was developed under the direction of the principal investigator, Dr. Bruce E. Woodgate, jointly with Ball Aerospace. The spectrograph (see Fig. 4-10) was designed to be versatile and efficient, taking advantage of modern technologies to provide a new two-dimensional capability to HST spectroscopy. The two dimensions can be used either for “long slit” spectroscopy, where spectra of many different points across an object are obtained simultaneously, or in an echelle mode, at very high spectral resolution, to obtain more wavelength coverage in a single exposure. STIS also can take both UV and visible images through a limited filter set.

During SM2 astronauts installed STIS as a replacement for the Goddard High Resolution Spectrograph and the Faint Object Spectrograph. Its capabilities include coverage of a broader wavelength range in two dimensions, coronagraphs and high time-resolution in the UV. It also can image and provide objective prism spectra in the intermediate UV. STIS carries its own aberration-correcting optics.

Physical Description

STIS resides in an axial bay behind the HST main mirror. Externally, the instrument measures 7.1 x 2.9 x 2.9 feet (2.2 x 0.98 x 0.98 m) and weighs 825 pounds (374 kg). Internally, STIS consists of a carbon fiber optical bench, which supports the dispersing optics and three detectors (see Fig. 4-11).

The spectrograph has been designed to work in three different wavelength regions, each with its own detector. Some redundancy is built into the design with overlap in the detector response and backup spectral modes. A mode selection mechanism (MSM) is used to select a wavelength region or mode. The MSM has 21 optical elements: 16 first-order gratings (including six order-sorting gratings used in the echelle modes), an objective prism and four mirrors. The optical bench supports the input corrector optics, focusing and tip/tilt motions, input slit and filter wheels, and MSM.

Light from the HST main mirror is first corrected and then brought to a focus at the slit wheel. After passing

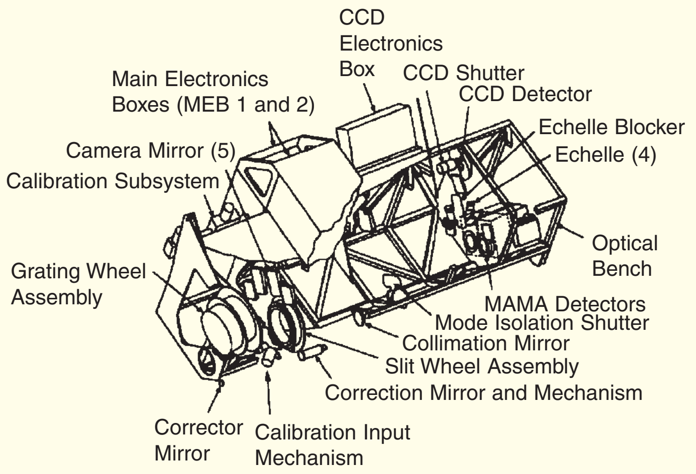

Fig. 4-10 Space Telescope Imaging Spectrograph

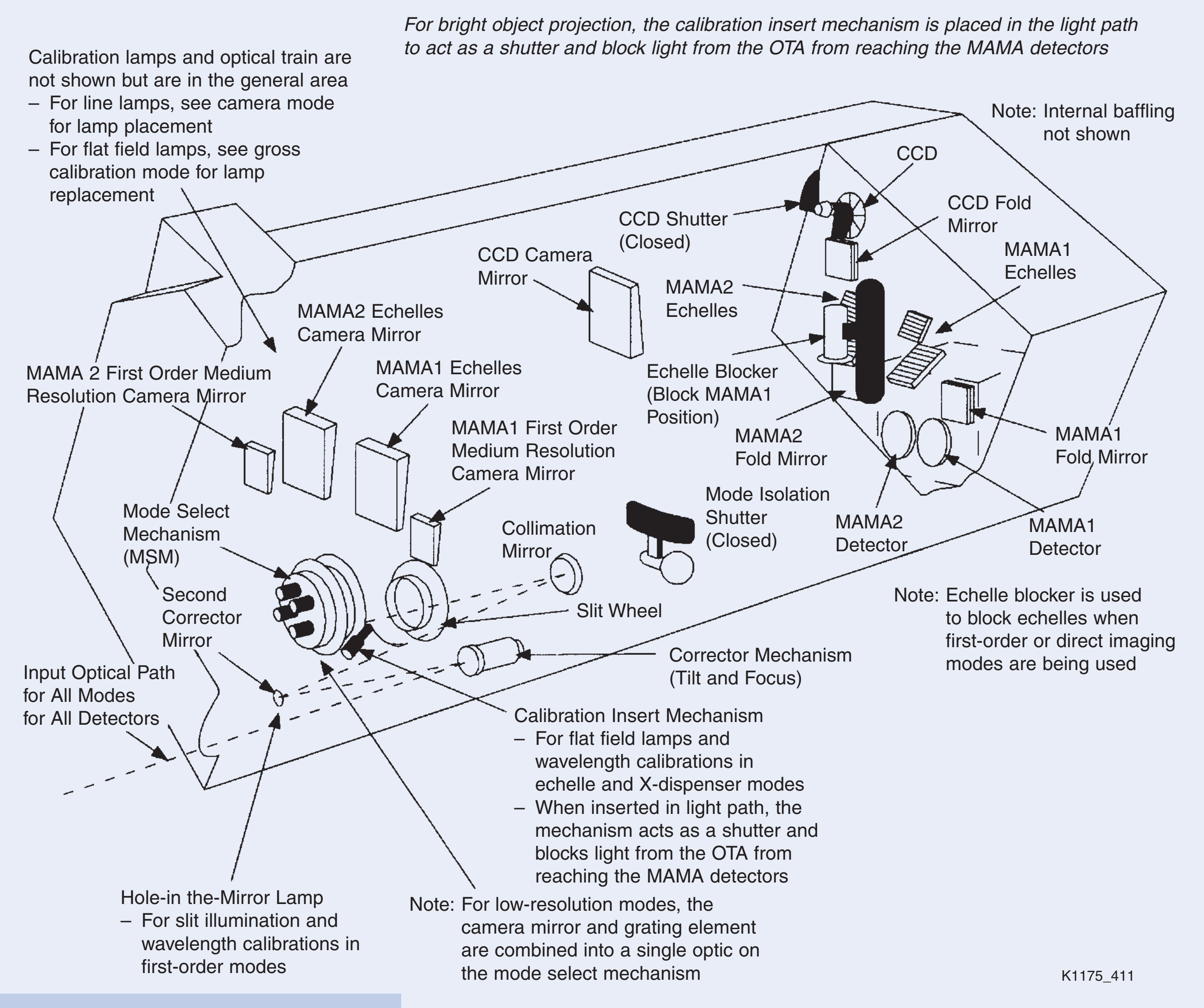

Fig. 4-11 STIS components and detectors

through the slit, it is collimated by a mirror onto one of the MSM optical elements. A computer selects the mode and wavelength. The MSM rotates and nutates to select the correct optical element, grating, mirror or prism and points the beam along the appropriate optical path to the correct detector.

For first-order spectra, a first-order grating is selected for the wavelength and dispersion. The beam then is pointed to a camera mirror, which focuses the spectrum onto the detector, or goes directly to the detector itself.

For an echelle spectrum, an order-sorting grating that directs the light to one of the four fixed echelle gratings is selected, and the dispersed echellogram is focused via a camera mirror onto the appropriate detector. The detectors are housed at the rear of a thermally controlled optical bench where they can easily dissipate heat through an outer panel. An onboard computer controls the detectors and mechanisms.

STIS has three detectors, each optimized for a specific wavelength region.

- Band 1, covering the wavelengths from 115 to 170 nm, uses a Multi-Anode Microchannel Plate Array (MAMA) with a cesium iodide (CsI) photocathode.
- Band 2, from 165 to 310 nm, also uses a MAMA but with a cesium telluride (CsTe) photocathode.
- Bands 3 and 4, from 305 to 555 nm and 550 to 1000 nm, use the same detector, a charge-coupled device (CCD).

Entrance Apertures. After a light beam passes through the corrector, it enters the spectrograph through one of several slits. The slits are mounted on a wheel and can be changed by wheel rotation.

There also are camera apertures of 50 x 50 and 25 x 25 arcsec. Some have occulting bars incorporated. The telescope can be positioned to place bright stars behind the occulting bars to allow viewing and observation of faint objects in the FOV. In addition, there is a special occulting mask or coronagraph—a finger in the aperture that can be positioned over a bright star to allow examination of any faint material nearby. In effect, it simulates a total eclipse of a nearby star. This mode is particularly useful to search for faint companion stars or planetary disks around stars.

Mode Selection Mechanism. The MSM is a rotating wheel with 16 first-order gratings, an objective prism and four mirrors. Its axis is a shaft with two inclined outer sleeves, one sleeve fitting inside the other. The sleeves are constructed so that rotation of one sleeve rotates a wheel to orient the appropriate optic into the beam. Rotation of the second sleeve changes the inclination of the wheel axis or the tilt of the optic to select the wavelength range and point the dispersed beam to the corresponding detector. One of three mirrors can be selected to take an image of an object.

Multi-Anode Microchannel Plate Array Detectors. For UV modes, STIS employs two types of MAMA detectors. A photocathode optimizes each detector to its wavelength region. Each detector's photocathode provides maximum sensitivity in the wavelength region selected while it rejects visible light not required for the observations.

The heart of each MAMA detector is a microchannel plate (MCP)—a thin disk of glass approximately 1.5 mm thick and 5 cm in diameter that is honeycombed with small (12.5-micron) holes or pores. The front and back surfaces are metal coated. When a voltage is applied across the plate, an electron entering any pore is accelerated by the electric field. It eventually collides with the wall of the pore, giving up its kinetic energy to liberate two or more secondary electrons. (The walls are treated to enhance the secondary electron production effect.) The secondary electrons continue down the pore and collide with the wall, emitting more electrons, and so the process continues, producing a cascade of a million electrons at the end of the pore.

The anode array is a complex fingerlike pattern. When electrons strike certain anodes, a signal is sent to the computer memory indicating the position and time of arrival of the photon. Figure 4-12 shows the detection scheme in simplified form.

Only 132 circuits are required to read out all 1024 x 1024 pixels (picture elements) in the anode array. As the MAMA records the arrival of each photon, it can provide a time sequence. For instance, if an object is varying in time, like a pulsar, the data can be displayed to show if there is any periodicity. To create an image, data must be integrated in the computer memory before it is displayed. The MAMA data is recorded to a time resolution of 125 microseconds.

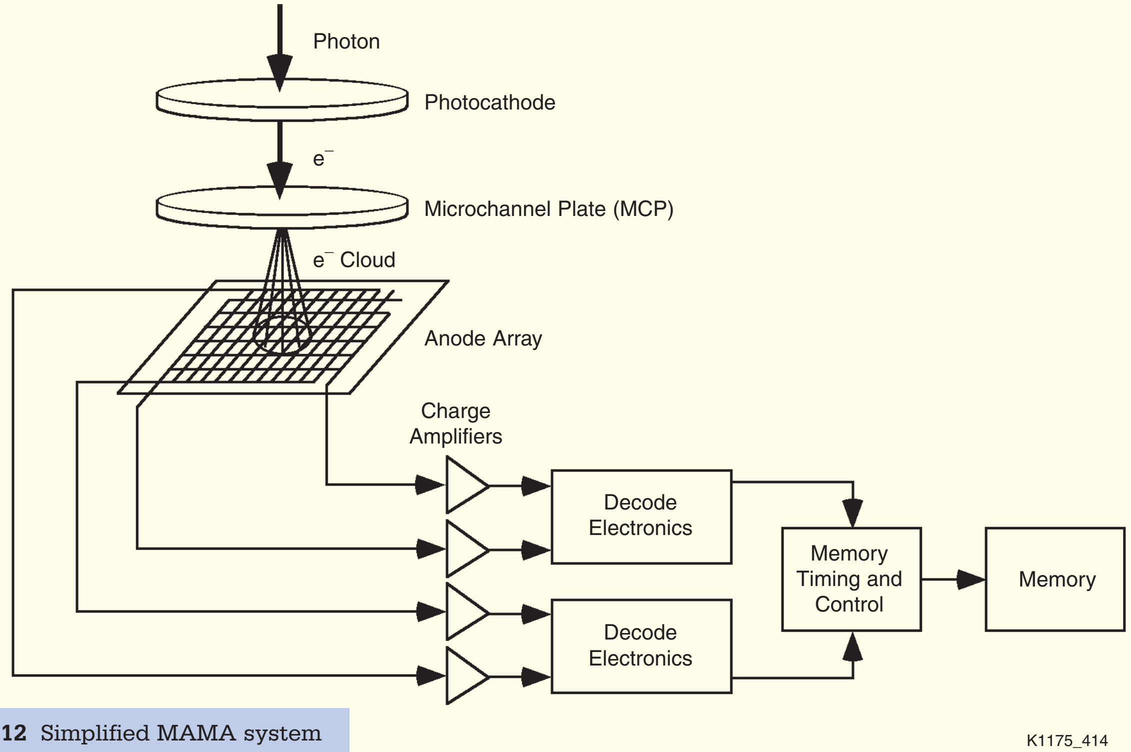

Fig. 4-12 Simplified MAMA system

When used in the normal mode, each detector has 1024 x 1024 pixels, each 25 x 25 microns square. However, data received from the anode array can be interpolated to give a higher resolution, splitting each pixel into four 12.5 x 12.5 micron pixels. This is known as the high-resolution mode. It provides higher spatial resolution for looking at fine structural details of an object and ensures full sampling of the optical images and spectra. Data taken in high-resolution mode can be transformed to normal resolution.

Charge-Coupled Detector. The STIS CCD was developed at Scientific Imaging Technologies (SITe) with GSFC and Ball input. Fabricated using integrated circuit technology, the detector consists of light-sensitive pixels deposited onto a thin wafer of crystalline silicon. Each element is 21 x 21 microns. The elements are arranged 1024 to a row in 1024 columns for a total of 1,048,576 pixels.

Each element acts as a small capacitance. As light falls on a pixel, it liberates electrons, which effectively charge the capacitance. The number of electrons stored is then proportional to the intensity or brightness of the light received. The charge in each pixel can be read out by applying a small voltage across the chip.

The CCD is most sensitive to red light, but the STIS chip has been enhanced through a “backside treatment” to provide a usable sensitivity in the near-UV. It is sensitive from approximately 200 nm to the near-infrared at 1000 nm.

The CCD can make exposures ranging from 0.1 second to 60 minutes. In space, above Earth’s protective atmosphere, radiation from cosmic rays is higher than at Earth’s surface. CCDs are sensitive to cosmic rays, which can produce large numbers of electrons in the pixels. For this reason, two shorter exposures of up to 1 hour are made. Comparison of the frames allows cosmic ray effects to be subtracted.

Imaging Operational Modes. STIS can be used to acquire an image of an object in UV or visible light. To do this, an open aperture is selected and a mirror placed in the beam by the MSM. The instrument has nine filters that can be selected. The cameras for the CCD and the MAMAs have different magnification factors. The FOV is 25 x 25 arcsec for the MAMAs and 50 x 50 arcsec for the CCD.

Target Acquisition. Normally an object is acquired using the CCD camera with a 50 x 50-arcsec field. Two short exposures are taken to enable subtraction of cosmic rays. The HST FGSs have a pointing accuracy of ±2 arcsec, and the target usually is easily identifiable in the field. Once identified, an object is positioned via small angle maneuvers to the center of the chosen science mode slit position. Two more exposures are made, the calibration lamp is flashed through the slit to confirm the exact slit position and a further peak up on the image is performed. Acquisition can take up to 20 minutes.

Data Acquisition. The MAMAs take data in the high-resolution mode. For normal imaging and spectroscopy, the data is integrated in the onboard computer and stored in this format on the solid-state recorders for later downlink. The MAMAs also have a time-tag mode, where each photon is stored individually with its arrival time and location (x, y, t). The data initially is stored in a 16-megabyte memory, then downloaded into the onboard recorder. The time-tag mode has a time resolution of 125 microseconds.

STIS Specifications

Fig. 4-13 shows STIS specifications.

Space Telescope Imaging Spectrograph (STIS)	
Weight	825 pounds (374 kg)
Dimensions	3 x 3 x 7 feet (0.9 x 0.9 x 2.2 m)
Principal investigator	Dr. Bruce E. Woodgate, GSFC
Prime contractor	Ball Aerospace
Field of view	MAMA 24.9 x 24.9 arcsec CCD 51 x 51 arcsec
Pixel format	1024 x 1024
Wavelength range	115 – 1000 nanometers

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Fig. 4-13 STIS specifications

Observations

Scientists use STIS in many areas:
- Searching for massive black holes by studying star and gas dynamics around the centers of galaxies
- Measuring the distribution of matter in the universe by studying quasar absorption lines
- Watching stars forming in distant galaxies
- Mapping fine details of planets, nebulae, galaxies and other objects
- Imaging Jupiter-sized planets around nearby stars
- Obtaining physical diagnostics, such as chemical composition, temperature, density and velocity of rotation or internal mass motions in planets, comets, stars, interstellar gas, nebulae, stellar ejecta, galaxies and quasars.

Wide Field and Planetary Camera 2

Hubble's "workhorse" camera is WFPC2. It records two-dimensional images at two magnifications through a selection of 48 color filters covering a spectral range from far-UV to visible and near-IR wavelengths. It provides pictorial views of the celestial universe on a grander scale than any other instrument flown to date.

Like its predecessor WFPC1, WFPC2 was designed and built at NASA's Jet Propulsion Laboratory (JPL), which is operated by the California Institute of Technology. Professor James A. Westphal of Caltech was the principal investigator for WFPC1. Dr. John T. Trauger of JPL is the principal investigator for WFPC2.

WFPC1, the first-generation instrument, was launched with the Telescope in 1990 and functioned flawlessly. WFPC2, the second-generation instrument, was already under construction when Hubble was launched. Its original purpose was to provide a backup for WFPC1 with certain enhancements, including an upgraded set of filters, advanced detectors and improved UV performance. With modifications introduced after 1990, WFPC2 also provided built-in compensation for the improper curvature of the Telescope's primary mirror. WFPC2 has four CCD cameras arranged to record simultaneous images in four separate FOVs at two magnifications.

In three WFC fields, each detector pixel occupies 0.1 arcsec and each detector array covers a square 800 pixels on a side—80 arcsec, slightly more than the diameter of Jupiter when it is nearest the Earth. The Telescope is designed to concentrate 70 percent of the light of a star image into a circle 0.2 arcsec (two WFC pixels) in diameter. Operating at a focal ratio of f/12.9, this three-field camera provides the greatest sensitivity for the detection of faint objects. Stars as faint as 29th magnitude are detectable in the longest exposures (29th magnitude is more than 1 billion times fainter than can be seen with the naked eye).

The Planetary Camera provides a magnification about 2.2 times larger: each pixel occupies only 0.046 arcsec and the single square FOV is only 36.8 arcsec on a side. It operates at a focal ratio of f/28.3. Originally incorporated for studying the finest details of bright planets, the Planetary Camera actually provides the optimum sampling of the Telescope's images at visible wavelengths. Brightness permitting, this camera is used whenever the finest possible spatial resolution is needed, even for stars, stellar systems, gaseous nebulas and galaxies.

With its two magnifications and built-in correction for the Telescope's spherical aberration, WFPC2 can resolve the fine details and pick out bright stellar populations of distant galaxies. It can precisely measure the brightness of faint stars and study the characteristics of stellar sources even in crowded areas such as globular clusters—ancient swarms of as many as several hundred thousand stars that reside within a huge spherical halo surrounding the Milky Way and other galaxies. WFPC2's high-resolution imagery of the planets in Earth's solar system allows continued studies of their atmospheric composition as well as discovery and study of time-varying processes on their surfaces.

Physical Description

WFPC2 occupies one of four radial bays in HST's focal plane structure. (The other three radial bays support the FGSs, used primarily to control pointing of the Telescope.) WFPC2's FOV is located at the center of the Telescope's FOV, where the telescopic images are nearly on axis and least affected by residual aberrations (field curvature and astigmatism) inherent in the Ritchey-Chretien design.

Because other instruments share the focal plane, WFPC2 is equipped with a flat pick-off mirror located about 18 inches ahead of the focal plane and tipped at almost 45 degrees to the axis of the Telescope. The pick-off mirror is attached to the end of a stiff truss, which is rigidly fastened to WFPC2's precisely located optical bench. The pick-off mirror reflects the portion of the Telescope's focal plane belonging to WFPC2 into a nearly radial direction. From there it enters the front of the instrument, allowing light falling on other portions of the focal plane to proceed without interference.

Figure 4-14 shows the overall configuration of WFPC2. It is shaped somewhat like a piece of pie, with the pick-off mirror lying at the point of the wedge and a large, white-painted cylindrical panel 2.6 feet (0.8 m) high and 7 feet (2.2 m) wide at the other end. The panel forms part of the curved outer skin of the Support Systems Module (SSM) and radiates away the heat generated by the cameras' electronics. WFPC2 is held in position by a system of latches and is clamped in place by a threaded fastener at the end of a long shaft that penetrates the radiator and is accessible to the astronauts.

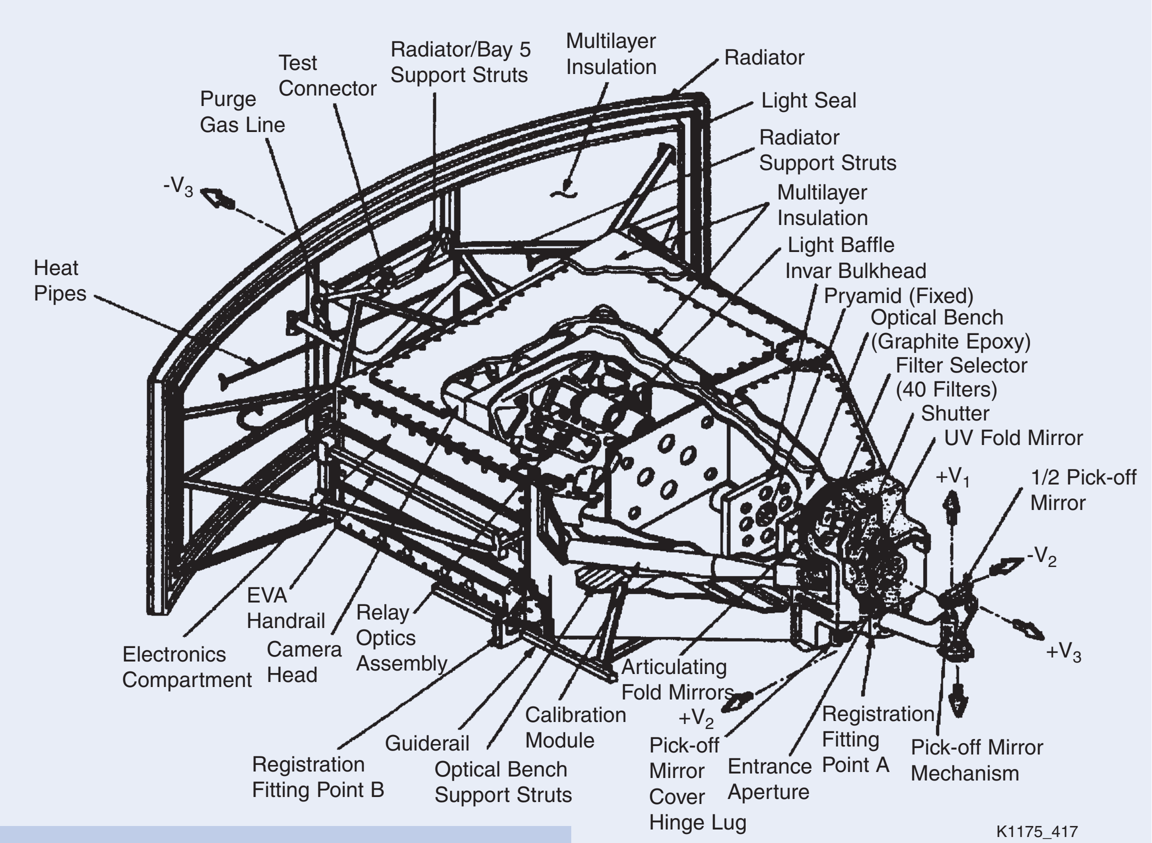

Fig. 4-14 Wide Field and Planetary Camera (WFPC) overall configuration

WFPC2 weighs 619 pounds (281 kg). The cameras comprise four complete optical subsystems, four CCDs, four cooling systems using thermoelectric heat pumps and a data-processing system to operate the instrument and send data to the Science Instrument Control and Data Handling (SI C&DH) subsystem.

Optical System. The WFPC2 optical system consists of the pick-off mirror, an electrically operated shutter, a selectable optical filter assembly and a four-faceted reflecting pyramid mirror used to partition the focal plane to the four cameras. Light reflected by the pyramid faces is directed by four “fold” mirrors into four two-mirror relay cameras. The relays re-image the Telescope’s original focal plane onto the four detector arrays while providing accurate correction for the spherical aberration of the primary mirror. Figure 4-15 shows the light path from the Telescope to the detectors.

As in an ordinary camera, the shutter controls the exposure time, which can range from about 1/10th second to 28 hours. Typical exposure time is 45 minutes, about the time required for the Telescope to complete half an orbit.

WFPC2’s pick-off mirror and three fold mirrors are equipped with actuators that allow them to be controlled in two axes (tip and tilt) by remote control from the ground. The actuators ensure that the spherical aberration correction built into WFPC2 is accurately aligned relative to the Telescope in all four channels.

The Selectable Optical Filter Assembly (SOFA) consists of 12 independently rotatable wheels, each carrying four filters and one clear opening (a total of 48 filters). These can be used singly or in certain pairs. Some of the WFPC2’s filters have a patchwork of areas with differing properties to provide versatility in measuring spectral characteristics of sources.

WFPC2 also has a built-in calibration channel in which stable incandescent light sources serve as references for photometric observations.

Charge-Coupled Detectors. A CCD is a device fabricated by methods developed for the manufacture of integrated electronic circuits. Functionally, it consists of an array of light-sensitive pixels built onto a thin wafer of crystalline silicon. Complex electronic circuits also built onto the wafer control the light-sensitive elements. The circuits include low-noise amplifiers to strengthen signals that originate at the light sensors. As light falls on the array, photons of light interact with the sensor material to create small electrical charges (electrons) in the material. The charge is nearly proportional to the number of photons absorbed. The built-in circuits read out the array, sending a succession of signals that will allow later reconstruction of the pattern of incoming light on the array.

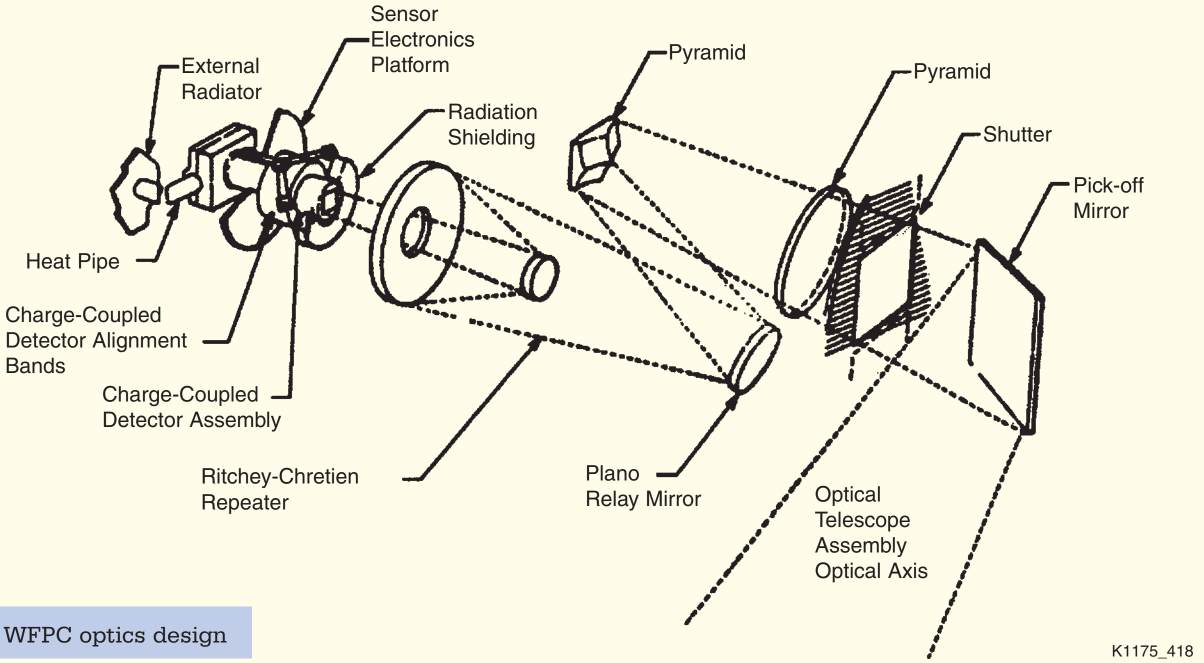

Fig. 4-15 WFPC optics design

The CCDs used in WFPC2 consist of 800 rows and 800 columns of pixels (640,000 pixels in each array). The pixels resemble tiny squares, 15 microns (about 6/10,000 inch) on a side. Their sensitivity to light is greatest at near-IR and visible wavelengths. In WFPC2 the pixels are coated with a thin fluorescent layer that converts UV photons to visible ones.

To achieve a very low noise background that does not interfere with measurements of faint astronomical light sources, the CCDs must be operated at a low temperature, approximately -50 to -70°C (-8 to -130°F). An electrically operated solid-state cooling system pumps heat from the cold CCDs to the warmer external radiator by means of heat pipes. The radiator faces away from the Earth and Sun so that its heat can be radiated into the cold vacuum of space.

CCDs are much more sensitive to light than photographic film and many older forms of electronic light sensors. They also have finer resolution, better linearity and the ability to convert image data directly into digital form. As a result, CCDs have found many astronomical and commercial applications following their early incorporation in WFPC1.

Processing System. A microprocessor controls all of WFPC2's operations and transfers data to the SI C&DH unit. Commands to control various functions of the instrument (including filter and shutter settings) are sent by radio uplink to the Telescope in the form of detailed encoded instructions that originated at the Space Telescope Science Institute (STScI) in Baltimore, Maryland. Because the information rate of the Telescope's communication system is limited, the large amount of data associated with even one picture from WFPC2 is digitally recorded during the CCD readout. The data then is transmitted at a slower rate via a communications satellite that is simultaneously in Earth orbit.

WFPC2 Specifications

Figure 4-16 shows the WFPC2 specifications.

Wide Field and Planetary Camera 2	
Weight	619 pounds (281 kg)
Dimensions	Camera: 3.3 x 5 x 1.7 feet (1 x 1.3 x 0.5 m) Radiator: 2.6 x 7 feet (0.8 x 2.2 m)
Principal investigator	John Trauger, Jet Propulsion Laboratory
Contractor	Jet Propulsion Laboratory
Optical modes	f/12.9 (WF), f/28.3 (PC)
Field of view	4.7 arcmin^2 (WP) 0.3 arcmin^2 (PC)
Magnitude range	9 to 28 m_v
Wavelength range	1200 – 10,000 angstroms

Fig. 4-16 WFPC2 specifications

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Observations

The WFPC2 can perform several tasks while observing a single object. It can focus on an extended galaxy and take a wide-field picture of the galaxy, then concentrate on the galaxy nucleus to measure light intensity and take photographic closeups of the center. In addition, the WFPC2 can measure while other instruments are observing.

Specific applications of this camera range from tests of cosmic distance scales and universe expansion theories to specific star, supernova, comet and planet studies. Important searches are being made for black holes, planets in other star systems, atmospheric storms on Mars and the connection between galaxy collisions and star formation.

Astrometry (Fine Guidance Sensors)

When two FGSs lock on guide stars to provide pointing information for the Telescope, the third FGS serves as a science instrument to measure the position of stars in relation to other stars. This astrometry helps astronomers determine stellar masses and distances.

Fabricated by Perkin Elmer, the sensors are in the focal plane structure, at right angles to the optical path of the Telescope and 90 degrees apart. As shown in Fig. 4-17, they have pick-off mirrors to deflect incoming light into their apertures. (See page 5-20 for details.)

Each refurbished FGS has been upgraded by the addition of an adjustable fold mirror (AFM). This device allows HST's optical beam to be properly aligned to the internal optics of the FGS by ground command. The first-generation FGSs did not contain this feature and their optical performance suffered as a consequence. During SM2 astronauts removed FGS 1 from HST and replaced it with FGS 1R, the first FGS to feature this active alignment capability. Now with its optical system properly aligned, FGS IR performs superbly and is the prime instrument on HST for astrometric science observations.

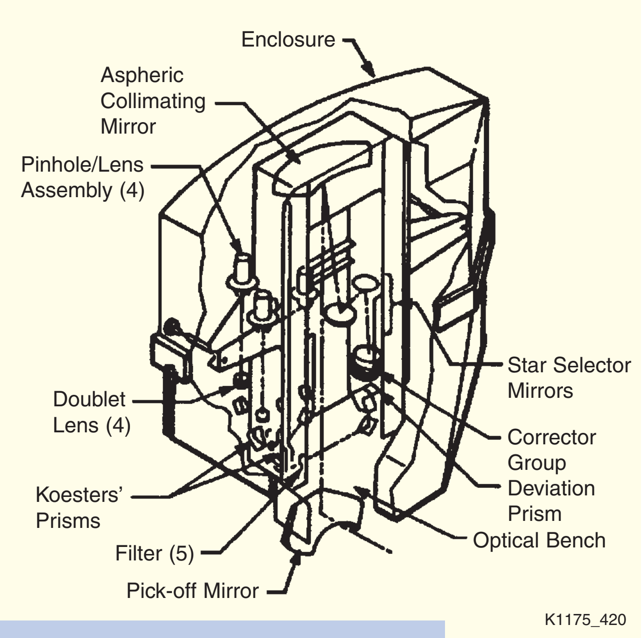
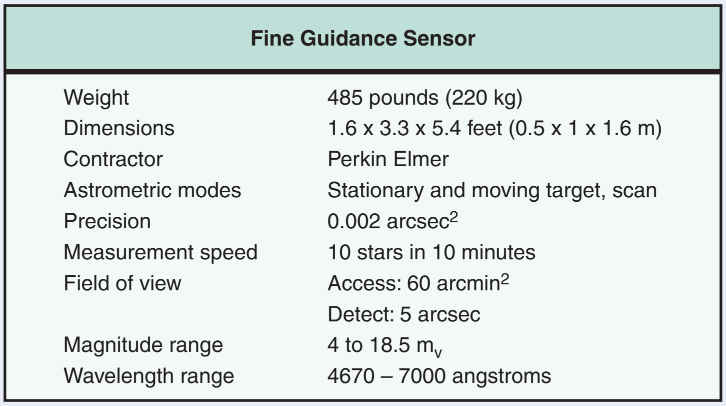


Fig. 4-17 Fine Guidance Sensor (FGS)

Fine Guidance Sensor Specifications

Figure 4-18 shows FGS specifications.



Fine Guidance Sensor	
Weight	485 pounds (220 kg)
Dimensions	1.6 x 3.3 x 5.4 feet (0.5 x 1 x 1.6 m)
Contractor	Perkin Elmer
Astrometric modes	Stationary and moving target, scan
Precision	0.002 arcsec^2
Measurement speed	10 stars in 10 minutes
Field of view	Access: 60 arcmin^2 Detect: 5 arcsec
Magnitude range	4 to 18.5 m_v
Wavelength range	4670 – 7000 angstroms

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Fig. 4-18 FGS specifications

Operational Modes for Astrometry

Astrometric observations of binary stars provide information about stellar masses that is important to understanding the evolution of stars. Once the two target-acquisition FGSs lock onto guide stars, the third sensor can perform astrometric operations on targets within the FOV set by the guide stars' positions. The sensor should be able to measure stars as faint as 18 apparent visual magnitude.

There are three operational modes for astrometric observations:
- Position
- Transfer-function
- Moving-target.

Position mode allows the astrometric FGSs to calculate the angular position of a star relative to the guide stars. Generally, up to 10 stars will be measured within a 20-minute span.

In the **transfer-function mode,** sensors measure the angular size of a target, either through direct analysis of a single-point object or by scanning an extended target. Examples of the latter include solar system planets, double stars and targets surrounded by nebulous gases.

In **moving-target mode,** sensors measure a rapidly moving target relative to other targets when it is impossible to precisely lock onto the moving target, for example, measuring the angular position of a moon relative to its parent planet.

Fine Guidance Sensor Filter Wheel

Each FGS has a filter wheel for astrometric measurement of stars with different brightness and to classify the stars being observed. The wheel has a clear filter for guide-star acquisition and faint-star (greater than 13 apparent visual magnitude) astrometry. A neutral-density filter is used for observation of nearby bright stars. Two colored filters are used to estimate a target's color (chemical) index, increasing contrast between close stars of different colors or reducing background light from star nebulosity.

Astrometric Observations

Astronomers measure the distance to a star by charting its location on two sightings from Earth at different times, normally 6 months apart. The Earth's orbit changes the perceived (apparent) location of the nearby star and the parallax angle between the two locations can lead to an estimate of the star's distance. Because stars are so distant, the parallax angle is very small, requiring a precise FOV to calculate the angle. Even with the precision of the FGSs, astronomers cannot measure distances by the parallax method beyond nearby stars in the Milky Way galaxy.

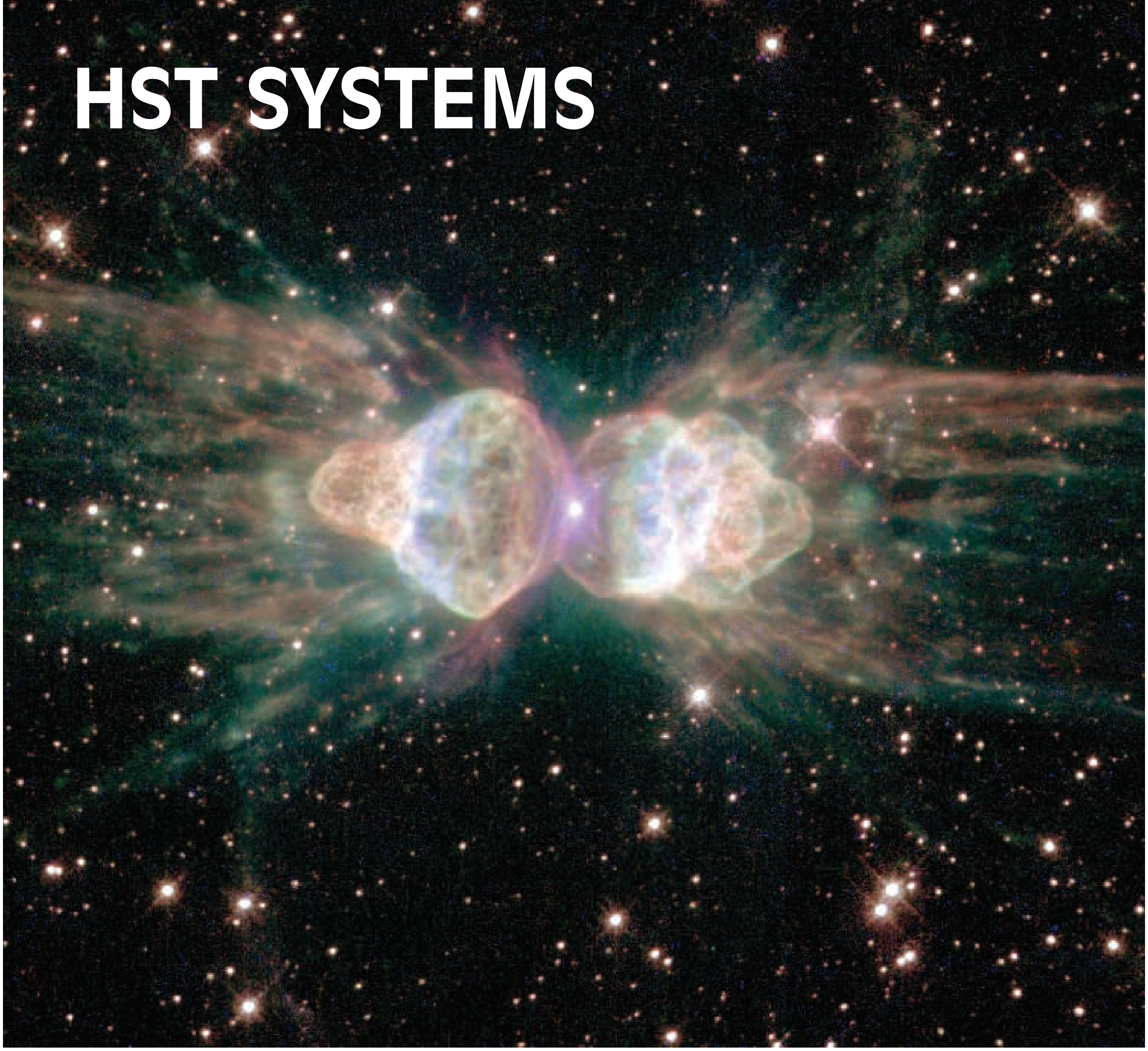
An important goal of the FGS astrometry project is to obtain improved distances to fundamental distance calibrators in the universe, for instance, to the Hyades star cluster. This is one of the foundations of the entire astronomical distance scale. Knowing the accurate distance to the Hyades would make it possible for astronomers to infer accurate distances to similar stars that are too distant for the direct parallax method to work.

Astronomers have long suspected that some stars might have a planetary system like that around the Sun. Unfortunately, the great distance of stars and the faintness of any possible planet make it very difficult to detect such systems directly. It may be possible to detect a planet by observing nearby stars and looking for the subtle gravitational effects that a planet would have on the star it is orbiting.

Astronomers use the FGS in two modes of operation to investigate known and suspected binary star systems. Their observations lead to the determination of the orbits and parallaxes of the binary stars and therefore to the masses of these systems. For example, 40 stars in the Hyades cluster were observed with the FGS. Ten of the targets were discovered to be binary star systems and one of them has an orbital period of 3.5 years.

Other objects, such as nearby M dwarf stars with suspected low-mass companions, are being investigated with the FGS with the hope of improving the mass/luminosity relationship at the lower end of the main sequence.

HST SYSTEMS



The Hubble Space Telescope (HST) performs much like a ground astronomical observatory. It has three interacting systems:

- Support Systems Module (SSM), an outer structure that houses the other systems and provides services such as electrical power, data communications, pointing control and maneuvering.
- Optical Telescope Assembly (OTA), which collects and concentrates incoming light in the focal plane for use by the science instruments.
- Eight major science instruments, four housed in an aft section focal plane structure (FPS) and four placed along the circumference of the spacecraft. The Science Instrument Control and Data Handling (SI C&DH) unit controls all the instruments except the Fine Guidance Sensors (FGS).

The SSM communicates with the OTA, SI C&DH unit and instruments to ready an observation. Light from an observed target passes through the Telescope and into one or more of the science instruments, where the light is recorded. This information goes to onboard computers for processing, then it is either temporarily stored or sent to Earth in real time, via the spacecraft communication system.

Two Solar Arrays (SA) also support HST operations. They generate electrical power and charge onboard batteries and communications antennas to receive commands and send telemetry data from the HST.

Figure 5-1 shows the HST configuration.

The Telescope completes one orbit every 97 minutes and maintains its orbital position along three axial planes. The primary axis, V1, runs through the center of the Telescope. The other two axes parallel the SA masts (V2) and the High Gain Antenna (HGA) masts (V3) (see Fig. 5-2). The Telescope points and maneuvers to new targets by rotating about its body axes. Pointing instruments use references to these axes to aim at a target in space, position the SA or change Telescope orientation in orbit.

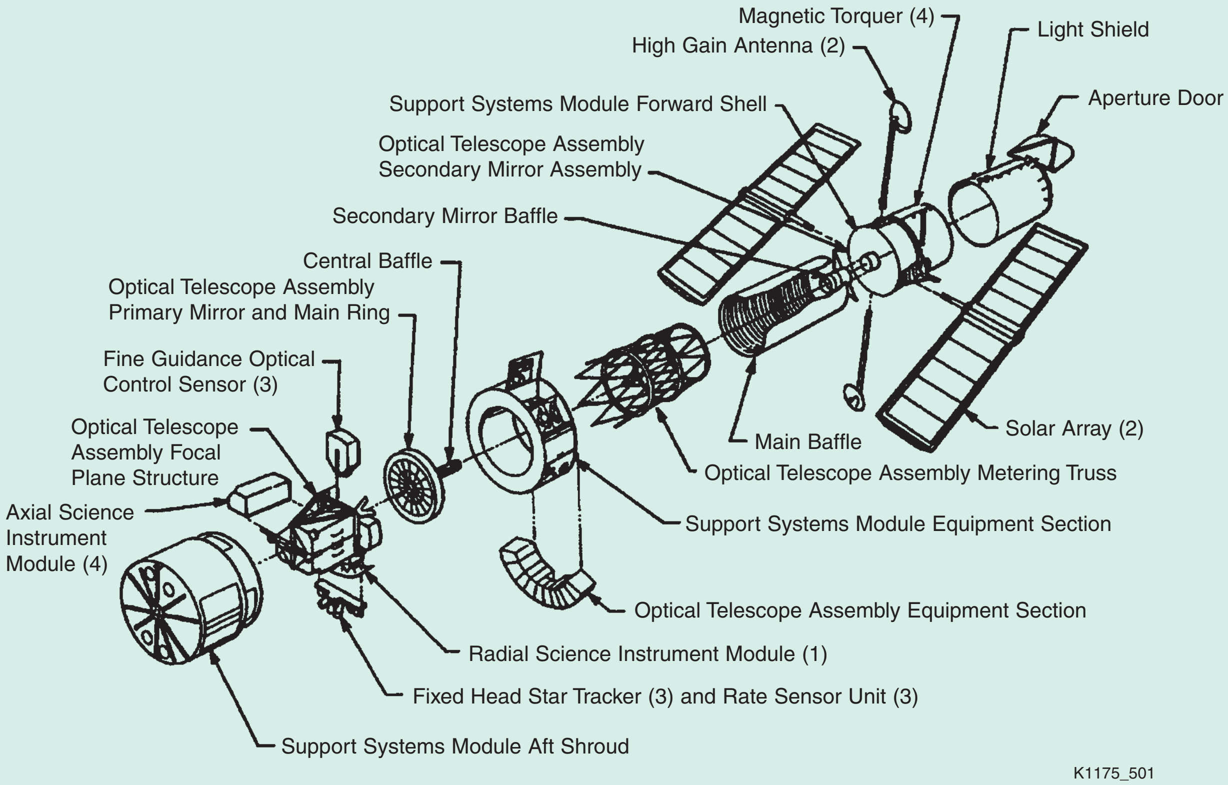


Fig. 5-1 Hubble Space Telescope – exploded view

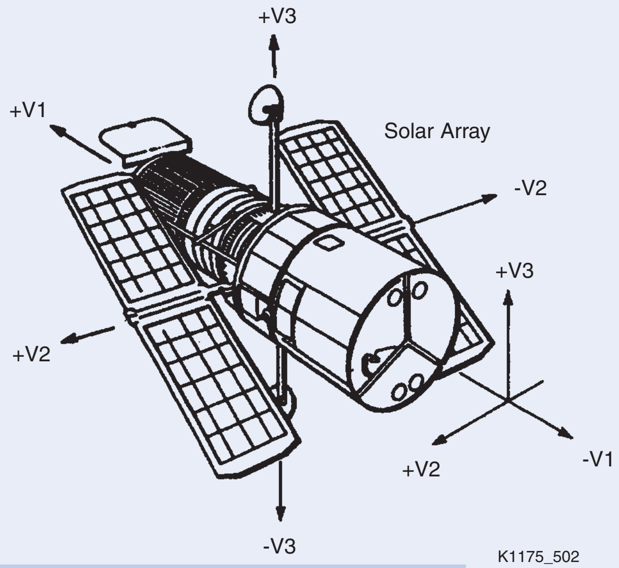


Fig. 5-2 Hubble Space Telescope axes

Support Systems Module

Design features of the SSM include:
- An outer structure of interlocking shells
- Reaction wheels and magnetic torquers to maneuver, orient and attitude stabilize the Telescope
- Two SAs to generate electrical power
- Communication antennas
- A ring of Equipment Section bays that contain electronic components, such as batteries, and communications equipment. (Additional bays are provided on the +V3 side of the spacecraft to house OTA electronics as described on page 5-19, OTA Equipment Section.)
- Computers to operate the spacecraft systems and handle data
- Reflective surfaces and heaters for thermal protection
- Outer doors, latches, handrails and footholds designed for astronaut use during on-orbit maintenance.

Figure 5-3 shows some of these features.

Major component subsystems of the SSM are:
- Structures and mechanisms
- Instrumentation and communications
- Data management
- Pointing control
- Electrical power
- Thermal control
- Safing (contingency) system.

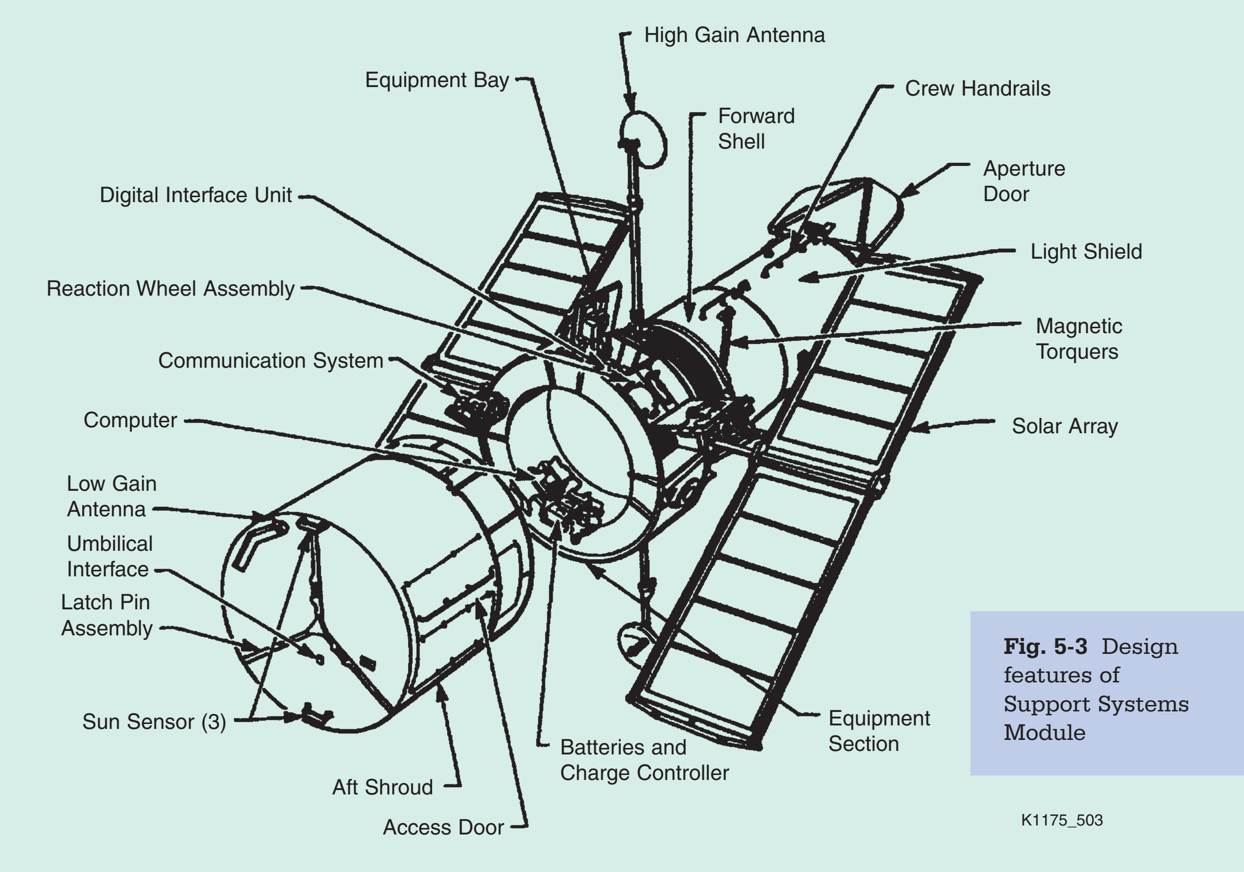


Fig. 5-3 Design features of Support Systems Module

Structures and Mechanisms Subsystem

The outer structure of the SSM consists of stacked cylinders, with the aperture door on top and the aft bulkhead at the bottom. Fitting together are the light shield, the forward shell, the SSM Equipment Section and the aft shroud/bulkhead—all designed and built by Lockheed Martin Space Systems Company (see Fig. 5-4).

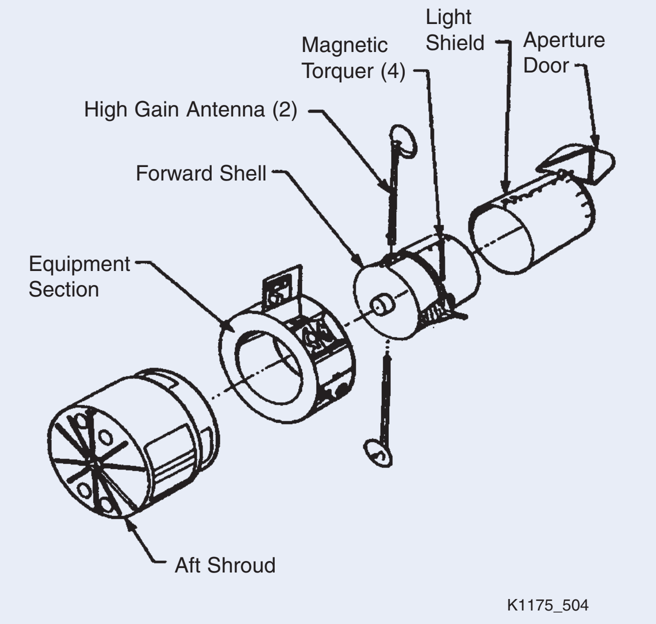


Fig. 5-4 Structural components of Support Systems Module

Aperture Door. A door approximately 10 feet (3 m) in diameter covers the opening to the Telescope's light shield. The door is made from honeycombed aluminum sheets. The outside is covered with solar-reflecting material, and the inside is painted black to absorb stray light.

The door opens a maximum of 105 degrees from the closed position. The Telescope aperture allows for a 50-degree field of view (FOV) centered on the +V1 axis. Sun-avoidance sensors provide ample warning to automatically close the door before sunlight can damage the Telescope's optics. The door begins closing when the Sun is within ±35 degrees of the +V1 axis and is closed by the time the sun reaches 20 degrees of +V1. This takes no longer than 60 seconds.

The Space Telescope Operations Control Center (STOCC) can override the protective door-closing mechanism for observations that fall within the 20-degree limit. An example is observing a bright object, using the dark limb (edge) of the Moon to partially block the light.

Light Shield. Used to block out stray light, the light shield (see Figs. 5-4 and 5-5) connects to both the aperture door and the forward shell. The outer skin of the Telescope has latches to secure the SAs and

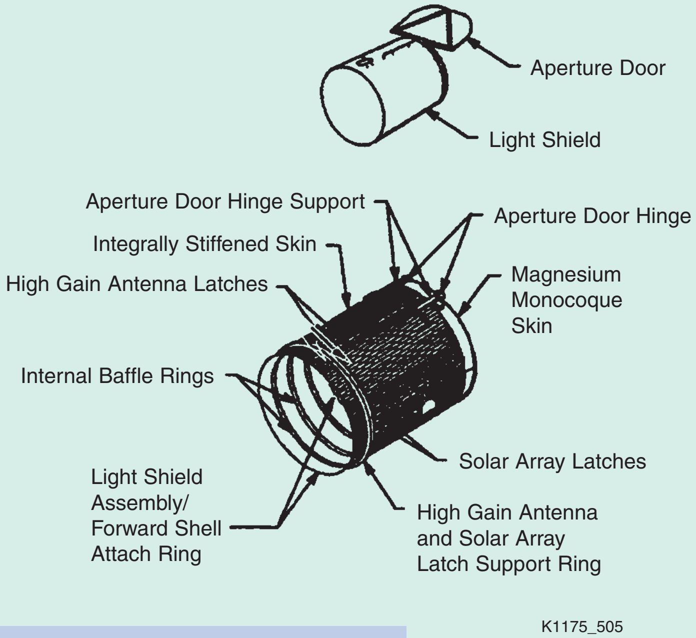


Fig. 5-5 Aperture door and light shield

HGAs when they are stowed. Near the SA latches are scuff plates—large protective metal plates on struts that extend approximately 30 inches from the surface of the spacecraft. Trunnions lock the Telescope into the Shuttle cargo bay by hooking to latches in the bay. The light shield supports the forward Low Gain Antenna (LGA) and its communications waveguide, two magnetometers and two sun sensors. Handrails encircle the light shield, and built-in foot restraints support the astronauts working on the Telescope.

The shield measures 13 feet (4 m) long and 10 feet (3 m) in internal diameter. It is a stiffened, corrugated-skin barrel machined from magnesium and covered by a thermal blanket. Internally the shield has 10 light baffles, painted flat black to suppress stray light.

Forward Shell. The forward shell, or central section of the structure, houses the OTA main baffle and the secondary mirror (see Fig. 5-6). When stowed, the SAs and HGAs are latched flat against the forward shell and light shield. Four magnetic torquers are placed 90 degrees apart around the circumference of the forward shell. The outer skin has two grapple fixtures next to the HGA drives, where the Shuttle's Remote Manipulator System can attach to the Telescope. The forward shell also has handholds, footholds and a trunnion, which is used to lock the Telescope into the Shuttle cargo bay.

Machined from aluminum plating, the forward shell is 13 feet (4 m) long and 10 feet (3 m) in diameter. It has internal stiffened panels and external reinforcing rings. These rings are on the outside to ensure clearance for the OTA inside. Thermal blankets cover the exterior.

Equipment Section. This section is a ring of storage bays encircling the SSM. It contains about 90 percent of the electronic components that run the spacecraft, including equipment serviced during extravehicular activities (EVA) by Space Shuttle astronauts.

The Equipment Section is a doughnut-shaped barrel that fits between the forward shell and aft shroud. It contains 10 bays for equipment and two bays to support aft trunnion pins and scuff plates. As shown in Fig. 5-7, clockwise from the +V3 (top) position, the bays contain:

1. Bay 8 – pointing control hardware
2. Bay 9 – Reaction Wheel Assembly (RWA)
3. Bay 10 – SI C&DH unit
4. Unnumbered trunnion support bay
5. Bay 1 – data management hardware

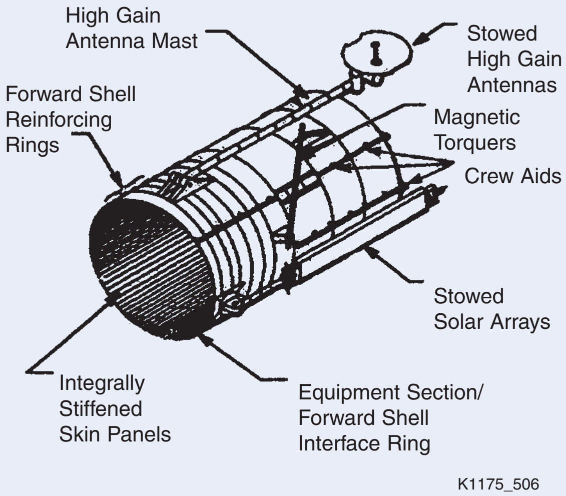


Fig. 5-6 Support Systems Module forward shell

6. Bays 2, 3 and 4 – electrical power equipment
7. Unnumbered trunnion support bay
8. Bay 5 – communication hardware
9. Bay 6 – RWA
10. Bay 7 – mechanism control hardware.

The cross section of the bays is shaped like a trapezoid: the outer diameter (the door) is 3.6 feet (1 m) and the inner diameter is 2.6 feet (0.78 m). The bays are 4 feet (1.2 m) wide and 5 feet (1.5 m) deep. The Equipment Section is constructed of machined and stiffened aluminum frame panels attached to an inner aluminum barrel. Eight bays have flat, honeycombed aluminum doors mounted with equipment. In Bays 6 and 9, thermal-stiffened panel doors cover the reaction wheels. A forward frame panel and aft bulkhead enclose the SSM Equipment Section. Six mounts on the inside of the bulkhead hold the OTA.

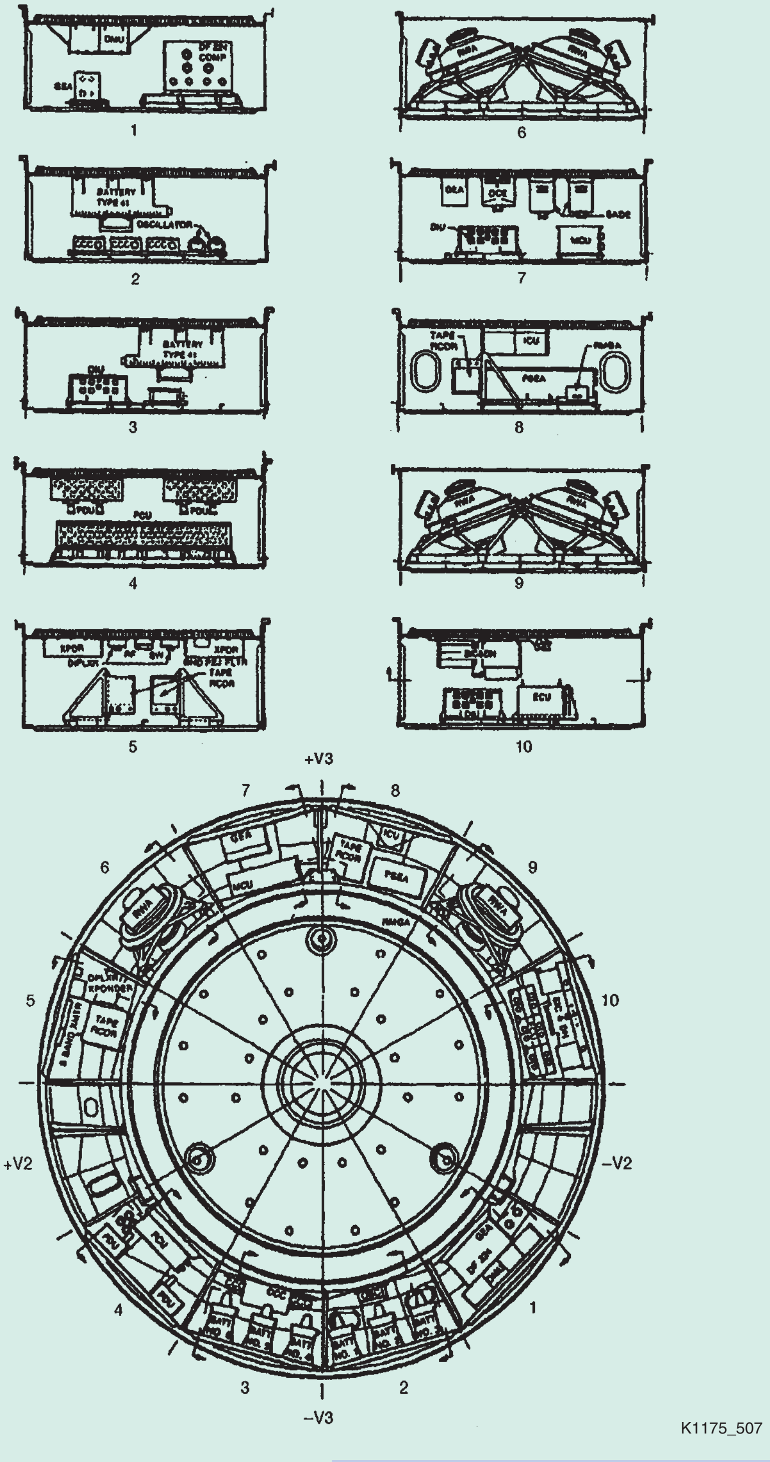


Fig. 5-7 Support Systems Module Equipment Section bays and contents

Aft Shroud and Bulkhead. The aft shroud (see Fig. 5-8) houses the FPS containing the axial science instruments. It is also the location of the Corrective Optics Space Telescope Axial Replacement (COSTAR) unit.

The three FGSs and the Wide Field and Planetary Camera 2 (WFPC2) are housed radially near the connecting point between the aft shroud and SSM Equipment Section. Doors on the outside of the shroud allow astronauts to remove and change equipment and instruments easily. Handrails and foot restraints for the crew run along the length and circumference of the shroud. During maintenance or removal of an instrument, interior lights illuminate the compartments containing the science instruments. The shroud is made of aluminum, with a stiffened skin, internal panels and reinforcing rings, and 16 external and internal longeron bars for support. It is 11.5 feet (3.5 m) long and 14 feet (4.3 m) in diameter.

The aft bulkhead contains the umbilical connections between the Telescope and the Shuttle, used during on-orbit maintenance. The rear LGA attaches

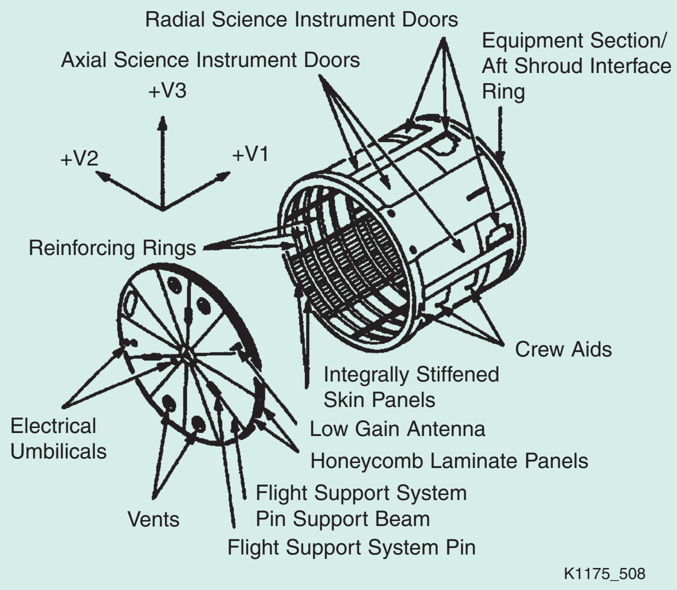


Fig. 5-8 Support Systems Module aft shroud and bulkhead

to the bulkhead, which is made of 2-in.-thick honeycombed aluminum panels and has three radial aluminum support beams.

The shroud and bulkhead support a gas purge system that was used to prevent contamination of the science instruments before launch. All vents used to expel gases are light tight to prevent stray light from entering the OTA focal plane.

Mechanisms. Along the SSM structure are mechanisms that perform various functions, including:

- Latches to hold antennas and SAs
- Hinge drives to open the aperture door and erect arrays and antennas
- Gimbals to move the HGA dishes
- Motors to power the hinges and latches and to rotate arrays and antennas.

There are nine latches: four for antennas, four for arrays and one for the aperture door. They latch and release using four-bar linkages. Stepper motors called Rotary Drive Actuators (RDA) drive the latches.

There are three hinge drives, one for each HGA and one for the door. The hinges also use an RDA. Both hinges and latches have hex-wrench fittings so an astronaut can manually operate the mechanism to deploy the door, antenna or array if a motor fails.

Instrumentation and Communications Subsystem

This subsystem provides the communications loop between the Telescope and the Tracking and Data Relay Satellites (TDRS), receiving commands and sending data through the HGAs and LGAs. All information passes through the Data Management Subsystem (DMS).

S-Band Single Access Transmitter (SSAT). HST is equipped with two SSATs. “S-band” identifies the frequency at which the science data is transmitted and “single access” specifies the type of antenna on the TDRS satellite to which the data is sent.

High Gain Antennas. Each HGA is a parabolic reflector (dish) mounted on a mast with a two-axis gimbal mechanism and electronics to rotate it 100 degrees in either direction (see Fig. 5-9). General Electric designed and manufactured the antenna dishes using honeycomb aluminum and graphite-epoxy facesheets.

The HGAs achieve a much higher RF signal gain than the LGAs. The higher signal gain is required, for example, when transmitting high-data-rate scientific data. Because of their characteristically narrow beam widths, the HGAs must be pointed at the TDRSs. Each antenna can be aimed with a 1-degree pointing accuracy. This accuracy is consistent with the overall antenna beam width of over 4 degrees. The antennas transmit over two frequencies: 2255.5 MHz or 2287.5 MHz (plus or minus 10 MHz).

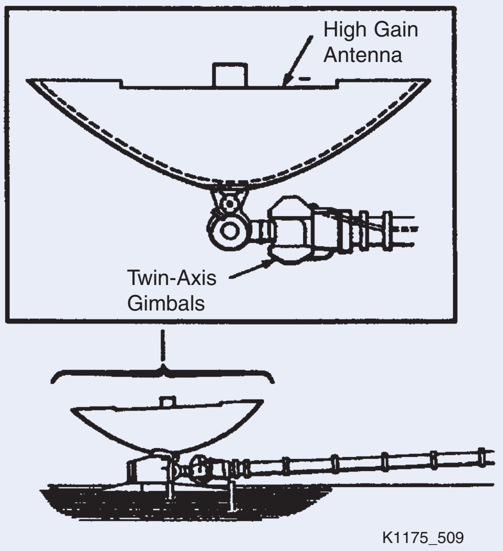


Fig. 5-9 High Gain Antenna

Low Gain Antennas. The LGAs are spiral cones, manufactured by Lockheed Martin, that provide spherical coverage (omnidirectional). They are set 180 degrees apart on the light shield and aft bulkhead of the spacecraft.

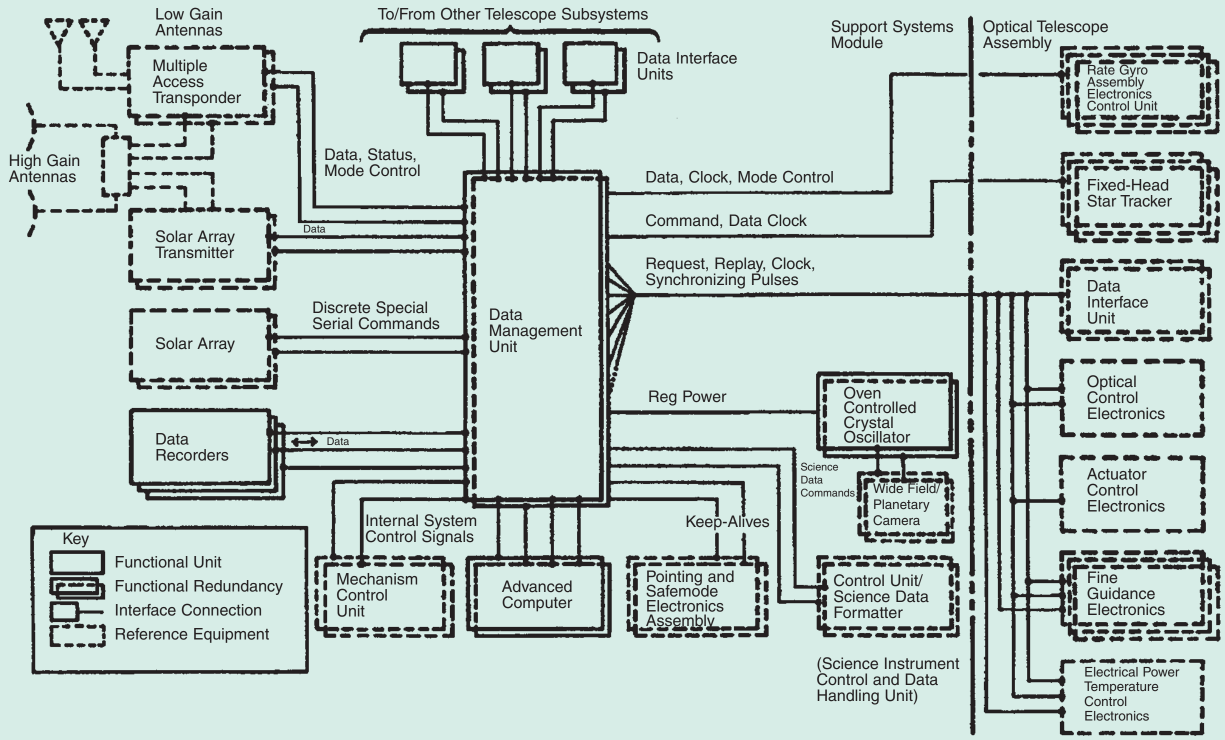


Fig. 5-10 Data Management Subsystem functional block diagram

Operating over a frequency range from 2100 MHz to 2300 MHz, the LGAs receive ground commands and transmit engineering data. These antennas are used for all commanding of the Telescope and for low-data-rate telemetry, particularly during Telescope deployment or retrieval on orbit and during safemode operations.

Data Management Subsystem

The DMS receives communications commands from the STOCC and data from the SSM systems, OTA and science instruments. It processes, stores and sends the information as requested (see Fig. 5-10).

Subsystem components are:
- Advanced Computer
- Data Management Unit (DMU)
- Four Data Interface Units (DIU)
- Three engineering/science data recorders
- Two oscillators (clocks).

The components are located in the SSM Equipment Section, except for one DIU stored in the OTA Equipment Section.

The DMS receives, processes, and transmits five types of signals:
1. Ground commands sent to the HST systems
2. Onboard computer-generated or computer-stored commands
3. Scientific data from the SI C&DH unit
4. Telescope engineering status data for telemetry
5. System outputs, such as clock signals and safemode signals.

Advanced Computer. The Advanced Computer is a general-purpose digital computer for onboard engineering computations. It executes stored commands, formats status data (telemetry), generates onboard commands to orient the SAs toward the Sun, evaluates the health status of the Telescope systems and commands the HGAs. It also performs all Pointing Control Subsystem (PCS) computations to maneuver, point and attitude stabilize the Telescope.

Based on the Intel 80486 microchip, the Advanced Computer operates 20 times faster and has six times as much memory as the DF-224 computer, which it replaced on SM3A. It is configured as three independent single-board computers (SBC). Each SBC has 2 megabytes of fast static random access memory and 1 megabyte of non-volatile memory.

The Advanced Computer communicates with the HST by using the direct memory access capability on each SBC through the DMU. Only one SBC controls the Telescope at a time. The other SBCs can be off, in an idle state or performing internal tasks.

Upon power on, each SBC runs a built-in self-test and then copies the operating software from slower non-volatile memory to faster random access memory. The self-test can diagnose any problems with the Advanced Computer and report them to the ground. The Advanced Computer uses fast static random access memory to eliminate wait states and allow it to run at its full-rated speed.

The Advanced Computer measures 18.8 x 18 x 13 inches (0.48 x 0.46 x 0.33 m) and weighs 70.5 pounds (32 kg). It is located in Bay 1 of the SSM Equipment Section (see Fig. 5-11).

Data Management Unit. The DMU links with the computer. It encodes data and sends messages to selected Telescope units and all DMS units, powers the oscillators and serves as the central timing source. The DMU also receives and decodes all incoming commands, then transmits each processed command to be executed.

In addition, the DMU receives science data from the SI C&DH unit. Engineering data, consisting of sensor and hardware status readings (such as temperature or voltages), comes from each Telescope subsystem. The data can be stored in the onboard data recorders if direct telemetry via a TDRS is unavailable.

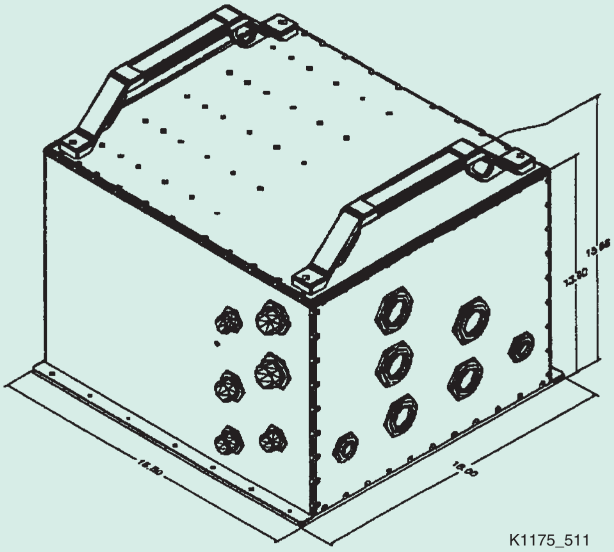


Fig. 5-11 Advanced computer

The DMU is an assembly of printed-circuit boards, interconnected through a backplate and external connectors and attached to the door of Equipment Section Bay 1 (see Fig. 5-12). The unit weighs 83 pounds (37.7 kg) and measures 26 x 30 x 7 inches (60 x 70 x 17 cm).

Data Interface Unit. Four DIUs provide a command and data link between the DMS and other electronic boxes. The DIUs receive commands and data requests from the DMU and pass data or status information back to the DMU. The OTA DIU is located in the OTA Equipment Section; the other units are in Bays 3, 7 and 10 of the SSM Equipment Section. As a safeguard, each DIU is two complete units in one: either part can handle the unit's functions. Each DIU measures 15 x 16 x 7 inches (38 x 41 x 18 cm) and weighs 35 lb (16 kg).

Engineering/Science Data Recorders. The DMS includes three data recorders that store engineering or science data that cannot be transmitted to the ground in real time. These recorders, located in Equipment Section Bays 5 and 8, hold up to 12 billion bits of information. Two solid state recorders (SSR) are used in normal operations; the third, a backup, is a reel-to-reel tape recorder. Each recorder measures 12 x 9 x 7 inches (30 x 23 x 18 cm) and weighs 20 pounds (9 kg).

The SSRs have no reels or tape and no moving parts to wear out and limit lifetime (their expected on-orbit life is at least 8 years). Data is stored digitally in computer-like memory chips until HST operators at GSFC command the SSR to play it back. Although they are the same size as the reel-to-reel recorders, the SSRs can store over 10 times more data—12 gigabits versus only 1.2 gigabits for the tape recorders they replaced.

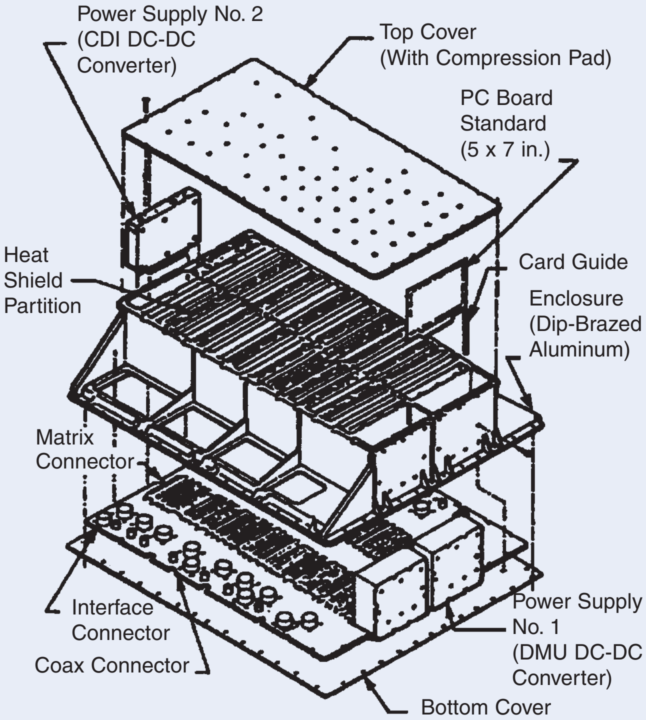


Fig. 5-12 Data Management Unit configuration

Each SSR can record two data streams simultaneously, allowing both science and engineering data to be captured on a single recorder. In addition, data can be recorded and played back at the same time.

Oscillator. The oscillator provides a highly stable central timing pulse required by the Telescope. It has a cylindrical housing 4 inches (10 cm) in diameter and 9 inches (23 cm) long and weighs 3 pounds (1.4 kg). The oscillator and a backup are mounted in Bay 2 of the SSM Equipment Section.

Pointing Control Subsystem

A unique PCS maintains Telescope pointing stability and aligns the spacecraft to point to and remain locked on any target. The PCS is designed for pointing within 0.01 arcsec and holding the Telescope in that orientation with 0.007-arcsec stability for up to 24 hours while HST orbits the Earth at 17,500 mph. If the Telescope were in Los Angeles, it could hold a beam of light on a dime in San Francisco without the beam straying from the coin's diameter.

Nominally, the PCS maintains the Telescope's precision attitude by locating guide stars in two FGSs and keeping the Telescope in the same position relative to these stars. When specific target requests require repositioning the spacecraft, the PCS selects different reference guide stars and moves the Telescope into a new attitude.

The PCS encompasses the Advanced Computer, various attitude sensors and two types of devices, called actuators, to move the spacecraft (see Fig. 5-13). It also includes the Pointing/Safemode Electronics Assembly (PSEA) and the Retrieval Mode Gyro Assembly (RMGA), which are both used by the spacecraft safemode system. See page 5-13, Safing (Contingency) System, for details.

Sensors. The PCS uses five types of sensors: Coarse Sun Sensors (CSS), Magnetic Sensing System (MSS), Rate Gyro Assemblies (RGA), Fixed Head Star Trackers (FHST) and FGSs.

Five CSSs, located on the light shield and aft shroud, measure the Telescope's orientation to the Sun. They also are used to calculate the initial deployment orientation of the Telescope, determine when to begin closing the aperture door and point the Telescope in special Sun-orientation modes during contingency operations. In addition, the CSSs provide signals to the PSEA, located in Bay 8 of the SSM Equipment Section.

The MSS measures the Telescope's orientation relative to Earth's magnetic field. Two systems are located on the front end of the light shield. Each consists of magnetometers and dedicated electronic units that send data to the Advanced Computer and the Safemode Electronics Assembly.

HST has three RGAs, each consisting of a Rate Sensor Unit (RSU) and an Electronics Control Unit (ECU). An RSU contains two rate-sensing gyroscopes that measure attitude rate motion about their sensitive axes. Two sets of dedicated electronics in each ECU process this output. Three of the six gyroscopes are required to continue the Telescope science mission.

The RSUs are located behind the SSM Equipment Section, next to three FHSTs in the aft shroud. The ECUs are located inside Bay 10 of the SSM Equipment Section. The RGAs provide input to the PCS to control the orientation of the Telescope's line of sight and to give the attitude reference when maneuvering the Telescope.

An FHST is an electro-optical detector that locates and tracks a specific star within its FOV. STOCC uses FHSTs as an attitude calibration device when the Telescope maneuvers into its initial orientation. The trackers also calculate attitude information before and after maneuvers to help the FGS lock onto guide stars.

Three FGSs provide angular position with respect to the stars (see page 5-20, Fine Guidance Sensor, for details). Their precise fine-pointing adjustments, accurate to within a fraction of an arcsecond, pinpoint the guide stars. Two of the FGSs perform guide-star pointing and the third is available for astrometry, the positional measurement of specific stars.

Pointing Control Subsystem Software. PCS software accounts for a large percentage of the flight code executed by Hubble's main computer. This software translates ground targeting commands into reaction wheel torque profiles that reorient the spacecraft and smooth spacecraft motion to minimize jitter during data collection. The software also determines Telescope orientation, or attitude, from FHST or FGS data and commands the magnetic torquer bars to minimize reaction wheel speeds. In addition, the software provides various telemetry formats.

Since the Telescope was launched, the PCS has been modified significantly. A digital filtering scheme,

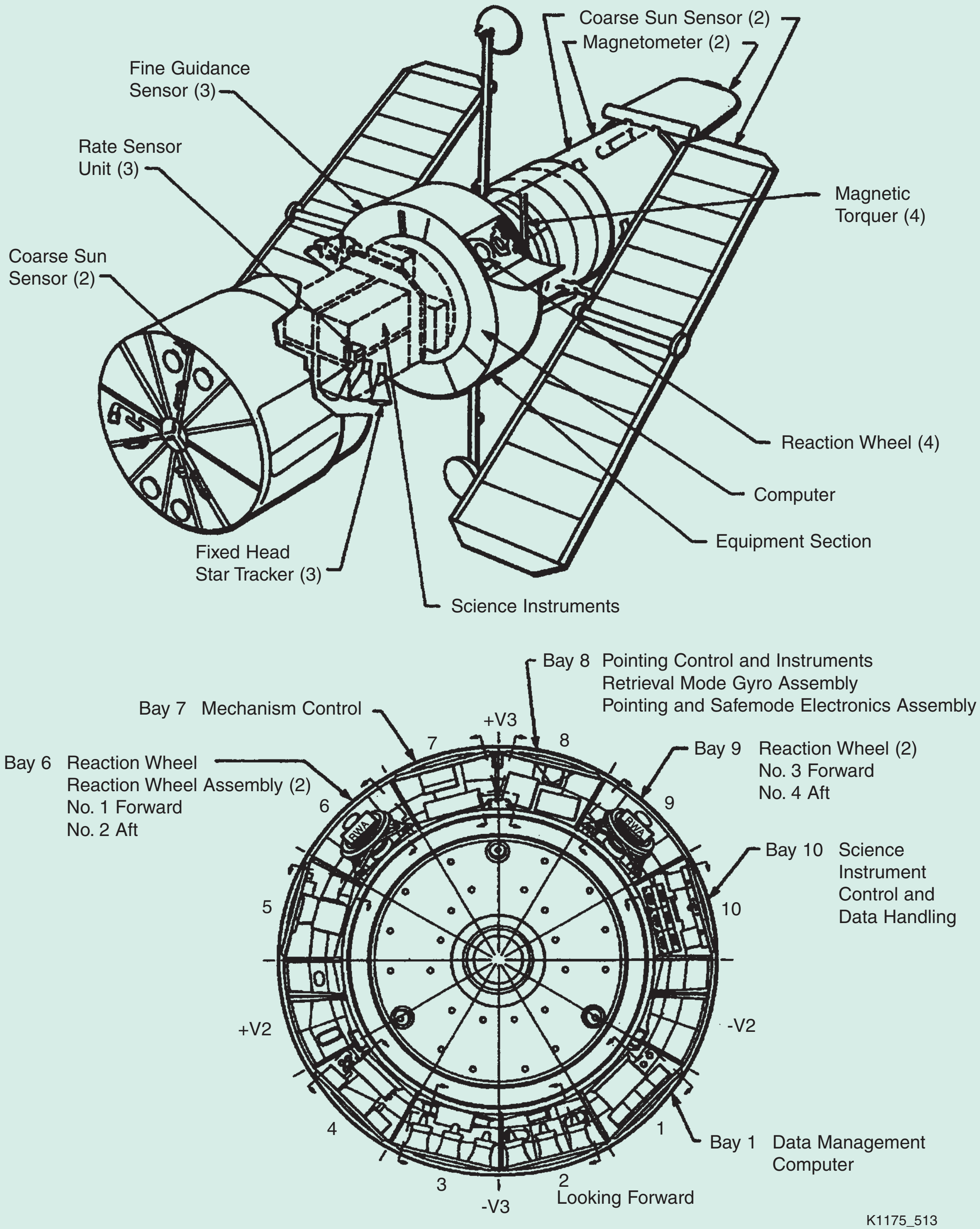


Fig. 5-13 Location of Pointing Control Subsystem equipment

known as Solar Array Gain Augmentation (SAGA), now mitigates the effect of any SA vibration or jitter on pointing stability and an FGS Re-Centering Algorithm improves FGS performance when the Telescope is subjected to the same disturbances.

Software is used extensively to increase Telescope robustness during hardware failures. Two additional software safemodes have been provided. The spin-stabilized mode enables pointing of the Telescope -V1 axis to the Sun with only two of the four RWAs operating. The other mode allows Sun pointing of the Telescope without any input from the RGA. Magnetometer and CSS data is used to derive all reference information needed to maintain Sun pointing (+V3 and -V1 are options).

A further software change “refreshes” the FGS configuration. Data is maintained in the Advanced Computer memory so it can be sent periodically to the FGS electronics, which are subject to single-event upsets (logic state change) when transitioning through the South Atlantic Anomaly.

Actuators. The PCS has two types of actuators: RWAs and magnetic torquers. Actuators move the spacecraft into commanded attitudes and provide control torques to stabilize the Telescope’s line of sight.

The reaction wheels rotate a large flywheel up to 3000 rpm or brake it to exchange momentum with the spacecraft. Wheel assemblies are paired, two each in Bays 6 and 9 of the SSM Equipment Section. The wheel axes are oriented so that the Telescope can provide science with only three wheels operating. Each wheel measures 23 inches (59 cm) in diameter and weighs about 100 pounds (45 kg). Figure 5-14 shows the RWA configuration.

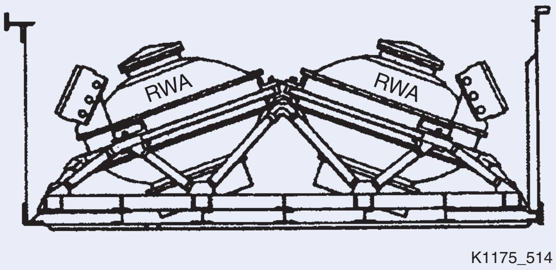


Fig. 5-14 Reaction Wheel Assembly

Magnetic torquers are primarily used to manage reaction wheel speed. The torquers react against Earth’s magnetic field. The torque reaction occurs in the direction that reduces the reaction wheel speed, managing the angular momentum.

Located externally on the forward shell of the SSM, the magnetic torquers also provide backup control to stabilize the Telescope’s orbital attitude during contingency modes (refer to page 5-6, Instrumentation and Communications Subsystem. Each torquer is 8.3 feet (2.5 m) long and 3 inches (8 cm) in circumference and weighs 100 lb (45 kg).

Pointing Control Operation. To point precisely, the PCS uses the gyroscopes, reaction wheels, magnetic torquers, star trackers and FGSs. The latter provide the precision reference point from which the Telescope can begin repositioning. Flight software commands the reaction wheels to spin, accelerating or decelerating as required to rotate the Telescope toward a new target. Rate gyroscopes sense the Telescope’s angular motion and provide a short-term attitude reference to assist fine pointing and spacecraft maneuvers. The magnetic torquers reduce reaction wheel speed.

As the Telescope nears the target area, star trackers locate preselected reference stars that stand out brightly in that region of the sky. Once the star trackers reduce the attitude error below 60 arcsec, the two FGSs take over the pointing duties. Working with the gyroscopes, the FGSs make it possible to point the Telescope within 0.01 arcsec of the target. The PCS can maintain this position, wavering no more than 0.005 arcsec, for up to 24 hours to guarantee faint-object observation.

Electrical Power Subsystem

Power for the Telescope and science instruments comes from the Electrical Power Subsystem (EPS). The major components are two SA wings and their electronics, six batteries, six Charge Current Controllers (CCC), one Power Control Unit (PCU) and four Power Distribution Units (PDU). All except the SAs are located in the bays around the SSM Equipment Section.

During the servicing mission, the Shuttle will provide the electrical power. After deployment, the SAs will begin converting solar radiation into electricity. Energy will be stored in nickel-hydrogen (NiH_2) batteries and distributed by the PCUs and PDUs to all Telescope components as shown in Fig. 5-15. Hubble will not be released until the batteries are fully charged.

Solar Arrays. The SA panels, discussed later in this section, are the primary source of electrical power. Each array wing has solar panels that convert the Sun’s energy into electrical energy. Electricity produced by the panels charges the Telescope batteries.

Each array wing has associated electronics. These consist of (1) a Solar Array Drive Electronics (SADE) unit to transmit positioning commands to the wing assembly, (2) a Deployment Control Electronics Unit to control the drive motors extending and retracting the wings and (3) diode networks to direct the electrical current flow.

Batteries and Charge Current Controllers. Developed for the 1990 deployment mission, the Telescope’s batteries were NASA’s first flight NiH_2

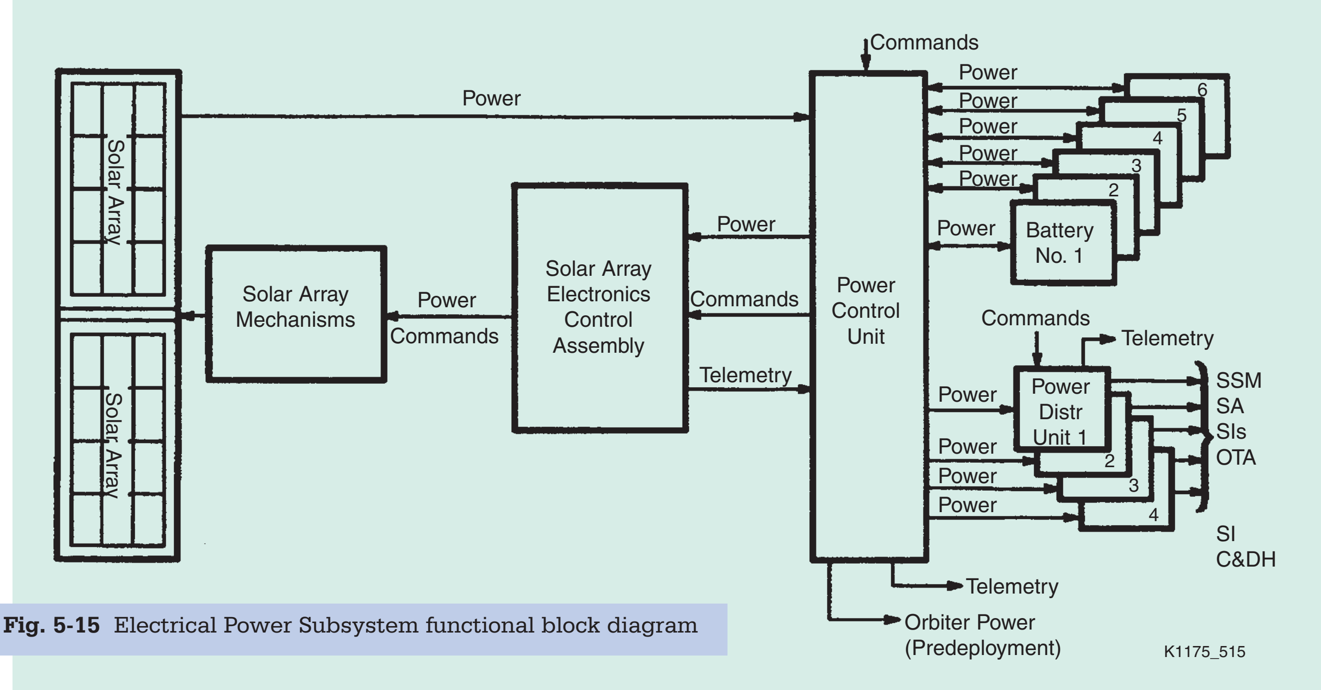


Fig. 5-15 Electrical Power Subsystem functional block diagram

batteries. They provide the observatory with a robust, long-life electrical energy storage system.

Six NiH_2 batteries support the Telescope's electrical power needs during three periods: when demand exceeds SA capability, when the Telescope is in Earth's shadow and during safemode entry. The design, operation and handling of the batteries—including special nondestructive inspection of each cell—have allowed them to be "astronaut-rated" for replacement during a servicing mission. To compensate for the effects of battery aging, SM3A astronauts installed a Voltage/Temperature Improvement Kit (VIK) on each battery. The VIK provides thermal stability by precluding battery overcharge when the HST enters safemode, effectively lowering the Charge Current Controller (CCC) recharge current.

The batteries reside in SSM Equipment Section Bays 2 and 3. Each battery has 22 cells in series along with heaters, heater controllers, pressure measurement transducers and electronics, and temperature-measuring devices and their associated electronics. Three batteries are packaged into a module measuring roughly 36 x 36 x 10 inches (90 x 90 x 25 cm) and weighing about 475 pounds (214 kg). Each module is equipped with two large yellow handles that astronauts use to maneuver the module in and out of the Telescope.

The SAs recharge the batteries every orbit following eclipse (the time in the Earth's shadow). Each battery has its own CCC that uses voltage-temperature measurements to control battery recharge.

Fully charged, each battery contains more than 75 amp-hours. This is sufficient energy to sustain the Telescope in normal science operations mode for 7.5 hours or five orbits. The batteries provide an adequate energy reserve for all possible safemode contingencies and all enhancements programmed into the Telescope since launch.

Power Control and Distribution Units. The PCU, to be replaced on SM3B, interconnects and switches current flowing among the SAs, batteries and CCCs. Located in Bay 4 of the Equipment Section, the PCU provides the main power bus to the four PDUs. The PCU weighs 120 pounds (55 kg) and measures 43 x 12 x 8 inches (109 x 30 x 20 cm).

Four PDUs, located on the inside of the door to Bay 4, contain the power buses, switches, fuses and monitoring devices for electrical power distribution to the rest of the Telescope. Two buses are dedicated to the OTA, science instruments and SI C&DH; two supply the SSM. Each PDU measures 10 x 5 x 18 inches (25 x 12.5 x 45 cm) and weighs 25 pounds (11 kg).

Thermal Control

Multilayer insulation (MLI) covers 80 percent of the Telescope's exterior. The insulation blankets have 15 layers of aluminized Kapton and an outer layer of aluminized Teflon flexible optical solar reflector (FOSR). Aluminized or silvered flexible reflector tape covers most of the remaining exterior. These coverings protect against the cold of space and reflect solar heat. Supplemental electric heaters and reflective or absorptive paints also are used to keep Hubble's temperatures safe.

The SSM Thermal Control Subsystem (TCS) maintains temperatures within set limits for the components mounted in the Equipment Section and structures interfacing with the OTA and science instruments. The TCS maintains safe component temperatures even for worst-case conditions such as environmental fluctuations, passage from “cold” Earth shadow to “hot” solar exposure during each orbit and heat generated from equipment operation.

Specific thermal-protection features of the SSM include:
- MLI thermal blankets for the light shield and forward shell
- Aluminum FOSR tape on the aperture door surface facing the Sun
- Specific patterns of FOSR and MLI blankets on the exteriors of the Equipment Section bay doors, with internal MLI blankets on the bulkheads to maintain thermal balance between bays
- Efficient placement of equipment and use of equipment bay space to match temperature requirements, such as placing heat-dissipating equipment on the side of the Equipment Section mostly exposed to orbit shadow
- Silvered FOSR tape on the aft shroud and aft bulkhead exteriors
- Radiation blankets inside the aft shroud doors and MLI blankets on the aft bulkhead and shroud interiors to protect the science instruments
- More than 200 temperature sensors and thermistors placed throughout the SSM, externally and internally, to monitor individual components and control heater operations.

Figure 5-16 shows the location and type of thermal protection used on the SSM.

During SM3A astronauts installed material to cover and restore some degraded MLI. The layer added to the SSM Equipment Section on SM3A is a composite-coated (silicone dioxide) stainless steel layer, known as the New Outer Blanket Layer (NOBL). The light shield/forward shell material is Teflon with a scrim backing for durability. The additional materials have been life-tested to an equivalent of 10 years.

SM3B astronauts will complete the task of replacing thermal protection in degraded areas as time permits.

Safing (Contingency) System

Overlapping or redundant equipment safeguards the Telescope against any breakdown. In addition, a contingency or Safing System exists for emergency operations. Using dedicated PSEA hardware and many pointing control and data management components, this system maintains stable Telescope attitude, moves the SAs for maximum Sun exposure and conserves electrical power by minimizing power drain. The Safing System can operate the spacecraft indefinitely with no communications link to ground control.

During scientific observations (normal mode), the Safing System automatically monitors Telescope onboard functions. It sends Advanced Computer-generated “keep-alive” signals to the PSEA that indicate all Telescope systems are functioning. When a failure is detected, entry into the Safemode is autonomous.

The Safing System is designed to follow a progression of contingency operating modes, depending on the situation aboard the Telescope. If a malfunction occurs and does not threaten the Telescope’s survival, the Safing System moves into a Software Inertial Hold Mode. This mode holds the Telescope in the last position commanded. If a

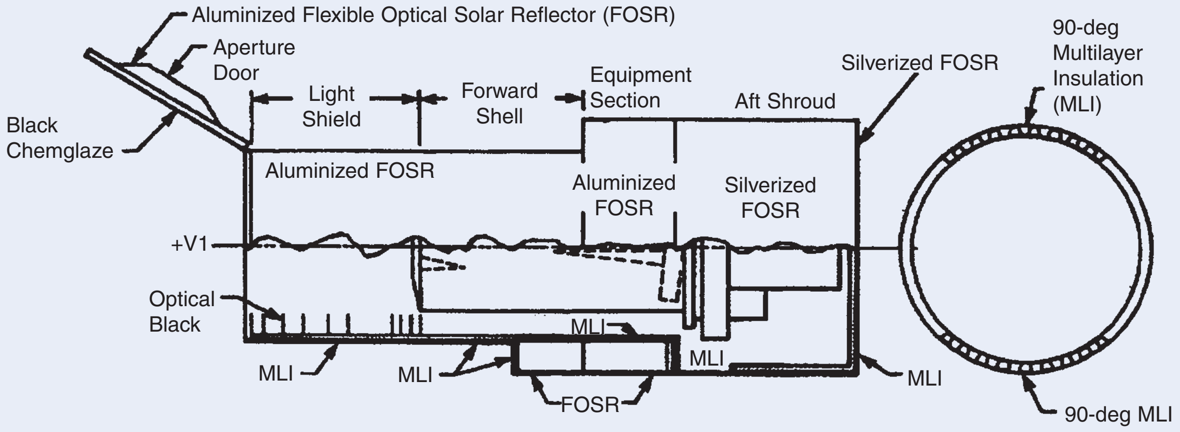


Fig. 5-16 Placement of thermal protection on Support Systems Module

maneuver is in progress, the Safing System completes the maneuver, then holds the Telescope in that position, suspending all science operations. Only ground control can return to science operations from Safemode.

If the system detects a marginal electrical power problem, or if an internal PCS safety check fails, the Telescope enters the Software Sun Point Mode. The Safing System maneuvers the Telescope so the SAs point toward the Sun to continuously generate solar power. Telescope equipment is maintained within operating temperatures and above survival temperatures, anticipating a return to normal operations. The STOCC must intercede to correct the malfunction before science operations or normal functions can be resumed.

Since deployment of the Telescope in 1990, the Safing System has seen additional improvements to increase its robustness to survive hardware failures and still protect the Telescope (refer to page 5-9, Pointing Control Subsystem).

For the modes described above, the Safing System operates through computer software. If conditions worsen, the system turns over control to the PSEA in Hardware Sun Point Mode. Problems that could provoke this action include:
- Computer malfunction
- Batteries losing more than 50 percent of their charge
- Two of the three RGAs failing
- DMS failing.

If these conditions occur, the Advanced Computer stops sending keep-alive signals. This is the "handshake" mechanism between the flight software and the PSEA.

In Hardware Sun Point Mode, the PSEA computer commands the Telescope and turns off selected equipment to conserve power. Components shut down include the Advanced Computer and, within 2 hours, the SI C&DH. Before this happens, a payload (instruments) safing sequence begins and, if it has not already done so, the Telescope turns the SAs toward the Sun, guided by the CSSs. The PSEA removes operating power from equipment not required for Telescope survival.

Once ground control is alerted to a problem, NASA management of the STOCC convenes a failure analysis team to evaluate the problem and seek the best and safest corrective action while the Safing System maintains control of the Telescope. The failure analysis team is led by a senior management representative from NASA/GSFC with the authority not only to call on the expertise of engineers and scientists employed by NASA or its support contractors, but also to draft support from any organization previously affiliated with the Telescope Project. The team is chartered to identify the nature of the anomaly and to recommend corrective action. This recommendation is reviewed at a higher management level of NASA/GSFC. All changes to the Telescope's hardware and all software configurations require NASA Level I concurrence as specified in the HST Level I Operations Requirements Document.

Pointing/Safemode Electronics and Retrieval Mode Gyro Assemblies. These assemblies are installed in Bay 8. The PSEA consists of 40 electronic printed-board circuits with redundant functions to run the Telescope, even in the case of internal circuit failure. It weighs 86 lb (39 kg). A backup gyroscope package, the RMGA, is dedicated for the PSEA. The RMGA consists of three gyroscopes. These are lower quality rate sensors than the RGAs because they are not intended for use during observations.

Optical Telescope Assembly

Perkin-Elmer Corporation (now Goodrich Corporation) designed and built the OTA. Although the OTA is modest in size by ground-based observatory standards and has a straightforward optical design, its accuracy—coupled with its place above the Earth's atmosphere—renders its performance superior.

The OTA uses a "folded" design, common to large telescopes, which enables a long focal length of 189 feet (57.6 m) to be packaged into a small telescope length of 21 feet (6.4 m). (Several smaller mirrors in the science instruments are designed similarly to lengthen the light path within them.) This form of telescope is called a Cassegrain. Its compactness is an essential component of an observatory designed to fit inside the Shuttle cargo bay.

Conventional in design, the OTA is unconventional in other aspects. Large telescopes at ground-based sites are limited in their performance by the resolution attainable while operating under the Earth's atmosphere, but the HST orbits high above the atmosphere and provides an unobstructed view of the universe. For this reason the OTA was designed and built with exacting tolerances to provide near-perfect image quality over the broadest possible region of the spectrum.

Hubble's OTA is a variant of the Cassegrain, called a Ritchey-Chretien, in which both mirrors are hyperboloidal in shape (having a deeper curvature than a parabolic mirror). This form is completely corrected for coma (an image observation with a "tail") and spherical aberrations to provide an aplanatic system in which aberrations are correct everywhere in the FOV. The only residual aberrations are field curvature and astigmatism.

Both of these are zero exactly in the center of the field and increase toward the edge of the field. These aberrations are easily corrected within the instrument optics.

Figure 5-17 shows the path of a light ray from a distant star as it travels through the Telescope to the focus. Light travels down the tube, past baffles that attenuate reflected light from unwanted bright sources, to the 94.5-inch (2.4-m) primary mirror. Reflecting off the front surface of the concave mirror, the light bounces back up the tube to the 12-inch (0.3-m)-diameter convex secondary mirror. The light is now reflected and converged through a 23.5-inch (60-cm) hole in the primary mirror to the Telescope focus, 3.3 feet (1.5 m) behind the primary mirror.

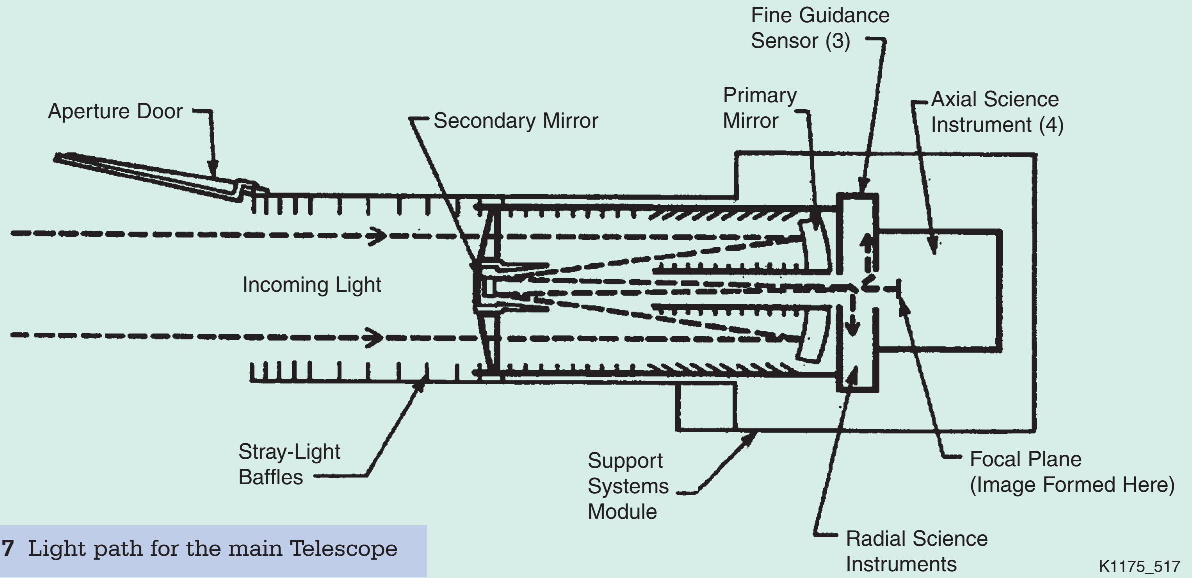


Fig. 5-17 Light path for the main Telescope

Four science instruments and three FGSs share the focal plane by a system of mirrors. A small “folding” mirror in the center of the FOV directs light into the WFPC2. The remaining “science” field is divided among three axial science instruments, each receiving a quadrant of the circular FOV. Around the outside of the science field, a “guidance” field is divided among the three FGSs by their own folding mirrors. Each FGS receives 60 arcmin$_2$ of field in a 90-degree sector. Figure 5-18 shows instrument/sensor fields of view.

The OTA hosts the science instruments and FGSs in that it maintains the structural support and optical-image stability required for these instruments to fulfill their functions (see Fig. 5-19). Components of the OTA are the primary mirror, the secondary mirror, the FPS and the OTA Equipment Section. Perkin-Elmer Corporation designed and built all the optical assemblies. Lockheed Martin built the OTA equipment section.

Primary Mirror Assembly and Spherical Aberration

As the Telescope was first put through its paces on orbit in 1990, scientists discovered its primary mirror had a spherical aberration. The outer edge of the 8-foot (2.4-m) primary mirror was ground too flat by a width equal to 1/50 the thickness of a sheet of paper (about 2 microns). After the discovery, Ball Aerospace scientists and engineers built the Corrective Optics Space Telescope Axial Replacement (COSTAR). It was installed during the First Servicing Mission in December 1993 and brought the Telescope back to its original specifications.

The primary mirror assembly consists of the mirror supported inside the main ring, which is the structural backbone of the Telescope, and the main and central baffles (see Fig. 5-20). This assembly provides the structural coupling to the rest of the spacecraft through a set of kinematic brackets linking the main ring to the SSM. The assembly also supports the OTA baffles. Its major parts are:

- Primary mirror
- Main ring structure
- Reaction plate and actuators
- Main and central baffles.

Primary Mirror. The primary mirror blank, a product of Corning Glass Works, is known as ultralow-expansion (ULE) glass. It was chosen for its very low-expansion coefficient, which ensures the Telescope minimum sensitivity to temperature

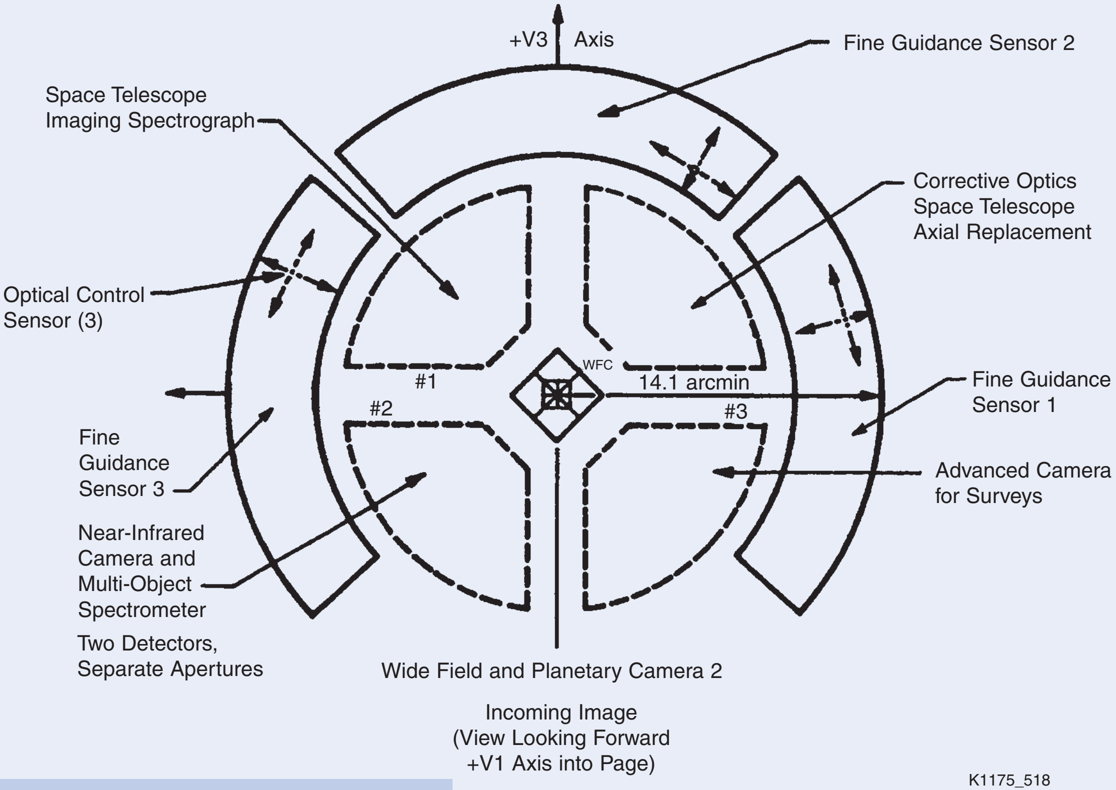


Fig. 5-18 Instrument/sensor field of view after SM3B

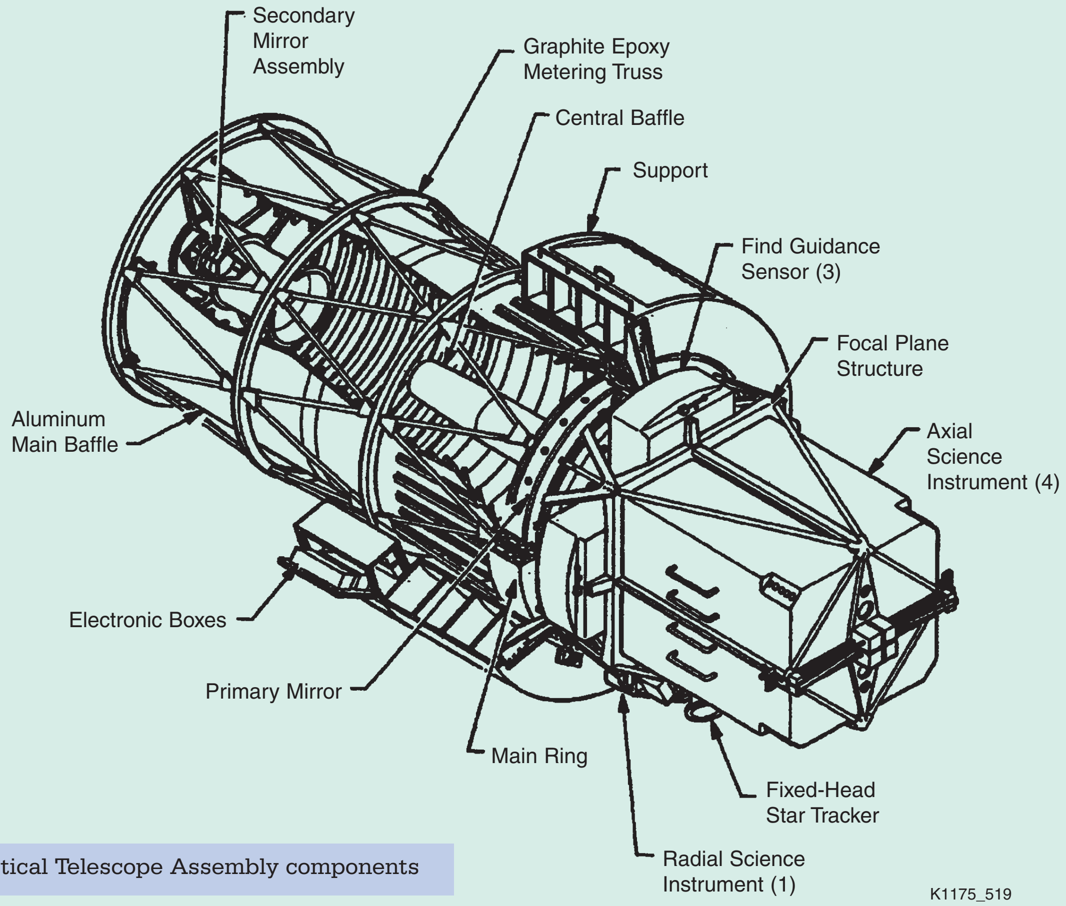


Fig. 5-19 Optical Telescope Assembly components

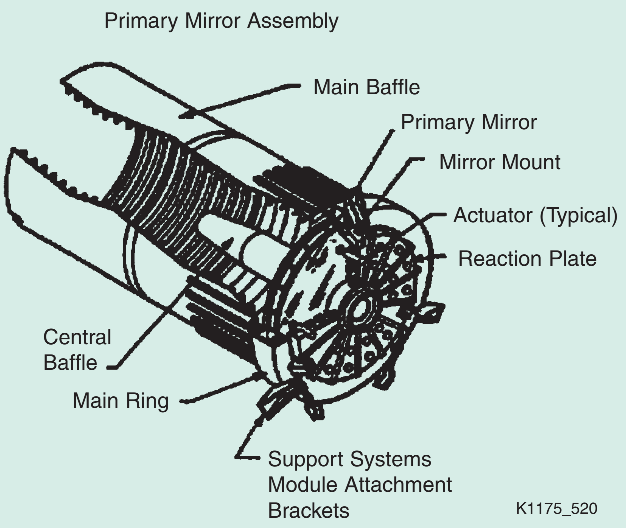
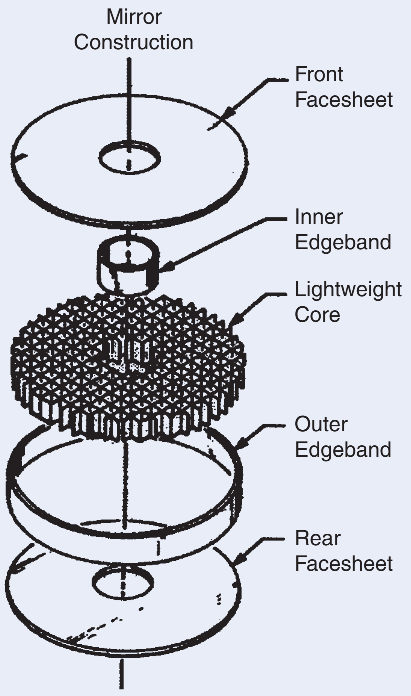


Fig. 5-20 Primary mirror assembly

changes. The mirror is of a “sandwich” construction: two lightweight facesheets separated by a core, or filling, of glass honeycomb ribs in a rectangular grid (see Fig. 5-21). This construction results in an 1800-pound (818-kg) mirror instead of an 8000-pound solid-glass mirror.

Perkin-Elmer ground the mirror blank, 8 feet (2.4 m) in diameter, to shape in its large optics fabrication facility. When it was close to its final hyperboloidal shape, the mirror was transferred to the company’s computer-controlled polishing facility.



The mirror is made of Corning Code 7971 ultralow expansion (ULE) silica glass

Fig. 5-21 Primary mirror construction

After being ground and polished, the mirror was coated with a reflective layer of aluminum and a protective layer of magnesium fluoride only 0.1- and 0.025-micrometer thick, respectively. The fluoride layer protects the aluminum from oxidation and enhances reflectance at the important hydrogen emission line known as Lyman-Alpha. The reflective quality of the mirror is better than 70 percent at 1216 angstroms (Lyman-Alpha) in the ultraviolet spectral range and better than 85 percent for visible light.

The primary mirror is mounted to the main ring through a set of kinematic linkages. The linkages attach to the mirror by three rods that penetrate the glass for axial constraint and by three pads bonded to the back of the glass for lateral support.

Main Ring. The main ring encircles the primary mirror; supports the mirror, the main baffle and central baffle, and the metering truss; and integrates the elements of the Telescope to the spacecraft (see Fig. 5-22). This titanium ring, weighing 1200 pounds (545.5 kg), is a hollow box beam 15 inches (38 cm) thick with an outside diameter of 9.8 ft (2.9 m). It is suspended inside the SSM by a kinematic support.

Reaction Plate. The reaction plate is a wheel of I-beams forming a bulkhead behind the main ring, spanning its diameter. It radiates from a central ring that supports the central baffle. Its primary function is to carry an array of heaters that warm the back of the primary mirror, maintaining its temperature at 70 degrees Fahrenheit. Made of lightweight, stiff beryllium, the plate also supports 24 figure-control actuators attached to the primary mirror and arranged around the reaction plate in two concentric

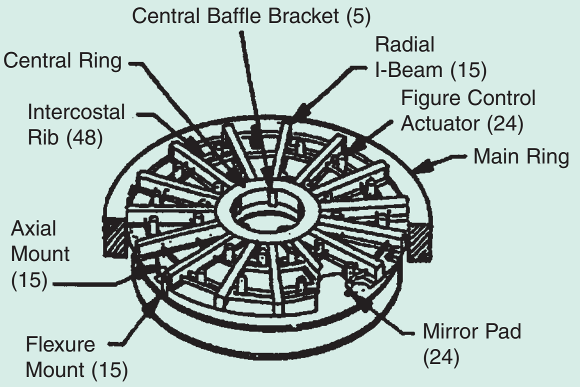


Fig. 5-22 Main ring and reaction plate

circles. These can be commanded from the ground, if necessary, to make small corrections to the shape of the mirror.

Baffles. The OTA's baffles prevent stray light from bright objects—such as the Sun, Moon and Earth—from reflecting down the Telescope tube to the focal plane. The primary mirror assembly includes two baffles. Attached to the front face of the main ring, the outer (main) baffle is an aluminum cylinder 9 feet (2.7 m) in diameter and 15.7 feet (4.8 m) long. Internal fins help it attenuate stray light. The central baffle is 10 feet (3 m) long, cone-shaped and attached to the reaction plate through a hole in the center of the primary mirror. It extends down the centerline of the Telescope tube. The baffle interiors are painted flat black to minimize light reflection.

Secondary Mirror Assembly

The Secondary Mirror Assembly cantilevers off the front face of the main ring and supports the secondary mirror at exactly the correct position in front of the primary mirror. This position must be accurate within 1/10,000 inch whenever the Telescope is operating. The assembly consists of the mirror subassembly, a light baffle and an outer graphite-epoxy metering truss support structure (see Fig. 5-23).

The Secondary Mirror Assembly contains the mirror, mounted on three pairs of alignment actuators that control its position and orientation. All are enclosed within the central hub at the forward end of the truss support.

The secondary mirror has a magnification of 10.4X. It converts the primary-mirror converging rays from f/2.35 to a focal ratio system prime focus of f/24 and sends them back toward the center of the primary mirror, where they pass through the central baffle to the focal point. The mirror is a convex hyperboloid 12 inches (0.3 m) in diameter and made of Zerodur glass coated with aluminum and magnesium fluoride. Steeply convex, it has a surface accuracy even greater than that of the primary mirror.

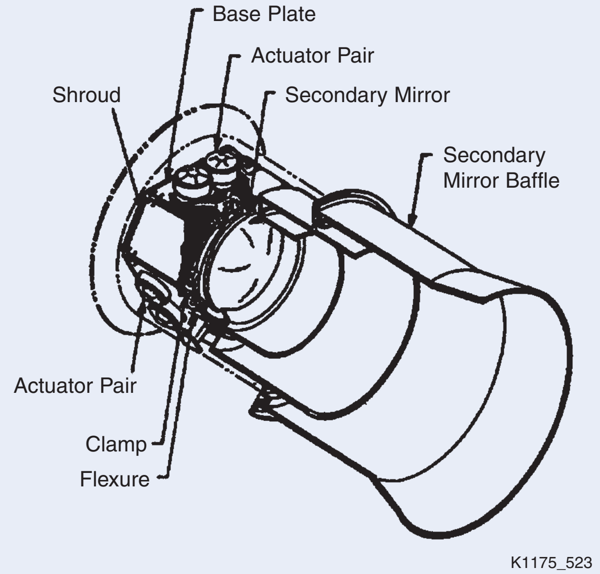


Fig. 5-23 Secondary mirror assembly

Ground command adjusts the actuators to align the secondary mirror to provide perfect image quality. The adjustments are calculated from data picked up by tiny optical control system sensors located in the FGSs.

The principal structural element of the Secondary Mirror Assembly is the metering truss, a cage with 48 latticed struts attached to three rings and a central support structure for the secondary mirror. The truss, 16 feet (4.8 m) long and 9 feet (2.7 m) in diameter, is a graphite, fiber-reinforced epoxy structure. Graphite was chosen for its high stiffness, light weight and ability to reduce the structure's expansiveness to nearly zero. This is vital because the secondary mirror must stay perfectly placed relative to the primary mirror, accurate to within 0.0001 inch (2.5 micrometers) when the Telescope operates.

The truss attaches at one end to the front face of the main ring of the Primary Mirror Assembly. The other end has a central hub that houses the secondary mirror and baffle along the optical axis. Aluminized mylar MLI in the truss compensates for temperature variations of up to 30 degrees Fahrenheit when the Telescope is in Earth's shadow so the primary and secondary mirrors remain aligned.

The conical secondary mirror subassembly light baffle extends almost to the primary mirror. It reduces stray bright-object light from sources outside the Telescope FOV.

Focal Plane Structure Assembly

The FPS is a large optical bench that physically supports the science instruments and FGSs and aligns them with the image focal plane of the Telescope. The -V3 side of the structure, away from the Sun in space, supports the FHSTs and RSUs (see Fig. 5-24). It also provides facilities for on-orbit replacement of any instruments and thermal isolation between instruments.

The structure is 7 feet (2.1 m) by 10 feet (3.04 m) long and weighs more than 1200 pounds (545.5 kg). Because it must have extreme thermal stability and be stiff, lightweight and strong, the FPS is constructed of graphite-epoxy, augmented with mechanical fasteners and metallic joints at strength-critical locations. It is equipped with metallic mounts and supports for Orbital Replacement Units (ORU) used during maintenance.

The FPS cantilevers off the rear face of the main ring, attached at eight flexible points that adjust to eliminate thermal distortions. The structure provides a fixed alignment for the FGSs. It has guiderails and latches at each instrument mounting location so Shuttle crews can easily exchange science instruments and other equipment in orbit.

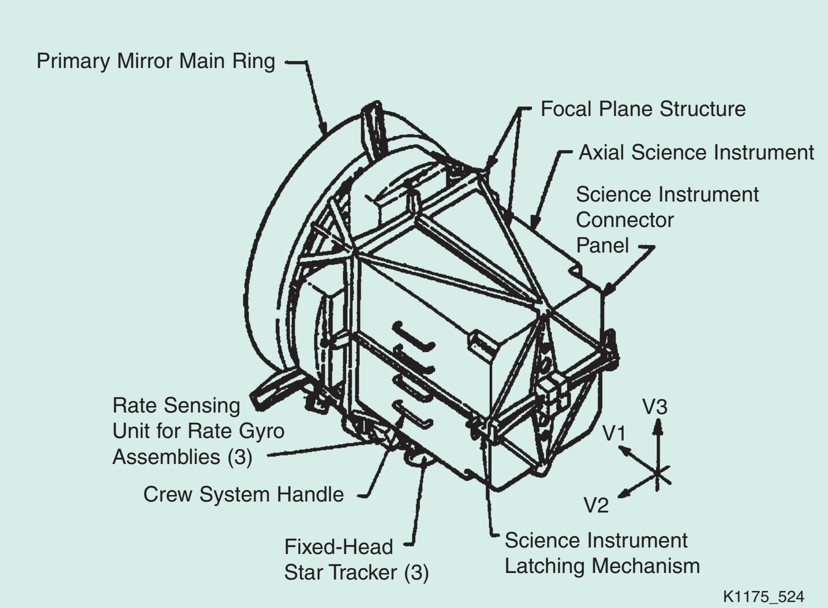


Fig. 5-24 Focal plane structure

OTA Equipment Section

The OTA Equipment Section is a large semicircular set of compartments mounted outside the spacecraft on the forward shell of the SSM (see Fig. 5-25). It contains the OTA Electrical Power and Thermal Control Electronics (EP/TCE) System, Fine Guidance Electronics (FGE), Actuator Control Electronics (ACE), Optical Control Electronics (OCE) and the fourth DMS DIU. The OTA Equipment Section has nine bays: seven for equipment storage and two for support. All bays have outward-opening doors for easy astronaut access, cabling and connectors for the electronics, and heaters and insulation for thermal control.

The EP/TCE System distributes power from the SSM EPS and the OTA system. Thermostats regulate mirror temperatures and prevent mirror distortion from the cold of space. The electrical and thermal electronics also collect thermal sensor data for transmission to the ground.

Three FGE units provide power, commands and telemetry to the FGSs. The electronics perform computations for the sensors and interface with the spacecraft pointing system for effective Telescope line-of-sight pointing

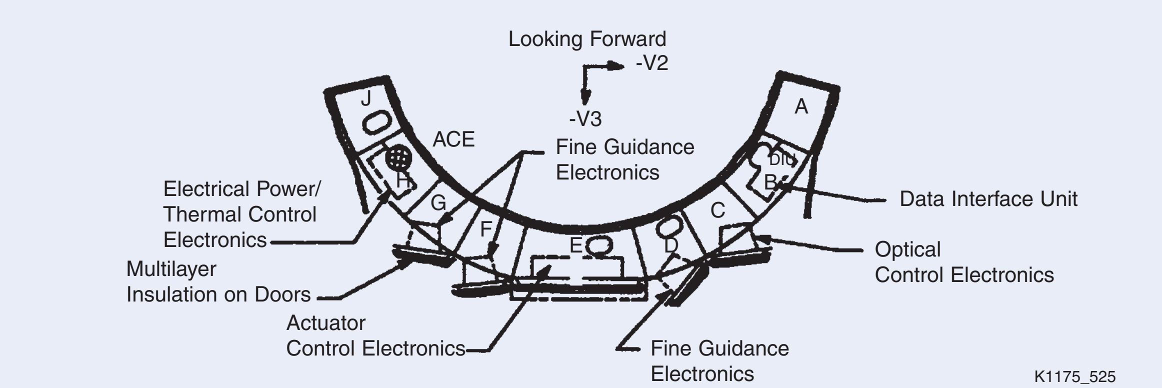


Fig. 5-25 Optical Telescope Assembly Equipment Section

and stabilization. There is a guidance electronics assembly for each guidance sensor.

The ACE unit provides the command and telemetry interface to the 24 actuators attached to the primary mirror and to the six actuators attached to the secondary mirror. These electronics select which actuator to move and monitor its response to the command. Positioning commands go from the ground to the electronics through the DIU.

The OCE unit controls the optical control sensors. These white-light interferometers measure the optical quality of the OTA and send the data to the ground for analysis. There is one optical control sensor for each FGS, but the OCE unit runs all control sensors. The DIU is an electronic interface between the other OTA electronics units and the Telescope command and telemetry system.

Fine Guidance Sensor

Three FGSs are located at 90-degree intervals around the circumference of the focal plane structure, between the structure frame and the main ring. Each sensor measures 5.4 feet (1.5 m) long and 3.3 feet (1 m) wide and weighs 485 pounds (220 kg).

Each FGS enclosure houses a guidance sensor and a wavefront sensor. The wavefront sensors are elements of the optical control sensor used to align and optimize the optical system of the Telescope.

The Telescope's ability to remain pointing at a distant target to within 0.005 arcsec for long periods of time is due largely to the accuracy of the FGSs. They lock on a star and measure any apparent motion to an accuracy of 0.0028 arcsec. This is equivalent to seeing from New York City the motion of a landing light on an aircraft flying over San Francisco.

When two sensors lock on a target, the third measures the angular position of a star, a process called astrometry. Sensor astrometric functions are discussed in Section 4, Science Instruments. During SM2 a re-certified FGS (S/N 2001) was installed as a replacement in the HST FGS Bay 1. During SM3A a re-certified FGS (S/N 2002) was installed in the HST FGS Bay 2.

FGS Composition and Function

Each FGS consists of a large structure housing a collection of mirrors, lenses, servos to locate an image, prisms to fine-track the image, beam splitters and four photomultiplier tubes (see Fig. 5-26). The entire mechanism adjusts to move the Telescope into precise alignment with a target star. Each FGS has a large (60 arcmin2) FOV to search for and track stars, and a 5.0 arcsec2 FOV used by the detector prisms to pinpoint the star.

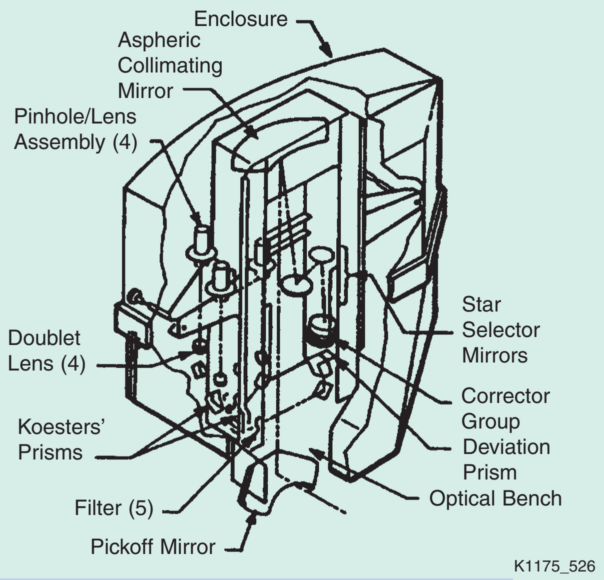


Fig. 5-26 Cutaway view of Fine Guidance Sensor

The sensors work in pairs to aim the Telescope. The Guide Star Selection System, developed by the Science Institute, catalogs and charts guide stars near each observation target to make it easier to find the target. One sensor searches for a target guide star. After the first sensor locks onto a guide star, the second sensor locates and locks onto another target guide star. Once designated and located, the guide stars keep the image of the observation target in the aperture of the selected science instrument.

Each FGS uses a 90-degree sector of the Telescope's FOV outside the central "science" field. This region of the FOV has the greatest astigmatic and curvature distortions. The size of the FGS's FOV was chosen to heighten the probability of finding an appropriate guide star, even in the direction of the lowest star population near the galactic poles.

An FGS "pickoff" mirror intercepts the incoming stellar image and projects it into the sensor's large FOV. Each FGS FOV has 60 arcmin^2 available. The guide star of interest can be anywhere within this field. After finding the star, the sensor locks onto it and sends error signals to the Telescope, telling it how to move to keep the star image perfectly still. Using a pair of star selector servos, the FGS can move its line of sight anywhere within its large FOV. Each can be thought of as an optical gimbal: one servo moves north and south, the other east and west. They steer the small FOV (5 arcsec^2) of the FGS detectors to any position in the sensor field. Encoders within each servo system send back the exact coordinates of the detector field centers at any point.

Because the exact location of a guide star may be uncertain, the star selector servos also can cause the detector to search the region around the most probable guide star position. It searches in a spiral pattern, starting at the center and moving out until it finds the guide star it seeks. Then the detectors are commanded to go into fine-track mode and hold the star image exactly centered in the FOV while the star selector servo encoders send information about the position of the star to the spacecraft PCS.

The detectors are a pair of interferometers, called Koester's prisms, coupled to photomultiplier tubes (see Fig. 5-27). Each detector operates in one axis, so two detectors are needed. Operating on the incoming wavefront from the distant guide star, the interferometers compare the wave phase at one edge of the Telescope's entrance aperture with the phase at the opposite edge. When the phases are equal, the star is exactly centered. Any phase difference shows a pointing error that must be corrected.

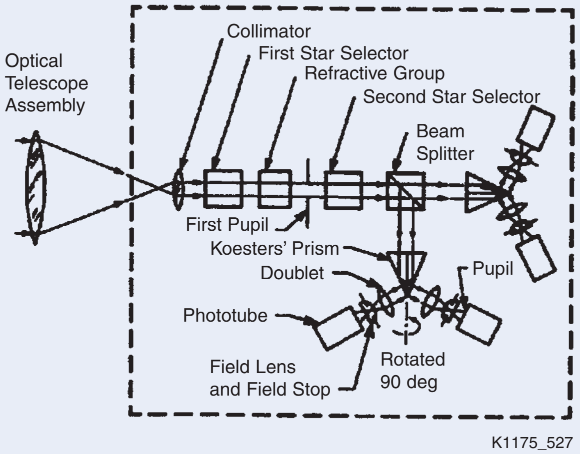


Fig. 5-27 Optical path of Fine Guidance Sensor

Along the optical path from Telescope to detector are additional optical elements that turn or fold the beam to fit everything inside the FGS enclosure and to correct the Telescope's astigmatism and field curvature. All optical elements are mounted on a temperature-controlled, graphite-epoxy composite optical bench.

Articulated Mirror System

Analysis of the FGS on-orbit data revealed that minor misalignments of the optical pupil centering on Koester's prism interferometer in the presence of spherical aberration prevented the FGS from achieving its optimum performance. During the recertification of FGS (S/N 2001), fold flat #3 in the radial bay module optical train was mechanized to allow on-orbit alignment of the pupil.

Implementation of this system utilized existing signals and commands by rerouting them with a unique interface harness enhancement kit (OCE-EK) interfacing the OCE, the DIU and the Fine Guidance System/Radial Bay Module (FGS/RBM). The OCE-EK was augmented with the Actuator Mechanism Electronics (AME) and the fold flat #3 Actuator Mechanism Assembly (AMA) located internal to the FGS/RBM. Ground tests indicate a substantial increase in FGS performance with this innovative design improvement.

Solar Arrays

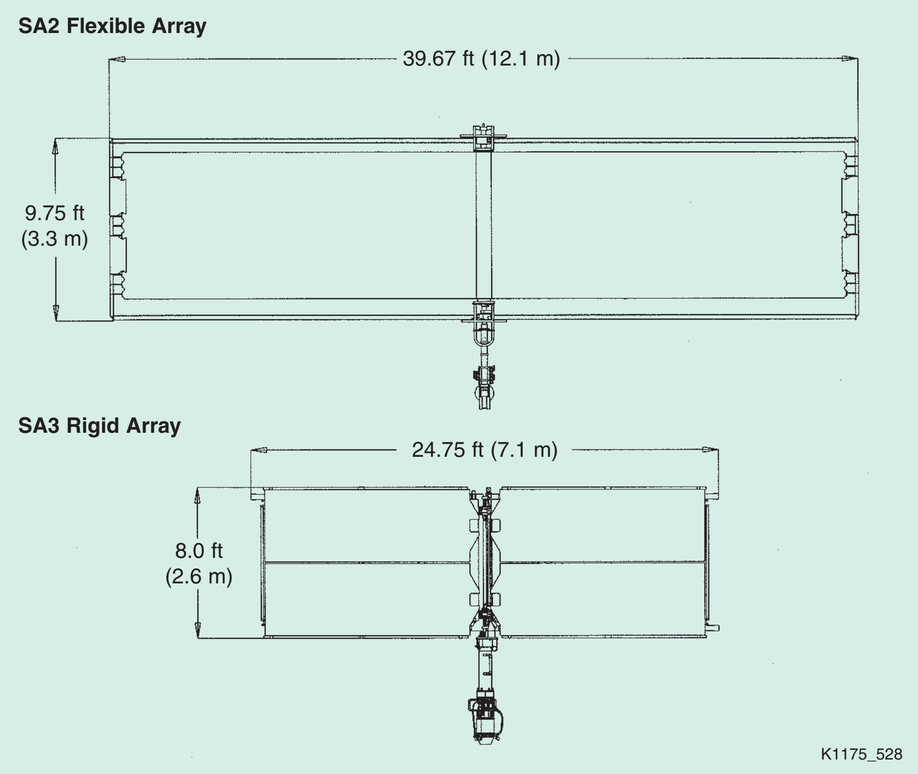
New rigid solar arrays will be attached to the Telescope during SM3B. The original arrays fitted to Hubble—designed by the European Space Agency and built by British Aerospace, Space Systems—are two large rectangular wings of retractable solar cell blankets fixed on a two-stem frame. The blanket unfurls from a cassette in the middle of the wing. A spreader bar at each end of the wing stretches the blanket and maintains tension.

Following deployment in 1990, engineers discovered two problems: a loss of focus and images that jittered briefly when the Telescope flew into and out of Earth's shadow. The jitter problem was traced to the two large SAs. Abrupt temperature changes, from -150 to 200 degrees Fahrenheit during orbit, caused the panels to distort twice during each orbit. As a temporary fix, software was written that commanded the PCS to compensate for the jitter automatically. The problem was mitigated during SM1 by the replacement of the old arrays with new ones that had been modified to reduce thermal swings of the bi-stems.

The two new solar array wings to be installed on SM3B are assembled from eight panels built at Lockheed Martin Space Systems Company in Sunnyvale, California, and designed originally for the commercial Iridium communications satellites. At Goddard Space Flight Center in Greenbelt, Maryland, four panels were mounted onto each aluminum-lithium support wing structure.

The new wing assemblies, which have higher efficiency Gallium Arsenide solar cells, will give Hubble approximately 20 percent more power than the current arrays. In addition, their smaller cross section and rigidity will reduce aerodynamic drag and produce significantly less vibration than the existing wings (see Fig. 5-28).

New Solar Array Drive Mechanisms (SADM) also will be installed during SM3B. These mechanisms will maneuver the new arrays to keep them constantly pointed at the Sun. The European Space Agency (ESA) designed, developed and tested the SADMs. ESA used its world-class test facility in The Netherlands to subject the new arrays and drive mechanisms to realistic simulations of the extreme temperature cycles encountered in Hubble's orbit—including sunrise and sunset.



Item	Power	Size	Weight	Comments
SA2 Flexible Array	4600 W at 6 years (actual)	39.67 ft x 9.75 ft (12.1 m x 3.3 m)	339 lb per wing	Actual on-orbit performance measured at Winter Solstice, December 2000
SA3 Rigid Array	5270 W at 6 years (predicted)	24.75 ft x 8.0 ft (7.1 m x 2.6 m)	640 lb per wing	Increased capability for planned science Less shadowing and blockage

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Fig. 5-28 Solar Array wing detail comparison

Science Instrument Control and Data Handling Unit

The SI C&DH unit keeps all science instrument systems synchronized. It works with the DMU to process, format, temporarily store on the data recorders or transmit science and engineering data to the ground.

Components

The SI C&DH unit is a collection of electronic components attached to an ORU tray mounted on the door of Bay 10 in the SSM Equipment Section (see Fig. 5-29). Small Remote Interface Units (RIU), also part of the system, provide the interface to individual science instruments.

Components of the SI C&DH unit are:

- NASA Standard Spacecraft Computer (NSCC-I)
- Two standard interface circuit boards for the computer
- Two control units/science data formatter units (CU/SDF)
- Two CPU modules
- A PCU
- Two RIUs
- Various memory, data and command communications lines (buses) connected by couplers.

These components are redundant so the system can recover from any single failure.

NASA Computer. The NSSC-I has a CPU and eight memory modules, each holding 8,192 eighteen-bit words. One embedded software program (the "executive") runs the computer. It moves data, commands and operation programs (called applications) for individual science instruments in and out of the processing unit. The application programs monitor and control specific instruments, and analyze and manipulate the collected data.

The memory stores operational commands for execution when the Telescope is not in contact

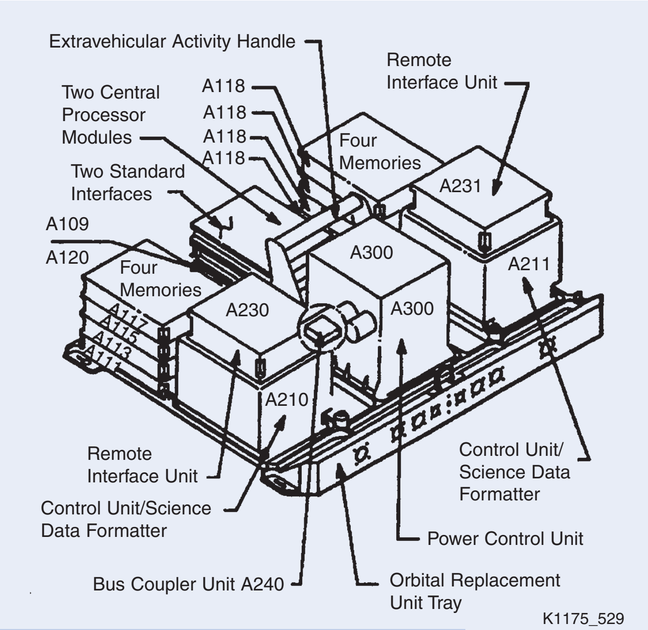

Fig. 5-29 Science Instrument Control and Data Handling unit

with the ground. Each memory unit has five areas reserved for commands and programs unique to each science instrument. The computer can be reprogrammed from the ground for future requests or for working around failed equipment.

Standard Interface Board. The circuit board is the communications bridge between the computer and the CU/SDF.

Control Unit/Science Data Formatter. The heart of the SI C&DH unit is the CU/SDF. It formats and sends all commands and data to designated destinations such as the DMU of the SSM, the NASA computer and the science instruments. The unit has a microprocessor for control and formatting functions.

The CU/SDF receives ground commands, data requests, science and engineering data, and system signals. Two examples of system signals are "time tags"—clock signals that synchronize the entire spacecraft—and "processor interface tables"—communications codes. The CU/SDF transmits commands and requests after formatting them so that the specific destination unit can read them. For example, ground commands and SSM commands are transmitted with different formats. Ground commands use 27-bit words and SSM commands use 16-bit words. The formatter translates each command signal into a common format. The CU/SDF also reformats and sends engineering and science data. Onboard analysis of the data is an NSSC-I function.

Power Control Unit. The PCU distributes and switches power among components of the SI C&DH unit. It conditions the power required by each unit. For example: The computer memory boards typically need +5 volts, -5 volts and +12 volts while the CU/SDF requires +28 volts. The PCU ensures that all voltage requirements are met.

Remote Interface Unit. RIUs transmit commands, clock and other system signals, and engineering data between the science instruments and the SI C&DH unit. However, the RIUs do not send science data. There are six RIUs in the Telescope: five attached to the science instruments and one dedicated to the CU/SDF and PCUs in the SI C&DH unit. Each RIU can be coupled with up to two expander units.

Communications Buses. The SI C&DH unit contains data bus lines that pass signals and data between the unit and the science instruments. Each bus is multiplexed: one line sends system messages, commands and engineering data requests to the module units, and a reply line transmits requested information and science data back to the SI C&DH unit. A coupler attaches the bus to each remote unit. This isolates the module if the RIU fails. The SI C&DH coupler unit is on the ORU tray.

Operation

The SI C&DH unit handles science instrument system monitoring (such as timing and system checks), command processing and data processing.

System Monitoring. Engineering data tells the monitoring computer whether instrument systems are functioning. At regular intervals, varying from every 500 milliseconds to every 40 seconds, the SI C&DH unit scans all monitoring devices for engineering data and passes data to the NSCC-I or SSM computer. The computers process or store the information. Any failure indicated by these constant tests could initiate a "safing hold" situation (refer to page 5-13, Safing (Contingency) System), and thus a suspension of science operations.

Command Processing. Figure 5-30 shows the flow of commands within the SI C&DH unit. Commands enter the CU/SDF (bottom right in the drawing) through the SSM Command DIU (ground commands) or the DIU (SSM commands). The CU/SDF checks and reformats the commands, which then go either to the RIUs or to the NSCC-I for storage. “Time-tagged” commands, stored in the computer’s memory (top right of drawing), also follow this process.

Each command is interpreted as “real time,” as if the SI C&DH just received it. Many commands actually are onboard stored commands activated by certain situations. For example, when the Telescope is positioned for a programmed observation using the Space Telescope Imaging Spectrograph, that program is activated. The SI C&DH can issue certain requests to the SSM, such as to execute a limited number of pointing control functions to make small Telescope maneuvers.

Science Data Processing. Science data can come from all science instruments at once. The CU/SDF transfers incoming data through computer memory locations called packet buffers. It fills each buffer in order, switching among them as the buffers fill and empty. Each data packet goes from the buffer to the NSCC-I for further processing, or directly to the SSM for storage in the data recorders or transmission to the ground. Data returns to the CU/SDF after computer processing. When transmitting, the CU/SDF must send a continuous stream of data, either full packet buffers or empty buffers called filler packets, to maintain a synchronized link with the SSM. Special checking codes (Reed-Solomon and pseudo-random noise) can be added to the data as options. Figure 5-30 shows the flow of science data in the Telescope.

Space Support Equipment

Hubble was designed to be maintained, repaired and enhanced while in orbit, extending its life and usefulness. For servicing, the Space Shuttle will capture and position the Telescope vertically in the aft end of the cargo bay, then the crew will perform maintenance and replacement tasks. The Space Support Equipment (SSE) provides a maintenance platform to hold the Telescope, electrical support of the Telescope during servicing and storage for replacement components known as ORUs.

The major SSE items to be used for SM3B are the Flight Support System (FSS) and and ORU Carriers (ORUC), comprising the Rigid Array Carrier (RAC), the Second Axial Carrier (SAC) and the Multi-Use Lightweight Equipment (MULE) carrier. Crew aids and tools also will be used during servicing. Section 2 of this guide describes details specific to SM3B.

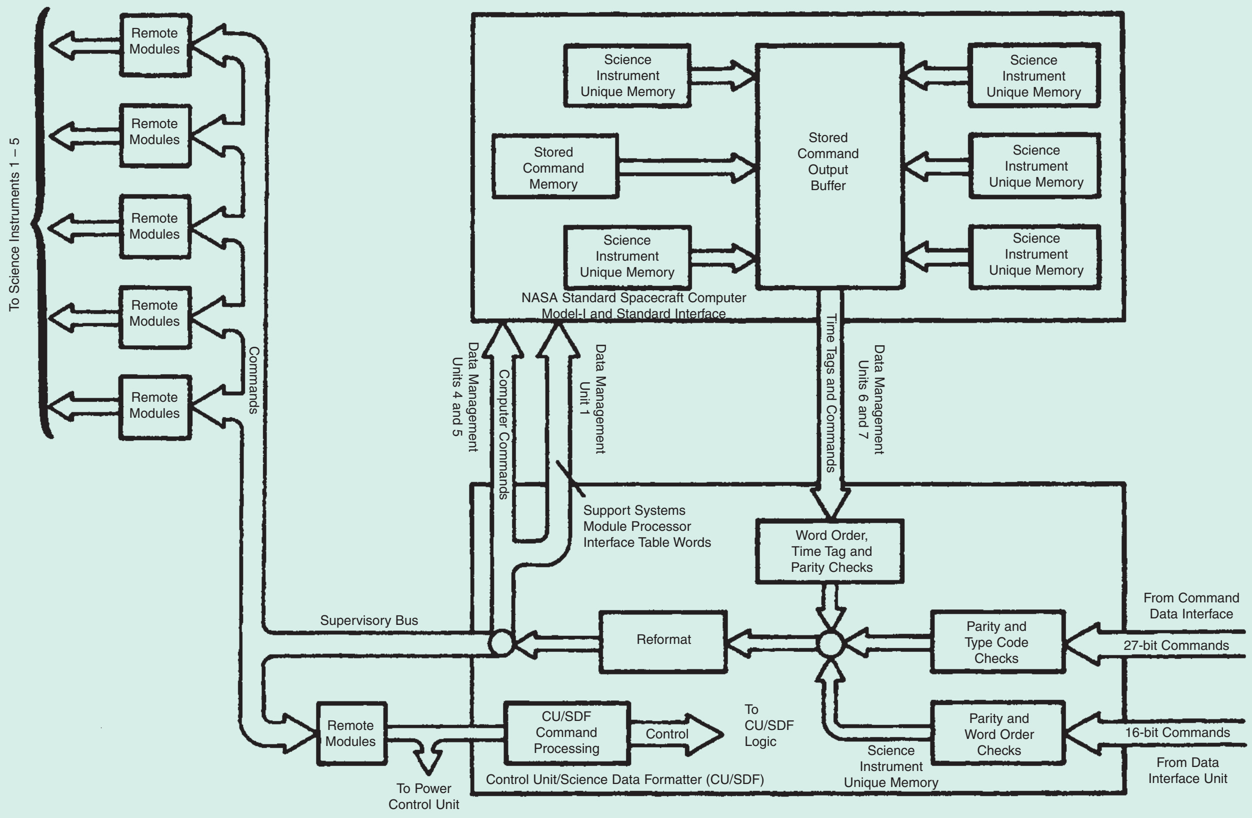

Fig. 5-30 Command flow for Science Instrument Control and Data Handling unit

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Orbital Replacement Unit Carrier

An ORUC is a pallet outfitted with shelves and/or enclosures that is used to carry replacements into orbit and to return replaced units to Earth. For SM3B the *Columbia* payload bay will contain three ORUCs. All ORUs and scientific instruments are carried within protective enclosures to provide them a benign environment throughout the mission. The enclosures protect the instruments from contamination and maintain the temperature of the instruments or ORUs within tight limits. Instruments are mounted in the enclosures using the same manually driven latch system that holds instruments in the Telescope.

During the change-out process, replaced science instruments are stored temporarily in the ORUC. A typical change-out begins with an astronaut removing the old instrument from the Telescope and attaching it to a bracket on the ORUC. The astronaut then removes the new instrument from its protective enclosure and installs it in the Telescope. Finally, the astronaut places the old instrument in the appropriate protective enclosure for return to Earth.

The ORUC receives power for its TCS from the FSS. The carrier also provides temperature telemetry data through the FSS for readout in the Shuttle and on the ground during the mission.

Crew Aids

Astronauts perform extravehicular activities using many tools to replace instruments and equipment, to move around the Telescope and the cargo bay, and to operate manual override drives. Tools and equipment, bolts, connectors and other hardware are standardized not only for the Telescope but also between the Telescope and the Shuttle. For example, grappling receptacles share common features.

To move around the Telescope, the crew uses 225 feet of handrails encircling the spacecraft. The rails are painted yellow for visibility. In addition, the crew can hold onto guiderails, trunnion bars and scuff plates fore and aft.

Astronauts can install portable handhold plates where there are no permanent holds, such as on the FGS. Another tool is the Portable Foot Restraint (PFR).

While the astronauts work, they use tethers to hook tools to their suits and tie replacement units to the Telescope. Each crew member has a ratchet wrench to manually crank the antenna and array masts if power for the mast drives fails. A power wrench also is available if hand-cranking is too time consuming. Other hand tools include portable lights and a jettison handle, which attach to sockets on the aperture door and to the SA wings so the crew can push the equipment away from the Telescope.

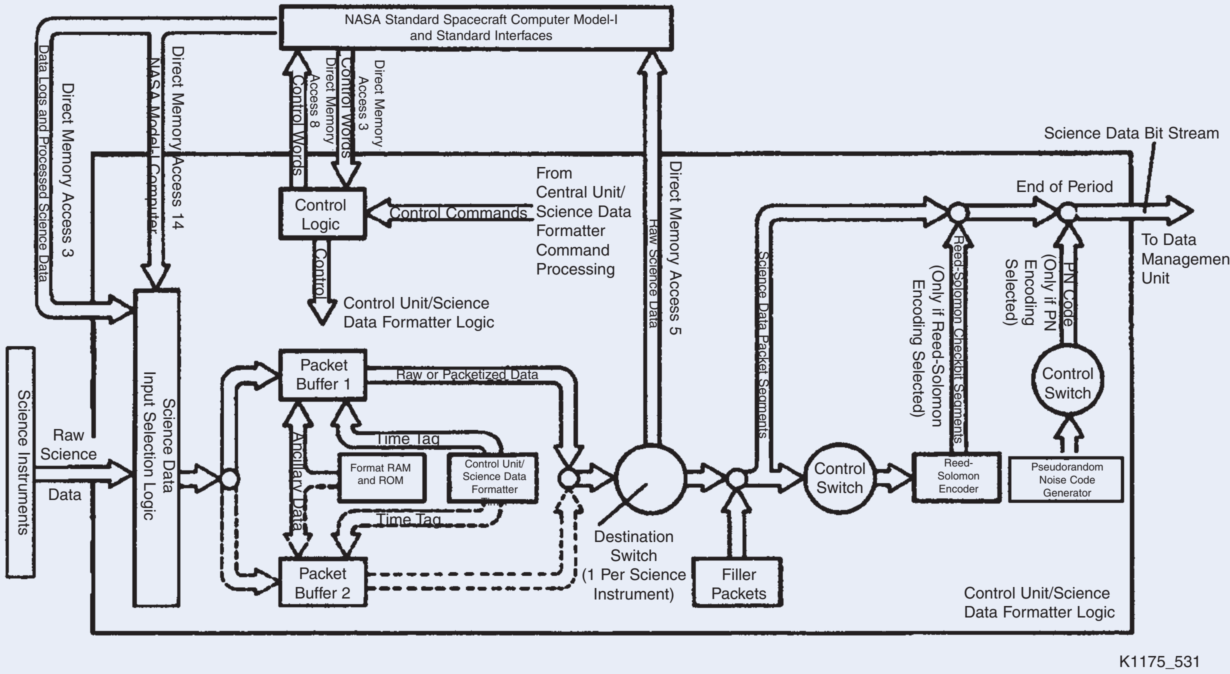
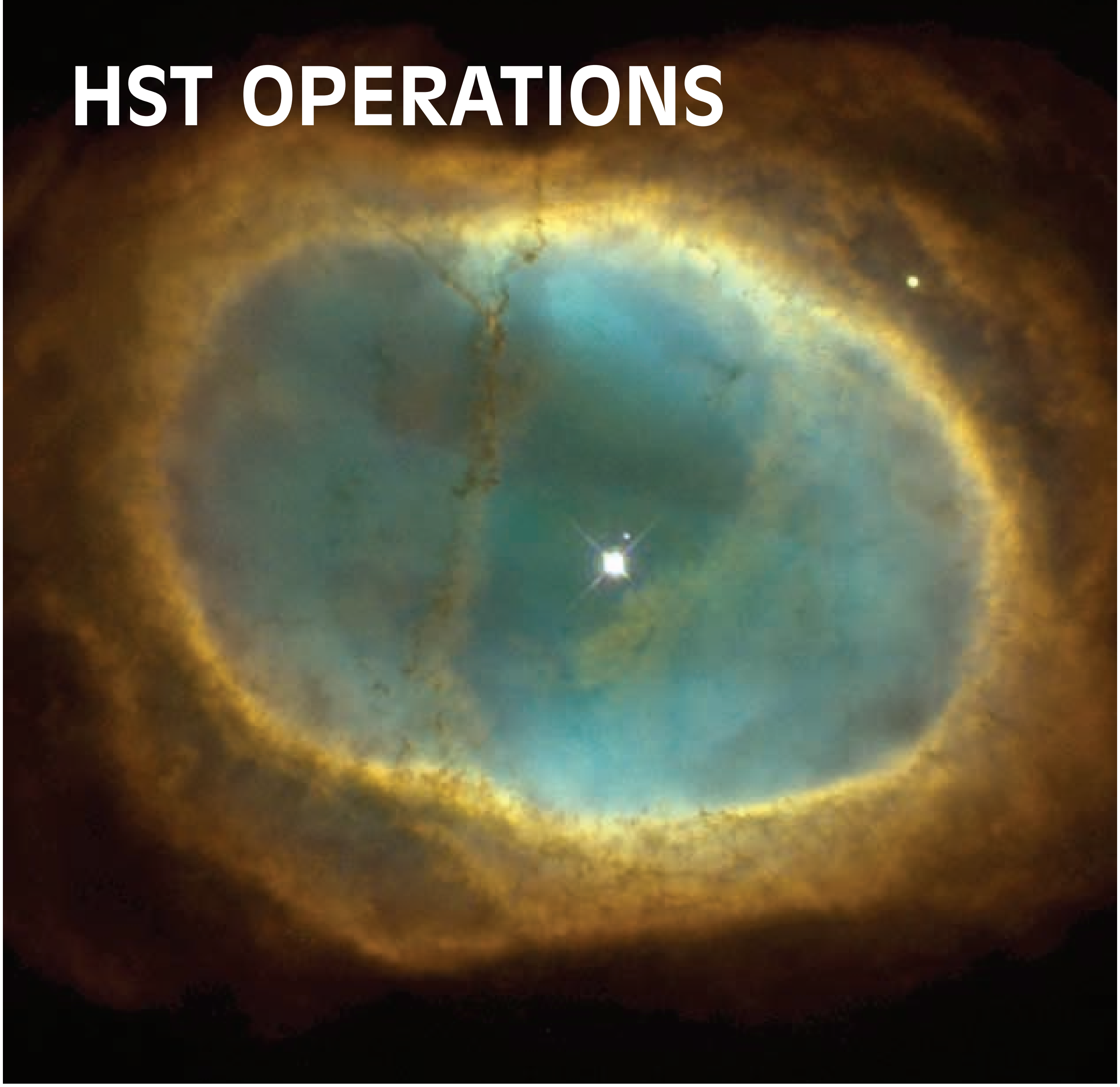


Fig. 5-31 Flow of science data in the Hubble Space Telescope

HST OPERATIONS



Hubble Space Telescope operations comprise (1) science operations and (2) mission operations. Science operations plan and conduct the HST science program—observing celestial objects and gathering data. Mission operations command and control HST to implement the observation schedule and maintain the Telescope's overall performance.

These two types of operations often coincide and interact. For example, a science instrument may observe a star and calibrate incoming wavelengths against standards developed during scientific verification. Mission operations monitor observations to ensure that Telescope subsystems have functioned correctly.

The HST ground system carries out day-to-day mission operations. This system consists of the Space Telescope Operations Control Center (STOCC) and other facilities at the Space Telescope Science Institute (STScI) in Baltimore, Maryland, and the Packet Processing Facility (PACOR) and other institutional facilities at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. A second STOCC at GSFC conducts the Servicing Missions.

Space Telescope Science Institute

The STScI oversees science operations for GSFC. Among its functions are to:

- Host astronomers.
- Evaluate proposals and choose observation programs.
- Schedule the selected observations and assist guest observers in their work.
- Generate an overall mission timeline and command sequences.
- Store and analyze science data from the Telescope.

STScI also monitors the Telescope and science instruments for characteristics that could affect science data collection, such as instrument performance quality, pointing inaccuracies and Telescope focus.

The flight operations team conducts mission operations from STOCC.

Scientific Goals

The Association of Universities for Research in Astronomy (AURA) operates STScI. AURA is a consortium of 29 United States universities that run several national facilities for astronomy.

STScI helps conduct the science program to meet the overall scientific goals of the Telescope program, set by the Institute and NASA in consultation with AURA's Space Telescope Institute Council and committees representing the international astronomical community.

STScI Software

Computer hardware and software play an important role in STScI work, including a mission planning and scheduling system and a science data processing system. STScI also created a guide star catalog used to support the precise pointing requirements of the HST pointing control subsystem. In addition, Science Data Analysis Software (SDAS) provides analytical tools for astronomers studying observational data.

As part of the Planning and Scheduling System, the STScI Guide Star Selection System (GSSS) provides reference stars and other bright objects so the Fine Guidance Sensors (FGS) can point the Telescope accurately. GSSS selects guide stars that can be located unambiguously in the sky when the sensors point the Telescope. The guide star catalog has information on 20 million celestial objects, created from 1,477 photographic survey plates covering the entire sky.

After STScI collects, edits, measures and archives science data, observers can use SDAS to analyze and interpret the data.

Selecting Observation Proposals

Astronomers worldwide may use the Telescope. Any scientist may submit a proposal to STScI outlining an observing program and describing the scientific objectives and instruments required.

STScI evaluates these requests for technical feasibility, conducts peer reviews and then chooses the highest ranked proposals. The final decision rests with the STScI director, advised by a review committee of astronomers and scientists from many institutions.

Because individual astronomers and astronomy teams submit many more proposals than can possibly be accepted, STScI encourages a team approach.

Scheduling Telescope Observations

The primary scheduling consideration is availability of a target, which may be limited by environmental and stray-light constraints. For example, a faint object occasionally must be observed when the Telescope is in Earth's shadow. The schedule takes into consideration system limits, observations that use more than one instrument and required time for special observations.

Data Analysis and Storage

STScI is responsible for storing the massive amount of data collected by the Telescope. The Hubble Data Archive catalog records the location and status of data as it pours into the storage banks. Observers and visiting astronomers can easily retrieve the stored data for examination or use data manipulation procedures created by the STScI.

The European Space Agency (ESA) provides approximately 15 staff members co-located with STScI staff and operates its own data analysis facility in Garching, Germany.

In addition to science data, the STScI stores engineering data. This is important for developing more efficient use of the Telescope systems and for adjusting Telescope operations based on engineering findings, for example, if an instrument provides unreliable data in certain temperature ranges.

STScI processes all data within 24 hours after receipt. When STScI receives science data from PACOR, it automatically formats the data and verifies its quality. STScI also calibrates data to remove the instrument's properties such as a variation in the detector's sensitivity across the data field. Then the software places the data on digital archive media from which the data can be formatted and distributed to an observer or archival researcher.

Space Telescope Operations Control Center

The STOCC flight operation team runs day-to-day spacecraft operations at STScI. In addition, the STOCC team works with the NASA Communications Network (NASCOM) and the Tracking and Data Relay Satellite System (TDRSS) to facilitate HST data communications.

NASA built the Vision 2000 Control Center System (CCS) specifically to support the HST

Third Servicing Missions (SM3A and SM3B). The CCS provides distributed capabilities with a completely new user interface that is on the forefront of spacecraft operations.

STOCC has three major operational responsibilities:
- Spacecraft operations, including sending commands to the spacecraft
- Telemetry processing
- Offline support.

Most spacecraft operations derive from time-tagged commands managed by the Telescope's onboard software. Using the CCS, the STOCC flight operations team uplinks the commands to the HST computers.

Engineering telemetry, received in the STOCC from the GSFC institutional communication system, provides information on the HST spacecraft subsystem status. For example, telemetry can verify Pointing Control System operation and stability performance of the Telescope. Many cases require consultation between STOCC and STScI, particularly if the data affects an ongoing observation.

An important part of the ground system is PACOR processing. When data arrives from NASCOM for science handling, PACOR reformats the data, checks for noise or transmission problems, and passes the data to the STScI along with a data quality report.

Another important STScI function is to support observers requiring a "quick-look" analysis of data. STScI alerts PACOR to that need, and the incoming data can be processed for the observers.

TDRSS has two communications relay satellites 130 degrees apart and a ground terminal at White Sands, New Mexico. There is a small "zone of exclusion" where Earth blocks the Telescope signal to either satellite, but up to 91 percent of the Telescope's orbit is within communications coverage. Tracking and Data Relay Satellites (TDRS) receive and send both single-access (science data) and multiple-access (commands and engineering data) channels.

Operational Characteristics

Three major operational factors affect the success of the Telescope:
- Orbital characteristics for the spacecraft
- Maneuvering characteristics
- Communications characteristics for sending and receiving data and commands.

Orbital Characteristics

The Telescope's orbit is approximately 320 nmi (593 km). The orbit inclines at a 28.5-degree angle from the equator because the Shuttle launch was due east from Kennedy Space Center. This orbit puts the Sun in the Telescope orbital plane so that sunlight falls more directly on the Solar Arrays. In addition, 320 nmi is high enough that aerodynamic drag from the faint atmosphere will not decay the Telescope's orbit to below the minimum operating altitude.

HST completes one orbit every 97 minutes, passing into the shadow of the Earth during each orbit. The time in shadow varies from 28 to 36 minutes. During a nominal 30-day period, the variation is between 34.5 and 36 minutes. If Earth blocks an object from the Telescope, the Telescope reacquires the object as the spacecraft comes out of Earth's occultation. Faint-object viewing is best while the Telescope is in Earth's shadow.

TDRSS tracks the Telescope's orbit, plotting the orbit at least eight times daily and sending the data to the Flight Dynamics Facility at GSFC. Although this helps predict future orbits, some inaccuracy in predicting orbital events, such as exit from Earth's shadow, is unavoidable. The environmental elements with greatest effect on the Telescope's orbit are solar storms and other solar activities. These thicken the upper atmosphere and increase the drag force on the Telescope, accelerating the orbit decay rate.

Celestial Viewing

As a normal orientation, the Telescope is pointed toward celestial targets to expose instrument detectors for up to 10 hours. A continuous-viewing zone exists, parallel to the orbit plane of the Telescope and up to 18 degrees on either side of the north and south poles of that orbital plane (see Fig. 6-1). Otherwise, celestial viewing depends on how long a target remains unblocked by Earth.

The amount of shadow time available for faint-object study also affects celestial observations. Shadow time for an observation varies with the time of year and the location of the target relative to the orbit plane. Astronomers use a geometric formula to decide when a target will be most visible.

Other sources affecting celestial viewing are zodiacal light and integrated or background starlight.

Solar System Object Viewing

The factors mentioned for celestial viewing also affect solar system objects. In addition, the Telescope works with imprecise orbit parameters for itself and objects such as the outer planets and comets. For example, Neptune's center may be off by 21 km when the sensors try to lock onto it because the Telescope is changing its position in orbit,

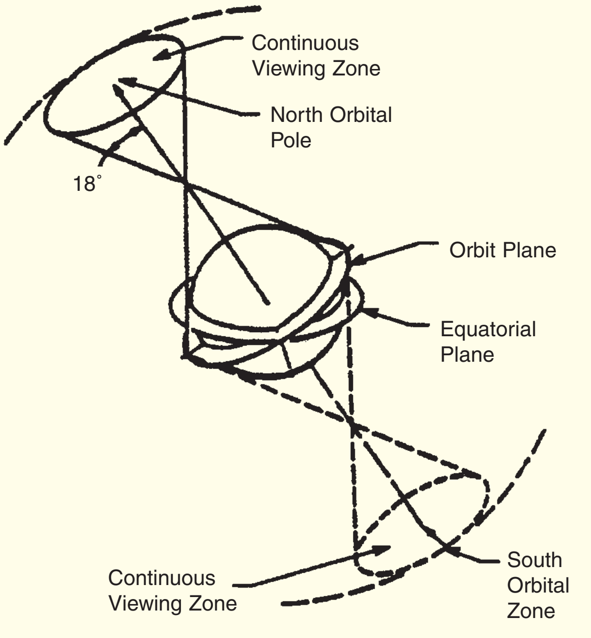


Fig. 6-1 "Continuous-zone" celestial viewing

altering the pointing direction to nearby objects. However, most solar system objects are so bright the Telescope needs only a quick snapshot of the object to fix its position. Tracking inaccuracies are more likely to cause a blurred image if they occur during long-exposure observations of dim targets.

The Telescope's roll attitude also may affect the view of the object and require a maneuver that rolls the spacecraft more than the 30-degree limit—for example, to place the image into a spectrographic slit aperture.

Tracking interior planets (Mercury and Venus) with the Telescope places the Sun within the Telescope opening's 50-degree Sun-exclusion zone. For this reason, HST never observes Mercury and has observed Venus only once, using Earth to block (occult) the Sun.

Natural Radiation

Energetic particles from different sources continuously bombard the Telescope as it travels around the Earth. Geomagnetic shielding blocks much of the solar and galactic particle radiation. When the Telescope passes through the South Atlantic Anomaly (SAA), a "hole" in Earth's magnetic field, charged particles can enter the Telescope and strike its detectors, emitting electrons and producing false data.

The Telescope passes through the SAA for segments of eight or nine consecutive orbits, then has no contact with it for six or seven orbits. Each encounter lasts up to 25 minutes. In addition, the SAA rotates with Earth, so it occasionally coincides with the Telescope as the spacecraft enters Earth-shadow observation periods. Careful scheduling minimizes the effects of the anomaly, but it has some regular impact.

Solar flares are strong pulses of solar radiation, accompanied by bursts of energetic particles. Earth's magnetic field shields the lower magnetic latitude regions, such as the Telescope's orbit inclination, from most of these charged particles. NASA regularly monitors the flares, and the Telescope can stop an observation until the flares subside.

Maneuvering Characteristics

The Telescope changes its orientation in space by rotating its reaction wheels, then slowing them. The momentum change caused by the reaction moves the spacecraft at a baseline rate of 0.22 degree per second or 90 degrees in 14 minutes. Figure 6-2 shows a roll-and-pitch maneuver. When the Telescope maneuvers, it takes a few minutes to lock onto a new target and accumu-

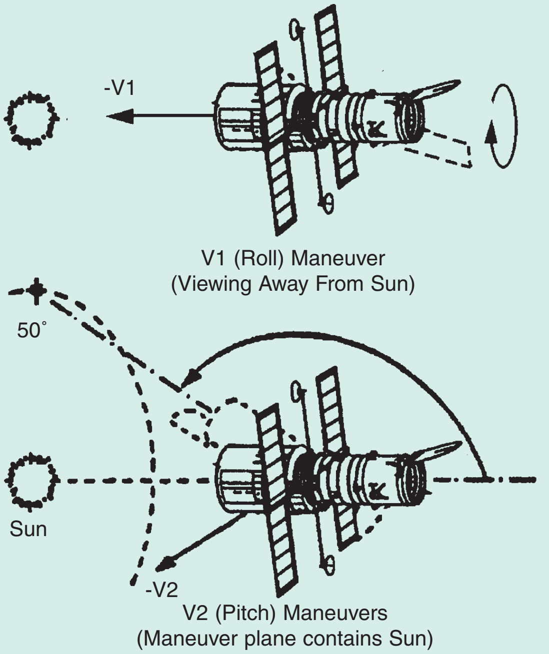


Fig. 6-2 HST single-axis maneuvers

late drift errors. This means that a larger region of the sky must be scanned for guide stars.

One consideration with maneuvering is the danger of moving the Solar Array wings out of the Sun's direct radiation for too long. Therefore, maneuvers beyond a certain range in angle and time are limited.

When the Telescope performs a pitch to a target near the 50-degree Sun-avoidance zone, the Telescope curves away from the Sun. For example, if two targets are opposed at 180 degrees just outside the 50-degree zone, the Telescope follows an imaginary circle of 50 degrees around the Sun until it locates the second target (see Fig. 6-3).

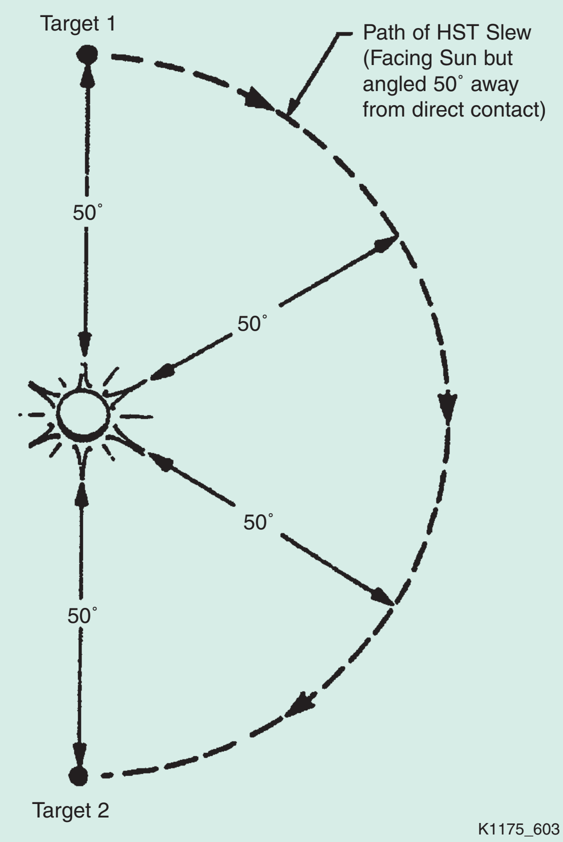


Fig. 6-3 Sun-avoidance maneuver

Communications Characteristics

HST communicates with the ground via TDRSS. With two satellites 130 degrees apart in longitude, the maximum amount of contact time is 94.5 minutes of continuous communication, with only 2.5 to 7 minutes in a zone of exclusion out of reach of either TDRS (see Fig. 6-4). However, orbital variations by the Telescope and communications satellites slightly widen the zone of exclusion.

GSFC's Network Control Center (NCC) schedules all TDRS communications. The Telescope has a general orbital communication schedule, supplemented by specific science requests. The NCC prepares schedules 14 days before the start of each mission week.

The backup communications link is the Ground Network, which receives engineering data or science data if the High Gain Antennas (HGA) cannot transmit to TDRSS. The longest single contact time is 8 minutes. The limiting factor of this backup system is the large gap in time between contacts with the Telescope. In practical terms, at least three contacts are required to read data from a filled science data recorder—with gaps of up to 11 hours between transmissions.

To avoid unnecessary gaps in communication, each HGA maintains continuous contact with one TDRS. Each antenna tracks the communication satellite, even during fine-pointing maneuvers.

Low Gain Antennas provide at least 95 percent orbital coverage via a TDRS for the minimum multiple-access command rate used.

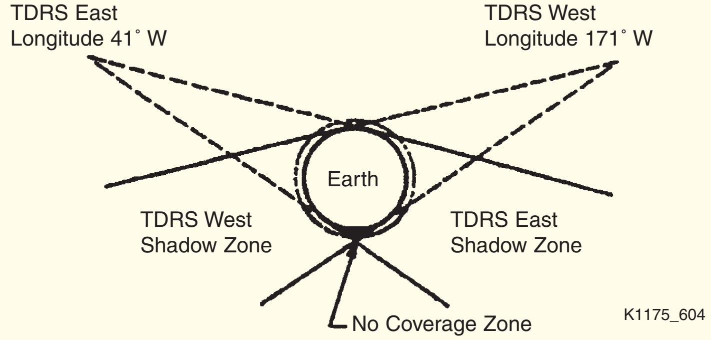


Fig. 6-4 TDRS-HST contact zones

Acquisition and Observation

The major steps in the observation process are (1) target acquisition and observation, (2) data collection and transmission and (3) data analysis.

Each science instrument has an entrance aperture, located in different portions of the Hubble's focal plane. These positions make precise pointing a sometimes-lengthy procedure for the FGSs, which must center the target in small apertures. Additional time is required to reposition the Telescope: an estimated 18 minutes to maneuver 90 degrees plus the time the sensors take to acquire the guide stars. If the Telescope overshoots its target, the Fixed Head Star Trackers may have to make coarse-pointing updates before the Telescope can use the FGSs again.

To increase the probability of a successful acquisition, Telescope flight software allows the use of multiple guide-star pairs to account for natural contingencies that might affect a guide-star acquisition—such as a guide star being a binary star and preventing the FGSs from getting a fine lock on the target. Therefore, an observer can submit a proposal that includes a multiple selection of guide-star pairs. If one pair proves too difficult to acquire, the sensors can switch to the alternate pair. However, each observation has a limited total time for acquiring and studying the target. If the acquisition process takes too long, the acquisition logic switches to coarse-track mode for that observation to acquire the guide stars.

Three basic modes are used to target a star.

Mode 1 points the Telescope, then transmits a camera image, or spectrographic or photometric pseudo-image, to STOCC. Ground computers make corrections to precisely point the Telescope, and the coordinates pass up through the Advanced Computer.

Mode 2 uses onboard facilities, processing information from the larger target apertures, then aiming the Telescope to place the light in the chosen apertures.

Mode 3 uses the programmed target coordinates in the star catalog or updated acquisition information to reacquire a previous target. Called blind pointing, this is used mostly for generalized pointing and for the Wide Field and Planetary Camera 2, which does not require such precise pointing. Mode 3 relies increasingly on the updated guide-star information from previous acquisition attempts, stored in the computer system.

VALUE ADDED:
The Benefits of Servicing Hubble

Every few years, a team of astronauts carries a full manifest of new equipment on the Space Shuttle for the ultimate “tune-up” in space: maintaining and upgrading the Hubble Space Telescope on orbit.

This ability is one of Hubble’s important features. When the Telescope was being designed, the Space Shuttle was being readied for its first flights. NASA realized that if a shuttle crew could service HST, it could be maintained and upgraded indefinitely. So from the beginning, Hubble was designed to be modular and astronaut friendly.

The modular design allows NASA to periodically re-equip HST with state-of-the-art scientific instruments—giving the Telescope exciting new capabilities (see Fig. 7-1). In addition to science upgrades, the servicing missions permit astronauts to replace limited-life components with systems incorporating the latest technology (see Fig. 7-2).

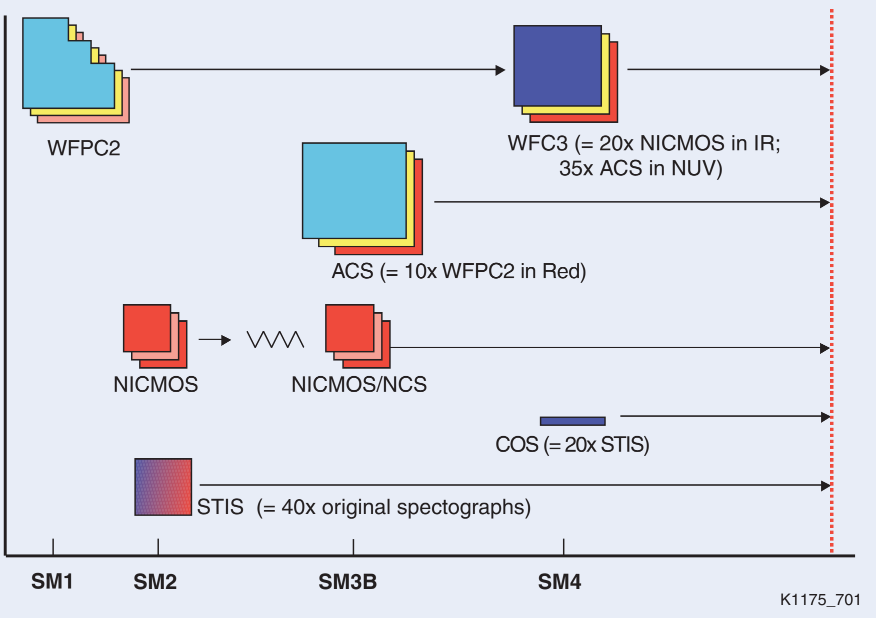


Fig. 7-1 Advanced scientific instruments installed (or to be installed) on HST pave the way to new discoveries.

Cost-Effective Modular Design

The 1993 and 1997 servicing missions increased Hubble’s scientific exposure time efficiencies 11-fold. Astronauts installed two next-generation scientific instruments, giving the Telescope infrared and ultraviolet vision, and a Solid State Recorder (SSR), further expanding its observing capability.

During Servicing Mission 3B (SM3B), astronauts will add a camera 10 times more powerful than the

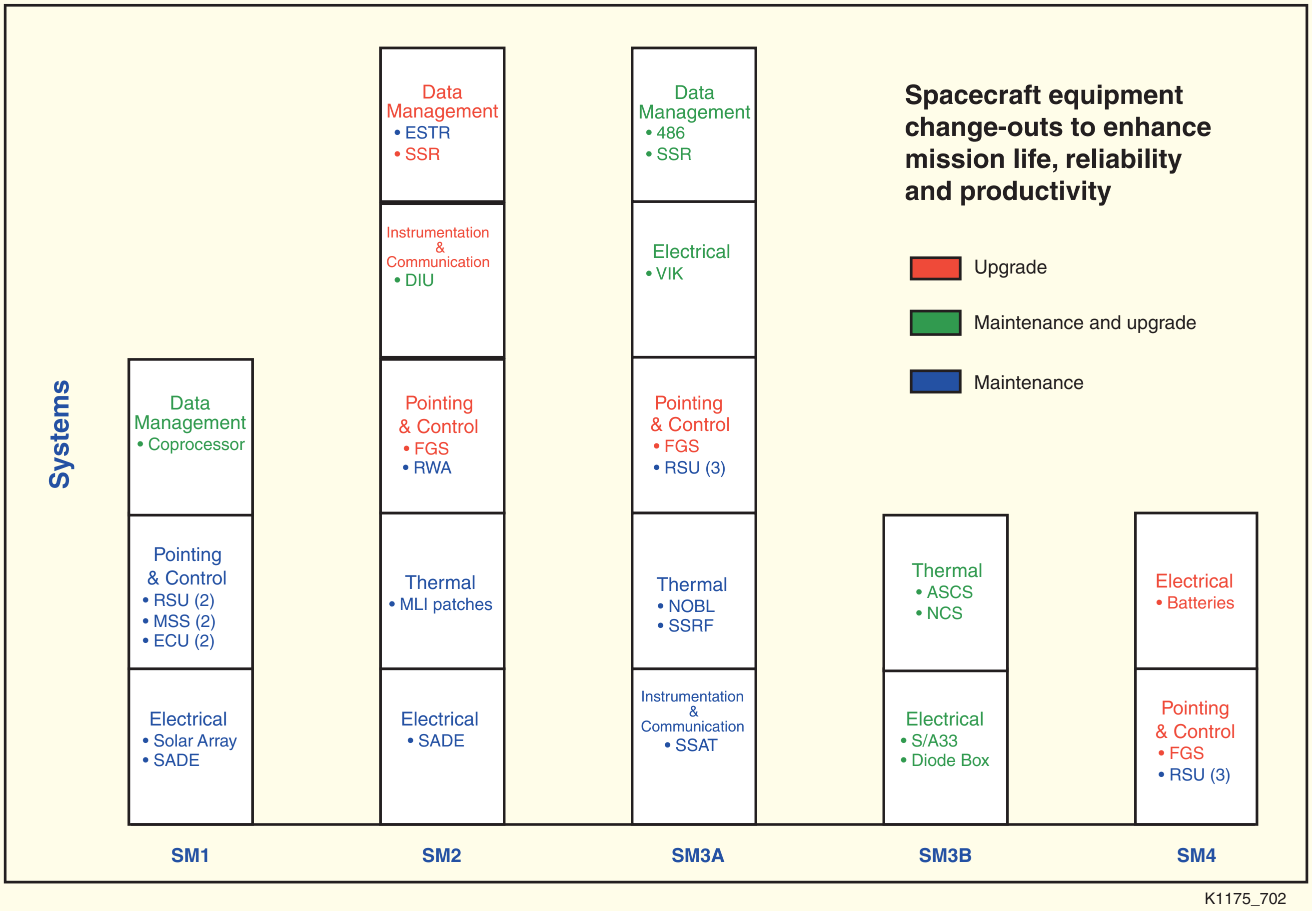


Fig. 7-2 Systems maintained and upgraded during each servicing mission

already extraordinary cameras on board. They also will fit the Telescope with new, super-efficient solar array panels that will allow simultaneous operation of scientific instruments. These technologies were not available when Hubble was designed and launched.

The following sections identify some of the planned upgrades to HST and their anticipated benefits to performance. These improvements demonstrate that servicing HST results in significant new science data at greatly reduced cost.

Processor

During Servicing Mission 3A (SM3A), astronauts replaced Hubble's original main computer, a DF-224/coprocessor combination, with a completely new Advanced Computer based on the Intel 80486 microchip. This computer is 20 times faster and has six times as much memory as the one it replaced (see Fig. 7-3).

In a good example of NASA's goal of "faster, better, cheaper," commercially developed and commonly available equipment was used to build the new computer at a fraction of the cost of a computer designed specifically for the spaceflight environment.

The new computer's capabilities have increased Hubble's productivity by performing more work in space and less work on the ground. In addition, the

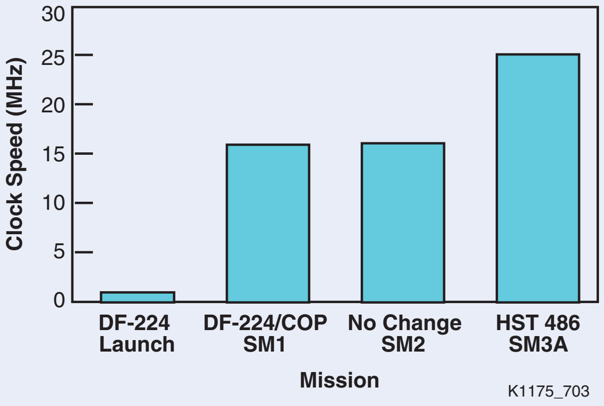


Fig. 7-3 Processor improvements

computer uses a modern programming language, which decreases software maintenance cost.

Data Archiving Rate

The addition of a second SSR during SM3A dramatically increased Hubble's data storage capability. The science data archiving rate is more than 10 times greater than First Servicing Mission (1993) rates (see Fig. 7-4). Prior to the Second Servicing Mission (SM2 in 1997), Hubble used three reel-to-reel tape recorders designed in the 1970s. SM2 astronauts replaced one of the mechanical recorders with a digital SSR.

Unlike the reel-to-reel recorders, the SSRs have no reels, no tape and no moving parts that can wear out and limit lifetime. Data is stored digitally in computer-like memory chips until Hubble operators command its playback.

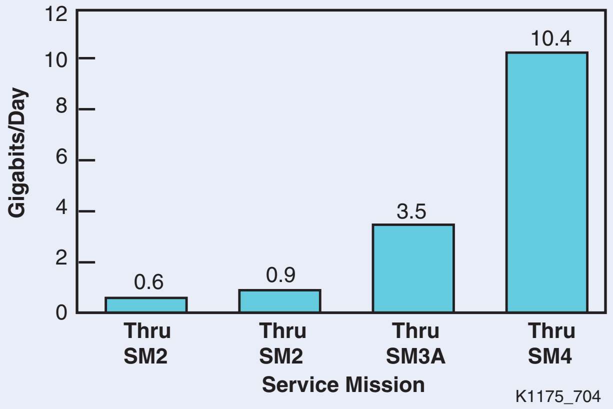


Fig. 7-4 Data archiving rate improvements

Although an SSR is about the same size and shape as a reel-to-reel recorder, it can store 10 times as much data: 12 gigabits instead of only 1.2 gigabits. This greater storage capacity allows Hubble's second- generation scientific instruments to be fully productive.

Detector Technology

Advanced detector technology allows the Telescope to capture and process faint amounts of light from the far reaches of space. Increased power and resolution refinements will enhance Hubble's performance, delivering even sharper, clearer and more distinct images.

Adding the Advanced Camera for Surveys during SM3B will increase the total number of onboard pixels *4800 percent* (see Fig. 7-5).

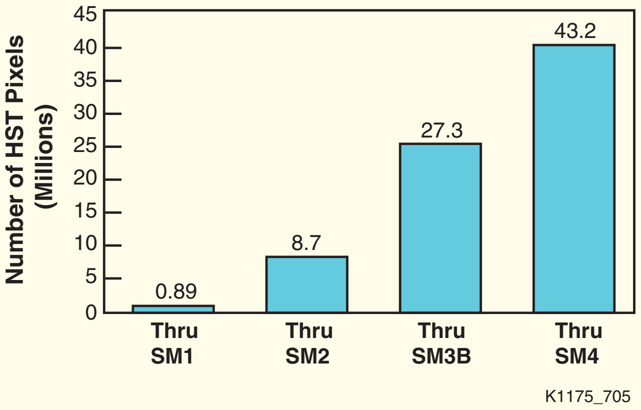


Fig. 7-5 Increase in onboard pixels

Cryogenic Cooler

Installation of the Near Infrared Camera and Multi Object Spectrograph (NICMOS) Cryogenic Cooler (NCC) during SM3B will greatly extend the life of Hubble's infrared cameras.

NICMOS, which was installed on Hubble in 1997, has been a spectacular success. However, in January 1999 it ran out of the coolant necessary for conducting scientific operations. The new NCC will increase NICMOS's lifetime seven-fold—from 1.8 years to 10 years (see Fig. 7-6).

The cost to develop and install the NCC is approximately $21 million, while the cost of NICMOS was $100 million. Installing the cryocooler will preserve and extend the instrument's unique science contribution, ensuring a greater return on the original investment.

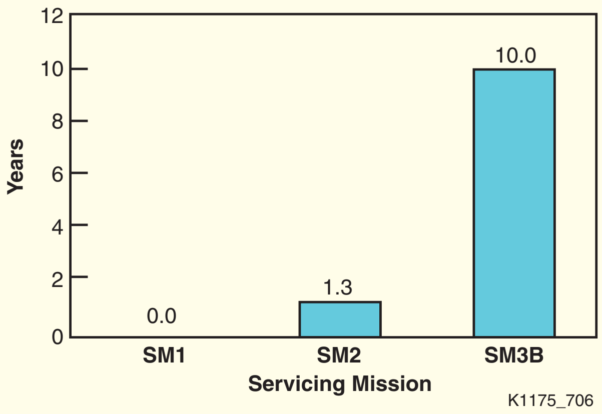


Fig. 7-6 Increase in HST infrared capability

Solar Arrays

New, rigid solar arrays installed during SMB3 will provide substantially more energy to Hubble. The increased power will enhance productivity by allowing simultaneous operation of up to four Hubble instruments (see Fig. 7-7).

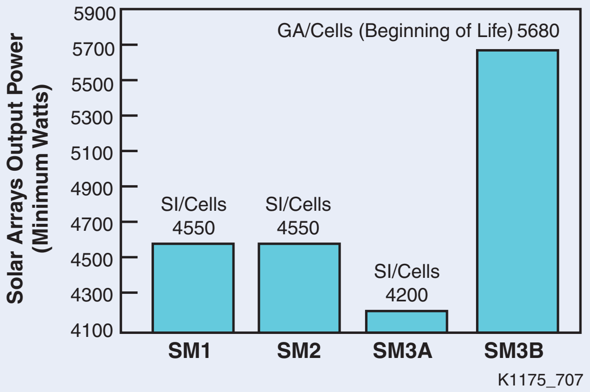


Fig. 7-7 Productivity gains with new solar arrays

Simultaneous Science

One of the most exciting advances afforded by servicing is the ability to double the simultaneous operations of scientific instruments. Originally, the instruments were designed to work in pairs. Following SM3B, developments in solar array technology and thermal transport systems will allow four science instruments to operate at the same time, dramatically increasing Hubble's ability to study the universe (see Fig. 7-8).

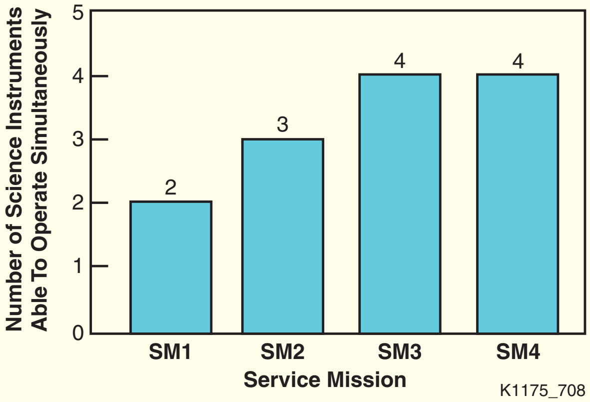


Fig. 7-8 Simultaneous use of science instruments

-A-

Å	Angstrom
aberration	Property of an optical system that causes an image to have certain easily recognizable flaws. Aberrations are caused by geometrical factors such as the shapes of surfaces, their spacing and alignments. Image problems caused by factors such as scratches or contamination are not called aberrations.
ACE	Actuator Control Electronics
ACS	Advanced Camera for Surveys
acquisition, target	Orienting the HST line of sight to place incoming target light in an instrument's aperture
actuator	Small, high-precision, motor-driven device that can adjust the location and orientation of an optical element in very fine steps, making fine improvements to the focus of the image
Advanced Computer	A 486-based computer that replaced the DF-224 on SM-3A. Performs onboard computations and handles data and command transmissions between HST systems and the ground system
AFM	Adjustable Fold Mirror
aft	Rear of the spacecraft
alignment	Process of mounting optical elements and adjusting their positions and orientations so that light follows exactly the desired path through the instrument and each optical element performs its function as planned
altitude	Height in space
AMA	Actuator Mechanism Assembly
AME	Actuator Mechanism Electronics
APE	Articulating PFR Extender
aperture	Opening that allows light to fall onto an instrument's optics
aplanatic	Image corrected everywhere in the field of view
apodizer	Masking device that blocks stray light
arcsec	A wedge of angle, 1/3600th of 1 degree, in the 360-degree "pie" that makes up the sky. An arcminute is 60 seconds; a degree is 60 minutes.
ASCS	Aft Shroud Cooling System
ASLR	Aft Shroud Latch Repair (kits)
ASIPE	Axial Scientific Instrument Protective Enclosure

astigmatism	Failure of an optical system, such as a lens or a mirror, to image a point as a single point
astrometry	Geometrical relations of the celestial bodies and their real and apparent motions
ATM	Auxiliary Transport Module
attitude	Orientation of the spacecraft's axes relative to Earth
AURA	Association of Universities for Research in Astronomy
axial science instruments	Four instruments—the STIS, NICMOS, FOC and COSTAR—located behind the primary mirror. Their long dimensions run parallel to the optical axis of the HST.

-B-

baffle	Material that extracts stray light from an incoming image
BAPS	Berthing and Positioning System
BPS	BAPS Support Post

-C-

C	Celsius
Cassegrain	Popular design for large, two-mirror reflecting telescopes in which the primary mirror has a concave parabolic shape and the secondary mirror has a convex hyperbolic shape. A hole in the primary allows the image plane to be located behind the large mirror.
CASH	Cross Aft Shroud Harness
CAT	Crew Aids and Tools
CCC	Charge Current Controller
CCD	Charge-coupled device
CCS	Control Center System
CDI	Command data interface
change-out	Exchanging a unit on the satellite
cm	Centimeter
collimate	To straighten or make parallel two light paths
coma	Lens aberration that gives an image a "tail"
concave	Mirror surface that bends outward to expand an image

convex	Mirror surface that bends inward to concentrate on an image
coronograph	Device that allows viewing a light object's corona
COS	Cosmic Origins Spectrograph
COSTAR	Corrective Optics Space Telescope Axial Replacement
CPL	Capillary Pumped Loop
CPM	Central Processor Module
CPU	Central Processing Unit
CSS	Coarse Sun Sensor
CTVC	Color television camera
CU/SDF	Control Unit/Science Data Formatter
CVL	NICMOS Cryo Vent Line

-D-

DBA	Solar array Diode Box Assembly
DBC	Diode Box Controller
diffraction grating	Device that splits light into a spectrum of the component wavelengths
DIU	Data Interface Unit
DMS	Data Management Subsystem
DMU	Data Management Unit
drag, atmospheric	Effect of atmosphere that slows a spacecraft and forces its orbit to decay

-E-

ECA	Electronic Control Assembly
ECU	Electronics Control Unit
electron	Small particle of electricity
ellipsoid	Surface whose intersection with every plane is an ellipse (or circle)
EPDSU	Enhanced Power Distribution and Switching Unit
EPS	Electrical Power Subsystem
EP/TCE	Electrical Power/Thermal Control Electronics

ESA	European Space Agency
ESM	Electronics Support Module
E/STR	engineering/science data recorders
EVA	extravehicular activity
extravehicular	Outside the spacecraft; activity in space conducted by suited astronauts

-F-

F	Fahrenheit
FGE	Fine Guidance Electronics
FGS	Fine Guidance Sensor
FHST	Fixed Head Star Tracker
FOC	Faint Object Camera
focal plane	Axis or geometric plane where incoming light is focused by the telescope
FOSR	Flexible optical solar reflector
FOV	Field of view
FPS	Focal plane structure
FPSA	Focal plane structure assembly
FRB	Fastener retention block
FS	Forward Shell
FSIPE	FGS Scientific Instrument Protective Enclosure
FSS	Flight Support System

-G-

GA	Gallium arsenide
G/E	Graphite-epoxy
GE	General Electric
GGM	Gravity Gradient Mode
GSE	Ground support equipment
GSFC	Goddard Space Flight Center

GSSS	Guide Star Selection System
GSTDN	Ground Spaceflight Tracking and Data Network

-H-

HGA	High Gain Antenna
HRC	ACS High Resolution Channel
HST	Hubble Space Telescope
hyperboloidal	Slightly deeper curve, mathematically, than a parabola; shape of the primary mirror
Hz	Hertz (cycles per second)

-I-

IBM	International Business Machines Corporation
in.	Inch
interstellar	Between celestial objects; often refers to matter in space that is not a star, such as clouds of dust and gas
intravehicular	Inside the spacecraft
IOU	Input/output unit
IR	Infrared
IV	Intravehicular
IVA	Intravehicular activity

-J-

JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center

-K-

k	Kilo (1000)
kB	Kilobytes
kg	Kilogram
km	Kilometer
KSC	Kennedy Space Center

-L-

Latch	Mechanical device that attaches one component, such as a science instrument, to the structure of the telescope and holds it in precisely the right place
LGA	Low Gain Antenna
LGA PC	Low Gain Antenna Protective Cover
Light-year	The distance traveled by light in 1 year, approximately 6 trillion miles
LMSSC	Lockheed Martin Space Systems Company
LOPE	Large ORU Protective Enclosure
LOS	Line of sight
LS	Light Shield
luminosity	Intensity of a star's brightness

-M-

m	Meter; apparent visual magnitude
M	Absolute visual magnitude
μm	Micrometer; 1 millionth of a meter
mm	Millimeter
MA	Multiple access
magnitude, absolute	How bright a star appears without any correction made for its distance
magnitude, apparent	How bright a star would appear if it were viewed at a standard distance
MAMA	Multi-Anode Microchannel Plate Array
MAT	Multiple Access Transponder
MCC	Mission Control Center
MCP	Microchannel plate
metrology	Process of making extremely precise measurements of the relative positions and orientations of the different optical and mechanical components
MFR	Manipulator Foot Restraint
MHz	Megahertz
MLI	Multi-layer insulation

Mpc	Megaparsec (1 million parsecs)
MOPE	Multimission ORU Protective Enclosure
MSFC	Marshall Space Flight Center
MSM	Mode Selection Mechanism
MSS	Magnetic Sensing System
MT	Magnetic torquer
MTA	Metering Truss Assembly
MTS	Metering Truss Structure
MULE	Multi-Use Lightweight Equipment carrier

-N-

NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Laboratory at JSC
NASCOM	NASA Communications Network
NCC	Network Control Center; NICMOS Cryocooler
NCS	NICMOS Cooling System
nebula	Mass of luminous interstellar dust and gas, often produced after a stellar nova
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
nm	Nanometers
nmi	Nautical miles
NOBL	New Outer Blanket Layer
nova	Star that suddenly becomes explosively bright
NPE	NOBL Protective Enclosure
NSSC-I	NASA Standard Spacecraft Computer, Model-I
NT	NOBL Transporter

-O-

occultation	Eclipsing one body with another
OCE	Optical Control Electronics

OCE-EK	OCE Enhancement Kit
OCS	Optical Control Subsystem
Orientation	Position in space relative to Earth
ORU	Orbital Replacement Unit
ORUC	Orbital Replacement Unit Carrier
OSS	Office of Space Science, NASA Headquarters
OTA	Optical Telescope Assembly

-P-

PACOR	Packet Processing Facility
parallax	Change in the apparent relative orientations of objects when viewed from different positions
parsec	A distance equal to 3.26 light-years
PCEA	Pointing Control Electronics Assembly
PCS	Pointing Control Subsystem
PCU	Power Control Unit
PDA	Photon Detector Assembly
PDM	Primary Deployment Mechanism
PDU	Power Distribution Unit
PFR	Portable Foot Restraint
photon	Unit of electromagnetic energy
PIP	Push in-pull out (pin)
pixel	Single picture element of a detection device
POCC	Payload Operations Control Center
polarity	Light magnetized to move along certain planes. Polarimetric observation studies the light moving along a given plane.
primary mirror	Large mirror in a reflecting telescope the size of which determines the light-gathering power of the instrument
prism	Device that breaks light into its composite wavelength spectrum
PSEA	Pointing/Safemode Electronics Assembly
PSO	HST Project Science Office at GSFC

-Q-

quasar	Quasi-stellar object of unknown origin or composition

-R-

RAC	Rigid Array Carrier
RAM	Random-access memory
radial	Perpendicular to a plane (i.e., instruments placed at a 90-degree angle from the optical axis of the HST)
RBM	Radial Bay Module
RDA	Rotary Drive Actuator
reboost	To boost a satellite back into its original orbit after the orbit has decayed because of atmospheric drag
reflecting telescope	Telescope that uses mirrors to collect and focus incoming light
refracting telescope	Telescope that uses lenses to collect and focus light
resolution	Ability to discriminate fine detail in data. In an image, resolution refers to the ability to distinguish two objects very close together in space. In a spectrum, it is the ability to measure closely separated wavelengths.
resolution, spectral	Determines how well closely spaced features in the wavelength spectrum can be detected
resolution, angular	Determines how clearly an instrument forms an image
RF	Radio frequency
RGA	Rate Gyro Assembly
Ritchey-Chretien	A modern optical design for two-mirror reflecting telescopes. It is a derivative of the Cassegrain concept in which the primary mirror has a hyperbolic cross section.
RIU	Remote Interface Unit
RMGA	Retrieval Mode Gyro Assembly
RMS	Remote Manipulator System
ROM	Read-only memory
RS	Reed-Solomon
RSU	Rate Sensor Unit
RWA	Reaction Wheel Assembly

-S-

SA	Solar Array
SAA	South Atlantic Anomaly
SAC	Second Axial Carrier
SADA	Solar Array Drive Assembly
SADE	Solar Array Drive Electronics
SADM	Solar Array Drive Mechanism
SAGA	Solar Array Gain Augmentation
SBA	Secondary Baffle Assembly
SBC	Single-Board Computer; Solar Blind Channel
SCP	Stored Command Processor
SDAS	Science Data Analysis Software
SDM	Secondary Deployment Mechanism
secondary mirror	In a two-mirror reflecting telescope, the secondary mirror sits in front of the larger primary mirror and reflects light to the point at which it will be detected and recorded by an instrument. In simple telescopes, the secondary mirror is flat and bounces the light out the side of the tube to an eyepiece. In more complex and larger telescopes, it is convex and reflects light through a hole in the primary mirror.
Servicing Mission	NASA’s plan to have the Space Shuttle retrieve the HST and have astronauts perform repairs and upgrades to equipment in space
SI	Science Instrument
SI C&DH	SI Control and Data Handling (subsystem)
SIPE	Science Instrument Protective Enclosure
SM	Secondary Mirror
SMA	Secondary Mirror Assembly
SM1	First HST Servicing Mission, December 1993
SM2	Second HST Servicing Mission, February 1997
SM3A	HST Servicing Mission 3A, December 1999
SM3B	HST Servicing Mission 3B, February 2002
SM4	HST Servicing Mission 4

SOFA	Selectable Optical Filter Assembly
SOGS	Science Operations Ground System
SOPE	Small ORU Protective Enclosure
spectral devices	These include spectrographs, instruments that photograph the spectrum of light within a wavelength range; spectrometers, which measure the position of spectral lines; and spectrophotometers, which determine energy distribution in a spectrum.
spectrograph	Instrument that breaks light up into its constituent wavelengths and allows quantitative measurements of intensity to be made
spectrum	Wavelength range of light in an image
spherical aberration	Image defect caused by a mismatch in the shapes of the reflecting surfaces of the primary and secondary mirrors. Light from different annular regions on the primary mirror comes to a focus at different distances from the secondary mirror, and there is no one position where all of the light is in focus.
SSAT	S-band Single-Access Transmitter
SSC	Science Support Center
SSE	Space Support Equipment
SSM	Support Systems Module
SSM-ES	SSM Equipment Section
SSR	Solid State Recorder
SSRF	Shell/Shield Repair Fabric
STDN	Space (flight) Tracking and Data Network
STINT	Standard interface
STIS	Space Telescope Imaging Spectrograph
STOCC	Space Telescope Operations Control Center
STS	Space Transportation System
STScI	Space Telescope Science Institute

-T-

TA	Translation Aids
TAG	Two-axis gimbal
TCE	Thermal Control Electronics

TCS	Thermal Control Subsystem
TDRS	Tracking and Data Relay Satellite
TDRSS	TDRS System
TECI	Thermoelectric-cooled inner (shield)
TECO	Thermoelectric-cooled outer (shield)
telemetry	Data and commands sent from the spacecraft to ground stations
TLM	Telemetry

-U-

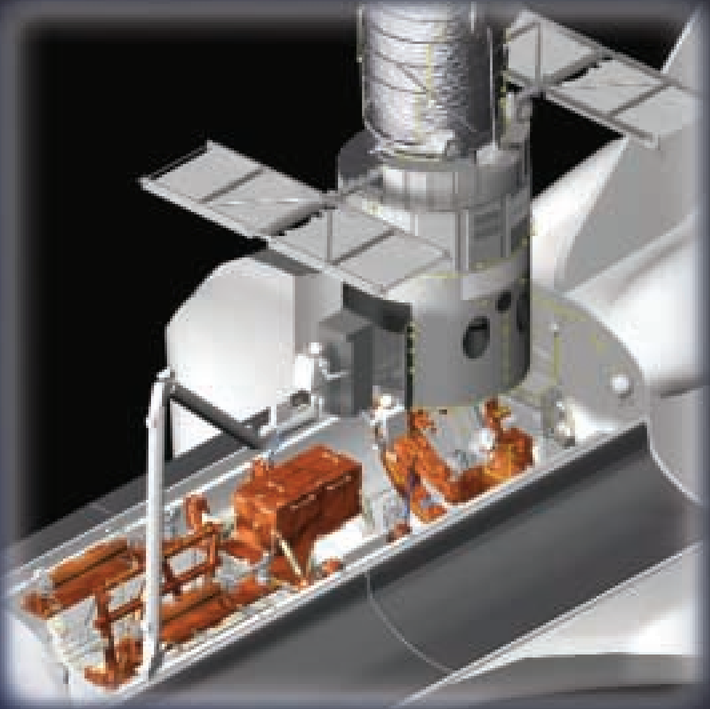
UDM	Umbilical disconnect mechanism
ULE	Ultralow expansion
USA	United States Army
USAF	United States Air Force
USN	United States Navy
UV	ultraviolet

-V-

V	Volt
V1, V2, V3	HST axes
VCS	Vapor-cooled shield
VIK	Voltage/Temperature Improvement Kit

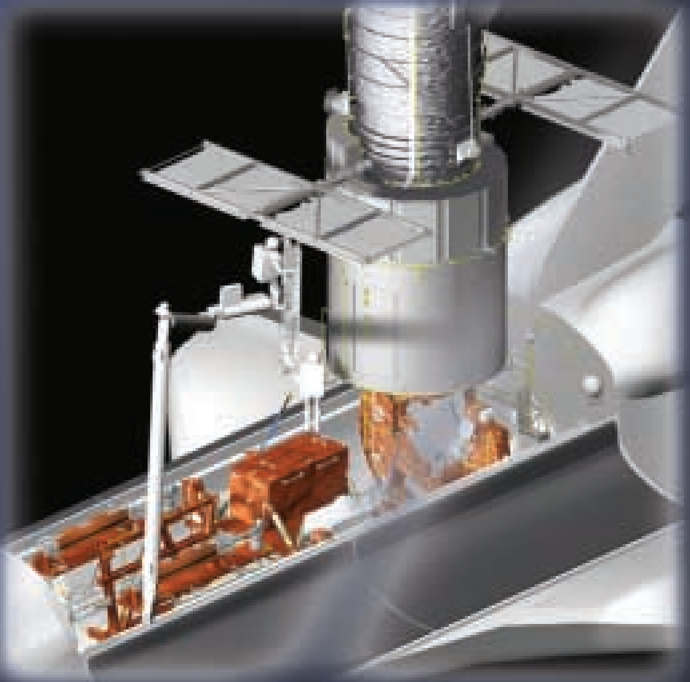
-W-

W	Watt
Wavelength	Spectral range of light in an image
WFC	ACS Wide Field Channel
WFPC	Wide Field and Planetary Camera. The camera currently in use is the second-generation instrument WFPC2, installed during the First Servicing Mission in December 1993. It replaced WFPC1 and was built with optics to correct for the spherical aberration of the primary mirror.



Advanced Camera for Surveys

SM3B spacewalkers maneuver the Advanced Camera for Surveys into position inside Hubble.



NICMOS Radiator

The SM3B extra-vehicular activity crew installs a new radiator for the NICMOS Cooling System.

LOCKHEED MARTIN

HST Servicing Mission 3B

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HST

Servicing Mission 3B

Media Reference Guide

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