CONTENTS

ILLUSTRATIONS

INTRODUCTION

Gazing through the first crude telescopes, Galileo, Kepler, and their contemporaries of the 17th century discovered the moon's craters, the satellites of Jupiter, and the rings of Saturn, leading the way to today's quest for in-depth knowledge and understanding of the cosmos. Since its launch in April 1990, NASA's Edwin P. Hubble Space Telescope (HST) has continued this historic quest, providing scientific data and photographs of unprecedented resolution from which many new and exciting discoveries have been made.

This unique observatory operates around the clock above the Earth's atmosphere to gather information for teams of scientists studying virtually all the constituents of our universe, including planets, stars, star-forming regions of the Milky Way galaxy, distant galaxies and quasars, and the tenuous hydrogen gas lying between the galaxies.

The Telescope can produce images of the outer planets in Earth's solar system that rival the clarity of those achieved by the Voyager flybys. Astronomers have been able to resolve previously unsuspected details of star-forming regions of the Orion Nebula in the Milky Way. They have detected expanding gas shells blown off by exploding stars. Using the high resolution and light-gathering power of the Telescope, scientists have calibrated the distances to remote galaxies and detected cool disks of matter trapped in the gravitational field of the cores of galaxies that portend the presence of massive black holes.

Spectroscopic observations at ultraviolet wavelengths inaccessible from the ground have given astronomers their first opportunity to study the abundance and spatial distribution of intergalactic hydrogen in relatively nearby regions of the universe and have forced scientists to rethink some of their earlier theories about galactic evolution. (Section 4 of this guide contains additional information on the Telescope's scientific discoveries.)

The Telescope's mission is to spend 15 years probing the farthest and faintest reaches of the cosmos. Crucial to fulfilling this promise is a series of on-orbit manned servicing missions. The First Servicing Mission took place in December 1993.

During these missions, astronauts perform a number of planned repairs and maintenance activities to restore and upgrade the observatory's capabilities. To facilitate this process, the Telescope's designers configured the various 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).

Flying aboard the shuttle *Discovery* in February 1997, the highly experienced, expertly trained STS-82 crew will carry out Hubble's Second Servicing Mission. Space-walking astronauts will remove the Goddard High Resolution Spectrograph (GHRS) and install the Space Telescope Imaging Spectrograph (STIS). They will replace the Faint Object Spectrograph (FOS) with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). They also will install and replace other components needed to maintain or augment Telescope operations. These include:

- Reaction Wheel Assembly (RWA)
- Fine Guidance Sensor (FGS)
- Data Interface Unit (DIU)
- Solar Array Drive Electronics (SADE)
- Engineering/Science Tape Recorder (E/STR)
- Solid State Recorder (SSR)

K70110-101

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

- Magnetic Sensing System (MSS) covers
- Optical Control Electronics Enhancement Kit (OCE-EK).

Figure 1-2 shows the servicing activities as scheduled at press time. Section 2 provides more details of the Second Servicing Mission.

In the last 18 years, the HST team has overcome enormous technical obstacles to successfully develop and launch the orbiting observatory. This tradition continues with the Second Servicing Mission, a challenging endeavor that promises to significantly expand the scientific capabilities of Hubble Space Telescope.

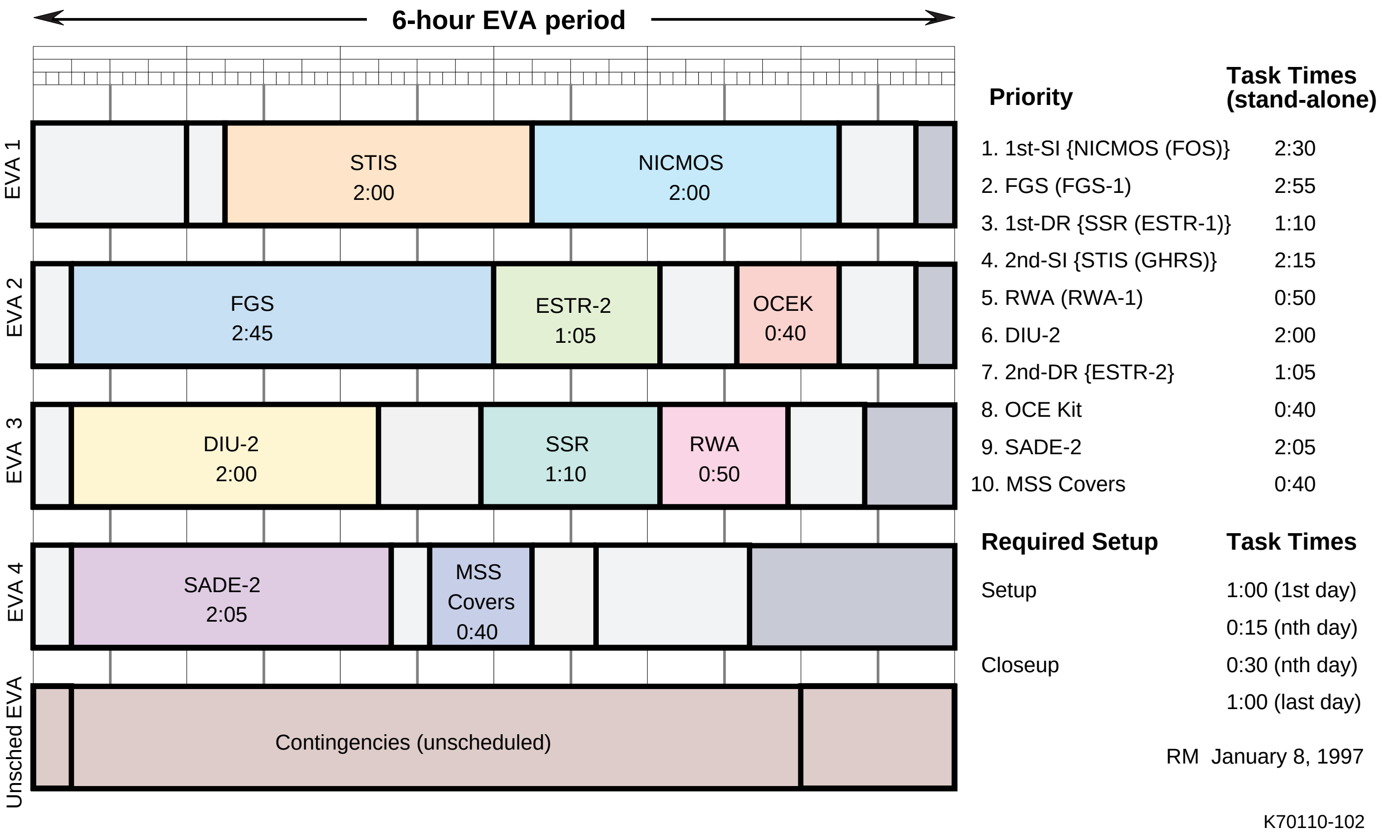
1.1 Hubble Space Telescope Configuration

Figures 1-3 and 1-4 show the overall Telescope configuration. Figure 1-5 lists specifications for the Telescope and its science instruments. 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.

1.1.1 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 serve to form focused images over the largest possible field of view. Incoming light travels down a tubular baffle that absorbs



Priority	Task Times (stand-alone)
1. 1st-SI {NICMOS (FOS)}	2:30
2. FGS (FGS-1)	2:55
3. 1st-DR {SSR (ESTR-1)}	1:10
4. 2nd-SI {STIS (GHRS)}	2:15
5. RWA (RWA-1)	0:50
6. DIU-2	2:00
7. 2nd-DR {ESTR-2}	1:05
8. OCE Kit	0:40
9. SADE-2	2:05
10. MSS Covers	0:40

Required Setup	Task Times
Setup	1:00 (1st day)
	0:15 (nth day)
Closeup	0:30 (nth day)
	1:00 (last day)

RM January 8, 1997

Fig. 1-2 Schedule of extravehicular activities

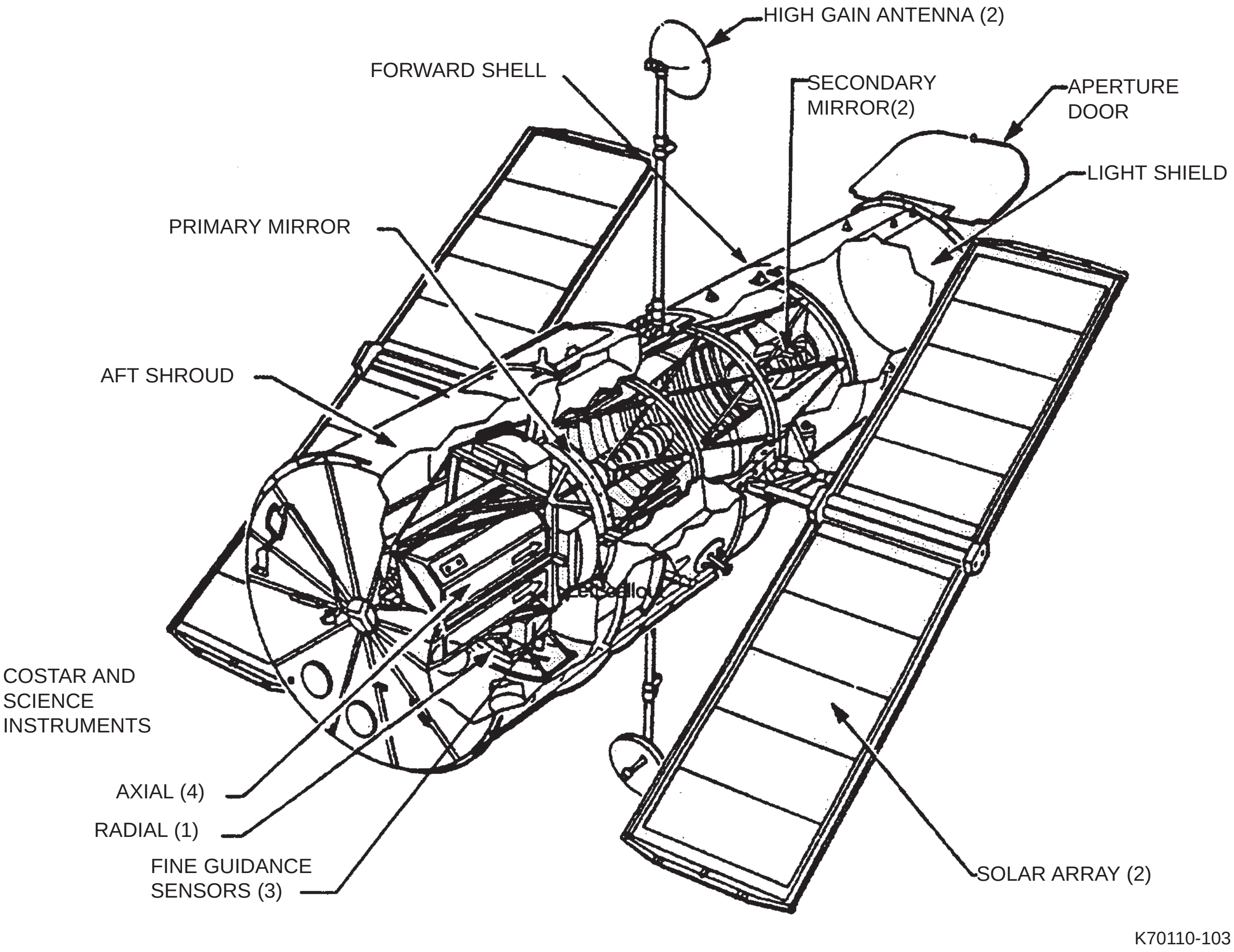


Fig. 1-3 HST overall configuration

stray light. The light is collected by the concave 94.5-in. (2.4 m) primary mirror and converged 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.

1.1.2 The Science Instruments

The Telescope can accommodate eight science instruments. Four are aligned with the Telescope's main optical axis and are mounted immediately behind the primary mirror. Before the Second Servicing Mission, the *axial* science instruments consisted of:

- Faint Object Camera (FOC)
- Faint Object Spectrograph (FOS)
- Goddard High Resolution Spectrograph (GHRS)
- 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 / Planetary Camera II (WF / PC II)
- Three Fine Guidance Sensors (FGS).

Faint Object Camera. This camera records images of faint, celestial objects. It reflects light

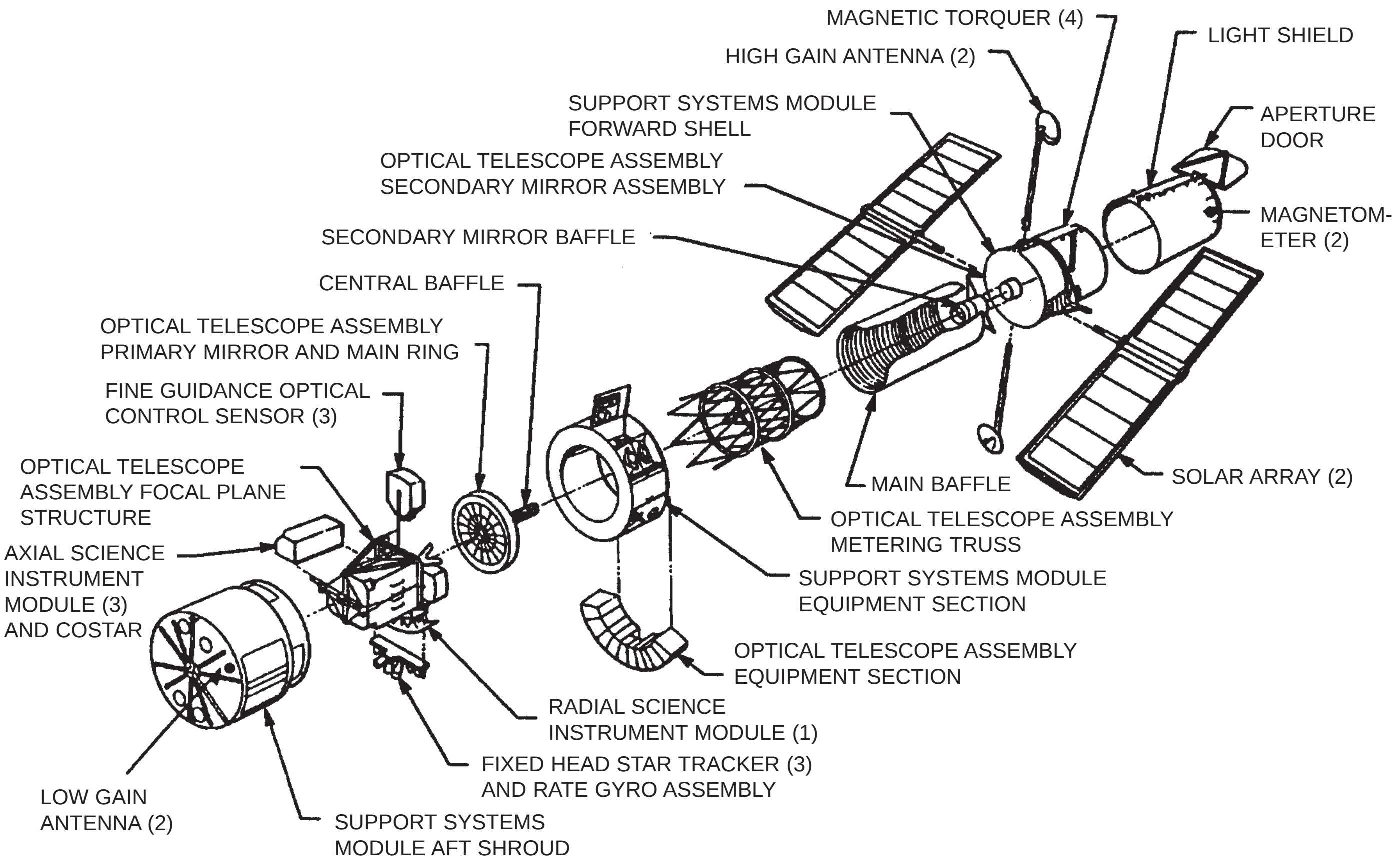


Fig. 1-4 HST exploded view

down one of two optical pathways. The light enters a detector after passing through filters or devices that can block out light from bright objects, thus allowing better background images. The detector intensifies an image, then records it much like a television camera. Images of faint objects can be built up over longer exposure times. The total image is translated into digital data, transmitted to Earth, and then reconstructed at the Space Telescope Science Institute (STScI).

Spectrographs. FOS and GHRS separate incoming light into its component wavelengths, revealing information about the atomic composition of the light source. These spectrographs 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 stellar atmosphere producing the light – all from spectral data.

The FOS detects detail in very faint objects, such as those at great distances, and light ranging from ultraviolet to red spectral bands. The GHRS detects fine detail in somewhat brighter objects but only in ultraviolet light.

Both spectrographs operate essentially the same. Incoming light passes through a small aperture then through filters and diffraction gratings, which work like prisms. The filter or grating used determines the range of wavelength to be examined and in what detail. Spectrograph detectors record the strength of each wavelength band and send it back to Earth.

Hubble Space Telescope (HST)

Weight	24,500 lb (11,110 kg)
Length	43.5 ft (15.9 m)
Diameter	10 ft (3.1 m) Light Shield and Forward Shell 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 29 m_v (visual magnitude)
Wavelength range	1100 to 11,000 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	15 years

Faint Object Camera (FOC)

Weight	700 lb (318 kg)
Dimensions	3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m)
Principal investigator	F. Duccio Macchetto, STScI/ESA
Contractor	European Space Agency, Dornier Systems, and Matra-Espace Corporation
Optical modes	f/151, f/75.5
Field of view	14, 28 arcsec^2
Magnitude range	5 to 28 m_v
Wavelength range	1150 to 6500 Å

Wide Field/Planetary Camera II (WF/PC II)

Weight	619 lb (281 kg)
Dimensions	Camera: 3.3 x 5 x 1.7 ft (1 x 1.3 x 0.5 m) Radiator: 2.6 x 7 ft (0.8 x 2.2 m)
Principal investigator	John Trauger, NASA/JPL
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 to 10,000 Å

Space Telescope Imaging Spectrograph (STIS)

Weight	825 lb (374 kg)
Dimensions	3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m)
Principal investigator	Dr. Bruce E. Woodgate, GSFC
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

Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

Weight	861 lb (390 kg)
Dimensions	7.1 x 2.8 x 2.8 ft (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

Fine Guidance Sensors (FGS)

Weight	485 lb (220 kg)
Dimensions	1.6 x 3.3 x 5.4 ft (0.5 x 1 x 1.6 m)
Principal investigator	William H. Jefferys, U. of Texas
Contractor	Perkin-Elmer Corporation
Astrometric models	Stationary and Moving Target, Scan
Precision	0.002 arcsec^2
Measurement speed	10 stars in 10 min
Field of view	Access: 60 arcmin^2 Detect: 5 arcsec
Magnitude range	4 to 18.5 m_v
Wavelength range	4670 to 7000 Å

Corrective Optics Space Telescope Axial Replacement (COSTAR)

Weight	640 lb (290 kg)
Dimensions	3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m)
Number of parts	5300 (approx)
Mirror diameter	0.81 in. (20 mm), the size of a nickel
Contractor	Ball Aerospace
Project engineer	James H. Crocker, STScI
Project scientist	Holand Ford, STScI
Instrument manager	Paul Geithner, GSFC
Purpose	To correct the effects of spherical aberration on the FOC, FOS, and GHRS

K70110-105

Fig. 1-5 Telescope science instrument specifications

COSTAR. Mechanical arms on COSTAR position corrective mirrors in front of the apertures of the FOC, the FOS, and the GHRS.

Investigations into the spherical aberration of the primary mirror revealed the specific errors that caused the fault. This knowledge allowed optical experts to design and fabricate small pairs of corrective mirrors that successfully refocused the light reflected from the primary mirror before it entered the three axial science instruments. The first mirror (M1) of each pair intercepts light from the Telescope's secondary mirror and reflects that light into a second mirror (M2), which in turn reflects light into the three axial science instruments. The second mirror of each pair is shaped to cancel out the spherical aberration from the primary mirror. Such refocusing has increased the amount of light energy entering the axial science instruments. This increase in optical performance helped to restore the Telescope's capability to near-original expectations.

Wide Field/Planetary Camera II. WF/PC II is an electronic camera that records images at two magnifications. The WF/PC II was developed by the Jet Propulsion Laboratory (JPL) team in Pasadena, California. They also built the first WF/PC. When Hubble's mirror was found to be flawed, the science team immediately began working on an optical correction that could be built into WF/PC II. The new design incorporated an optical correction by the refiguring of 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) to provide data to the spacecraft's pointing system to keep the Telescope pointed accurately at a target when one of the science instruments is being used to take data and (2) to 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.

1.1.3 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 Solar Arrays (SA) and High Gain Antennas (HGA) are mounted. Electrical energy from the 40-ft (12-m) 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 is done 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.

1.1.4 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. Each array stands on a 4-ft mast that supports a retractable wing of solar panels 40 ft (12.2 m) long and 8.2 ft (2.5 m) wide.

The SAs are rotated so the solar cells face the sun. Each wing's solar cells absorb the sun's energy and convert that light energy 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.

Prior to the First Servicing Mission, as the Telescope orbited in and out of direct sunlight, the resulting thermal gradients caused oscillation of the SAs that induced jitter in the Telescope's line of site. This in turn caused some loss of fine lock of the FGSs during science observations. New SAs installed during the First Servicing Mission with thermal shields over the array masts minimized the effect.

1.1.5 Computers

The Hubble Telescope Data Management Subsystem (DMS) contains two computers: the DF-224 flight computer and the Science Instrument Control and Data Handling (SI C&DH) unit. The DF-224 performs onboard computations and also 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.

During the First Servicing Mission, astronauts installed a coprocessor to augment the capacity of DF-224 flight computer. The new 386-coprocessor increased flight computer redundancy and significantly enhanced on-orbit computational capability.

1.2 The Hubble Space Telescope Program

Hubble Space Telescope represents the fulfillment of a 50-year dream and 23 years of dedicated scientific effort and political vision to advance humankind's knowledge of the universe. To accomplish the mission, the program brought together an international community of engineers and scientists, contractors, and institutions under the auspices of the NASA Office of Space Science. On-orbit servicing is the fifth phase of NASA's program. The other four phases were:

- Development, assembly, and test
- Launch and deployment
- On-orbit verification of system and science instrument functions
- Initial operations to produce scientific data.

Marshall Space Flight Center managed the first three phases. Figure 1-6 summarizes organizations and tasks for completed phases of the Telescope program.

The NASA Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, has coordinated overall operational and servicing mission preparations for the Telescope since its deployment. GSFC works with Kennedy Space Center (KSC), where the Second Servicing Mission will be launched, and with Johnson Space Center (JSC), which operates as Mission Control during servicing. JSC also is responsible for Shuttle operations and

Phase	Organization
Development, assembly, and test	• Lockheed Martin Missiles & Space (formerly Lockheed Missiles & Space Company, Inc.) built or supervised subcontract equipment development and the entire Support Systems Module (SSM); assembled and tested complete HST. • Hughes Danbury Optical Systems (formerly Perkin-Elmer) designed and built the Optical Telescope Assembly, mirrors, and Fine Guidance Sensors. • Principal investigators led teams to create original five science instruments.
Launch and deployment	• Kennedy Space Center was the site of Shuttle launch. • Johnson Space Center ran flight control and trained astronauts to deploy the Telescope.
Verification	• Marshall Space Flight Center controlled functional system testing. • Goddard Space Flight Center controlled science instrument verification testing.
Operations	• Goddard Space Flight Center has overall program management during this continuous phase.

K70110-106

Fig. 1-6 Space Telescope program phase summary

oversees astronaut crew training and mission safety.

Figure 1-7 summarizes major contributions of scientists and companies to the development of the array of science instruments that will be in place following the Second Servicing Mission. The roles of NASA centers and contractors for the fifth phase of the HST program, on-orbit servicing, are:

(1) GSFC – Responsible for overall management of daily on-orbit operations of HST; development, integration and test of replacement hardware, space support equipment, and crew aids and tools.
(2) JSC – Overall mission management, flight crew training, and crew aids and tools responsibility.
(3) KSC – Overall management of launch and post-orbit operations for mission hardware.
(4) Ball Aerospace – Designed, developed, and provided the Science Instruments for the HST First and Second Servicing Missions.
(5) Lockheed Martin – Provides personnel support to GSFC to accomplish (a) the development, integration, and test of replacement hardware and space support equipment; (b) system integration with the Space Transportation System (STS); (c) launch and post-orbit operations; and (d) daily operations of the HST.

Instrument	Principal Investigator	Team Subcontractor
Faint Object Camera (FOC)	F. D. Macchetto, European Space Agency	Dornier Systems British Aerospace Matra-Espace
Near Infrared Camera and Multi-Object Spectrometer (NICMOS)	Dr. Rodger I. Thompson, University of Arizona	Ball Aerospace
Space Telescope Imaging Spectrograph (STIS)	Dr. Bruce E.Woodgate Goddard Space Flight Center	Ball Aerospace
Wide Field/ Planetary Camera II (WF/PC II)	John Trauger, Jet Propulsion Laboratory	Jet Propulsion Laboratory
Corrective Optics Space Telescope Axial Replacement (COSTAR)	James H. Crocker, Holland Ford, STScI	Ball Aerospace
Fine Guidance Sensors (FGS)	William H. Jefferys, University of Texas	Perkin-Elmer Corporation

K70110-107

Fig. 1-7 Development teams for science instruments and COSTAR

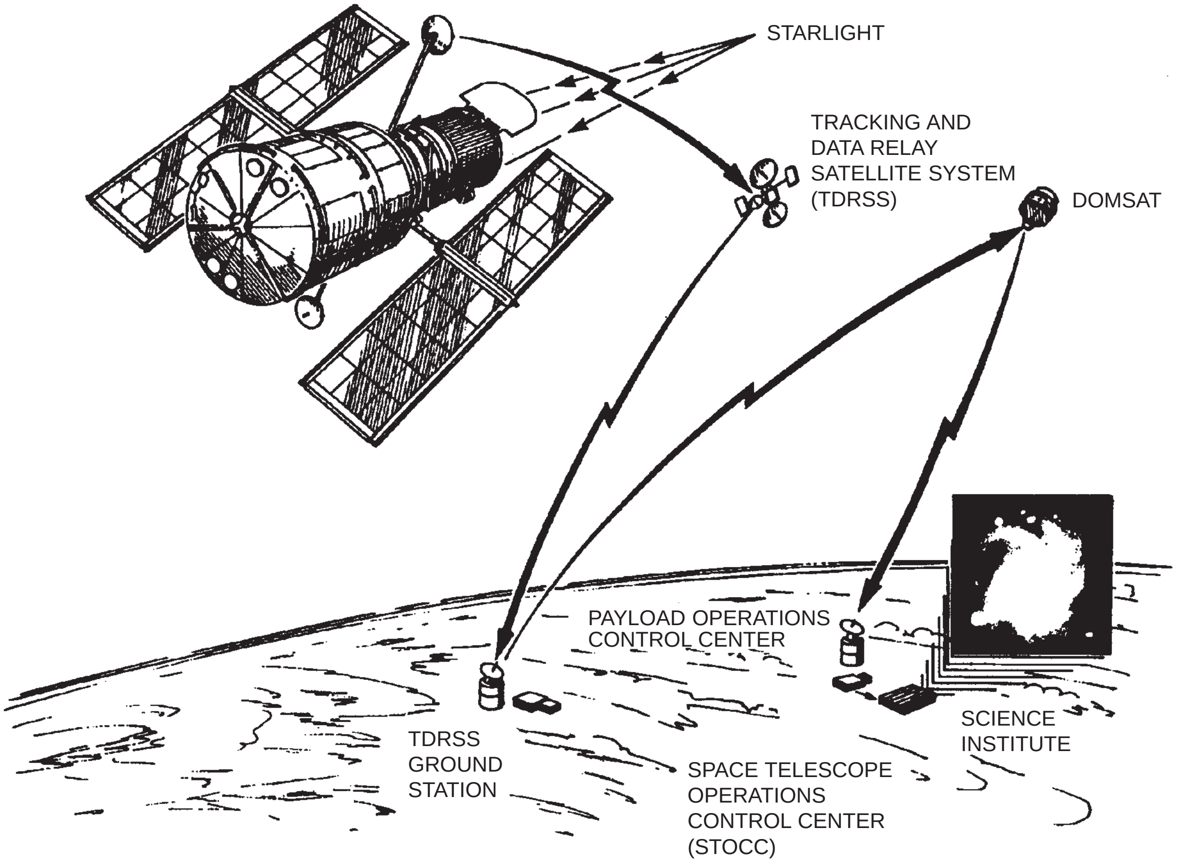
Major subcontractors for the Second Servicing Mission include Hughes Danbury Optical, Allied Signal, Jackson and Tull, Orbital Sciences Corporation, Odetics, Honeywell, ETA, and Hughes STX.

The HST program requires a complex network of communications among GSFC, the Telescope, Space Telescope Ground System, and STScI. Figure 1-8 summarizes the major organizations that oversee the program. Figure 1-9 shows communication links.

Organization	Function
Goddard Space Flight Center –Office of the Associate Director of Flight Projects for HST –HST Operations and Ground Systems Project	• Overall HST Program Management • HST Project Management • Responsible 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

K70110-108

Fig. 1-8 Organization summary for HST program operational phase



K70110-109

Fig. 1-9 HST data collecting network

The Hubble Space Telescope (HST) is the first observatory designed for extensive maintenance and refurbishment in orbit. While other U.S. spacecraft have been retrieved or repaired by astronauts, none was so thoroughly designed for orbital servicing as HST. Its science instruments and many other components were designed as Orbital Replacement Units (ORU) – modular in construction with standardized fittings and accessible to extravehicular astronauts. Features such as handrails and footholds are built into the Telescope to help astronauts perform servicing tasks in the Shuttle cargo bay as they orbit Earth at 17,000 mph.

The *Discovery* cargo bay is equipped with several devices to help the astronauts: the Flight Support System (FSS) to berth and rotate the Telescope; large, specially designed equipment containers to house the ORUs; and a remote manipulator arm from which astronauts can work and be maneuvered as needed.

The Second Servicing Mission will benefit from lessons learned on NASA's previous on-orbit repair missions, ranging from the 1984 Solar Maximum repair mission to the 1993 HST First Servicing Mission. NASA has incorporated these lessons in detailed planning and training sessions for astronauts Cdr. Kenneth Bowersox, Lt. Col. Scott Horowitz, Col. Mark Lee, Gregory Harbaugh, Steven Smith, Joseph Tanner, and Steven Hawley. All of NASA's planning and the skills of the astronauts will be put to the test during the 10-day Second Servicing Mission in February. Four extravehicular activity (EVA) days are scheduled for the actual servicing.

2.1 Reasons for Orbital Servicing

The Hubble Telescope is an invaluable international scientific resource that has revolutionized modern astronomy. To achieve its full potential, it will continue to conduct many years of extensive, integrated scientific observations, including follow-up work on its many discoveries. The Telescope was designed with numerous backup parts and safemode systems, but it is impossible and impractical to design such a complex spacecraft with sufficient backups to handle every contingency likely to occur during a 15-year mission. Orbital servicing is the key to keeping the Telescope in optimum operating condition. The Telescope's orbital servicing plans address three primary maintenance scenarios:

- **Incorporating technological advances into the science instruments.** During the Telescope's 15-year life, scientists and engineers will continue to upgrade the science instruments. For example, when the Telescope was launched in 1990, work already had begun on an improved Wide Field/Planetary Camera (WF/PC). When a flaw in the primary mirror was discovered later that year, Hubble planners redesigned the new WF/PC's mirrors to compensate for the Telescope's aberrated images and accelerated the development of that science instrument so it would be ready for the First Servicing Mission in December 1993.
- **Normal degradation of components.** Servicing plans take into account the need for routine replacement of some items, for example, restoring HST system redundancy and limited-life items such as tape recorders and Reaction Wheels.
- **Random equipment failure or malfunction.** 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 respond to and correct unforeseen problems that arise from random equipment failures or malfunctions.

NASA's Space Shuttle program provides a proven system for transporting crews of fully trained servicing technicians to the Telescope. Originally, planners considered using the Shuttle to return the Telescope to Earth approximately every 5 years for maintenance, but the idea was rejected for both technical and economic reasons. Returning it 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.

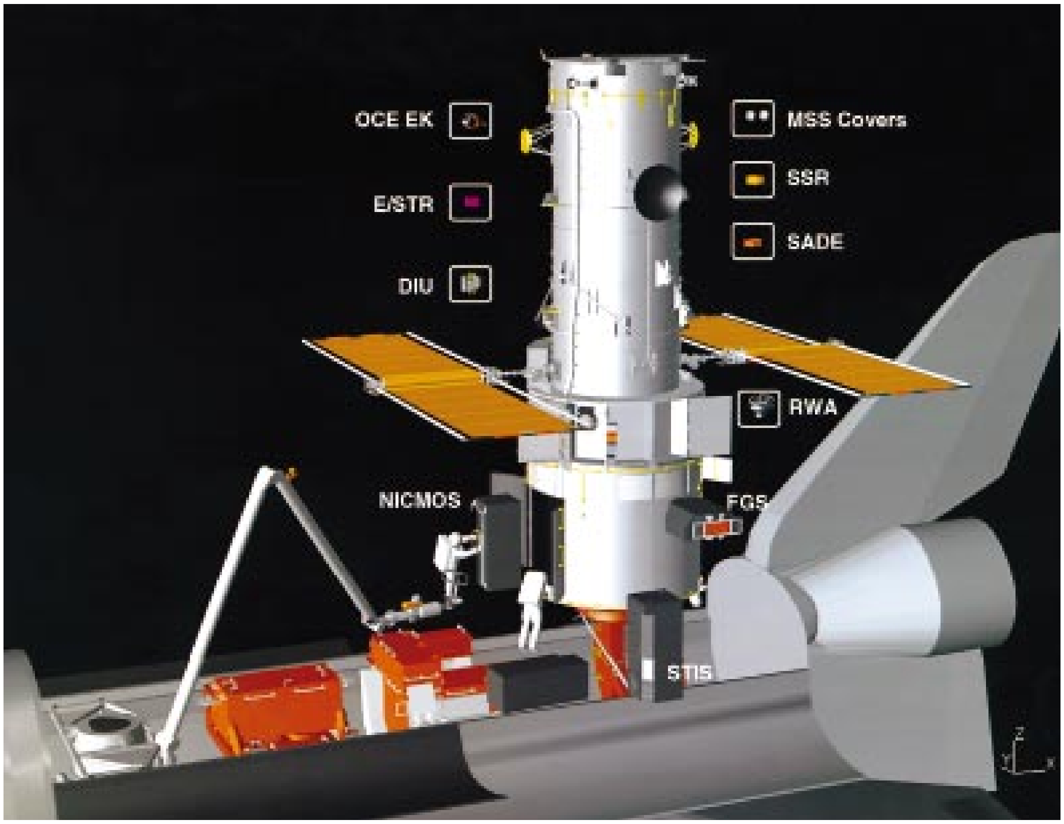
With on-orbit servicing by Shuttle astronauts, most maintenance and refurbishment can be accomplished within two weeks – a brief interruption to scientific operations – without the additional facilities and staff needed for ground servicing.

2.2 Orbital Replacement Units

Modularity. Engineers studied various technical and human factors criteria to simplify Telescope maintenance. Because of the limited time available for an EVA astronaut to make repairs and the limitations in mobility and dexterity in the EVA environment, designers have simplified the maintenance tasks by planning entire components for replacement. The modular ORU concept is key to successfully servicing the Telescope on orbit.

The typical ORU is a self-contained box installed and removed using fasteners and connectors. The ORUs range from small fuses to phone-booth-sized science instruments weighing more than 700 lb (318 kg). Figure. 2-1 shows the ORUs for the Second Servicing Mission.

Standardization. In addition to modularity, a key feature that simplifies on-orbit repair is



ACRONYMS

DIU	Data Interface Unit
E/STR	Engineering and Science Tape Recorder
FGS	Fine Guidance Sensor
MSS	Magnetic Sensing System
NICMOS	Near-Infrared Camera and MultI-Object Spectrometer
OCE-EK	Optical Control Electronics Enhancement Kit
RWA	Reaction Wheel Assembly
SADE	Solar Array Drive Electronics
SSR	Solid State Recorder
STIS	Space Telescope Imaging Spectrograph

K70110-201

Fig. 2-1 Hubble Space Telescope Second Servicing Mission Orbital Replacement Units standardized bolts and connectors. ORU components are held in place by captive bolts with 7/16-in., double-height hex heads. To remove or install them, astronauts require only a 7/16-in. socket fitted to a power tool or manual wrench.

Although most ORUs require these fasteners, some do not. When reliability assessments and ground testing indicated that additional components may need replacing, some components were selected as replaceable units after their design had matured. These exceptions add a greater variety of fasteners to the servicing requirements, including noncaptive 5/16-in.-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 also 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 the 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.

Crew Aids. Handrails, foot restraint sockets, and tether attachments are essential to efficient, safe on-orbit servicing. In anticipation of servicing missions, 31 foot restraint sockets and 225 ft of handrails were designed into the Telescope. The foot restraint sockets and handrails greatly increase the mobility and stability of the EVA astronauts, giving them safe, conveniently located worksites near ORUs. Other crew aids such as portable lights, special tools, installation guiderails, handholds, and portable foot restraints (PFR) also ease access to the components being serviced.

2.3 Shuttle Support Equipment

To assist the astronauts in servicing the Telescope, the *Discovery* will carry into orbit 16,000 pounds of hardware and Space Support Equipment, including the Remote Manipulator System (RMS), FSS, ORU Carrier (ORUC), and Second Axial Carrier (SAC).

2.3.1 Remote Manipulator System

The *Discovery* Remote Manipulator System (RMS), also known as the robotic arm, will be used extensively during the Second Servicing Mission. The astronaut operating this device from inside the cabin is designated the intravehicular activity (IVA) crew member. The RMS will be used to capture, berth, and release the Telescope; transport new components, instruments, and extravehicular activity (EVA) astronauts between worksites; and provide a temporary work platform for one of the EVA astronauts.

2.3.2 Space Support Equipment

Ground crews will outfit the cargo bay of *Discovery* with three major assemblies essential for the servicing mission: the FSS, ORUC, and SAC. Figure 2-2 shows a cargo bay view of these assemblies.

Flight Support System. The FSS is a maintenance platform used to berth the HST in the cargo bay after the *Discovery* crew has rendezvoused with and captured the Telescope (see Fig. 2-3). The platform was adapted from the FSS first used for the 1984 Solar Maximum repair mission. This system has a U-shaped cradle that spans the rear of the cargo bay. The platform has a circular berthing ring with three latches that secure the Telescope to the cradle. The berthing ring can rotate the Telescope

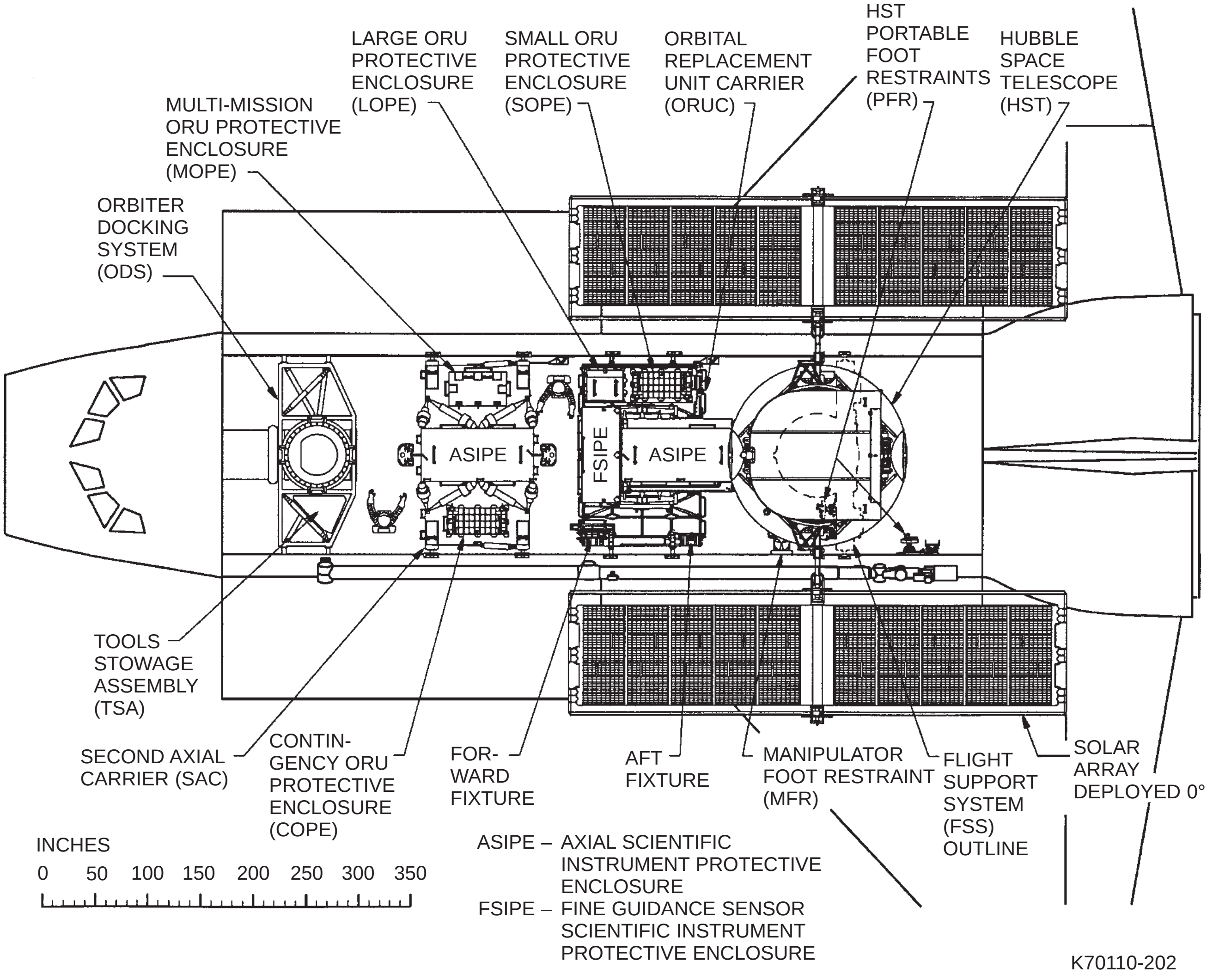


Fig. 2-2 Second Servicing Mission configuration

almost 360 degrees (175 degrees clockwise or counterclockwise from center) 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 *Discovery* to maintain thermal control of the Telescope and the ORUC, and permits ground engineers to test and monitor Telescope systems during the mission.

2.3.3 Orbital Replacement Unit Carrier

The ORUC is centered in *Discovery's* cargo bay. A Spacelab pallet modified with a shelf, it has provisions for safe transport of ORUs to and from orbit (see Fig. 2-4). In this assembly, the Fine Guidance Sensor (FGS) #1 and STIS are stored in a Science Instrument Protective Enclosure (SIPE). The OCE-EK primary and backup units, a primary and backup Solid State Recorder (SSR), Engineering / Science Tape Recorder (E / STR) #2, Solar Array Drive Electronics (SADE) #2, a primary and backup Solid State Recorder (SSR) "T" harness, and the E / STR delay harness reside in a Small ORU Protective Enclosure (SOPE). The Reaction Wheel Assembly (RWA) is contained in a Large ORU Protective Enclosure (LOPE) on the ORUC shelf.

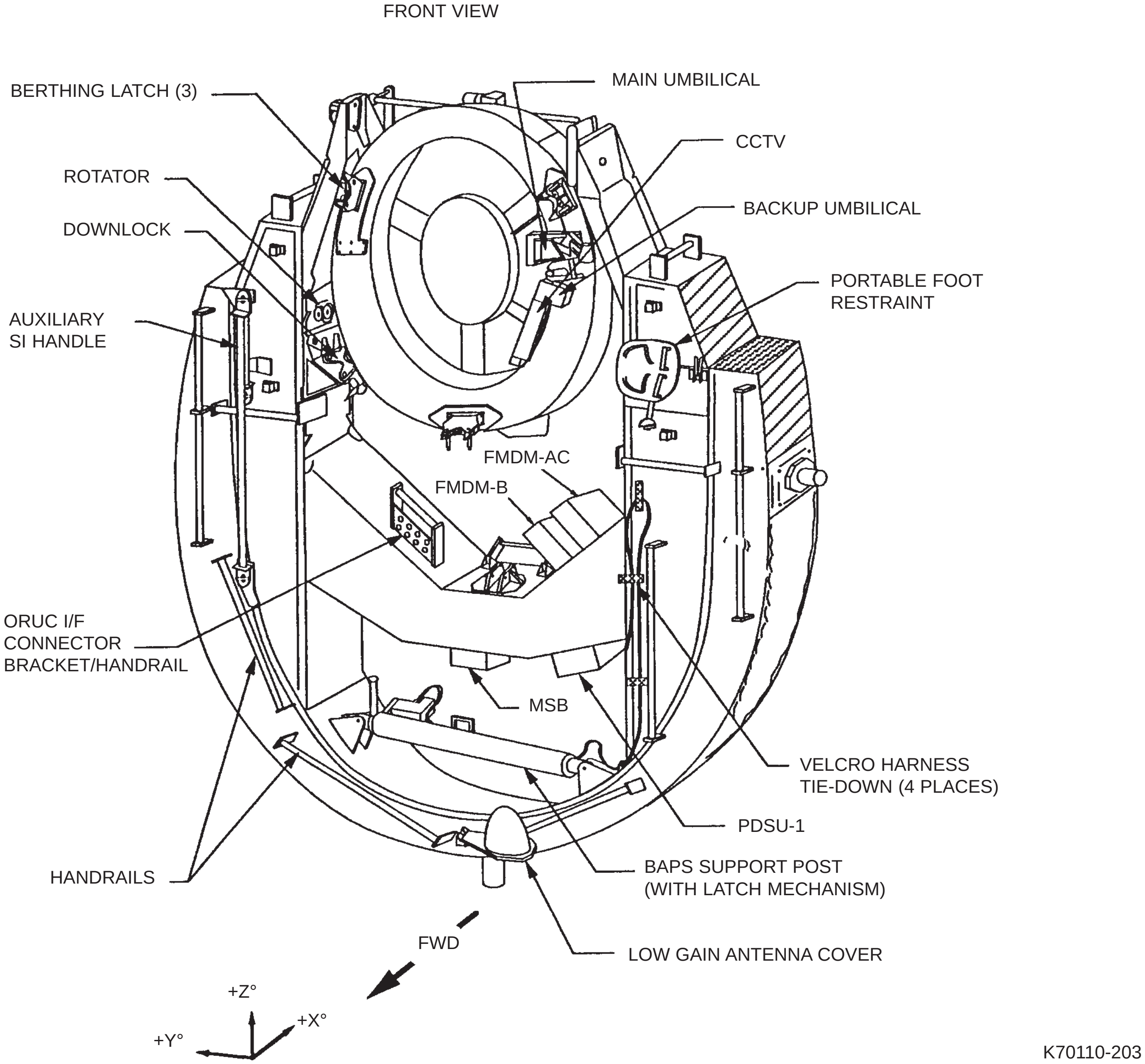


Fig. 2-3 Flight Support System configuration

The protective enclosures, their heaters, and thermal insulation control the temperature of the new ORUs and provide an environment equivalent to that inside the Telescope. Struts and springs between the enclosures and the pallet protect the ORUs from the loads generated at liftoff.

2.3.4 Second Axial Carrier

The SAC is being flown on the Second Servicing Mission to transport and protect the NICMOS and a complement of ORUs. The SAC structure (see Fig. 2-5) is based on the Goddard Pallet Assembly, a multimission Shuttle payload carrier built to support Shuttle-based HST servicing activities. For the First Servicing Mission, the Pallet Assembly was configured as the Solar Array Carrier, with a Solar Array Support Structure (SASS) designed to transport HST Solar Arrays.

For the Second Servicing Mission, the Pallet Assembly has been modified and is the base

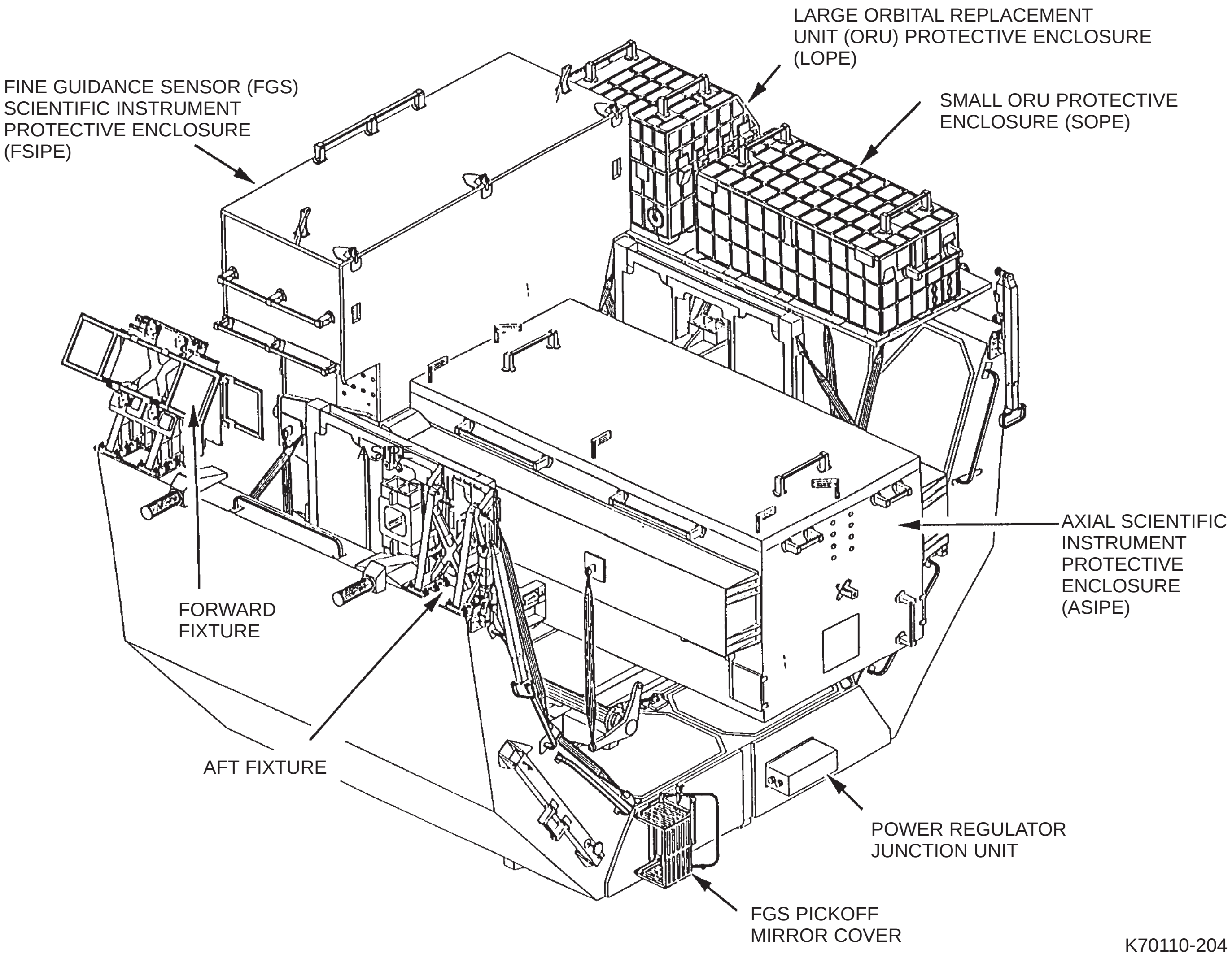


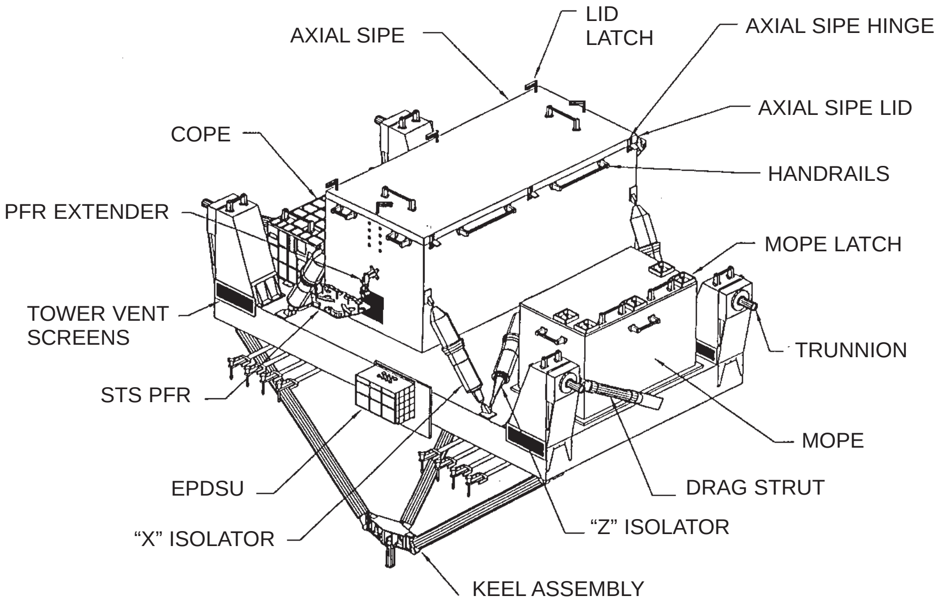
Fig. 2-4 Orbital Replacement Unit Carrier

structure of the SAC. The SASS has been replaced with an Axial Scientific Protective Enclosure (ASIPE) to transport into orbit the new NICMOS. The Contingency ORU Protective Enclosure (COPE) and a new ORU Protective Enclosure, called the Multimission ORU Protective Enclosure (MOPE), are used to house and thermally protect the ORUs, also mounted on the Pallet Assembly.

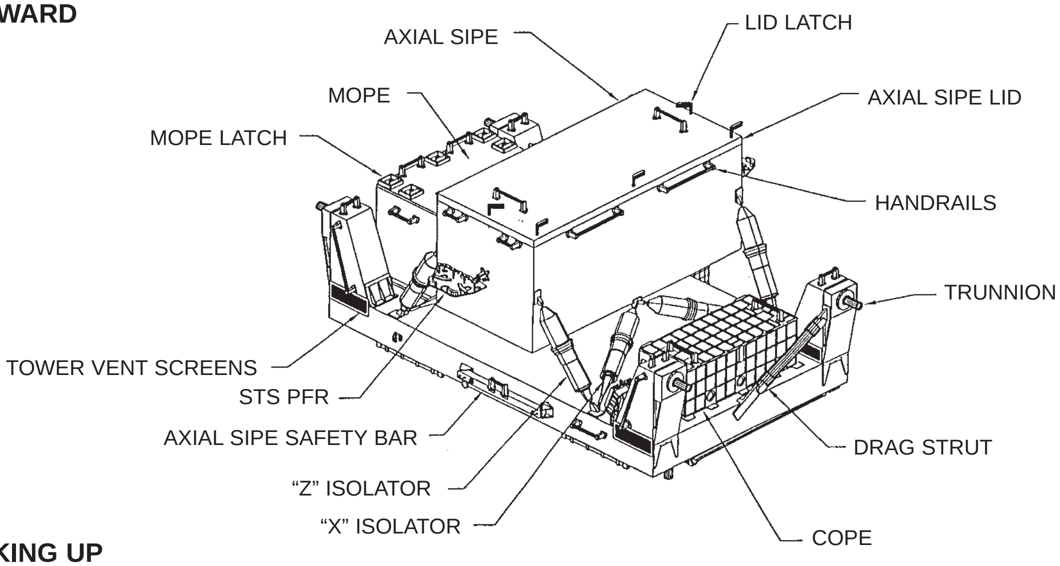
The SAC spans the cargo bay and structurally ties into the Shuttle at five points, four longeron and one keel trunnion. To reduce launch and landing vibration loads transmitted to the NICMOS, active isolators similar to automobile shock absorbers are used. Each isolator consists of a spring and a magnetic damper. The magnetic damper converts the mechanical vibration energy from the launch event into heat energy, reducing the loading on NICMOS. The SAC incorporates eight isolators, configured in four sets of two each. Each isolator is attached to the Pallet Assembly and also to the ASIPE at its base or end plate.

The SAC ASIPE is based on the ORUC ASIPE, with design modifications to be flown as a stand-alone enclosure. Aside from the unique NICMOS/FOS latch configuration, all EVA and instrument interfaces are the same for both

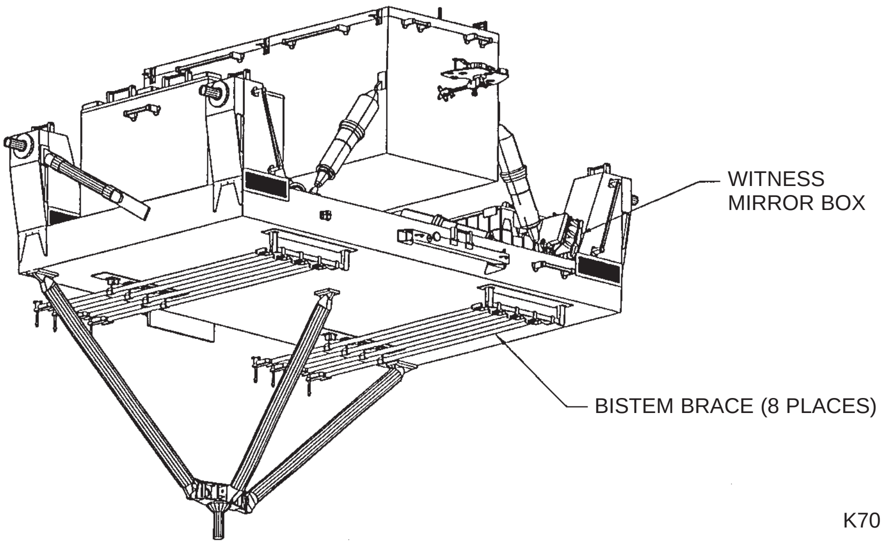
AFT



FORWARD



LOOKING UP



K70110-205

Fig. 2-5 Second Axial Carrier

ASIPEs. The ASIPE is thermally controlled using a heater system designed to precondition NICMOS prior to EVA changeout operations.

ORUs transported on the SAC for the Second Servicing Mission are two DIUs in the MOPE and two RSUs and an ECU in the COPE. The MOPE will also carry electrical harnesses for the DIUs, spare fuse plugs and push in-pull out (PIP) pins, and crew aids and tools. The crew aids and tools are the Pistol Grip Tool, the Power Ratchet Tool and its controller, a DIU portable handle, and the NICMOS cryo vent line. In addition to the ORUs, the COPE will house the MSS Covers, MLI Repair Kit, spare electrical harnesses, and a JSC-provided tool called the PFR Attachment Device.

Within the MOPE and COPE, transport modules protect ORUs from launch and landing vibration loading. These transport modules are designed to custom fit each ORU using foam to surround the ORU. Transport modules for each ORU are integrated into the OPEs as a module unit, simplifying system integration.

The SAC receives power directly from the Orbiter through the Enhanced Power Distribution and Switching Unit (EPDSU). The EPDSU is modular avionics for Shuttle payloads designed to be readily configured for unique payload power, command, and telemetry requirements. Custom applications are easily serviced using the EPDSU. An EPDSU, configured for the FSS, is also available for backup to the FSS PDSU.

2.4 Astronaut Roles and Training

To prepare for the Second Servicing Mission, the seven-member *Discovery* crew trained extensively at NASA's Johnson Space Center (JSC) in Houston, Texas; Marshall Space Flight Center (MSFC) in Huntsville, Alabama; and Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. Although there has been extensive cross-training, each crew member also has trained for specific tasks.

Training for Mission Commander Bowersox and Pilot Horowitz 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 *Discovery* cabin.

The five Mission Specialists also received specific training, starting with classroom instruction on the various ORUs; tools and crew aids available to assist them; Space Support Equipment (SSE) such as the RMS (the robotic arm); and the FSS. Principal operator of the robotic arm is Mission Specialist Hawley, who also performs IVA duties. The alternate operator is Pilot Horowitz.

Hawley and Horowitz trained together specifically for capture and redeployment of the Telescope, rotation and pivoting of the Telescope on 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 of the actual Telescope.

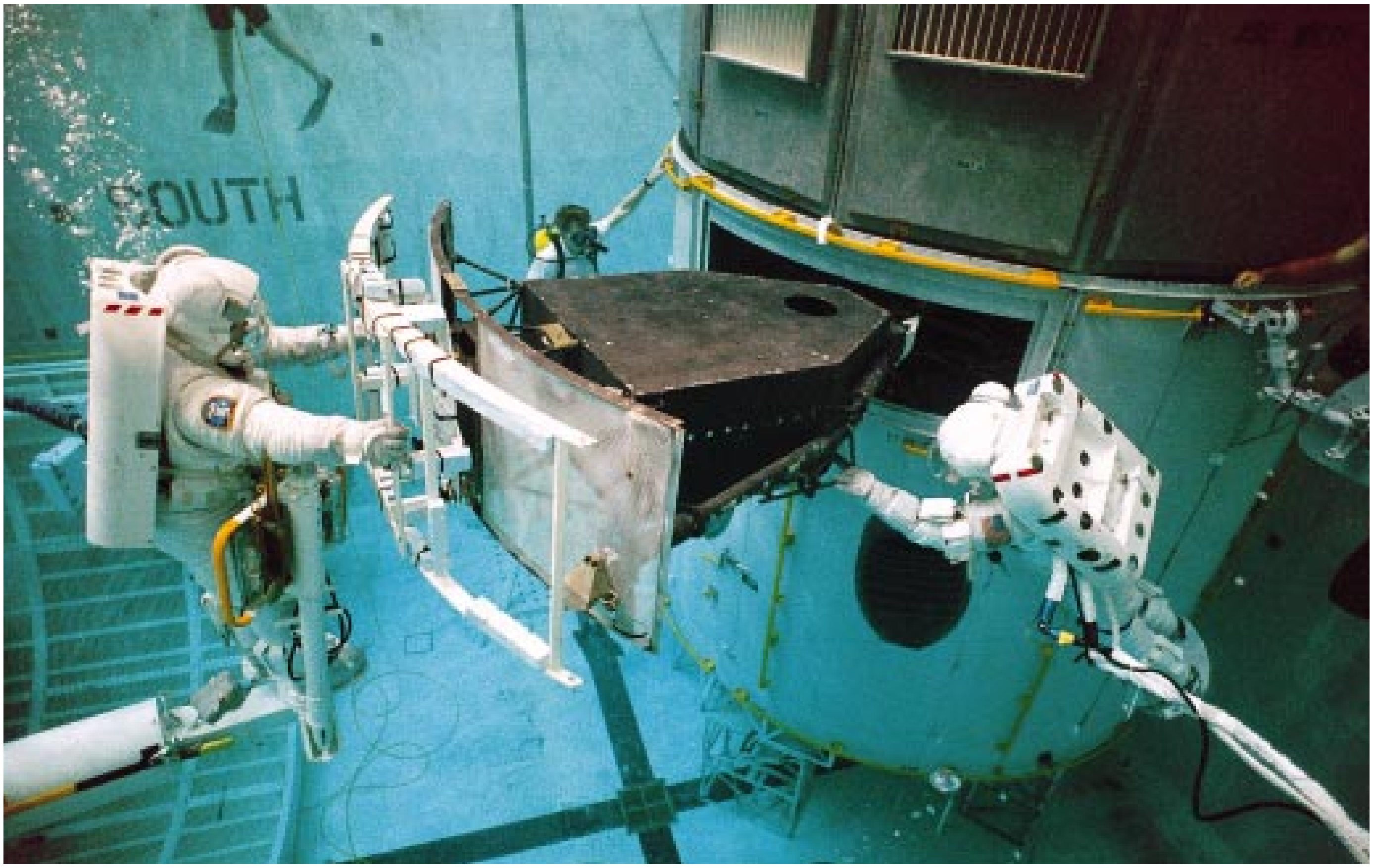
EVA crew members work in teams of two in the cargo bay doing hands-on HST servicing. To train for this important role, EVA astronauts Lee, Harbaugh, Smith, and Tanner logged many days of training in MSFC's Neutral

Buoyancy Simulator Facility (NBSF). In this 40-ft (12-m)-deep water tank (see Fig. 2-6) pressure-suited astronauts and their equipment were made neutrally buoyant, a condition that simulates weightlessness.

Underwater mockups of the Telescope, FSS, ORUs, ORUC, RMS, and the Shuttle cargo bay enabled the astronauts to practice entire EVA servicing procedures in simulated weightlessness. Such training activities help the astronauts to efficiently use the limited number of days (four) and duration (six hours) of each EVA period during the servicing mission. Additional underwater training took place at the Weightless Environmental Training Facility (WETF) at JSC in Houston.

Other training aids at JSC helped recreate orbital conditions for the Discovery astronauts. In the weightlessness of space, the tiniest shove can set 800-lb instruments, such as NICMOS or STIS, 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, giving crew members an opportunity to practice carefully nudging the instruments into their proper locations. In another room at JSC, the astronauts worked in a vacuum chamber where temperatures varied from plus to minus 200 degrees Fahrenheit, just as they do in orbit. Astronauts also used virtual reality technologies in their training. With this kind of ultrarealistic simulation, astronauts wearing virtual reality devices "see" themselves next to the Telescope as their partners maneuver them into position with the robotic arm.



K70110-206

Fig. 2-6 Neutral Buoyancy Simulator at Marshall Space Flight Center

2.5 Extravehicular Crew Aids and Tools

Astronauts servicing HST use two different kinds of foot restraints to counteract their weightless environment. When anchored in a Manipulator Foot Restraint (MFR), an astronaut can be transported from one worksite to the next with the robotic arm. With the PFR, an astronaut establishes a stable worksite by mounting the restraint to any of 31 different receptacles strategically placed on the Telescope or 22 receptacles on the ORUC, the FSS, and the tool box.

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; others are unique to this servicing mission. All tools are designed to be used by astronauts wearing pressurized gloves.

The most commonly used ORU fasteners are bolts with 7/16-in., 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, the astronauts use a 7/16-in. extension socket on a ratchet wrench. Extensions up to 2 ft long are available to extend an astronaut's reach. Multisetting 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 so that nothing floats away in the weightless space environment. To grip fasteners in hard-to-reach areas, astronauts use wobble sockets or flex-tip screwdrivers.

Some ORU electrical connectors require special tools. For these components, astronauts loosen standard D-connectors by carefully removing them with a special gripper tool after releasing two slotted screws. If connectors have no wing tabs, astronauts use another special gripper to get a firm hold on the rotating sleeve of the connector.

Portable handles have been attached to many larger ORUs. These handles greatly facilitate removal or installation. Other tools and crew aids used during the servicing mission are tool caddies (carrying aids), tethers, transfer bags, and protective covers for instrument mirrors, umbilical connectors, and the Low Gain Antenna (LGA). When astronauts work within the Telescope's aft shroud area, they must guard against optics contamination by using special tools that will not outgas or shed particulate matter.

2.6 Astronauts of the Second Servicing Mission

NASA carefully selected and trained the Second Servicing Mission STS-82 crew (see Fig. 2-7). All are experienced astronauts who have flown missions involving either extensive EVA or the capture and deployment of various types of spacecraft. Their unique set of experiences and capabilities makes them eminently qualified for this challenging assignment.

Brief biographies of the STS-82 astronauts follow.

Kenneth Bowersox: NASA Astronaut (Commander, USN). Kenneth Bowersox of Bedford, Indiana, is the Commander of the Second Servicing Mission. He received a bachelor of science degree in aerospace engineering from the United States Naval Academy and a master of science degree in mechanical engineering from Columbia University. This former test pilot has logged more than 3,000 hours of

K70110-207

Fig. 2-7 The STS-82 mission has seven crew members. They are (front row, from left) Commander Kenneth D. Bowersox, Steven A. Hawley, and Pilot Scott J. Horowitz; (back row) Joseph R. Tanner, Gregory J. Harbaugh, Mark C. Lee, and Steven L. Smith.

flight time. He joined the astronaut corps in 1988. A three-flight veteran, Bowersox has logged over 40 days in space. He flew as pilot on STS-50 in 1992 and STS-61 in 1993, and commanded the spacecraft on STS-73 in 1995.

Scott J. "Doc" Horowitz, Ph.D.: NASA Astronaut (Lieutenant Colonel, USAF). *Discovery* pilot Scott Horowitz was born in Philadelphia, Pennsylvania, but considers Thousand Oaks, California, to be his hometown. He received a bachelor of science degree in engineering from California State University at Northridge in 1978; a master of science degree in aerospace engineering from Georgia Institute of Technology in 1979; and a doctorate in aerospace engineering from the Georgia Institute of Technology in 1982. Horowitz served as pilot on STS-75 in 1996 and has logged over 377 hours in space. The principal payloads on STS-75 were the reflight of the Tethered Satellite System (TSS) and the third flight of the United States Microgravity Payload (USMP-3).

Mark C. Lee: NASA Astronaut (Colonel, USAF). Payload Commander Mark Lee of Viroqua, Wisconsin, received a bachelor of science degree in civil engineering from the U.S. Air Force Academy in 1974 and a master of science degree in mechanical engineering from Massachusetts Institute of Technology in 1980. A veteran of three space flights, Lee has traveled over 9 million miles, going around the world 368 times and spending over 550 hours in orbit. He flew on STS-30 in 1989, STS-47 in 1992, and STS-64 in 1994. During STS-64, he logged EVA hours totaling 6 hours, 51 minutes. He is currently the Chief of the Astronaut Office EVA / Robotics Branch.

Gregory J. Harbaugh: NASA Astronaut. Mission Specialist Gregory Harbaugh of Willoughby, Ohio, received a bachelor of science degree in aeronautical and astronautical engineering from Purdue University in 1978 and a master of science degree in physical science from University of Houston-Clear Lake in 1986.

A veteran of three space flights, Harbaugh has logged a total of 578 hours, 23 minutes in space. He flew first as a Mission Specialist aboard the Space Shuttle Discovery on STS-39 April 28 – May 6, 1991. Harbaugh then served as Flight Engineer (Mission Specialist) aboard Space Shuttle Endeavour on STS-54, January 13 – 19, 1993. From June 27 to July 7, 1995, Harbaugh flew as the Flight Engineer (Mission Specialist) on a seven-member (up) eight-member (down) crew on Space Shuttle mission STS-71. This was the first docking with the Russian Space Station Mir, and involved an exchange of crews.

Steven L. Smith: NASA Astronaut. Mission Specialist Steven Smith was born in Phoenix, Arizona, but considers San Jose, California, to be his hometown. He received a bachelor of science degree in electrical engineering, a master of science degree in electrical engineering, and a master's degree in business administration from Stanford University.

Smith served as a mission specialist aboard the Space Shuttle Endeavour on Mission STS-68 in 1994. His responsibilities during the 11-day flight were split between Shuttle systems, Space Radar Lab 2 (SRL-2, the flight's primary payload), and several experiments located in the crew cabin.

From November 1994 until March 1996, Smith was one of three astronauts assigned to duties at the Kennedy Space Center as members of the astronaut support team. The team was responsible for Space Shuttle prelaunch vehicle checkout, crew ingress and strap-in prior to launch, and crew egress post landing.

Joseph R. "Joe" Tanner: NASA Astronaut. Mission Specialist Joseph Tanner received a bachelor of science degree in mechanical engineering from the University of Illinois.

Tanner started working for NASA JSC in 1984 as an aerospace engineer and research pilot. His primary flying responsibilities involved teaching the astronaut pilots Space Shuttle landing techniques in the Shuttle Training Aircraft and instructing the pilots and mission specialists in the T-38. He has accumulated more than 7,000 hours in military and NASA aircraft.

Tanner flew aboard the Space Shuttle Atlantis on the STS-66, November 3 – 14, 1994, performing the Atmospheric Laboratory for Applications and Science-3 (ATLAS-3) mission. ATLAS-3 was the third in a series of flights to study the Earth's atmosphere composition and solar effects at several points during the sun's 11-year cycle.

Steven A. Hawley, Ph.D.: NASA Astronaut. Mission Specialist Steven Hawley of Salina, Kansas, received bachelor of arts degrees in physics and astronomy (graduating with highest distinction) from the University of Kansas in 1973 and a doctor of philosophy in astronomy and astrophysics from the University of California in 1977.

Dr. Hawley was selected as a NASA astronaut in January 1978. A veteran of three space flights, he served as a mission specialist on STS-41D in 1984, STS-61C in 1986, and STS-31 in 1990. As a Mission Specialist on STS-31, Dr. Hawley used the RMS to deploy the Hubble Space Telescope.

In June 1990 Dr. Hawley left the Astronaut Office to assume the post of Associate Director of NASA's Ames Research Center in Mountain View, California. In August 1992 he returned to JSC as Deputy Director of Flight Crew Operations. In February 1996 Dr. Hawley was returned to astronaut flight status and named to the crew of the HST Second Servicing Mission.

2.7 Servicing Mission Activities

As the *Discovery* approaches the Hubble Space Telescope in orbit February 1997, the seven-person crew will begin one of the most ambitious servicing missions in the history of space travel. Four days of EVA activities are scheduled, with a fifth day available if needed. Each EVA session is scheduled for six hours.

2.7.1 Rendezvous With the Hubble Space Telescope

Discovery will rendezvous with the Hubble in orbit 316 nautical miles (506 km) above the Earth. As Discovery approaches the Telescope, Commander Bowersox will control the thrusters to avoid contaminating HST with propulsion residue. During this approach the Shuttle crew will be in close contact with Mission Control at JSC. In concert with the Space Telescope Operations Control Center (STOCC) at GSFC, Mission Control will command HST to stow the High Gain Antennas (HGA) and close the aperture door.

As the distance between *Discovery* and HST decreases to approximately 200 ft (60 m), the STOCC ground crew will command HST to perform a final roll maneuver to position itself for grappling. The SAs will remain fully deployed parallel to the optical axis of the Telescope.

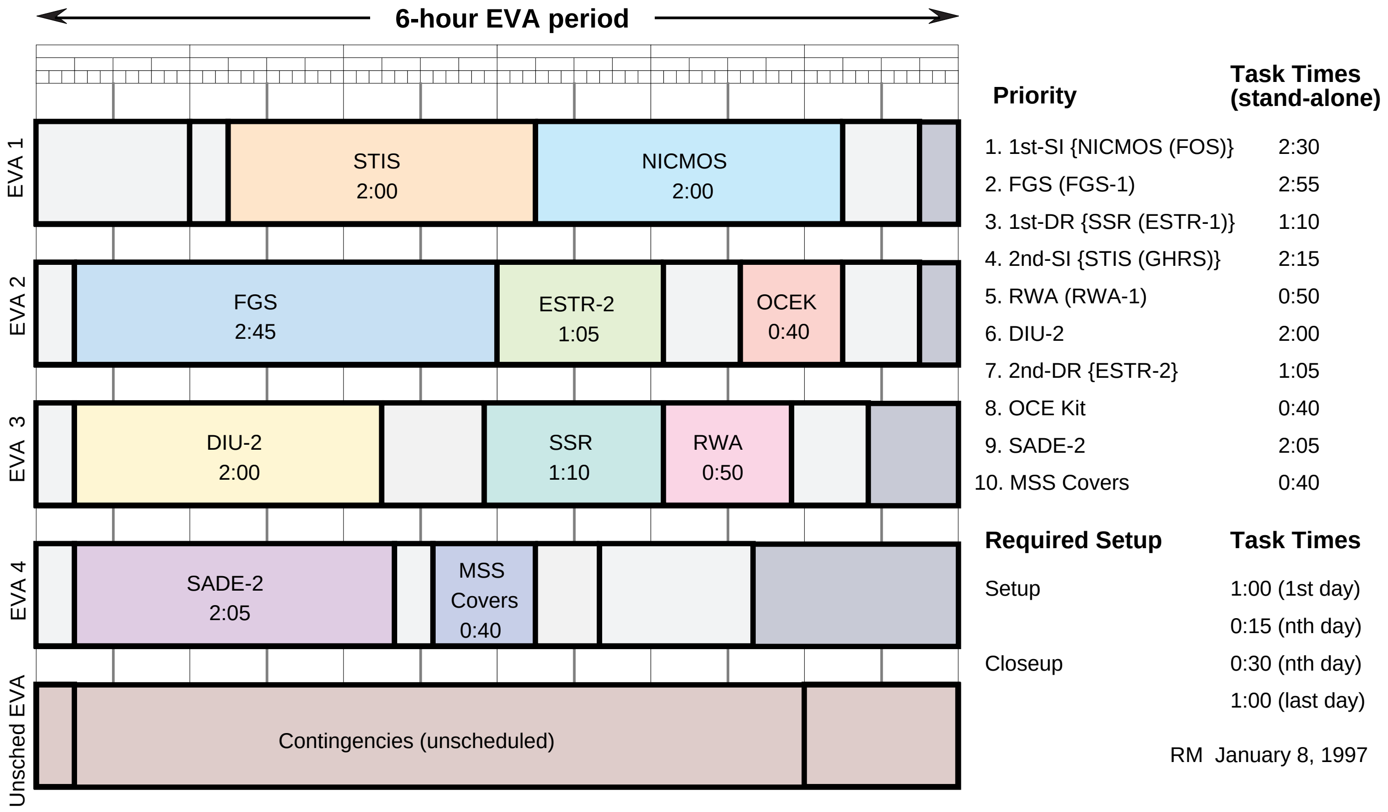
When *Discovery* and HST achieve the proper position, Mission Specialist Hawley will operate the robotic arm to grapple the Telescope. Using a camera mounted at the base of the FSS platform in the cargo bay, he will maneuver HST to the FSS, where the Telescope will be berthed and latched.

Once the Telescope is secured, the crew will remotely engage the electrical umbilical and switch Hubble from internal power to external power from *Discovery*. The pilot also will maneuver the Shuttle so that the SAs face the sun to recharge the Telescope's six onboard nickel-hydrogen (NiH_2) batteries.

2.7.2 Extravehicular Servicing Activities – Day by Day

Figure 2-8 shows the schedule for four six-hour EVA servicing periods. These time spans are planning estimates; the schedule will be modified as needed as the mission progresses. During most of the EVAs, HST will be vertical relative to *Discovery's* cargo bay. Four EVA mission specialists will work in two-person teams on alternate days. One team is Mark Lee and Steve Smith; the other is Greg Harbaugh and Joe Tanner.

One astronaut, designated EV1, accomplishes primarily the free-floating portions of the EVA tasks. He can operate from a PFR or can accomplish the tasks free floating. The other astronaut, EV2, works from an MFR mounted on Discovery'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 Second Servicing Mission carriers. Inside *Discovery's* aft flight deck, the off-shift EVA crew members and the designated RMS operator assist the EVA team



Priority	Task Times (stand-alone)
1. 1st-SI {NICMOS (FOS)}	2:30
2. FGS (FGS-1)	2:55
3. 1st-DR {SSR (ESTR-1)}	1:10
4. 2nd-SI {STIS (GHRS)}	2:15
5. RWA (RWA-1)	0:50
6. DIU-2	2:00
7. 2nd-DR {ESTR-2}	1:05
8. OCE Kit	0:40
9. SADE-2	2:05
10. MSS Covers	0:40

Required Setup	Task Times
Setup	1:00 (1st day)
	0:15 (nth day)
Closeup	0:30 (nth day)
	1:00 (last day)

RM January 8, 1997

K70110-102

Fig. 2-8 Schedule of extravehicular activities by reading out the procedures and operating the RMS.

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

EV1 accomplishes a variety of specific tasks to prepare for that day's EVA servicing activities. These include removing the MFR from its stowage location on the RMS grapple fixture; installing the Low Gain Antenna Protective Cover (LGA PC); deploying the Translation Aids (TA); and removing the BAPS Support Post from its stowage location and installing it on the FSS with the assistance of EV2.

Meanwhile, EV2 brings out of the airlock the Crew Aids and Tools (CAT) that will be attached to the handrails of the RMS. He transfers the CAT to EV1 to secure on the Second Axial Carrier (SAC) ASIPE, opens the contamination mirror box lid, and reconfigures the SAC aft PFR. He installs the CAT handrail to the RMS and the color television camera (CTVC) on the MFR. Next he is moved to the Berthing and Positioning System (BAPS) Post installation worksite by the IVA RMS operator to install the BAPS Post forward end on the BAPS.

EVA Day 1: Change-out of Goddard High Resolution Spectrograph with Space Telescope Imaging Spectrograph, and Faint Object Spectrograph with Near Infrared Camera and Multi-Object Spectrometer. During EVA Day 1, Lee and Smith are scheduled to install two new axial scientific instruments. They begin with the initial setup, which includes installation of the LGA protective cover, TA deployments, and installation and deployment of the BAPS Support Post (BSP).

The BSP is required to dampen the vibration that the servicing activities will induce into the deployed SAs. Prior to its installation on the initial day, HST is commanded to an 85-degree pivot by the IVA team. The two center push in-pull out (PIP) pins are installed each day and removed each night in the event that the Shuttle must make an emergency return to Earth. EV1 removes the BPS from its stowage position in the cradle of the FSS and hands the forward end to EV2 who installs his end to the BAPS ring with a PIP pin. EV1 then installs the aft end of the BPS to the FSS cradle with a PIP pin. Finally the BPS is commanded to its 90-degree limit and the two center PIP pins are installed.

When the BPS is installed and other initial setup tasks are completed, the crew starts the specific tasks for the SI change-outs. EV1 deploys the ORUC Aft Fixture, which temporarily secures the old instrument while the new instrument is installed. EV1 and EV2 translate and open the HST V3 aft shroud doors.

Working as a team on the change-out of the GHRS, EV1 demates and secures the GHRS Repair Kit and HST side of the electrical and data connectors and the ground strap. EV2 then loosens the A latch and grasps the GHRS EVA handles. EV2 applies downward pressure while EV1 loosens the B latch. To assist the crew in loosening and tightening the A and B latches, indicator lights show the status of the latches. When the latches are loosened, EV2 slowly begins to remove the GHRS from the HST while EV1 provides clearances and direction calls.

When the GHRS is removed, EV1 does a bay inspection and EV2 translates to the aft fixture, stows the GHRS into the aft fixture using the GHRS EVA handles, and secures the instrument with a PIP pin. EV1 then translates to the ORUC Axial Scientific Instrument Protective Enclosure (ASIPE), opens the ASIPE lid, and disconnects the ASIPE ground strap. Both astronauts then position themselves at the latches. EV1 again loosens the A latch and positions himself on the STIS EVA handles. EV2 loosens the B latch while EV1 applies slight aft pressure to keep STIS against the B latch. With latches disengaged, EV2, with clearance instructions from EV1, removes STIS from the ASIPE.

While the IVA team moves EV2 into position for STIS insertion into the HST, EV1 closes the ASIPE lid and latches one latch. When EV1 and EV2 are in position, EV2 begins insertion of the STIS into the HST (see Fig. 2-9). Again, clearance and directional instructions by EV1 are critical to successful insertion of the STIS. After the STIS is inserted, EV1 tightens the B latch. In parallel to the A latch tightening by EV2, EV1 mates the ground strap and the electrical and data connectors. When EV1 has mated the connectors, IVA gives MCC a “go” for the STIS aliveness test.

Next, EV2 translates to the aft fixture and removes the GHRS from the fixture. While EV2 is translating with the GHRS to the ASIPE worksite, EV1 opens and secures the ASIPE lid.

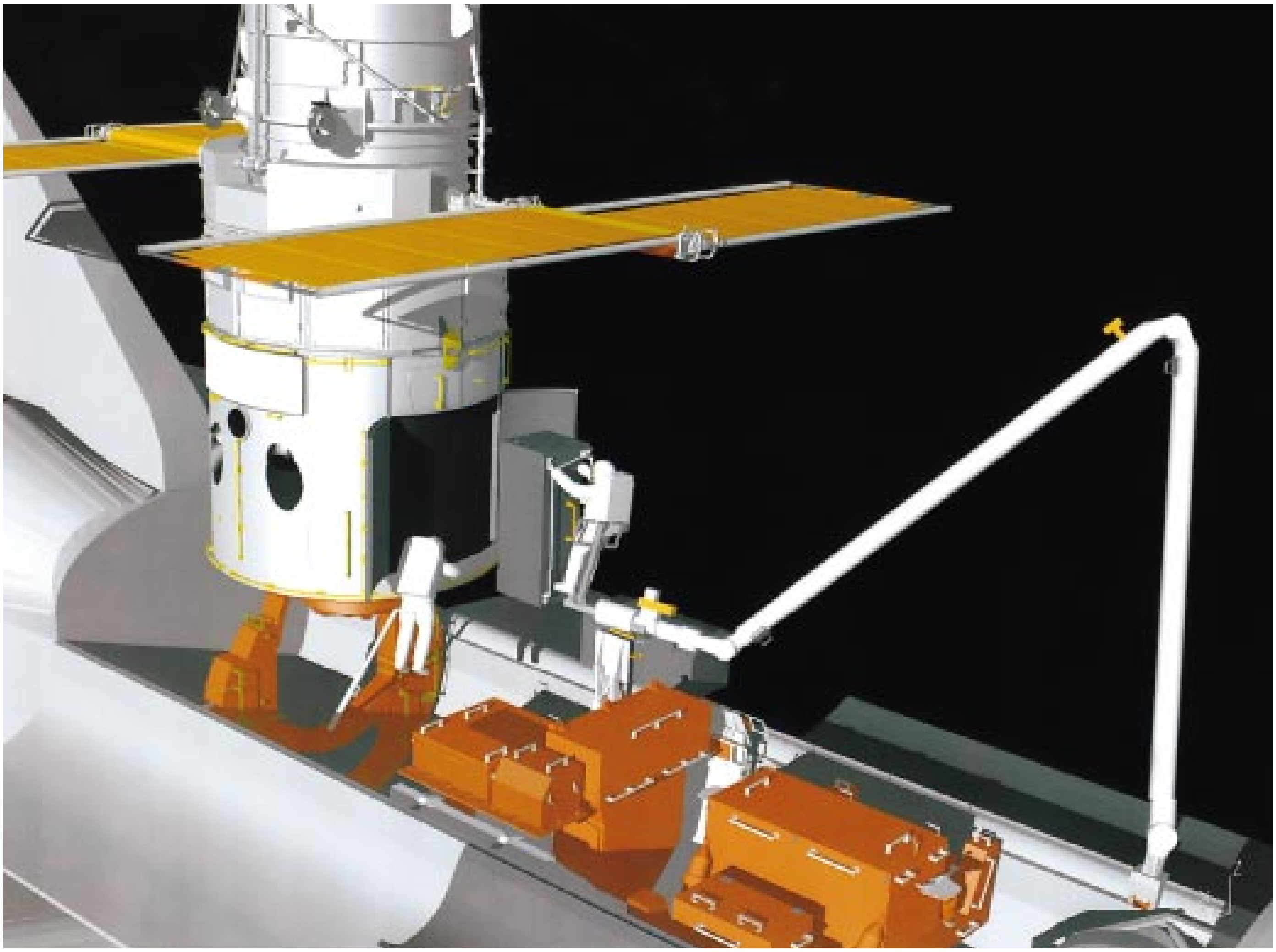

K70110-209

Fig. 2-9 Change-out of Goddard High Resolution Spectrograph and Space Telescope Imaging Spectrograph

Again with instructions, EV2 inserts the GHRS into the ASIPE. EV1 tightens the B latch and EV2 tightens the A latch. EV1 then installs the ground strap and removes the GHRS Repair Kit from the GHRS and secures it where it will be stowed in the Contingency ORU Protective Enclosure (COPE) on the SAC, after NICMOS is installed and the HST aft shroud doors are closed.

The change-out of the FOS, and replacement by NICMOS, uses the same scenario as the GHRS and STIS. EV2 and EV1 translate to the HST where EV2 loosens the A latch and applies downward pressure while EV1 loosens the B latch. EV2 with EV1 instructions removes the FOS. While EV2 installs FOS into the aft fixture, EV1 translates to the SAC ASIPE, opens the lid, and removes the ground strap from NICMOS. With EV1 and EV2 at the SAC ASIPE, EV2 loosens the A latch and EV1 loosens the B latch. EV2 carefully removes NICMOS with EV1 instructions. While EV2 translates to HST, EV1 closes the ASIPE lid and latches one latch.

At the HST, EV2 inserts NICMOS with assistance from EV1. As before, EV1 tightens the B latch and EV2 tightens the A latch. EV1 mates the NICMOS ground strap and electrical and data connectors while EV2 removes the cryo vent cover and translates to the Multiple ORU Protective Enclosure (MOPE), opens the lid, removes the NICMOS cryo vent line from its stowage location, and stows the cryo vent cover. After EV1 mates all of the electrical connectors, IVA gives MCC a “go” for the NICMOS aliveness test. EV2 closes the lid and secures five latches, routes the vent line under and to the center guide rail, installs the NICMOS cryo vent line on the HST cryo vent hole, and secures the line to the guide rail standoff. EV1 opens the NICMOS capillary line plug, routes the vent line through the HST aft bulkhead handrail, and attaches the vent line to NICMOS. EV1 then opens the cryo vent line valve and secures the vent line to the handrail.

EV2 completes close-out photographs. Then EV1 and EV2 close and secure the doors. Next, EV1 opens the SAC ASIPE lid so that EV2 can remove the FOS from the ORUC aft fixture. EV1 then closes the aft fixture and stores the GHRS repair kit in the COPE. EV2 inserts the FOS into SAC ASIPE with assistance from EV1. When the FOS is fully inserted, EV1 tightens the B latch and EV2 tightens the A latch. In parallel to the A latch tightening, EV1 installs the ground strap. EV1 closes and secures the ASIPE lid and lid latches. EV1 then configures the SAC aft PFR to launch configuration.

Meanwhile, EV2 prepares the MFR handhold for return to the airlock. For the daily close-out, EV1 removes the center pins on the BPS and retracts the TAs while EV2 prepares the CAT installed on the MFR handrail for return into the airlock. Additionally, EV1 releases the MFR safety tether from the grapple fixture for contingency Earth return and releases the lower CTVC cable. After the completion of EVA Day 1, both astronauts return to the airlock with the Day 1 CAT installed on the MFR handrail.

EVA Day 2: Change-out of Fine Guidance Sensor #1 and Engineering/Science Tape Recorder #2, and Installation of Optics Control Electronics Enhancement Kit. During EVA Day 2, EVA astronauts Harbaugh and Tanner are scheduled to change out a malfunctioning Fine Guidance Sensor (FGS) in position number 1 (see Fig. 2-10) and the Engineering / Science Tape Recorder (E / STR) in position number 2 (see Fig. 2-11). To increase the capability of the FGS, installation of the Optical Control Electronics Enhancement Kit (OCE-EK) also is scheduled.

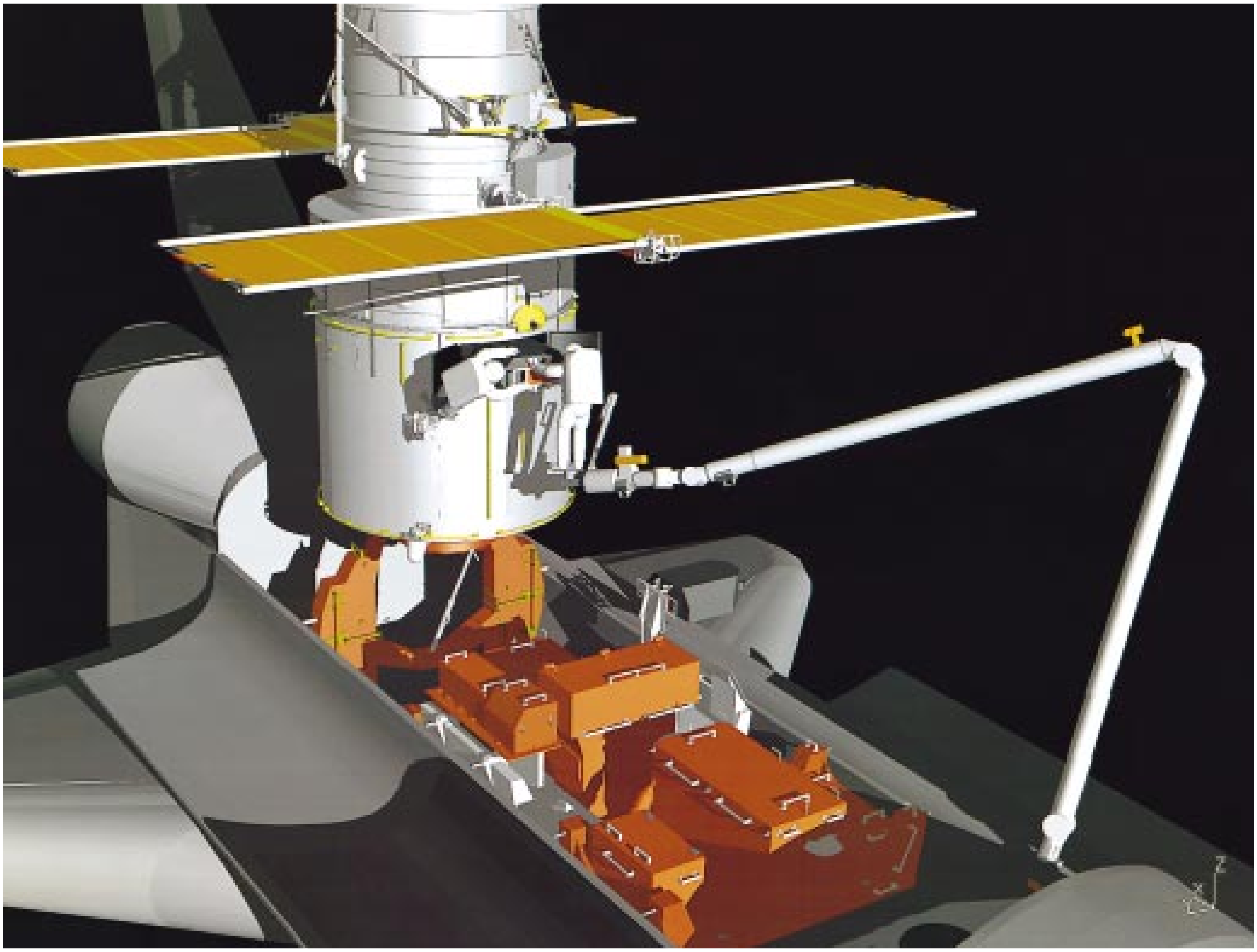


Fig. 2-10 Installation of Fine Guidance Sensor #1

Fewer daily setup tasks are required for EVA Day 2 than for EVA Day 1. EV2 still exits the airlock with the EVA Day 2 required CAT installed on the MFR handrail. EV1 reconnects the safety strap on the MFR and connects the CTVC cable to the RMS end effector. EV2 then installs the MFR handrail and the CTVC on the RMS. EV1 simultaneously deploys the TAs, installs the BPS center PIP pins, and deploys the aft fixture for FGS use. When EV2 has completed his daily set, he gets the PFR and installs it in the HST PFR socket for EV1 FGS change-out use. EV1 and EV2 open and secure the FGS bay doors, and EV2 installs four guide studs on the FGS. While EV1 demates the FGS connectors and ground strap, EV2 translates to the ORUC forward fixture to retrieve an FGS handhold. EV2 installs the FGS handhold and loosens the A latch. The FGS is now ready to be removed.

With EV1 in the PFR and EV2 holding the FGS handhold, the team removes the FGS as EV1 gives clearance instructions. To ensure a successful installation of the replacement FGS, the team partially removes the old FGS and then reinstalls it without latching the latches or mating connectors for mass handling evaluation.

After this practice insertion, EV2 removes the FGS and stows it on the aft fixture. EV1 then

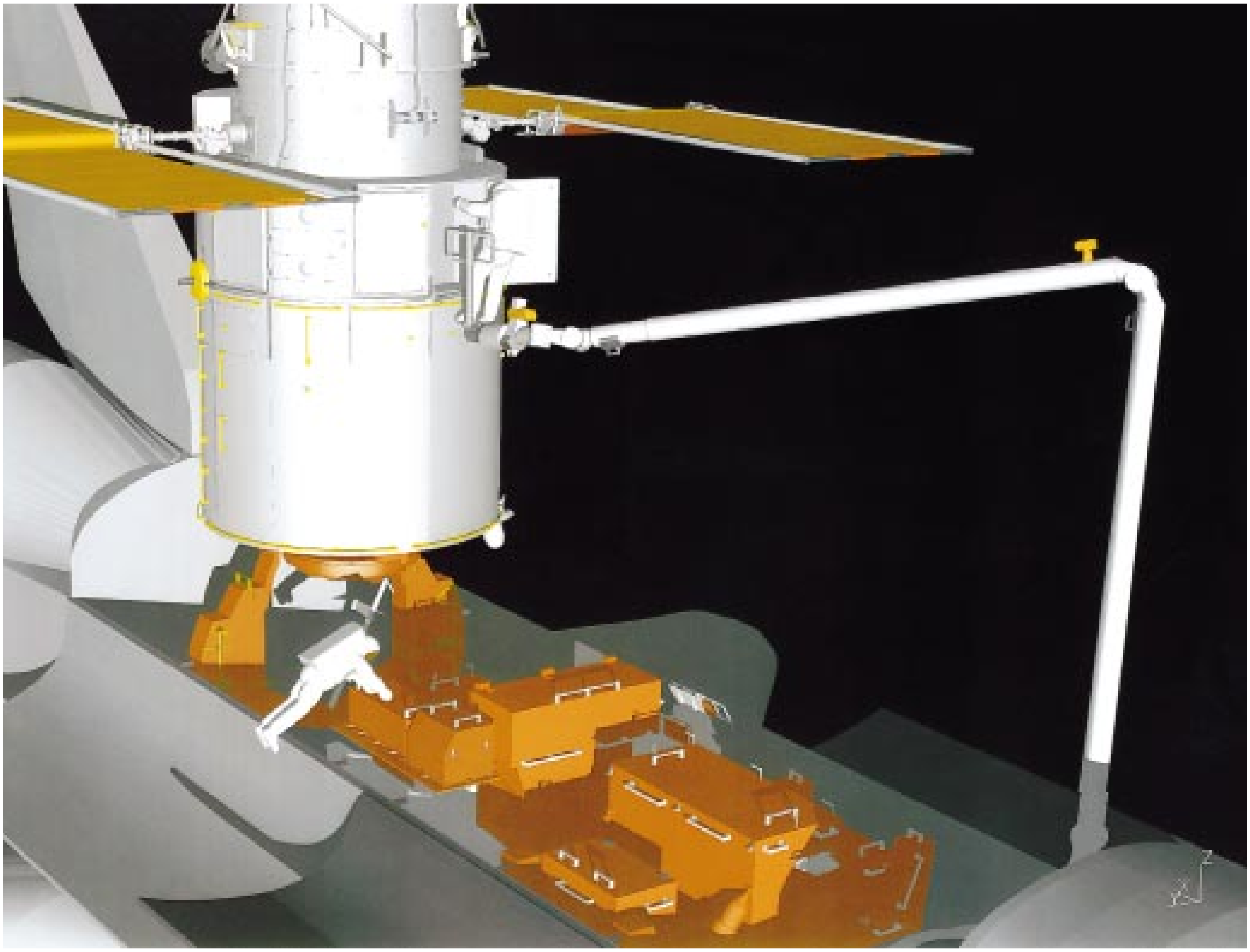

K70110-211

Fig. 2-11 Replacement of Engineering/Science Tape Recorder #2 in Bay 8

conducts a bay inspection. Next, EV1 translates to the ORUC FGS Scientific Instrument Protective Enclosure (FSIPE), opens the lid, latches the lid in the open position, and demates and secures the ground strap. In parallel, EV2 retrieves the other FGS handhold from the ORUC forward fixture and positions himself for installation on the replacement FGS in the FSIPE.

After installing the handhold on the FGS, EV2 loosens the A latch. EV2, with instructions and assistance from EV1, removes the FGS from the FSIPE and translates to the HST with the FGS. EV1 closes the FSIPE lid and engages one lid latch. He then ingresses the PFR mounted on the HST and prepares to remove the FGS mirror cover. EV2 presents the FGS to EV1 so that the FGS mirror cover can be removed. EV1 tethers to the cover, releases the slide lock lever, and operates the handle to remove the mirror cover. When the mirror cover is removed, IVA repositions the EV2 and MFR so that the FGS can be installed. EV2 inserts the FGS with assistance from EV1. EV2 tightens the A latch, removes the FGS handhold, and stows it temporarily on the MFR. EV1 installs the ground strap and electrical connectors. After the electrical connectors are mated, IVA informs MCC to perform an aliveness test. EV2 returns to the FGS bay, takes the close-out photographs, closes and latches the doors, and repositions the scuff plates to launch configuration. He then retrieves the HST PFR and stows it for later installation. EV1 stows the mirror cover on the ORUC.

EV1 translates to the FSIPE and opens the lid. EV2 stows the FGS handrail in the forward fixture, then translates to the ORUC aft fixture, removes the FGS, and translates to the FSIPE with the FGS. EV1 assists EV2 during the FGS insertion into FSIPE. After full insertion, EV2 tightens the A latch while EV1 mates the ground strap. EV1 releases the FSIPE on-orbit latches, closes and secures the lid, and closes the aft fixture. At this time EV2 retrieves the PFR that was used for the FGS change-out and reinstalls it on the Shuttle bay adaptive payload carrier.

EV2 then translates to Bay 8 for the change-out of the E/STR #2. With assistance from EV1, EV2 opens and secures the bay door. EV2 then demates the three connectors, ensuring that the power-on connector P1 is prevented from touching structure ground. He secures the P1 connector behind the Pointing/Safemode Electronics Assembly (PSEA) cable harnesses. After removing the four keyhole fasteners, EV2 removes the E/STR and carefully transports it to the Small ORU Protective Enclosure (SOPE). EV1 translates ahead of EV2 and opens the SOPE lid and the E/STR #2 transport module. EV2 hands EV1 the old E/STR and retrieves the new E/STR from its transport module. EV1 installs the E/STR into the E/STR #2 transport module and secures the transport module lid latch. EV1 then retrieves the timing cable and closes the SOPE lid and engages three latches. He then translates to Bay 3 to assist E/STR installation.

Meanwhile, EV2 transports the E/STR up to Bay 8, being very careful not to exceed the E/STR's angular acceleration limits. EV2 then installs the E/STR and torques the four keyhole fasteners. EV1 transfers the timing cable to EV2 who installs it in line with the HST and E/STR sides of the P2 connector. The other connectors are mated, close-out photographs are taken, and the bay door is secured via its six J-hooks.

HST is rotated to the -V3 side in preparation for the OCE-EK installation. As part of the OCE-EK preparation, EV1 changes places with EV2 on the RMS (see Fig. 2-12). When the crew member swap and HST rotation have been completed, EV1 on the RMS translates to the Optical Telescope Assembly (OTA) Bay C door and opens the door via the three J-hooks. EV2 has returned to the SOPE, opened the three lid latches, retrieved the OCE-EK from its stowage pouch, and closed the SOPE lid latches.

While EV2 translates to Bay C, EV1 demates the P6 and P10 connectors from the OCE. EV1 then mates the OCE-EK J/P6 A and J/P10A connectors with the OCE J6 and J10 and HST P6 and P10 connectors. When this is completed, EV1 removes the connector cover from the OCE J13 connector and mates the OCE-EK P13 connector to the OCE. The close-out photographs are taken and the Bay C door is secured with its three J-hooks.

For the EVA Day 2 daily close-out, EV2 removes the center pins on the BPS, inspects the FSS main umbilical mechanism, and retracts the TAs while EV1 prepares the CAT installed on the MFR handrail for return to the airlock. Additionally, EV1 releases the MFR safety tether from the RMS in the event of contingency Earth return. Both astronauts return to the airlock with the MFR handrail with CAT installed.

EVA Day 3: Change-outs of Data Interface Unit #2 and Solid State Recorder #1 for

K70110-212

Fig. 2-12 Installation of Optical Control Electronics Enhancement Kit in Bay C

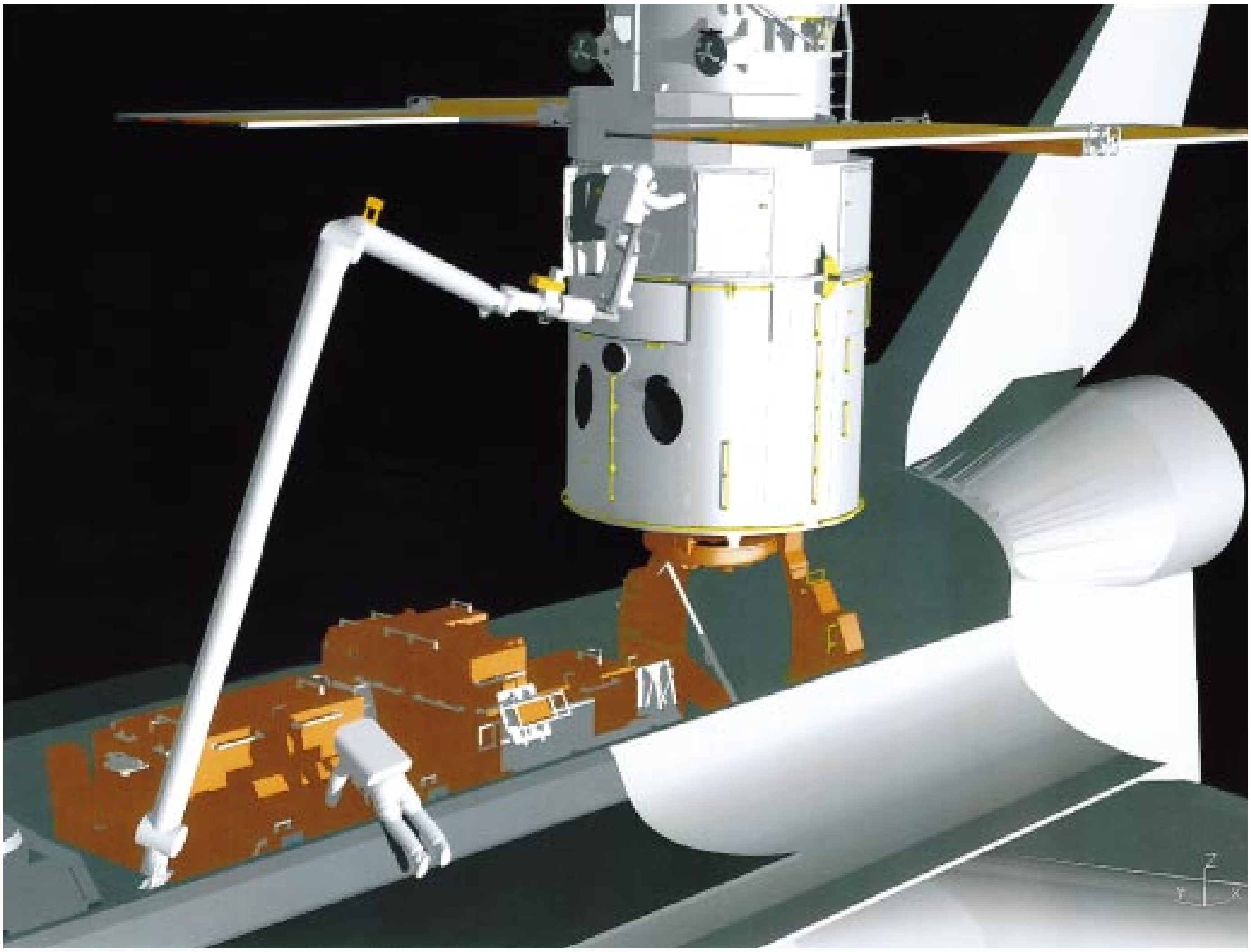
Engineering/Science Tape Recorder #1 and Reaction Wheel Assembly #1. The daily setup for EVA Day 3 is almost identical to EVA Day 2 except that EV1 starts the day in the MFR. EV1 still exits the airlock with the required CAT and CTVC installed on the MFR handrail and transfers them to EV2. EV2 reconnects the safety strap on the MFR/RMS and connects the CTVC to the RMS end effector. EV1 then installs the MFR handrail and the CTVC on the RMS. EV2 simultaneously deploys the TA and installs the BPS center PIP pins. EV1 also retrieves the DIU gender changers and DIU portable ORU handle after EV2 opens the Multimission ORU Protective Enclosure (MOPE).

EV1 translates to SSM Bay 3 and operates the six J-hooks to open the door. With assistance from EV2, EV1 demates the powered-on P1, P2, and P3 connectors and mates them with gender changers to eliminate the possibility of them touching structure ground and shorting out. The gender changers are secured out of the worksite. EV1 then demates the remaining 15 connectors. Two of the 20 connectors are not used on DIU #2 and have connector covers installed on them. The DIU portable ORU handle is installed on the DIU to enable the EVA crew members to handle and tether to it before the six 7/16-in. noncaptive fasteners are loosened to remove the DIU. When the DIU is removed, EV1 translates on the RMS to the

MOPE where EV2 has opened the lid and raised the tool board that holds the replacement DIU in its transport module. EV2 secures himself and receives the old DIU from EV1 who, in turn, opens and removes the replacement DIU. EV2 installs the old DIU in the transport module, removes the DIU portable ORU handle, closes the transport module, and then lowers the tool board to its stowed position. EV2 then closes and secures one MOPE lid latch, and translates to the Bay 3 worksite to assist with the DIU installation.

While EV2 is at the MOPE worksite, EV1 translates to the Bay 3 DIU #2 worksite (see Fig. 2-13). EV1 installs the DIU using the two center alignment marks as aids and tightening the four captive fasteners. Once the DIU is installed by the fasteners, EV1 mates the 18 connectors to the harness extensions mounted on the replacement DIU. When the connectors are mated, EV1 removes the cable restraint device and transfers it to EV2. EV1 then takes the closeout photographs and closes and secures the bay door via the six J-hooks.

After the DIU #2 change-out is completed, EV1 and EV2 swap positions on the RMS, and HST is rotated approximately 110 degrees to align the SSR and RWA worksite forward. The next

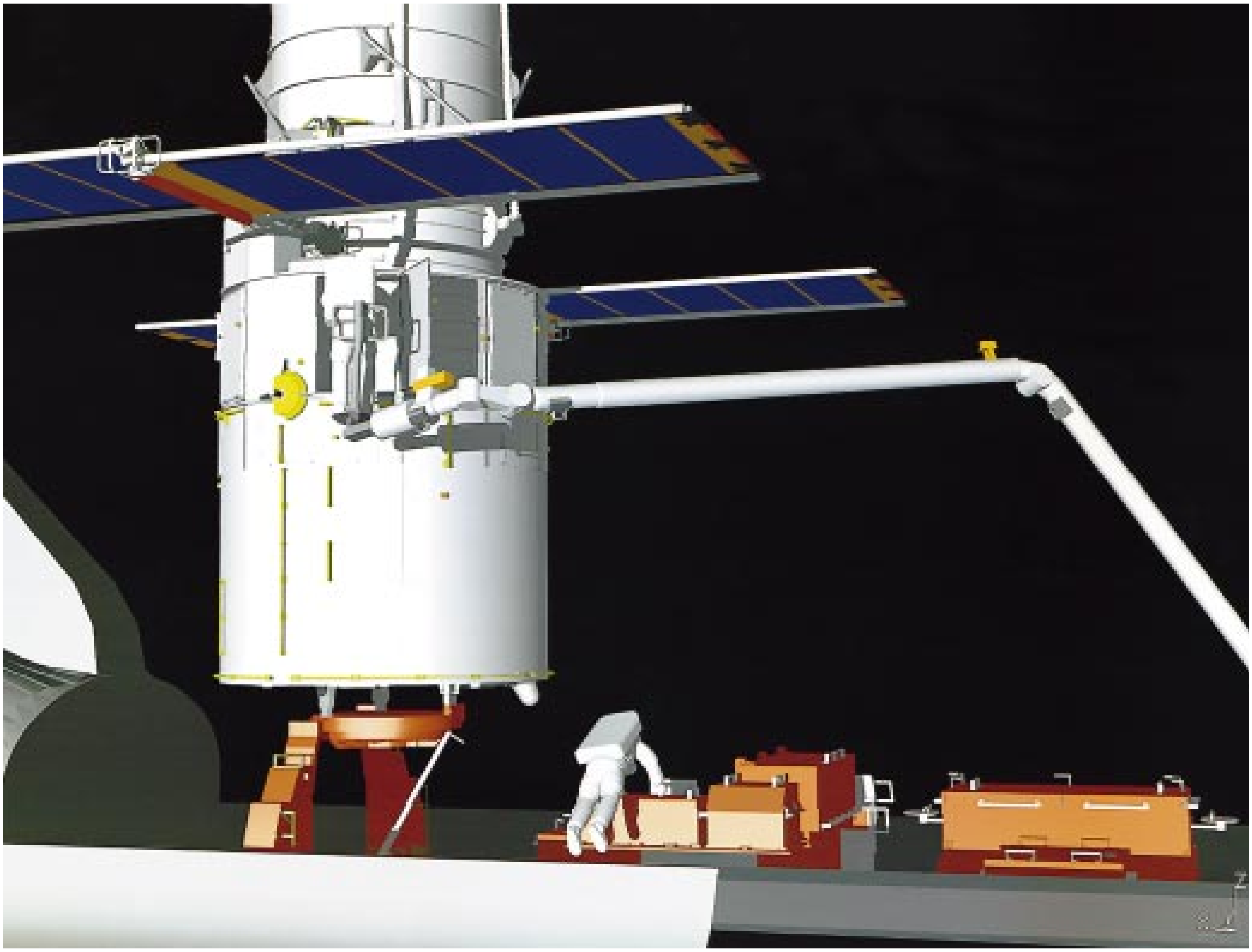


K70110-213

Fig. 2-13 Replacement of Data Interface Unit #2 in Bay 3 change-out task is replacement of the E/STR #1 with a newer technology SSR #1. EV2 translates from the swap position to SSM Bay 5 where he opens the door via six J-hooks. EV2 demates the three connectors, being careful not to allow the powered-on P1 connector to touch structure ground. He secures the P1 connector behind the cable harness along the side wall, demates the four keyhole fasteners, and removes the E/STR.

While EV2 translates to the SOPE with the E/STR, EV1 translates to the SOPE via the HST and Shuttle handrails. EV1 opens the SOPE lid latches and the lid. EV2 installs the E/STR directly into the E/STR #1 transport module, then removes the SSR from its transport module and translates back to the Bay 5 worksite. EV1 secures the transport module, removes the "T" harness from its stowage pouch, and closes and latches the SOPE lid. He then translates to Bay 5 to assist in SSR installation.

In parallel to closure of the SOPE by EV1, EV2 installs the SSR into the #1 position (see Fig. 2-14). The SSR #1 is mounted via the same four keyhole bolts as E/STR #1. The SSR #1 to E/STR #3 "T" harness is installed from the SSR P4 connector to a "T" at the E/STR #3 P2 connector. The "T" harness provides increased capability to the E/STR and HST. EV2 then mates the two remaining connectors and takes the



K70110-214

Fig. 2-14 Installation of Solid State Recorder in Bay 5 close-out photographs. With the assistance of EV1, EV2 closes the door and secures it with the six J-hooks.

EV2 then translates to the RWA worksite in Bay 6. The bay doors are opened after the six J-hook fasteners are operated. Four connectors must be demated for removal of the RWA: two small heater connectors and two RWA electronic box connectors. In addition, three keyhole fasteners that secure the RWA to its isolators must be loosened for RWA removal. Once the fasteners are removed, EV2 removes the RWA and translates to the ORUC Large ORU Protective Enclosure (LOPE). EV1 opens the LOPE lid by operating the lid J-hooks. EV2, with assistance from EV1, stows the old RWA out of the way and removes the replacement RWA from the LOPE.

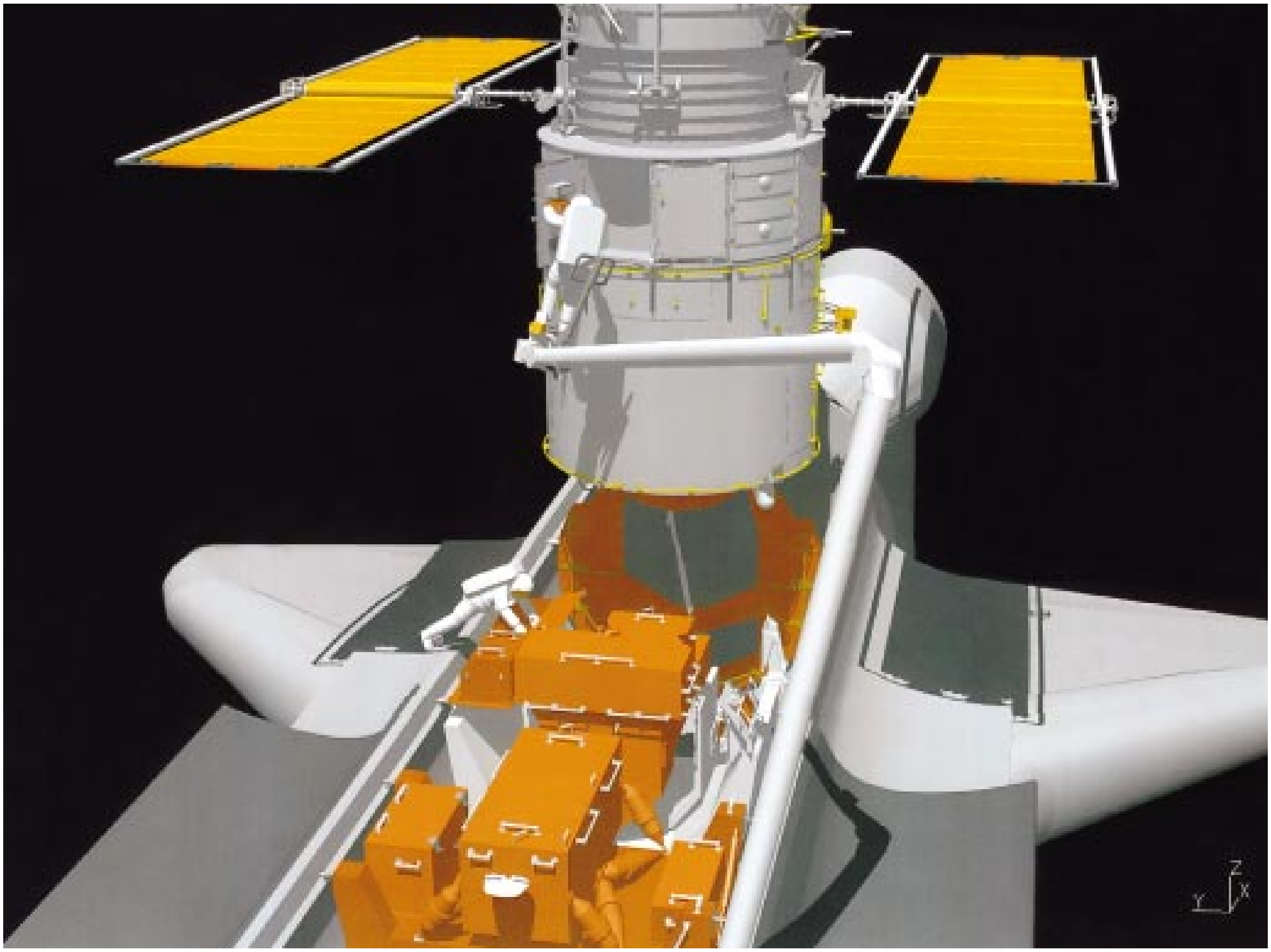
With the new RWA secure, EV1 and EV2 install the old RWA into the LOPE via the three keyhole fasteners. EV1 closes the LOPE lid while EV2 translates to Bay 6. EV2 installs the RWA using the three keyhole fasteners. After tightening the fasteners, EV2 mates the two heater connectors and two electronic box connectors. Close-out photographs are taken and the bay door is closed and secured by the six J-hooks.

For the Day 3 EVA close-out, EV1 removes the center pins on the BPS, inspects the FSS main umbilical mechanism, and retracts the TAs while EV2 prepares the CAT installed on the MFR handrail for return into the airlock. EV2 releases the MFR safety tether from the RMS in the event of contingency Earth return. During the daily close-out, the HST is reboosted to a higher altitude. After completion of EVA Day 3 close-outs, both astronauts return to the airlock with the MFR handrail with CAT installed.

EVA Day 4: Change-out of Solar Array Drive Electronics (SADE) #2 and installation of the Magnetic Sensing System (MSS) Covers. EVA Day 4 has a daily setup similar to that of the prior EVA days. EV1 starts the day in the MFR. EV1 exits the airlock with the required CATs installed on the MFR handrail and the CTVC and hands them to EV2. EV2 reconnects the safety strap on the MFR/RMS and connects the CTVC cable to the RMS end effector. EV1 then installs the MFR handrail and the CTVC to the RMS. EV2 simultaneously deploys the TAs and installs the BPS center PIP pins.

Upon completion of the daily setup, EV2 and EV1 translate to SSM Bay 7 and open the door. Both astronauts then translate to the SOPE and open the lid. EV2, on the MFR, removes the SADE #2 from its transport module. While EV2 translates back to Bay 7, EV1 closes the SOPE lid, engages one latch, then translates to Bay 7 to assist EV2. EV2 secures the new SADE #2 to the door and begins the demate of the old SADE connectors. As each old SADE connector is demated, it is mated to the corresponding replacement SADE harness extension.

After the replacement SADE harnesses have been mated, EV2 demates the six noncaptive 5/16-in. fasteners that secure the SADE. The fasteners are installed into the fastener retention block (FRB) mounted on the new SADE. After the old SADE is removed and secured on the MFR, the new SADE with mated connectors is installed into the SADE #2 position where it is secured in place by its two alignment pins and four captive 5/16-in. fasteners (see Fig. 2-15). The FRB is mounted on the old SADE for “T” fastener installation. The close-out photographs are taken and the bay door is closed and secured. EV2 translates with SADE #2 and installs it in the SOPE transport module. EV2 and EV1 then close and secure the SOPE lid and latches. After the SOPE closure, the BPS center PIP pins are removed to enable

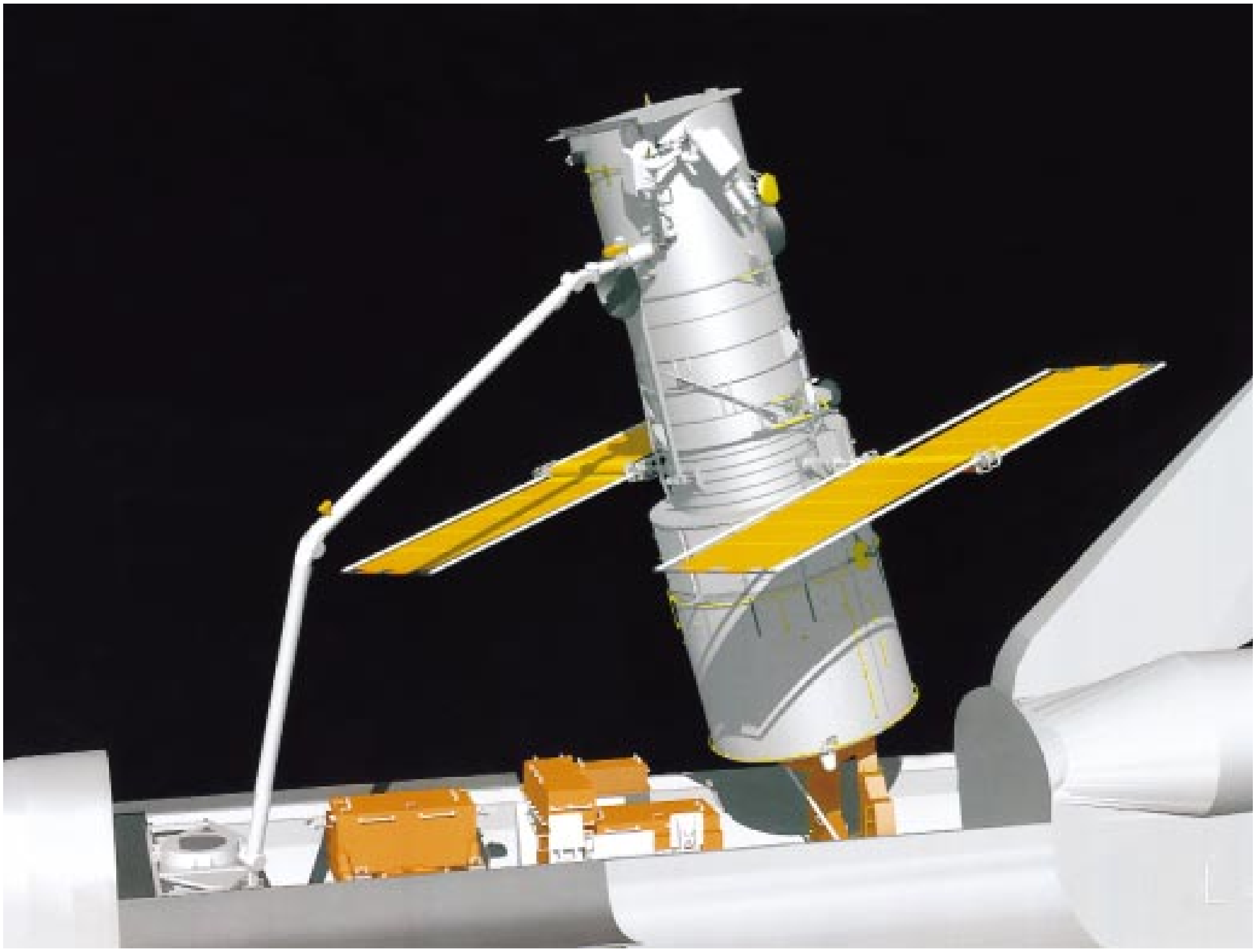


K70110-216

Fig. 2-15 Replacement of Solar Array Drive Electronics #2 in Bay 7

the EVA crew members to gain access to the MSS for installation of the MSS covers. Before they can reach the MSS, HST must be pivoted and rotated. The task is very similar to the HST First Servicing Mission task when the MSS sensor covers were manufactured on orbit. In parallel to HST positioning, both crew members translate to the Contingency ORU Protective Enclosure (COPE), open the COPE lid, remove the MSS covers from their stowage brackets, and close and secure the COPE lid and latches. The IVA RMS operator translates the MFR to the MSS worksites almost 40 ft above *Discovery's* bay. With assistance from EV2, EV1 installs the MSS covers on one and then the other MSS (see Fig. 2-16). After the MSS covers are installed and close-out photographs are taken, the crew returns to the Shuttle bay.

For final close-out, EV2 stows the TAs, removes and stows the LGA-PC, inspects the FSS main umbilical mechanism, and does a final sweep of the bay to ensure that everything is in place for Earth return. EV1 installs all the CAT on the MFR handrail for return to the cabin and demates and stows the MFR from the RMS. On the way back to the cabin, EV1 closes and secures the contamination mirror box lid. In parallel to the final close-out, the HST is reboosted to a higher altitude. When the tasks are complete, both crew members enter the airlock with the CAT-laden MFR handrail.



K70110-216

Fig. 2-16 Attaching cover to Magnetic Sensing System #2

EVA Contingency Day. A contingency day exists in which crew members can accomplish any required or contingency activities. This will be decided by the mission support management and personnel at MCC.

Day 5: Redeploying the Hubble Space Telescope. The day following the scheduled servicing tasks, and any contingency EVAs, will be devoted to the redeployment of the HST into Earth orbit (see Fig. 2-17).

The SAs are slewed to the sun to generate electrical power for the Telescope and to charge the batteries, and the High Gain Antennas (HGA) are commanded to their deployed position. When the battery charging is complete, the RMS crew member guides the robotic arm to engage HST's grapple fixture. The ground crew commands Hubble to switch to internal power. This accomplished, crew members command *Discovery'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 make a final EVA effort to manually override any faulty mechanisms.

2.8 Future Servicing Plans

As the Hubble Space Telescope enters the next century, other enhancements are planned. A

K70110-217

Fig. 2-17 Redeploying the Space Telescope

third-generation instrument, the Advanced Camera for Surveys (ACS), will greatly enhance the Telescope's imaging capabilities. Shuttle astronauts plan to install the camera on Hubble during the third servicing mission scheduled for 1999.

ACS is truly an advanced camera, with predicted performance improvements one to two orders of magnitude over existing Hubble science instruments. The unique characteristics and dramatically improved efficiencies of the ACS will anchor the Hubble science program at the turn of the 21st century, exploiting the full potential of the telescope to serve the needs of the science community.

Periodic upgrades and servicing will ensure that the Telescope continues to yield remarkable advances in our knowledge of the universe.

A new golden era of space exploration and discovery began April 24, 1990, with the launch and deployment of NASA's Hubble Space Telescope (HST). During nearly seven years of operation, Hubble's rapid-fire rate of unprecedented discoveries has invigorated astronomy. Not since the invention of the telescope nearly 400 years ago has our vision of the universe been so revolutionized over 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. Hubble has helped confirm some astronomical theories, challenged others, and has often come up with complete surprises for which theories do not yet even exist.

The 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.

This unique, powerful observatory has produced a vast amount of information and a steady stream of images that have astounded the world's astronomical and scientific community. The Telescope has looked at more than 10,000 objects in the sky, taken over 100,000 exposures, produced more than 2.5 trillion bytes of science data, and given rise to over 1,000 scientific reports and research papers by astronomers from more than 35 countries.

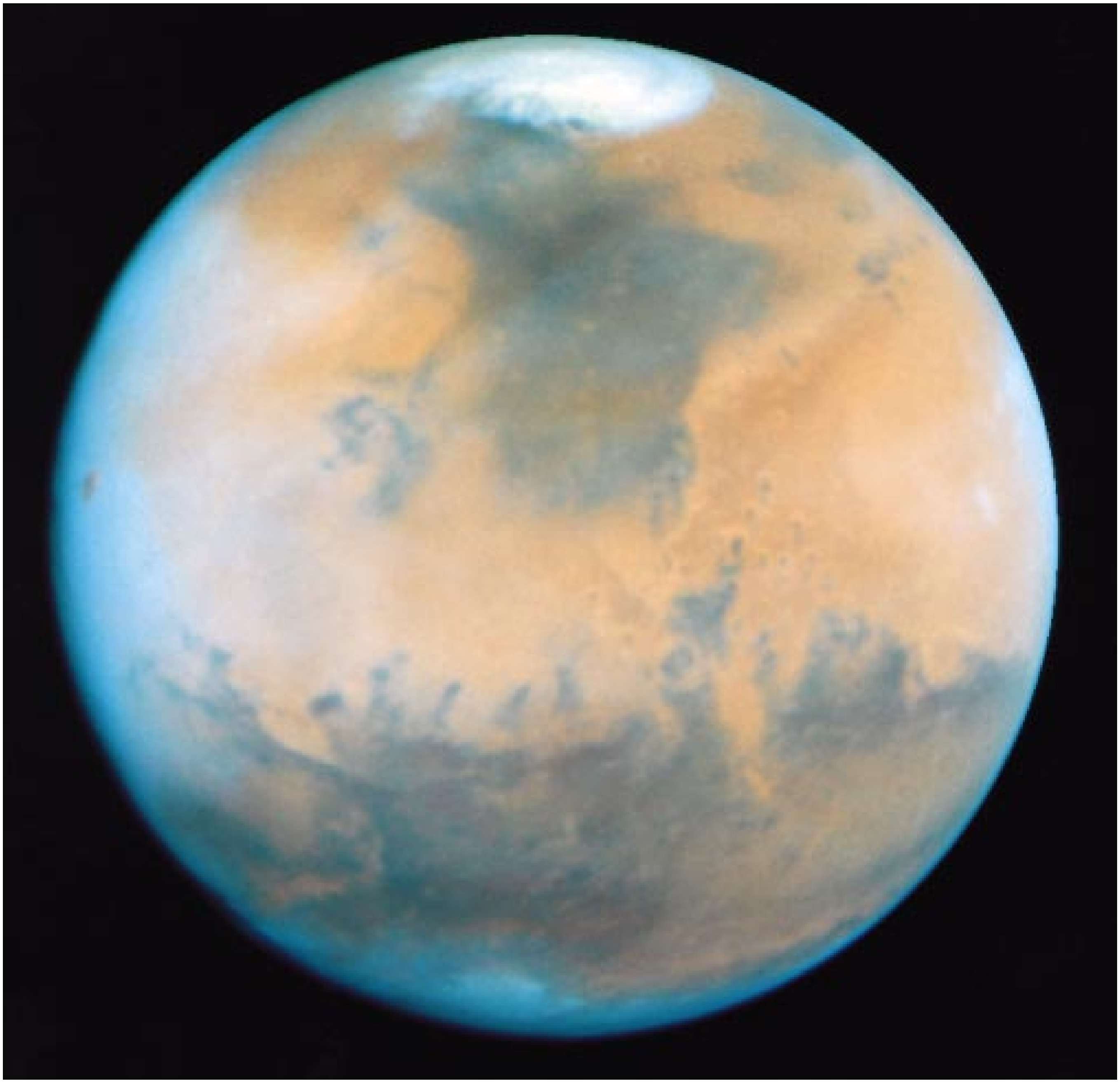
In addition to the thousands of observations already undertaken by astronomers using the Telescope, over a thousand new observing proposals each year are being received from astronomers around the world. In fact, the seventh observing cycle was over-subscribed by a factor of three.

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 emitted or absorbed by the objects.

Results of HST observations are being reported regularly in scientific papers presented at meetings of the American Astronomical Society and other major scientific conferences. Although the 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: planets, stellar evolution, and galaxies and cosmology.

3.1 Planets

HST has proved well suited for study of objects in the solar system. Figure 3-1 shows a view of the planet Mars that is the clearest picture ever taken from Earth, surpassed only by close-up shots sent back by visiting space probes. The picture was taken on February 25, 1995, when Mars was approximately 65 million miles (103 million km) from Earth. Because it is spring in Mars' northern hemisphere, much of the carbon dioxide frost around the permanent water-ice cap has sublimated, and the cap has receded to its core of solid water-ice several hundred miles across. The abundance of wispy white clouds indicates that the atmosphere is cooler than that seen by visiting space probes in the 1970s. Morning clouds appear along the planet's



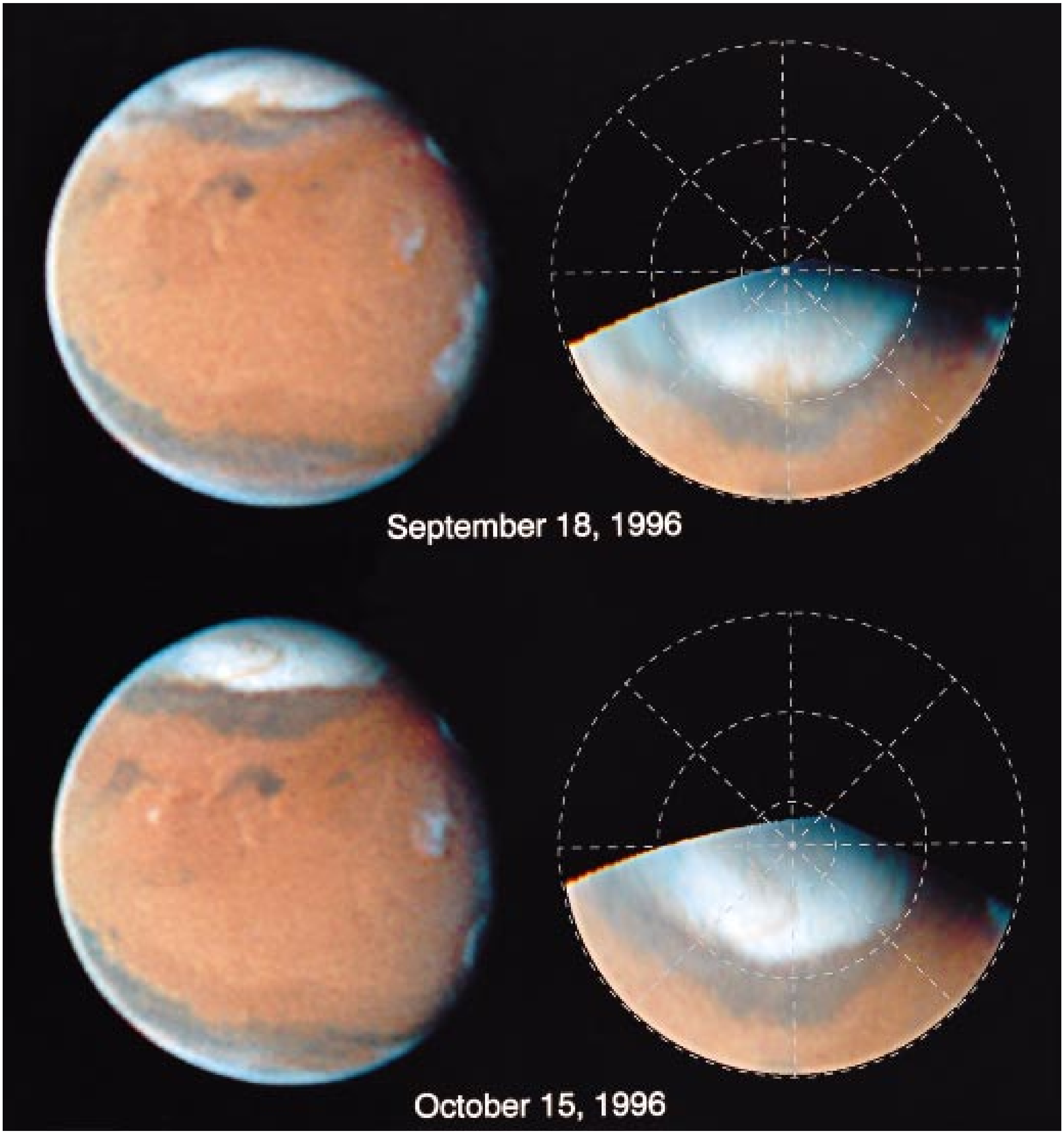
WF/PC II

K70110-301

Fig. 3-1 This view of the planet Mars is the clearest picture ever taken from Earth, surpassed only by close-up shots sent back by visiting space probes. Hubble's Wide Field/Planetary Camera II took the picture on February 25, 1995, when Mars was approximately 65 million miles (103 million km) from Earth.

western (left) limb. These form overnight when the planet's temperatures plunge and water in the atmosphere freezes to form ice crystals.

The distinct advantage of Hubble for planetary astronomers is that it provides superb image clarity any time an observer calls for it. Figure 3-2 shows a state-sized dust storm churning near the edge of Mars' north polar cap in 1996. The polar storm probably is a consequence of large temperature differences between the polar ice and the dark regions to the south, which are heated by the springtime sun. The increased sunlight also causes the dry



WF/PC II

K70110-302

Fig. 3-2 A state-sized dust storm churns near the edge of Mars' north polar cap in 1996. The polar storm probably is a consequence of large temperature differences between the polar ice and the dark regions to the south.

ice in the polar caps to sublime and shrink. HST will monitor the atmosphere of Mars for several years to study weather patterns and try to understand the events that trigger periodic, planetwide dust storms. Such research is an important prerequisite for any manned expedition to Mars. A similar systematic study of Jupiter's powerful weather systems also is under way.

The distant planet Neptune is yielding its secrets to the HST. The Telescope is allowing astronomers to study Neptune's remarkably dynamic atmosphere with a level of detail not possible since the Voyager 2 flyby in 1989. Building on Voyager's initial discoveries, HST is revealing that Neptune's atmosphere changes over just a few days.

The predominant blue color of Neptune (see Fig. 3-3) results from absorption of red and infrared light by Neptune's methane atmosphere. Clouds elevated above most of the methane absorption appear white, while the very highest clouds tend to be yellow-red as seen in the bright feature at the top. Neptune's powerful equatorial jet – where winds blow at nearly 900 mph – is centered on the dark blue belt just south of the equator. Farther south, the green belt indicates a region where the atmosphere absorbs blue light.

Figure 3-4 shows the never-before-seen surface of Pluto, which orbits at the dim outer reaches of the solar system nearly 3 billion miles (5 billion km) from the sun. Pluto is two-thirds the size of the Earth's moon but 12,000 times farther away. Viewing surface detail is as difficult as trying to read the printing on a golf ball located 30 miles away!

Hubble's Faint Object Camera (FOC) imaged nearly the entire surface of Pluto as it rotated through its 6.4-day period in late June and early July 1994. The images, made in blue light, show that Pluto is an unusually complex object, with more large-scale contrast than any planet except Earth. Pluto probably has even more contrast and perhaps sharper boundaries between light and dark than are shown here, but Hubble's resolution (just like early telescopic views of Mars) tends to blur edges and blend together small features sitting inside larger ones.

3.2 Stellar Evolution

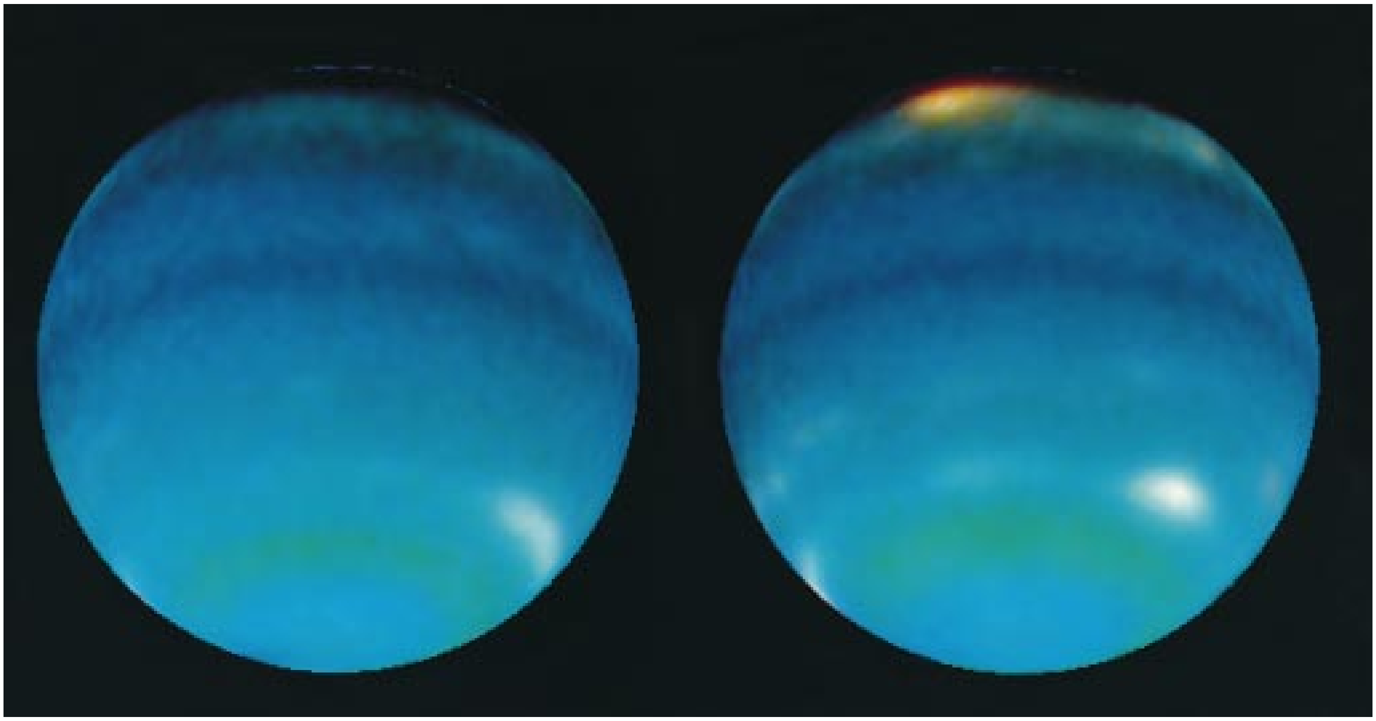
Looking beyond the solar system, the Hubble has provided hundreds of astounding images and answered some long-standing questions about the birth and death of stars.

The eerie, dark structure shown in Fig. 3-5, resembling an imaginary sea serpent's head, is a column of cool molecular hydrogen gas (two atoms of hydrogen in each molecule) and dust that serves as an incubator for new stars. Some of the stars are embedded in finger-like protrusions extending from the top of the nebula. Each "fingertip" is somewhat larger than Earth's solar system.

Ultraviolet light from nearby hot stars is slowly eroding the pillar – a process called photoevaporation. As the pillar erodes, small globules of especially dense gas buried within the cloud are uncovered. These globules have been dubbed "EGGs" – an acronym for evaporating gaseous globules. The shadows of the EGGs protect gas behind them, resulting in the finger-like structures at the top of the cloud.

Forming inside some of the EGGs are embryonic stars – stars that abruptly stop growing when the EGGs are uncovered and separated from the larger reservoir of gas from which they were drawing mass. Eventually the stars emerge as the material within the EGGs collapses onto the star or forms a protoplanetary disk around it. The EGGs are found in the Eagle Nebula, a star-forming region 7,000 light-years distant in the constellation Serpens.

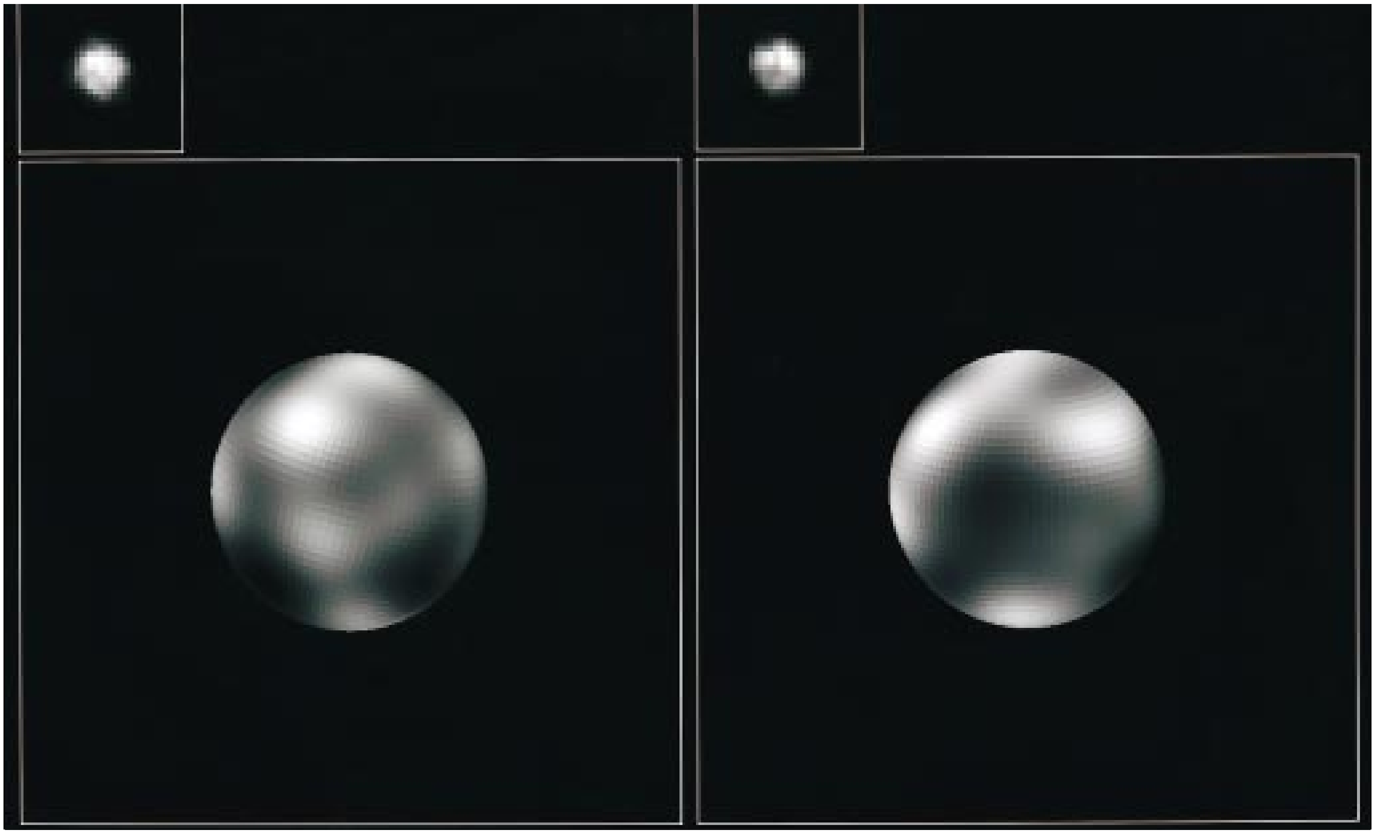
As stars are born, they also die. When a star like the Earth's sun nears the end of its life, it expands to more than 50 times its original diameter, becoming a red giant star. Then its outer layers are ejected into space, exposing



WF/PC II

K70110-303

Fig. 3-3 The Telescope is allowing astronomers to study Neptune's remarkably dynamic atmosphere with a level of detail not possible since the Voyager 2 flyby in 1989. The planet's predominant blue color results from absorption of red and infrared light by its methane atmosphere.



Faint Object Camera

K70110-304

Fig. 3-4 Hubble's Faint Object Camera imaged nearly the entire surface of Pluto as it rotated through its 6.4-day period in late June and early July 1994. Viewing the planet's surface detail is as difficult as trying to read the printing on a golf ball located 30 miles away!

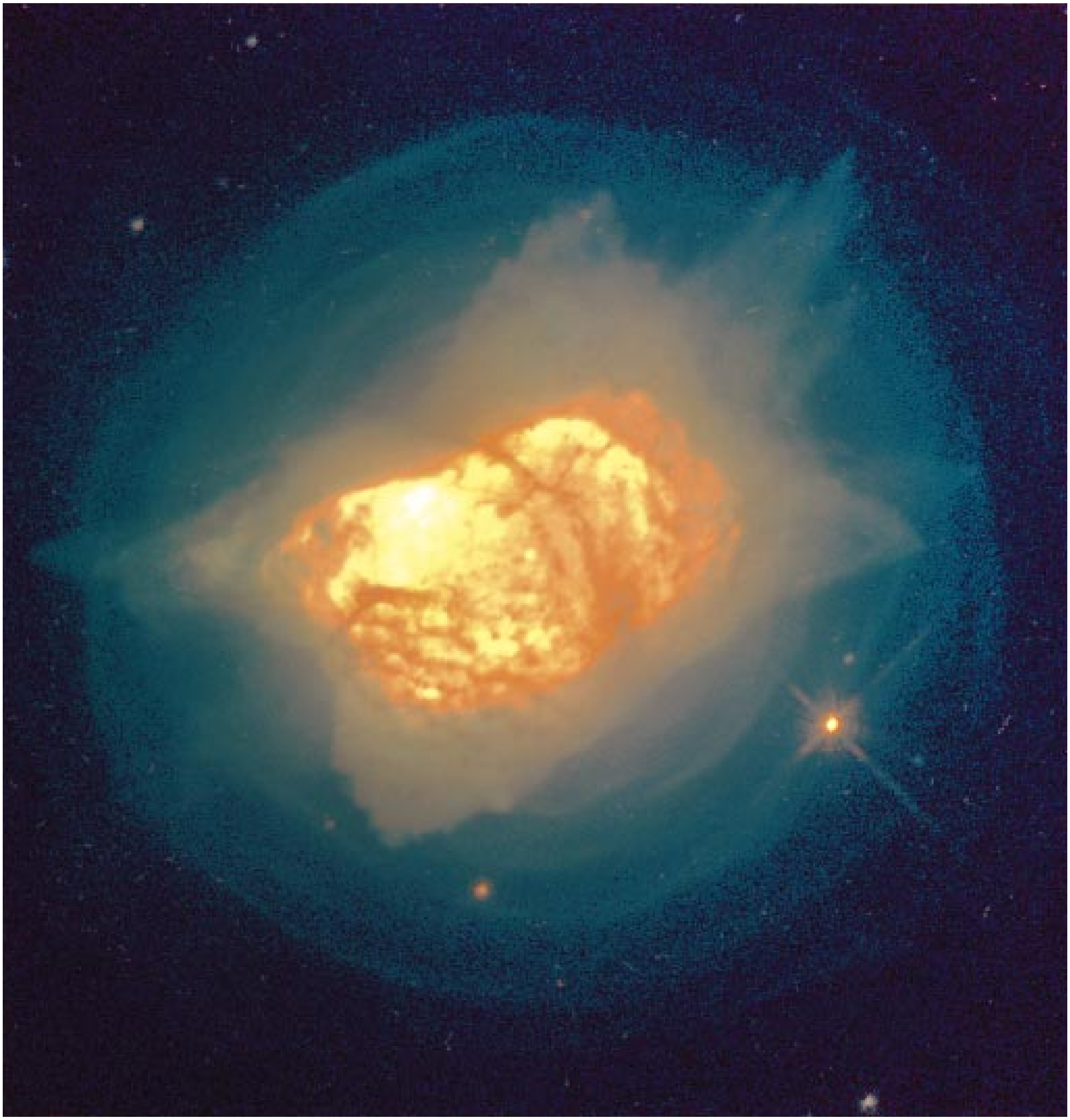
WF/PC II

K70110-305

Fig. 3-5 Resembling an imaginary sea serpent's head, this eerie, dark structure is a column of cool molecular hydrogen gas and dust that serves as an incubator for new stars. Some of the stars are embedded in finger-like protrusions extending from the top of the nebula. Each "fingertip" is larger than Earth's solar system.

the small, extremely hot core of the star, which cools off to become a white dwarf. Although a star like the sun can live for up to 10 billion years before becoming a red giant and ejecting a nebula, the actual ejection process takes only a few thousand years.

The planetary nebula NGC 7027 (see Fig. 3-6) was once a star like the sun. The HST photo reveals that the initial ejections occurred episodically to produce the concentric shells. This culminated in a vigorous ejection of all the remaining outer layers, producing the bright



WF/PC II K70110-306

Fig. 3-6 When a star like the Earth's sun nears the end of its life, it expands to more than 50 times its original diameter, becoming a red giant star and ejecting a nebula. This planetary nebula, NGC 7027, was once a star like the sun. The initial ejections occurred episodically to produce its concentric shells.

inner regions. At this later stage, the ejection was nonspherical, and dense clouds of dust condensed from the ejected material.

HST also has revealed that the gases ejected in the death throes of a star can collide after thousands of years, with dramatic results. The

Helix Nebula, the closest planetary nebula to Earth at 450 light-years away in the constellation Aquarius, provides a good example (see Fig. 3-7). Hubble captured an image of thousands of tadpole-like objects, in the upper right corner, that astronomers call "cometary knots." Each "tadpole" head is at least twice the size of Earth's solar system; each tail stretches 100 billion miles, 1,000 times the distance from the Earth to the sun.

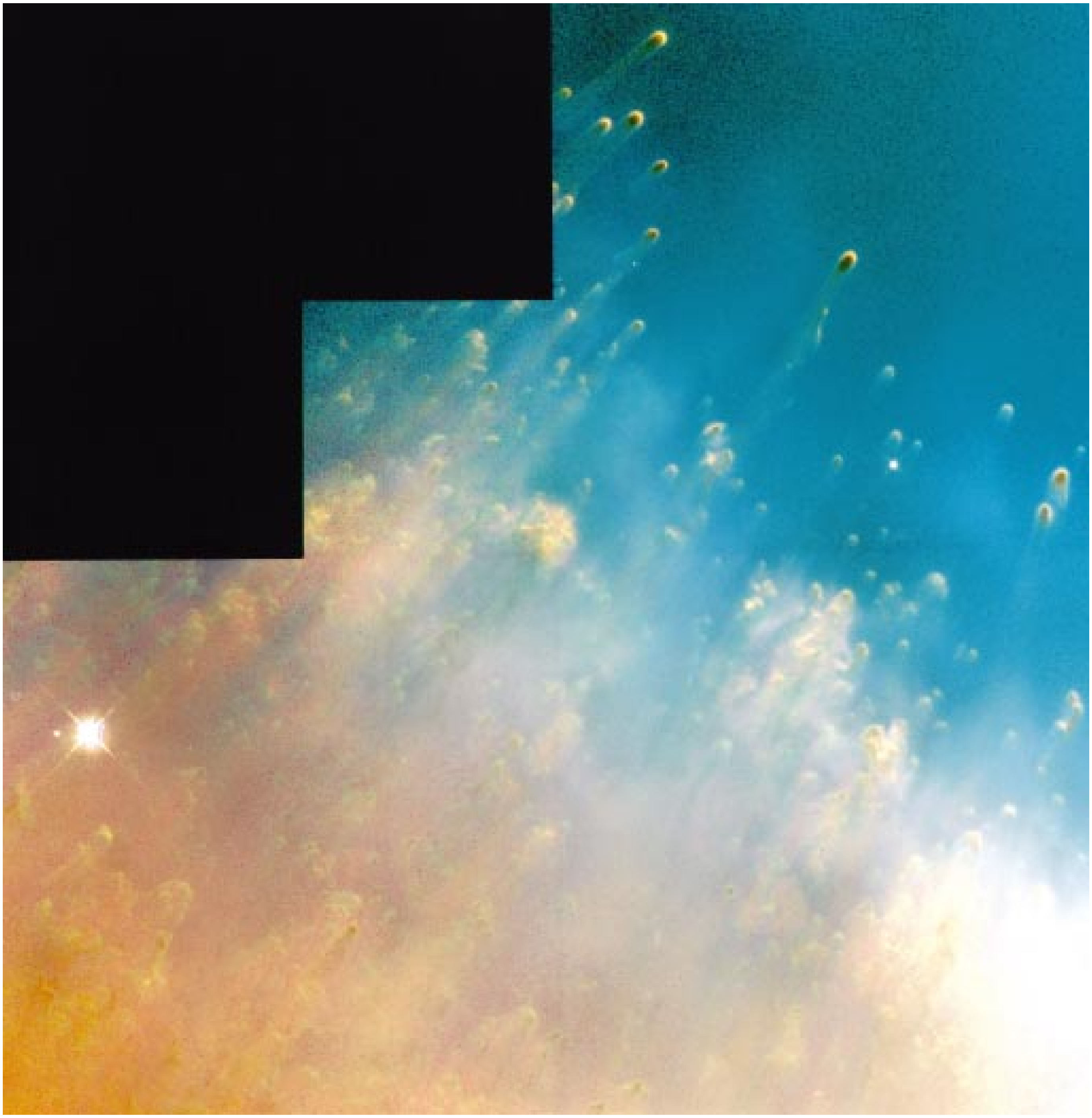
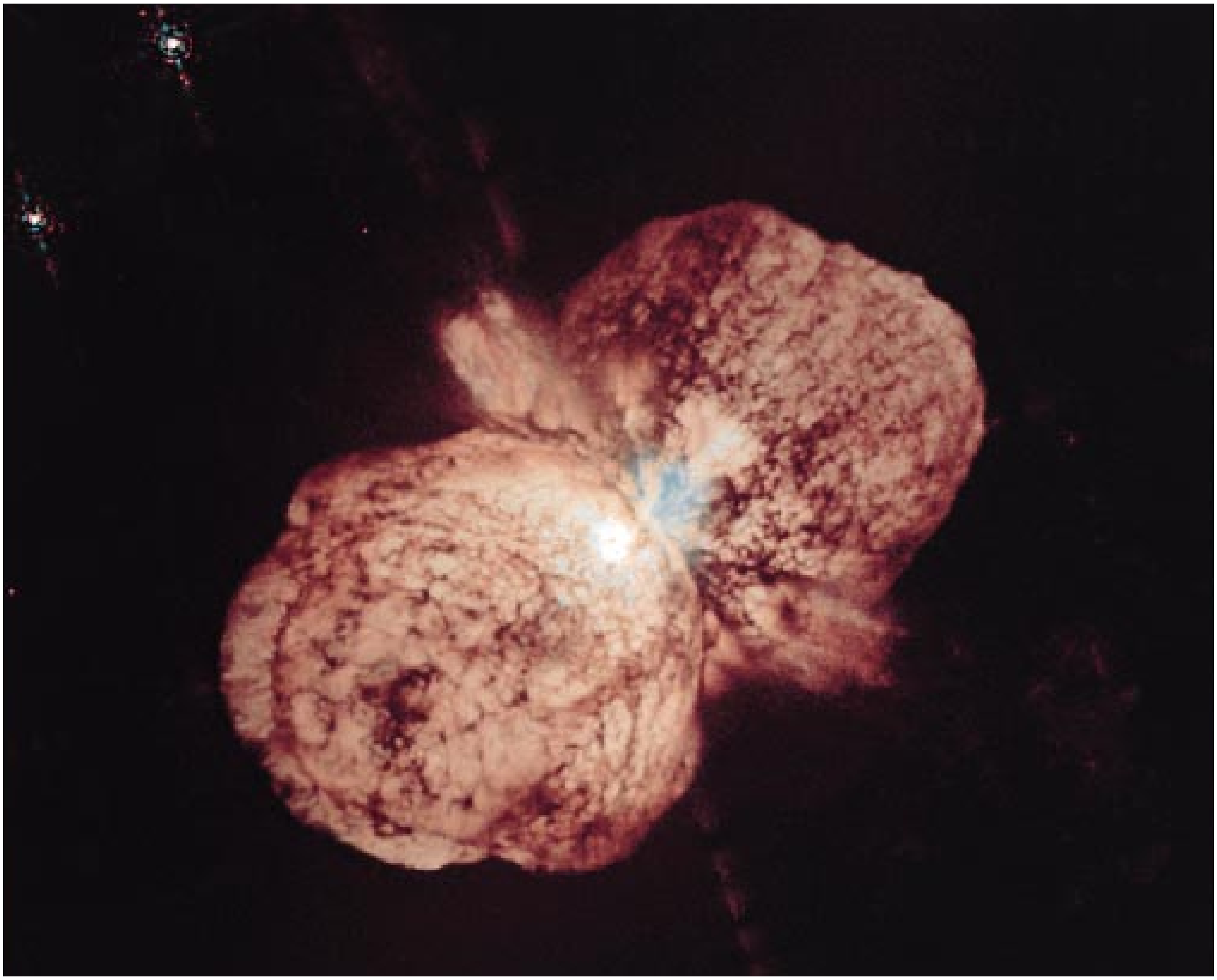


Fig. 3-7 Helix Nebula, the closest planetary nebula to Earth – 450 light-years away in the constellation Aquarius – has thousands of tadpole-like objects (upper right corner) that astronomers call "cometary knots." Each "tadpole" head is at least twice the size of Earth's solar system; each tail stretches 100 billion miles.

Astronomers theorize that the gaseous knots, each several billion miles across, resulted from a collision between gases. A doomed star spews hot gas from its surface, which collides with the cooler gas it had ejected 10,000 years before. The collision fragments the smooth cloud surrounding the star into smaller, denser droplets, like dripping paint. Astronomers expect the gaseous knots to eventually dissipate into the cold blackness of interstellar space.

While some stars end their lives with the puffing of their outer layers into space, some come to a violent end. The supermassive star Eta Carinae was the site of a giant outburst seen on Earth about 150 years ago, when it became one of the brightest stars in the southern sky. Although the star released as much visible light as a supernova explosion, it survived the outburst. Somehow, the explosion produced two polar lobes and a large, thin equatorial disk, all moving outward at about 1.5 million mph. Figure 3-8 shows a stunning image of Eta Carinae: a huge, billowing pair of gas and dust clouds. Using a combination of image processing techniques, astronomers


WF/PC II

K70110-308

Fig. 3-8 Astronomers used a combination of image-processing techniques to create this stunning image of Eta Carinae, a pair of gas and dust clouds more than 8,000 light-years away. It is one of the highest resolution images of an extended object ever produced by Hubble. Structures only 10 billion miles across (about the diameter of Earth's solar system) can be distinguished.

created one of the highest resolution images of an extended object ever produced by Hubble. Even though Eta Carinae is more than 8,000 light-years away, structures only 10 billion miles across (about the diameter of Earth's solar system) can be distinguished. Dust lanes, tiny condensations, and strange radial streaks all appear with unprecedented clarity.

3.3 Galaxies and Cosmology

Galaxies are the largest assemblages of stars in the universe. In a galaxy, billions of stars are bound together by the mutual pull of gravity. The sun resides in the Milky Way galaxy.

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 space, Edwin P. Hubble discovered that the universe is expanding. Hubble found that all galaxies in all directions are receding from Earth, with those farther away receding the fastest. Investigations since Hubble's time have increased the types of galaxies known. Strange, unusually active galaxies and faint, blue, odd-shaped galaxies have been discovered.

Astronomers have long thought that active galaxies are powered by black holes in their nuclei. However, until they viewed galaxy NGC 4261, some 100 million light-years away, they had never seen the enormous circulating disks of matter that have formed around a suspected black hole. Figure 3-9 shows a strikingly

WF/PC II

K70110-309

Fig. 3-9 Until they viewed galaxy NGC 4261, some 100 million light-years away, scientists had never seen the enormous circulating disks of matter that had formed around a suspected black hole. Astronomers calculate that the object at the center of the disk is 1.2 billion times the mass of the sun, yet concentrated into a region of space no larger than Earth's solar system.

geometric disk – 800 light-years wide and containing enough mass to make 100,000 stars like the sun – that was first identified in Hubble observations in 1992. A Hubble image taken in 1995 reveals for the first time structure in the disk, which may be produced by waves or instabilities.

By measuring the speed of gas swirling around the black hole, astronomers calculate that the object at the center of the disk is 1.2 billion times the mass of the sun, yet concentrated into a region of space no larger than Earth's solar system. This discovery is giving astronomers a ringside seat to bizarre, dynamic processes that may involve a titanic collision and a runaway black hole. Studying this relatively nearby galaxy could shed light on how far more distant active galaxies and quasars produce energy.

Discovered only 33 years ago, quasars are among the most baffling objects in the universe because of their apparently compact size and prodigious energy output. Quasars pour out 100 to 1,000 times as much light as a galaxy containing 100 billion stars.

Astronomers theorize that a super massive black hole – gobbling up stars, gas, and dust – is the "engine" powering a quasar. Most astronomers agree that an active black hole is the only credible explanation for how quasars can be so compact, variable, and powerful. Nevertheless, conclusive evidence has been elusive because quasars are so bright they mask any details of their environment. Quasars reside in a variety of galaxies, from normal to highly disturbed. When seen through ground-based telescopes, these compact, enigmatic light sources are unresolved points of light like stars, yet they are billions of light-years away and several hundred billion times brighter than normal stars.

Figure 3-10 shows HST images of different quasar home sites. All the sites must provide the fuel to power these unique light beacons. Astronomers believe that a quasar turns on when a massive black hole at the nucleus of a galaxy feeds on gas and stars. As the matter falls into the black hole, intense radiation is emitted. The black hole stops emitting radiation once it consumes all nearby matter. Then it needs debris from a collision of galaxies or another process to provide fuel. The column of images on the left represents normal-looking galaxies; the center, colliding galaxies; and the right, peculiar galaxies.

- Top left: Quasar PG 0052+251 is 1.4 billion light-years away, at the core of a normal spiral galaxy. Astronomers are surprised to find host galaxies, such as this one, that appear undisturbed by the strong quasar radiation.

- Bottom left: Quasar PHL 909 is 1.5 billion light-years away, at the core of an apparently normal elliptical galaxy.

- Top center: Here is evidence of a catastrophic collision between two galaxies traveling at about 1 million mph. The debris from the collision may be fueling quasar IRAS04505-2958, which is 3 billion light-years from Earth. Astronomers believe that a galaxy plunged vertically through the plane of a spiral galaxy, ripping out its core and leaving the spiral ring (at the bottom of the picture).

- Bottom center: HST has captured quasar PG 1012+008, located 1.6 billion light-years away, merging with a bright galaxy (the object just below the quasar). Although the galaxy and quasar are 31,000 light-years apart, the swirling wisps of dust and gas surrounding them provide strong evidence for an interaction between them. The compact galaxy on

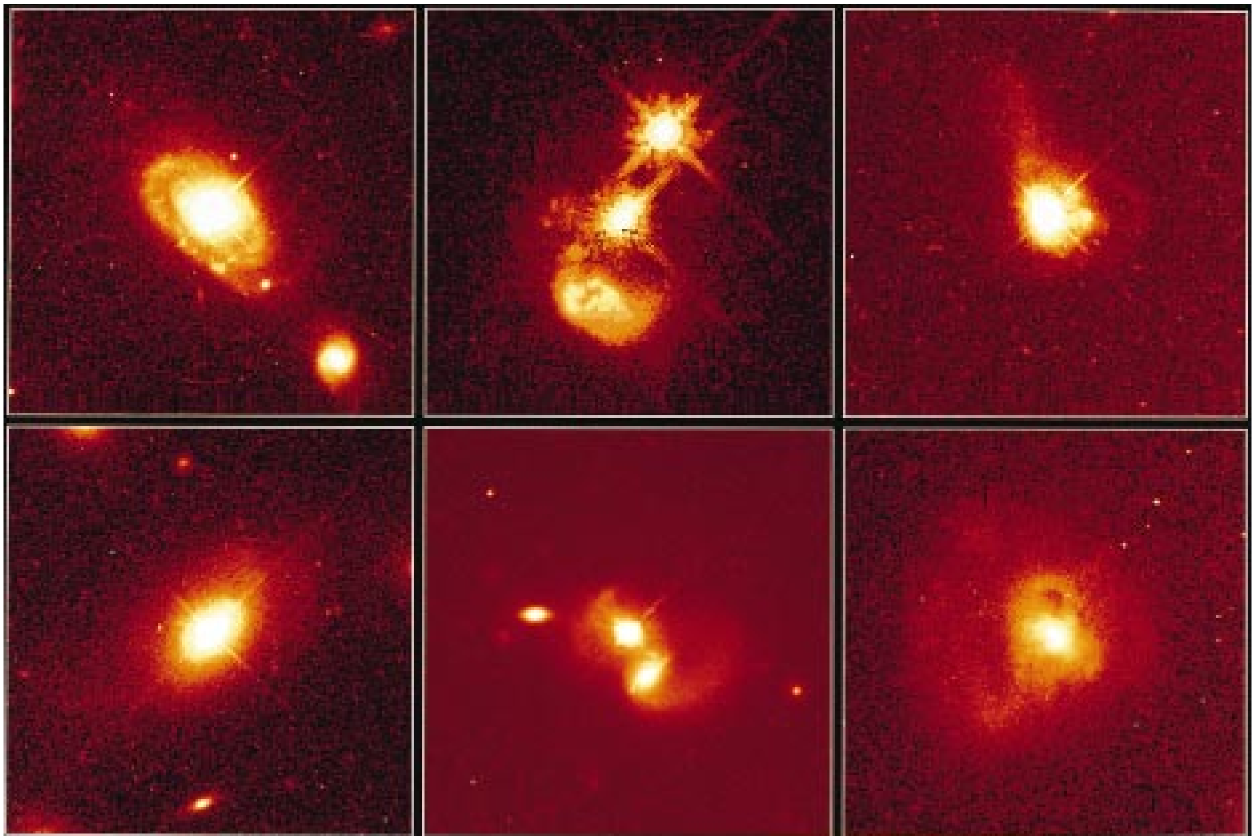


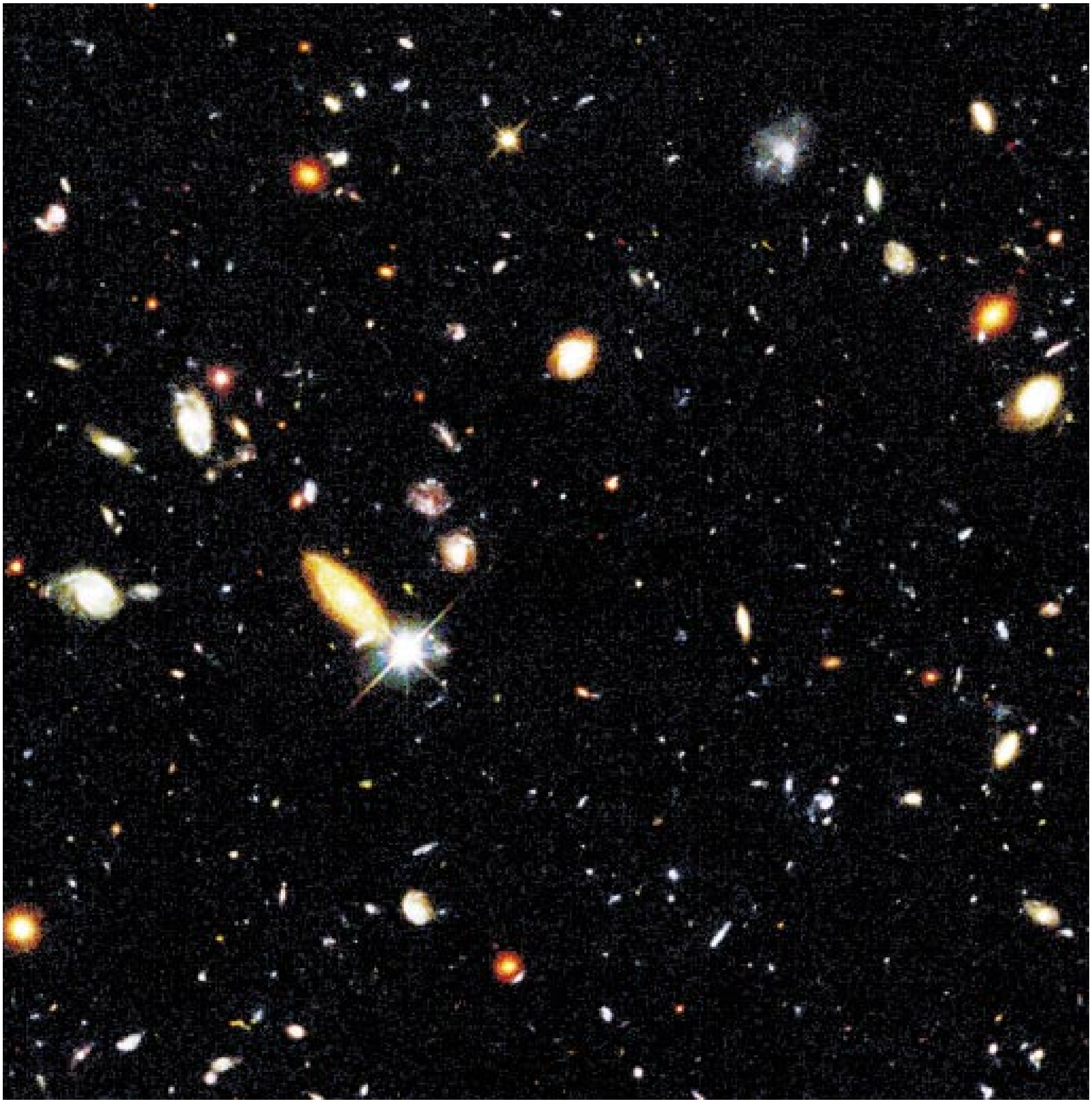
Fig. 3-10 HST images of different quasar home sites include evidence of a catastrophic collision between two galaxies traveling at about 1 million mph (top center) and evidence of a dance between two merging galaxies (bottom right).

the left of the quasar also may be beginning to merge with the quasar.

- Top right: Hubble has captured a tidal tail of dust and gas beneath quasar 0316-346, located 2.2 billion light-years from Earth. The peculiar-shaped tail suggests that the host galaxy has interacted with a passing galaxy that is not in the image.
- Bottom right: HST has provided evidence of a dance between two merging galaxies. The galaxies may have orbited each other several times before merging, leaving distinct loops of glowing gas around quasar IRAS 13218+0552. The quasar is 2 billion light-years away. The elongated core in the center of the image may comprise the two nuclei of the merging galaxies.

Humankind’s deepest, most detailed optical view of the universe was provided by the HST in late 1995 (see Fig. 3-11). The image, called the Hubble Deep Field (HDF), was assembled from 342 separate exposures taken by the Wide Field / Planetary Camera II (WF / PC II) for 10 consecutive days, December 18 – 28.

Representing a narrow, keyhole view stretching to the visible horizon of the universe, the HDF image covers a speck of the sky only about the width of a dime located 75 feet away. The tiny region in the constellation Ursa Major was chosen because it appeared to be one of the darkest, emptiest places on the sky. Although the field is a very small sample of the heavens, it is considered representative of the typical distribution of galaxies in space because the universe, statistically, looks largely



WF/PC II

K70110-311

Fig. 3-11 Humankind's most detailed optical view of the universe, called the Hubble Deep Field, was provided by Hubble in late 1995. This image was assembled from 342 separate exposures taken by the Wide Field/Planetary Camera II for 10 consecutive days, December 18 – 28. It covers a speck of the sky only about the width of a dime located 75 feet away.

the same in all directions. After counting the galaxies in the HDF, astronomers have revised upward their estimate of the total number of galaxies in the universe by a factor of four.

Gazing into this small field, HST uncovered a bewildering assortment of some 1,500 galaxies at various stages of evolution. Most of the galaxies are so faint (nearly 30th magnitude or about 4 billion times fainter than can be seen by the human eye) that they have never before been seen by even the largest telescopes. Some fraction of these galaxies probably dates back to nearly the beginning of the universe.

Scattered within the HDF are several dozen galaxies that astronomers believe exhibit characteristics making them appear more distant than any seen previously. Six of the galaxies appear to be more distant than the farthest quasars, the current distance record holders. These galaxies are so far away that they may have existed when the universe was less than 10 percent of its present age. If this early galaxy population can be confirmed through further observations, it means that such galaxies would have formed remarkably early in the history of the universe, only a few hundred million years after the Big Bang. The images also give an estimate of how many galaxies were forming at this time in the very early universe.

The Hubble Space Telescope is helping test and refine the Big Bang theory, which forms the foundation of modern cosmology. The theory states that the present universe, including all matter and space, exploded outward from a single point at the beginning of time.

One of the most important areas of inquiry that HST allows astronomers to probe is the value of the Hubble Constant, and a determination of the age and size of the universe. The Hubble Constant is the ratio of the recession velocities of galaxies to their distance in the expanding universe. Estimated from the Hubble Constant, the age of the universe currently is thought to be between 9 billion and 14 billion years. More precise measurements of the Hubble Constant may narrow this range.

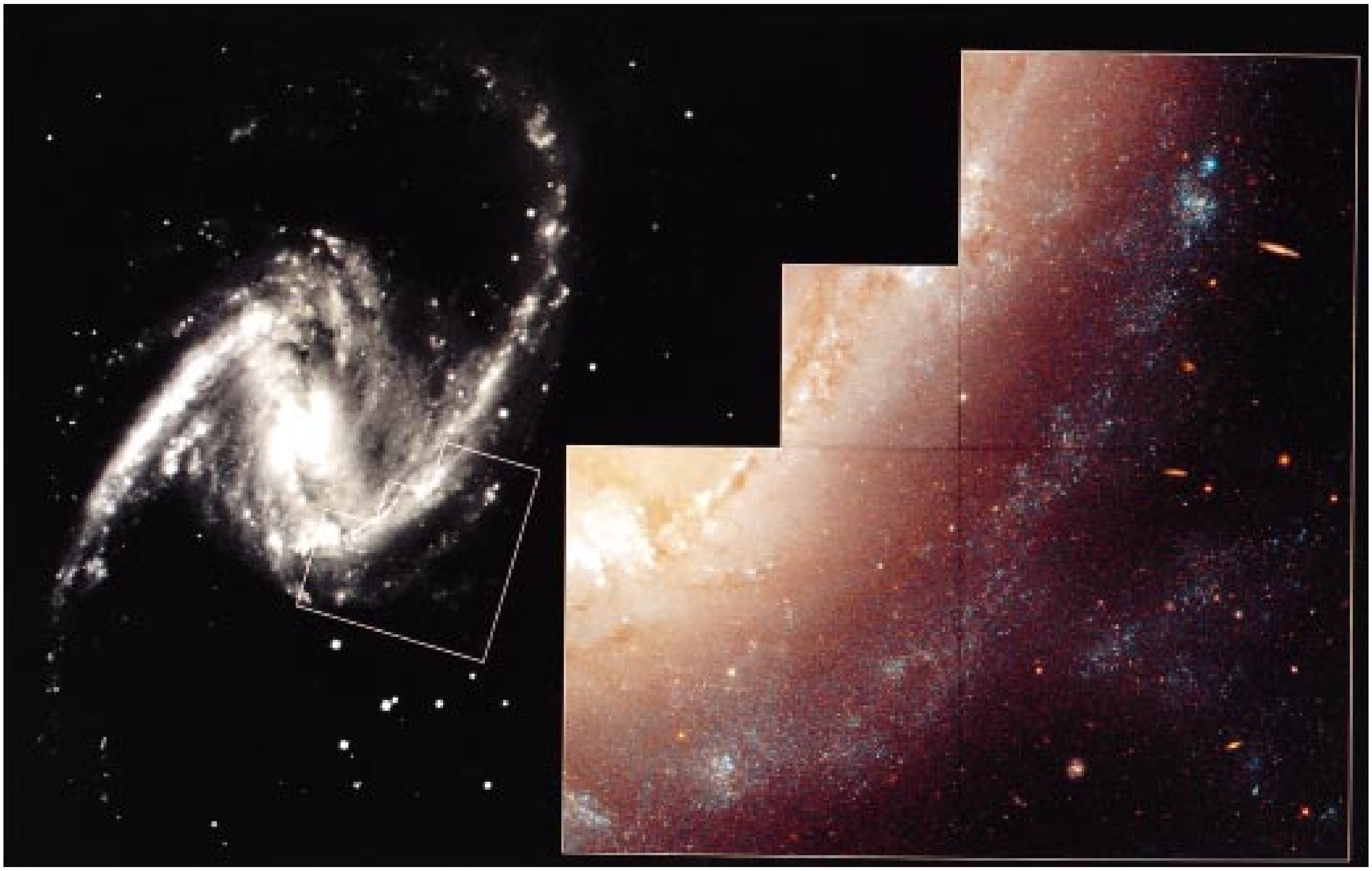
Variable stars called Cepheids are the most accurate and reliable tool that astronomers use to measure the distance to other galaxies. One of the major goals of the Hubble program has been to detect Cepheids in galaxies much farther away than has been possible from the ground. In achieving this goal, Hubble has significantly increased the accuracy of the calculation of the size of the universe. Combining our knowledge of the size of the universe with the rate of expansion results in an estimate for the age of the universe.

Cepheids are pulsating stars that become alternately brighter and fainter in periods ranging from 10 to 50 days. Astronomers have known for more than 50 years that the periods of these stars precisely predict their total luminous power, which allows their distance to be measured.

Figure 3-12 shows Galaxy NGC 1365, a rotating system of gas and stars similar to the Milky Way. The HST color image on the right is a region in NGC 1365, a barred spiral galaxy located in a cluster of galaxies called Fornax. A barred spiral galaxy is characterized by a “bar” of stars, dust, and gas across its center. The black-and-white photograph from a ground-based telescope shows the entire galaxy, which is visible from the Southern Hemisphere.

Hubble astronomers who have been measuring the distance to the Fornax cluster have estimated it to be 60 million light-years from Earth. The astronomers arrived at their preliminary estimate by using Cepheids. The line of small blue dots in the color image shows the formation of stars in the galaxy’s spiral arm, making them ideal targets for the discovery of Cepheids.

Astronomers have discovered about 50 Cepheids in the galaxy. They also have used the Fornax cluster to calibrate and compare many



WF/PC II

K70110-312

Fig. 3-12 A “bar” of stars, dust, and gas characterizes Galaxy NGC 1365, a barred spiral galaxy located in a cluster of galaxies called Fornax. The HST color image (right) shows a region in NGC 1365. The black-and-white photograph from a ground-based telescope shows the entire galaxy, visible from the Southern Hemisphere.

secondary distance methods. While Cepheids are accurate distance markers for galaxies at intermediate distances, secondary methods are needed to measure distances to galaxies much farther away. An accurate value for the Hubble Constant depends on reliable secondary distance methods. One secondary method relates the total luminosity of a galaxy to the rate at which the galaxy is spinning, the Tully-Fisher relation. Another secondary method uses a special class of exploding star known as a type Ia supernova. This phase of the Hubble Constant research will be completed within two years.

3.4 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 1993 First Servicing Mission, and the full restoration of Hubble’s unsurpassed optical capability, the Telescope was able to achieve 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
- Clearly elucidated the various processes by which stars form
- Provided the first map of the surface of Pluto
- Routinely monitored the meteorology of planets beyond the orbit of Earth
- Made the first detection of an ultraviolet high energy laser in Eta Carinae.

After the Second Servicing Mission, the Hubble Space Telescope will view the universe anew with significantly expanded scientific capabilities.

Science instruments currently operating in the Hubble Space Telescope (HST) are the Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), the Goddard High Resolution Spectrograph (GHRS), and the Wide Field/Planetary Camera II (WF/PC II). In addition, the three Fine Guidance Sensors (FGS) have a scientific role as astrometric instruments.

The FOC, FOS, and GHRS are located parallel to the Telescope's optical axis so that incoming images fall into their entrance apertures. These instruments share the same dimensions – roughly the size and shape of a telephone booth – so they fit into the focal plane structure interchangeably.

The WF/PC II and the three FGSs are placed just forward of the focal plane structure at a right angle to the optical axis. These four radial instruments rely on pickoff mirrors positioned in the optical path to deflect part of the incoming light into their respective entrances.

The Telescope's optical system was designed to provide light in the focal plane with a resolution close to the limit specified by the laws of nature. This so-called "diffraction limit" is a physical property of light that depends only on the size of the primary mirror and the wavelength of the light, and defines the minimum size of the image of a point-like object on the focal plane. The presence of a spherical aberration on the primary mirror discovered shortly after deployment of HST in 1990 hampered the potential resolution and motivated development of corrective optics for the instruments.

During the First Servicing Mission, the Corrective Optics Space Telescope Axial Replacement (COSTAR) replaced the High Speed Photometer, and the WF/PC II replaced the original camera (WF/PC I). WF/PC II significantly improved ultraviolet performance over that of the original instrument through more advanced detectors and more stringent contamination control. It also incorporated built-in correction optics.

Development of the COSTAR, designed specifically to correct the optics for the remaining axial instruments (FOC, FOS, and GHRS), started in 1990 after the aberration was discovered. A set of optics was deployed into the region near the focal plane to intercept the light that normally would be sensed by these instruments and replace it with light corrected for spherical aberration (see Fig. 4-1).

The FOC will be the only instrument using COSTAR optical correction after the Second Servicing Mission. Both new instruments, the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) and the Space Telescope Imaging Spectrograph (STIS), have corrective optics incorporated into their designs.

Descriptions of each science instrument and possible astronomical targets are included in this section. The astrometric function of the FGSs also is discussed.

4.1 Near Infrared Camera and Multi-Object Spectrometer

NICMOS is a second-generation instrument to be installed on the HST during the Second Servicing Mission. NICMOS will provide infrared imaging and limited spectroscopic observations of astronomical targets between 1.0 and 2.5 microns. NICMOS will extend HST's capabilities into the near-infrared by using a 5-year cryogenic dewar system. High-resolution images will be made for detailed analyses of:

- Protostellar clouds, young star clusters, and brown dwarfs
- Obscured active galaxy nuclei
- Temporal changes in planetary atmospheres.

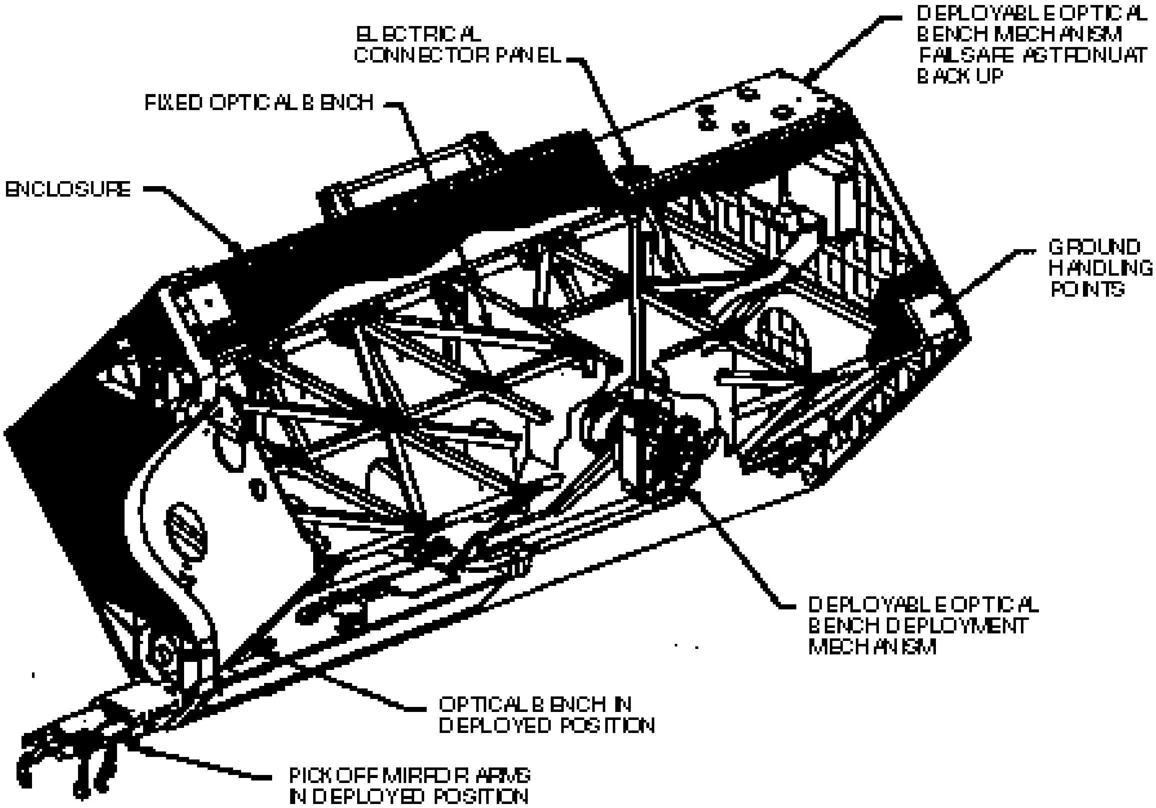


Fig. 4-1 Cutaway view of COSTAR showing its optical bench deployed and pickoff mirrors in position to capture light from the secondary mirror

NICMOS will provide an improved determination of the distance scale to the galaxies of the Coma cluster and beyond and will view distant quasi-stellar objects that are not observable at visible wavelengths. NICMOS also will provide deep, high-resolution images of obscured galactic centers and star formation regions as well as detailed imaging in infrared bands of planetary atmospheres, much like the infrared weather images of Earth.

4.1.1 Instrument Description

NICMOS is an all-reflective imaging system with near–room-temperature foreoptics that relay images to three focal plane cameras contained in a cryogenic dewar system (see Fig. 4-2). Each camera covers the same spectral band of 0.8 to 2.5 microns with a different magnification and an independent filter wheel. Each camera views a different segment of the HST field of view simultaneously. Figure 4-3 lists the cameras and their 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.

The corrected image then is relayed to a three-mirror field-dividing assembly, which divides the light into three separate, second-stage optical paths (see Fig. 4-4). 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

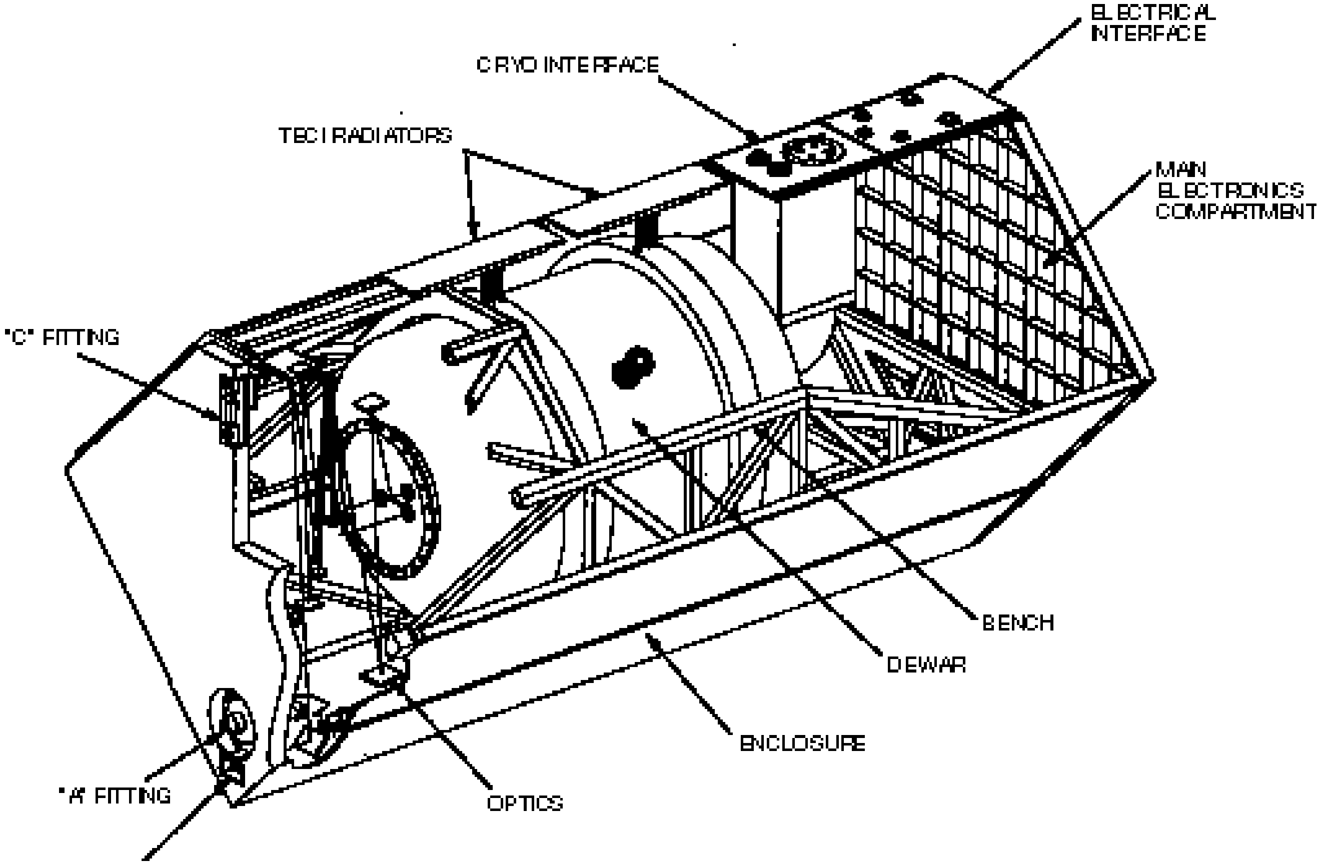


Fig. 4-2 Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

allows physical separation for the two-mirror relay sets for each camera and its field of view. 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.

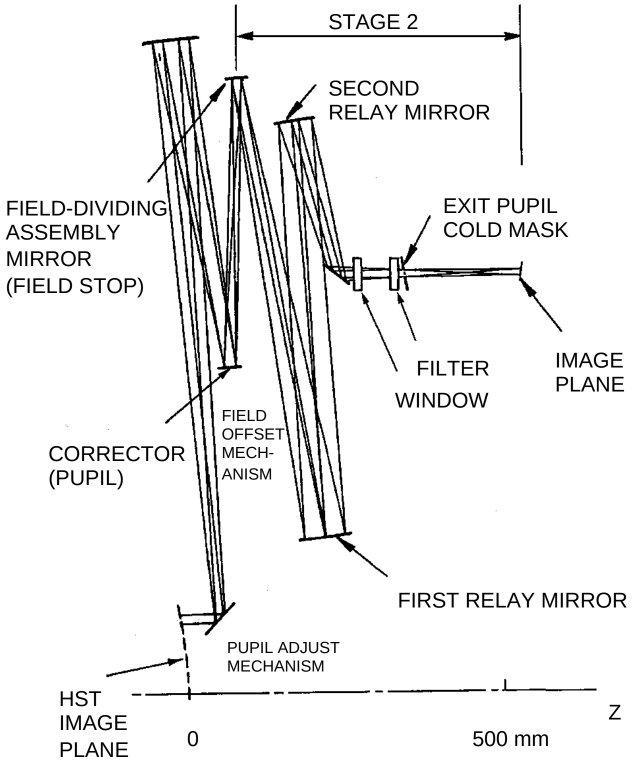
A corrected image is produced in the center of the Camera 1 field mirror. The remaining mirrors of Camera 1 are confocal parabolas with

NICMOS Optical Characteristics

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	45.7	17.2

K70110-403

Fig. 4-3 NICMOS optical characteristics



K70110-404

Fig. 4-4 NICMOS optical path

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. Infrared 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: the optics compartment and the electronics compartment. A graphite-epoxy optical bench is kinematically mounted within the enclosure and physically separates the two compartments. The foreoptics and the cryogenic dewar mount to the bench and are maintained at 270K. The electronics maintains a controlled 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 enclosure thermal environment.

The cryogen dewar contains solid-subliming nitrogen, which maintains the three cameras housed on a cold bench within its well at 58K. Surrounding the dewar are three thermal shields interspersed with MLI: the vapor-cooled shield (VCS), the thermoelectric-cooled inner (TECI) shield, and the thermoelectric-cooled outer (TECO) shield (see Fig. 4-5).

The VCS is the innermost shield and is cooled by vented nitrogen vapor. The TECI and TECO are each cooled by a set of two thermoelectric coolers, which rejects heat to radiators isolated from the enclosure and supported to prevent enclosure heat loads from passing to the dewar and bench.

The dewar system uses 124 layers of MLI made of double-aluminized mylar with polyester net spacer material. The blankets are distributed for maximum effectiveness: 17 layers between the dewar outer shell and the TECO, 17 layers between the TECO and TECI, 50 layers between the TECI and VCS, and 40 layers between the VCS and solid nitrogen tank.

The solid cryogen tank is suspended by six fiberglass/epoxy straps attached to girth rings on the vacuum shell. The three thermal shields are structurally and thermally attached at intermediate points along the straps.

The dewar uses three plumbing lines. The dewar is loaded with liquid nitrogen (LN_2) through a single, combined vent and fill line using a no-vent fill process. On orbit, this line

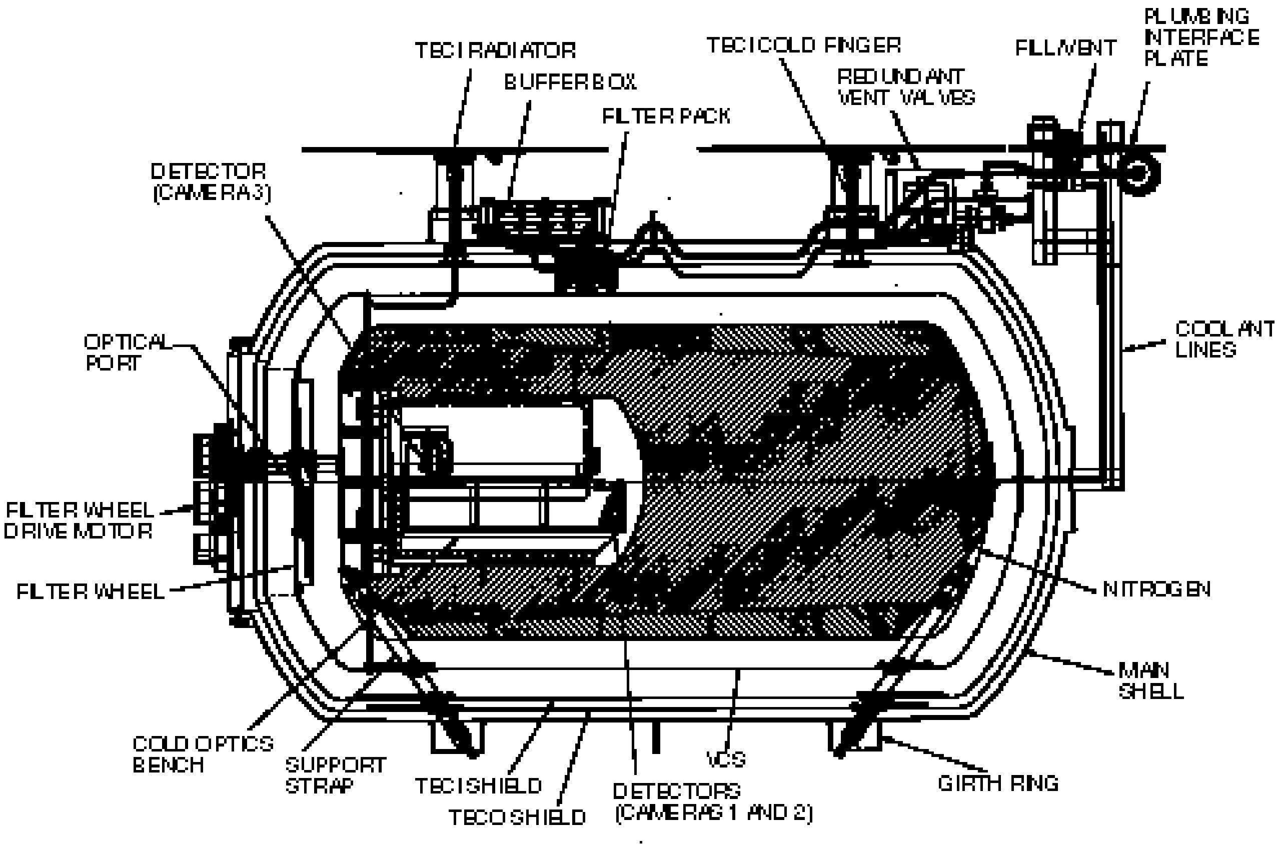


Fig. 4-5 NICMOS cryogen dewar

also serves as the vent path for nitrogen vapor. The other two lines form a coolant loop. Cold, gaseous helium is circulated through this loop to precool the dewar prior to loading, freeze the loaded LN_2 to a solid, and periodically supercool the solid N_2 during ground processing to keep it solid until on-orbit operations begin. To reduce the conductive path, these lines are not vapor cooled.

The 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. The filter wheels, mounted on the vapor-cooled shell, are turned by warm stepper motors mounted on the vacuum shell. Graphite-epoxy, thin-walled tubes are used for the drive shafts connecting the warm motors to the cold wheels. The drive shafts provide adequate torsional rigidity for accurately positioning the filter in the optical path while maintaining low thermal conductivity.

4.1.2 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. Shielding is an aluminized polyester film incorporated into drain wires. The cables are adequately shielded to minimize noise and crosstalk between channels and 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. These cables also contain the leads for accelerometers mounted on the solid nitrogen tank that are used during preflight testing. Heat leak into the solid nitrogen cryogen through the cable is 1.1 milliwatts.

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

Figure 4-6 shows the specifications for NICMOS.

4.2 Space Telescope Imaging Spectrograph

STIS was developed under the direction of the principal investigator, Dr. Bruce E. Woodgate jointly with Ball Aerospace (see Fig. 4-7). It is generally considered to be the most complex scientific instrument built for space science.

The spectrograph 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 to obtain more wavelength coverage in a single exposure. STIS also can take both UV and visible images through a limited filter set.

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 ft. (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

K70110-406

Fig. 4-6 NICMOS specifications

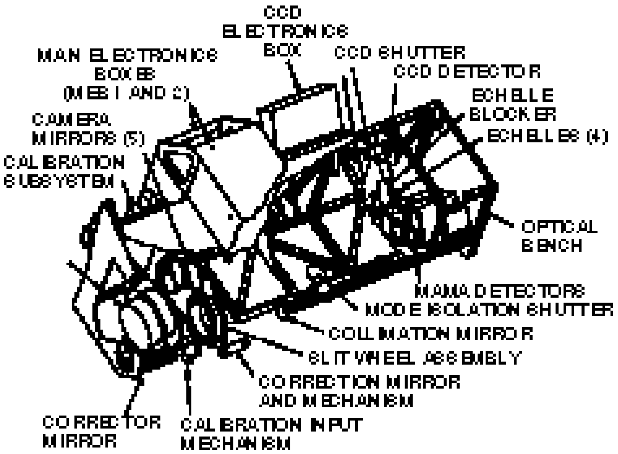


Fig. 4-7 Space Telescope Imaging Spectrograph (STIS)

Designed to replace many of the current capabilities of the GHRS and some of the FOS, STIS has some additional enhanced capabilities. It will cover a broader wavelength range with two-dimensional capability; it can image; it adds a coronagraph capability; it can provide objective prism spectra in the intermediate UV; and it has a high time-resolution capability in the UV.

STIS carries it own aberration correcting optics and will not require the use of COSTAR.

4.2.1 Physical Description

STIS has been designed to fit into the axial bay behind the HST main mirror, replacing the GHRS. It is therefore of comparable size and weight to GHRS. Externally, the instrument measures 7.1 ξ 2.9 ξ 2.9 ft (2.2 ξ 0.98 ξ 0.98m) and weighs 825 lb (374 kg). Internally, STIS consists of a carbon fiber optical bench, which supports the dispersing optics and three detectors.

STIS 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. To select a wavelength region or mode, a single mechanism, called the mode selection mechanism (MSM), is used. The MSM has 21 optical elements: 16 first-order gratings (six of which are 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, the input slit and filter wheels, and the MSM.

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

In the case of 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 the bench, so they can easily dissipate heat through an outer panel. The optical bench is thermally controlled. The detectors and mechanisms are controlled by an onboard computer.

Each of the three detectors has been optimized for a specific wavelength region. Band 1, 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, covering the wavelengths from 305 to 555 nm and 550 to 1000 nm, use the same detector, a charge-coupled device (CCD). Figure 4-8 shows the instrument schematically.

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

The first-order spectral imaging modes can select slits 50 arcsec long and from 0.05 to 2 arcsec wide. Three slits have occulting bars that can block out a bright star in the field. Four slits are tilted to an angle of 45 degrees for planetary observations.

For echelle spectroscopy, 16 slits ranging in length from 0.10 to 1 arcsec are available. The slit length is short to control the height of the echelle spectra in the image plane and avoid spectral order overlap. The echelle slits have widths of 0.05, 0.10, 0.12, 0.20, and 0.5 arcsec.

There also are camera apertures of 50 ξ 50 and 25 ξ 25 arcsec. Some of the apertures 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 field of view. In addition, there is a special occulting mask or coronagraph, which is a finger in the aperture that can be positioned over a bright star to allow

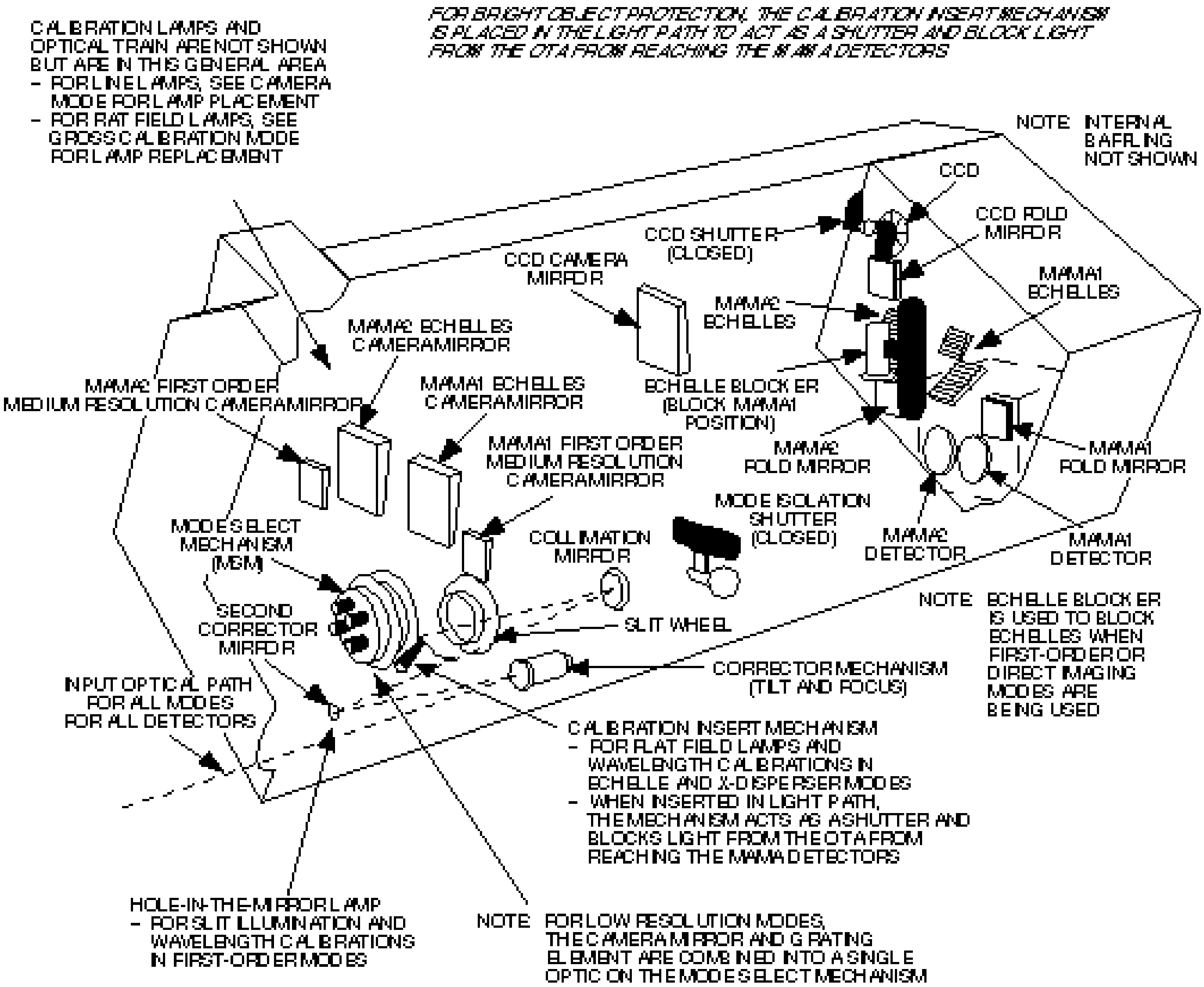


Fig. 4-8 STIS components and detectors

examination of any faint material nearby. It can be thought of as a simulation of a total eclipse on a nearby star. This mode is particularly useful to search for faint companion stars or planetary disks around stars.

Mode Selection Mechanism. The mode selection mechanism (MSM) is a rotating wheel that has 16 first-order gratings, an objective prism, and four mirrors mounted to it. The MSM 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 axis of the wheel or 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. The objective prism is used exclusively with the Band 2 MAMA (see Fig. 4-9). Of the 16 gratings, six are cross dispersers that direct dispersed light to one of the four echelle gratings for medium- and high-resolution modes.

Multi-Anode Microchannel Plate Array Detectors. For UV modes, two types of MAMA detectors are employed on STIS. A photocathode optimizes each detector to its wavelength

Mode	**Band Wavelength Range (nm) Detector**	**Band 1 115-170 Det #1 (MAMA/CsI)**	**Band 2 165-310 Det #2 (MAMA/Cs_2Te)**	**Band 3 305-555 Det #3 (CCD)**	**Band 4 550-1000 Det #3 (CCD)**
Low resolution spectral imaging (first order)	Mode number Resolving power (l/Dl) Slit length (arcsec) Exposures/band	1.1 770-1,130 24.9 1	2.1 415-730 24.9 1	3.1 445-770 51.1 1	4.1 425-680 51.1 1
Medium resolution spectral imaging (first order scanning)	Mode number Resolving power (l/Dl) Slit length (arcsec) Exposures/band	1.2 8,600-12,800 29.7 11	2.2 7,500-13,900 29.7 18	3.2 4,340-7,730 51.1 10	4.2 3,760-6,220 51.1 9
Medium resolution echelle	Mode number Resolving power (l/Dl) Exposures/band	1.3 37,000 1	2.3 23,900-23,100 2	—	—
High resolution echelle	Mode number Resolving power (l/Dl) Exposures/band	1.4 100,000 3	2.4 100,000 6	—	—
Objective spectroscopy (prism)	Mode number Resolving power (l/Dl) Field of view (arcsec)	—	2.5 (115-310 nm) 930-26 (at 120-310) 29.7 x 29.7	—	—

K70110-409

Fig. 4-9 STIS spectroscopic modes

region. Each detector's photocathode provides maximum sensitivity in the wavelength region selected, while it rejects visible light not required for the observations. The Band 1 MAMA uses a CsI cathode, which is sensitive to the wavelength region from 115 to 170 nm and very insensitive to wavelengths in the visible. Similarly, the Band 2 MAMA uses a CsTe photocathode, which is sensitive to the wavelength region from 120 to 310 nm.

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. With a voltage applied across the plate, an electron entering any pore is accelerated by the electric field, and 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 to emit more electrons, and so the process continues, producing a cascade of a million electrons at the end of the pore.

In the Band 1 tube, shown in Fig. 4-10, UV photons enter and hit the CsI photocathode that is deposited on the front surface of the MCP. The cathode produces an electron when a photon hits it and the electron is accelerated into the MCP pores. The MCP amplifies the number of electrons, which fall as a shower onto the anode array as they leave the MCP.

The anode array is a complex finger-like 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 4-11 shows the detection scheme in simplified form.

The anode array has been designed so that only 132 circuits are required to be able to read out all 1024 x 1024 pixels. 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

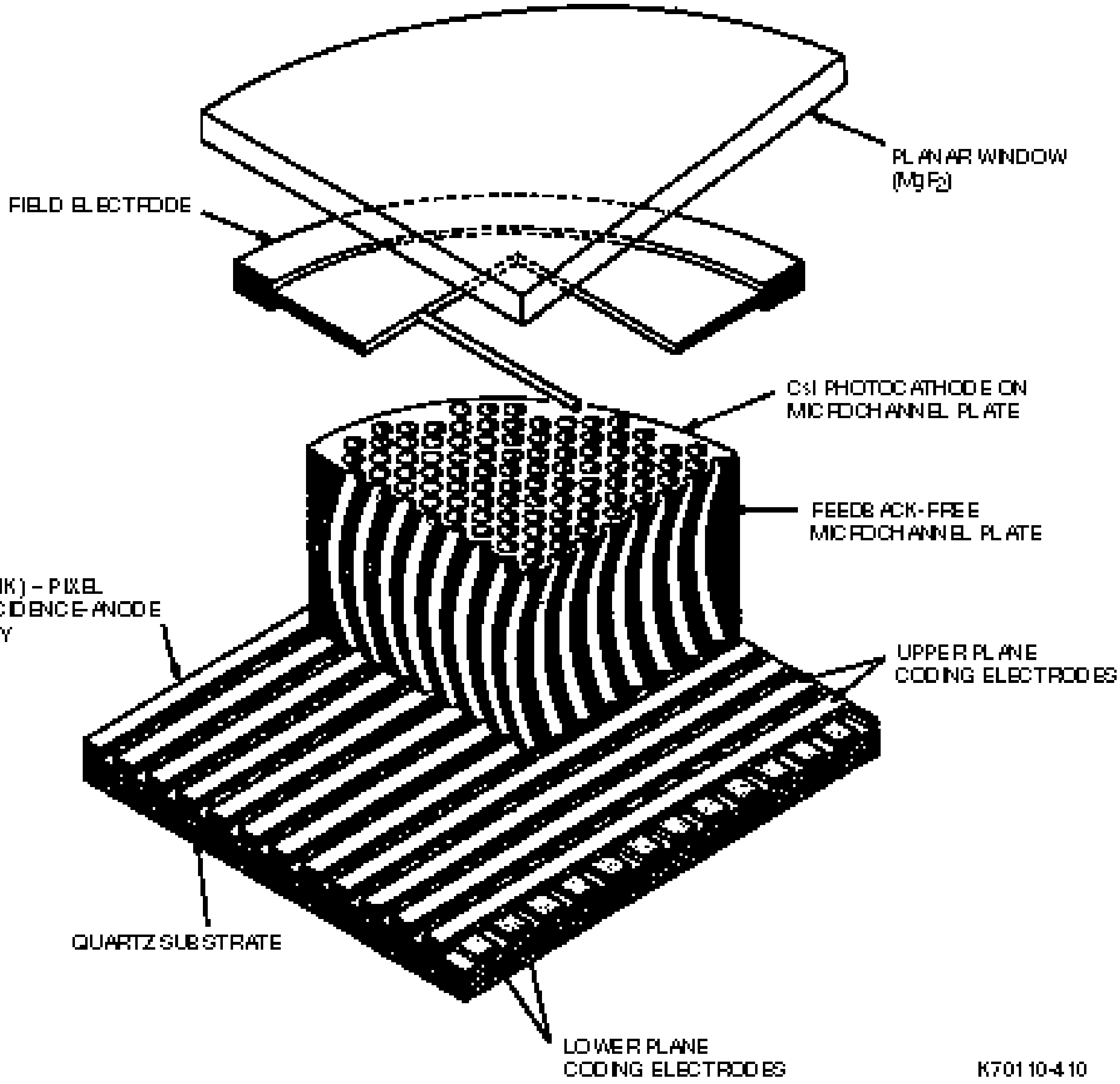


Fig. 4-10 Multi-Anode Microchannel Plate Array (MAMA) detector

show if there is any periodicity. Similarly, to create an image, the data must be integrated in the computer memory before it is displayed. The MAMA data is recorded to a time resolution of 125 microseconds.

In the case of Band 2, the CsTe photocathode is deposited on the inside surface of the front window as a semi-transparent film. Photons pass through the window, and some are stopped in the cathode film where they generate electrons, which are amplified and detected in the same manner as the Band 1 detector.

When used in the normal mode, each detector has 1024 ξ 1024 pixels, each 25 ξ 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 ξ 12.5 micron pixels. This is known as the high-resolution mode; however, data taken in this mode can be transformed to normal resolution if required. The high-resolution mode provides higher spatial resolution for looking at fine structural details of an object and ensures full sampling of the optical images and spectra.

Charge-Coupled Detector. The STIS CCD was developed with GSFC and Ball input at Scientific Imaging Technologies (SITe). Fabricated using integrated circuit technology, the detector consists of light-sensitive picture

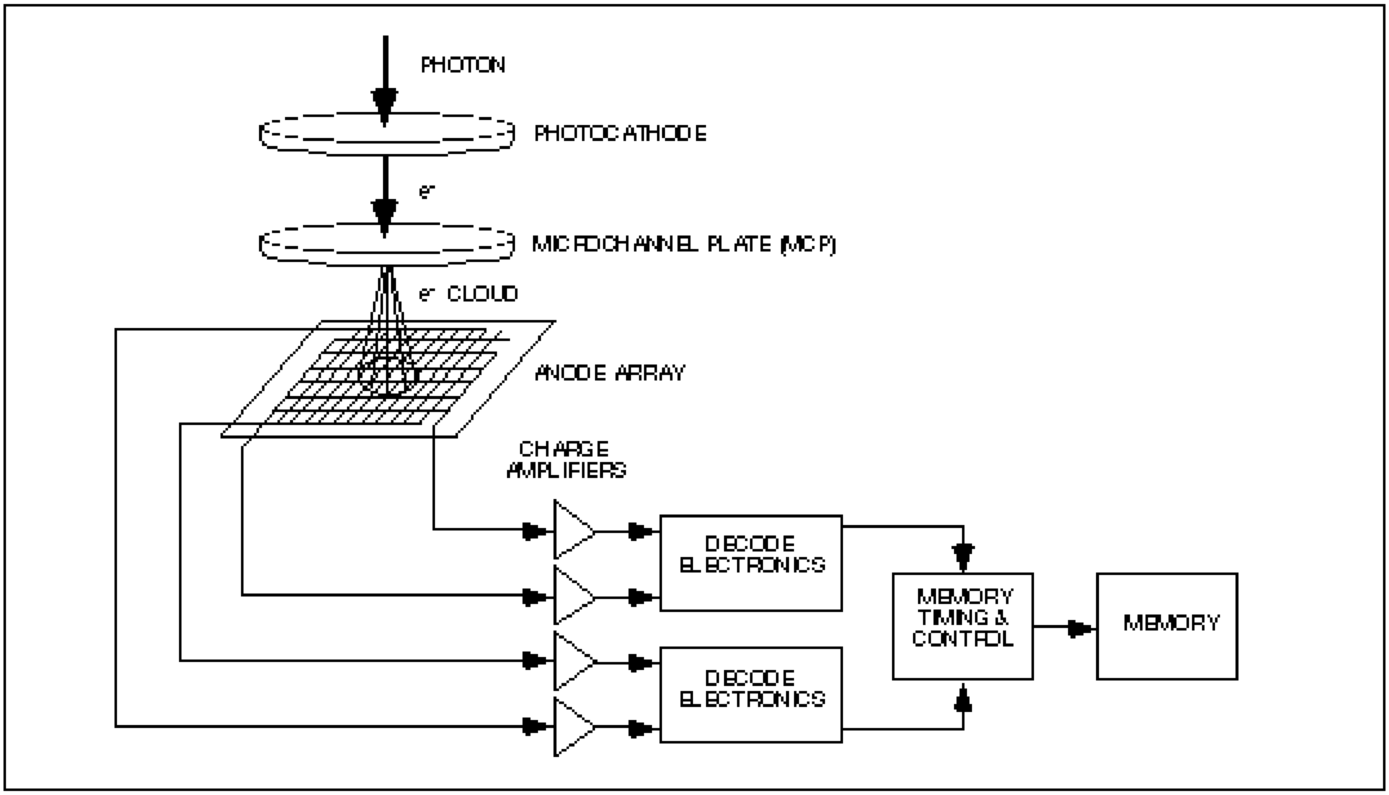


Fig. 4-11 Simplified MAMA system

elements (pixels) deposited onto a thin wafer of crystalline silicon. Each element is 21 ξ 21 microns. The elements are arranged 1024 to a row, in 1024 columns. The 1024 ξ 1024 format contains 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 what is known as a "backside treatment" to provide a usable sensitivity in the near-ultraviolet. The CCD is sensitive from approximately 200 nm to the near-infrared at 1000 nm. The violet extension allows the CCD to overlap with the Band 2 MAMA sensitivity and can serve as a backup detector.

To reduce thermionic noise generated in the CCD, the detector is integrated into a housing and cooled to below -80YC. The cooling is provided by a thermoelectric cooler, which is bonded onto the back of the CCD. The heat extracted from the CCD is dissipated through a radiative cooling panel on the outside of STIS. The housing has a front window made from fused silica and is kept close to 20YC, the design temperature of the optical bench.

The CCD can make exposures ranging from 0.1 seconds 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 and comparison of the frames allows cosmic ray effects to be subtracted.

The CCD is a 16-bit device, allowing a dynamic range from 1 to 65,535 to be recorded. The dynamic range can be further extended by changing the gain. The gain is commandable for 1 electron/bit to 8 electrons/bit.

Another useful feature is called binning, in which pixels are merged on the chip. Typically, binning is 2 ξ 2 for imaging, making the pixels larger, which can reduce the noise per pixel and increase sensitivity at the cost of resolution. Binning can be used to look for extended faint objects such as galaxies. Another binning application is in the long-slit mode on extended faint objects. In this mode, binning along the slit by 1 ξ 4, for instance, would maintain the spectral resolution but sum the spectra from different parts of an object seen along the slit to increase signal or detectivity.

Finally, to increase the CCD's performance at low light levels, the chip has incorporated a minichannel. The main problem with reading out a signal from a CCD is that a charge generated by light must be dragged across the chip, through all its adjacent pixels, to be read out of one corner. In so doing, the charge meets spurious defects in each pixel that add noise. Because the noise can be very path dependent, the minichannel ion implant is designed to restrict the path taken at low signal levels to improve CCD performance.

4.2.2 Spectra Operational Modes

Figure 4-9 shows the spectral operational modes. Each instrument mode is described by two numbers, W and R, where W refers to the wavelength range and R to the resolving power.

The low-resolution, or spectral-imaging mode, is R~500 to 1,000, and can be carried out in all four bands using a long slit. The medium resolution mode, R~5,000 to 10,000, is a spectral imaging mode that can be carried out in all four bands using long slits. However, as dispersion increases, not all of the spectrum falls on the detector. Obtaining an entire spectral range may require moving the spectrum and taking another image. Figure 4-9 indicates the number of exposures to cover the whole wavelength range.

The medium-resolution echelle spectroscopy with R~24,000 uses short slits and is available in the UV only. Band 2 requires two exposures to cover the whole wavelength region.

High-resolution echelle spectroscopy, with R~100,000, uses short slits and is available in the UV only. Both Bands 1 and 2 require multiple exposures.

Objective spectroscopy, R~26 (at 300 nm) and 930 (at 121 nm), is available using the Band 2 detector only. This mode uses a prism is used instead of a grating. The prism dispersion, unlike a grating, is not uniform with wavelength. The low-resolution gratings and the prism also can provide imaging spectroscopy of emission line objects such as planetary nebulae, supernova remnants, or active galaxies.

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 (see Fig. 4-12). The cameras for the CCD and the MAMAs have different magnification factors. The field of view 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 ξ 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

Filter Type	Central or Cutoff Wavelength	FWHM (nm)	Peak Transmission (%)
Emission line (Lyman α)	122 nm	8.5	10
Cutoff (SrF_2 crystal)	>128 nm	N/A	90
Cutoff (crystalline quartz)	>148 nm	N/A	85
Continuum	182 nm	49	40
Emission line (C III)	191 nm	15	15
Continuum	270 nm	22.8	72
Emission line (Mg II)	280 nm	5.6	65
Emission line (O II)	373 nm	7.1	53
Emission line (O III)	501 nm	0.6	73

K70110-412

Fig. 4-12 STIS filter set

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, then the calibration lamp is flashed through the slit to confirm the exact slit position. A further peak up on the image is then performed. Acquisition can be expected to take up to approximately 20 minutes.

Data Acquisition. The MAMAs take data in the high-resolution mode. For normal imaging and spectroscopy, the data will be 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 is stored in a 16-Mb memory and as the memory fills, the data is dumped into the onboard recorder. The time-tag mode has a time resolution of 125 microseconds.

4.2.3 STIS Specifications

Figure 4-13 shows STIS specifications.

4.2.4 Advantages Over Current Instrumentation

STIS has several advantages over current instrumentation:

(1) Two-dimensional detectors (1024 x 1024 pixels), allowing both long-slit spectroscopy and an echelle format in the UV, give wide simultaneous wavelength coverage. Current HST detectors are not two-dimensional.

(2) The UV detectors have a 100 to 200 times lower background – per resolution element – than GHRS. Additionally, the two-dimensional detector capability enables a good estimate of the lower background to be made for background subtraction, which in turn provides improved sensitivity.

(3) Use of a CCD detector to improve visible efficiency and wavelength coverage out to 1000 nm. This compares with coverage out to 700 nm of the FOS.

(4) Solar blind imaging in the UV.

(5) Coronagraphic capability for spectroscopy and imaging.

(6) Wide-field spectroscopy for spectra of many objects in a field at once.

Space Telescope Imaging Spectrograph (STIS)	
Weight	825 lb (374 kg)
Dimensions	3 x 3 x 7 ft (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 to 1000 nanometers

K70110-413

Fig. 4-13 STIS specifications

4.2.5 Observations

Scientists using STIS will focus their science on many areas, including:

- Search for massive black holes by studying star and gas dynamics around the centers of galaxies
- Measurement of the distribution of matter in the universe by studying quasar absorption lines
- Use of the high sensitivity and spatial resolution of STIS to study stars forming in distant galaxies
- Mapping – giving fine details of planets, nebulae, galaxies, and other objects
- Coronagraphic capability may enable it to image Jupiter-sized planets around nearby stars.

STIS also can provide physical diagnostics, such as chemical composition, temperature, density, velocity of rotation or internal mass motions in planets, comets, stars, interstellar gas, nebulae, stellar ejecta, galaxies, and quasars.

Studies of Black Holes in Centers of Galaxies. A black hole was discovered in the center of M87 using FOS. The black hole's mass provides the gravity required to hold in orbit gas and stars that are rapidly rotating about the galactic nucleus. From the spectra of stars surrounding the nucleus, a measure of how rapidly the velocity changes from one side of the nucleus to the other can be determined by measuring the Doppler shift. STIS's long-slit mode is particularly well suited for this type of measurement because all the spatial positions required can be measured along the slit in a single exposure. With STIS, a study of black holes can be made easily for many galaxies and compared from one galaxy to another.

Abundances and Dynamics of the Intergalactic Medium. STIS is well suited to observe the spectra of distant galaxies and quasars. Absorption lines from intervening material in the spectra of these objects give a measure of the dynamics and abundances of specific elements. However, because these objects are distant, we effectively are looking back in time to an earlier stage of the universe when the chemical composition was different from that seen in the vicinity of our sun today. Measuring these differences can provide important clues to how the universe has evolved over time.

Abundances in the Interstellar Medium. The STIS high-resolution mode is particularly well suited to measurements of the spectral absorption lines created in the interstellar medium and seen against distant O- and B-type stars. From the Doppler shift, a measure of gas speed is obtained. Temperature and density and chemical composition also can be measured. The interstellar medium is thought to play an important role in when star formation occurs in galaxies. Current theories point to hot material being expelled from supernovas into a galaxy's surrounding halo. Later, after cooling, the material returns to the galactic plane and eventually forms new stars. How quickly the interstellar medium circulates can be a clue to when star formation occurs.

Search for Protoplanetary Disks. STIS's coronagraphic mode can be used to image nearby stars and search for protoplanetary disks. These observations can provide complementary data to NICMOS, which will be able to sense warm gas around young stars. These observations could shed light on how planets form, what type of stars have planetary disks, and how quickly the disks evolve into planets.

4.3 Faint Object Camera

More than the other instruments, the FOC fully uses the optical resolution of the Telescope to record objects in deep space much more clearly than before. The FOC, with COSTAR, can detect celestial sources to 28th visual magnitude. Currently, only a ground-based observatory, the 10-meter Keck telescope, can detect objects that faint but with far less resolution. The FOC studies star formations, examines galaxies and faint objects like quasars, and could locate planets outside our solar system.

4.3.1 Physical Description

The FOC was designed by the European Space Agency (ESA) and built by Dornier Systems in West Germany, Matra in France, and British Aerospace Space Systems Ltd. (BAe) in England. Its physical dimensions are 3 ξ 3 ξ 7 ft (0.9 ξ 0.9 ξ 2.2 m), roughly the size of a telephone booth; it weighs about 700 lb (318 kg).

Figure 4-14 shows the FOC's four major subsystems. The load-carrying structure assembly houses the optical elements and the photon-detector head elements. The optomechanical assembly contains an optical bench that supports the main optical and mechanical equipment. The electronic bay assembly holds the data-processing and data-handling equipment and system control. The photon-detector assembly consists of the photon-detection system, data-processing electronics, and power supply for the detectors.

After the Telescope is positioned correctly, light from an object is focused on the FOC aperture. This light is channeled down one of two optical pathways. At the end of the pathway, each photon enters the camera's detection device. The recorded image is placed in a science data store. The data is transmitted to Earth, where it is processed by computer into an image of the celestial object.

Optical System. The optical system consists of two independent systems, using two different apertures and focal ratios, f/75.5 and f/151. These are similar to the f-stops on conventional cameras except for the larger ratios.

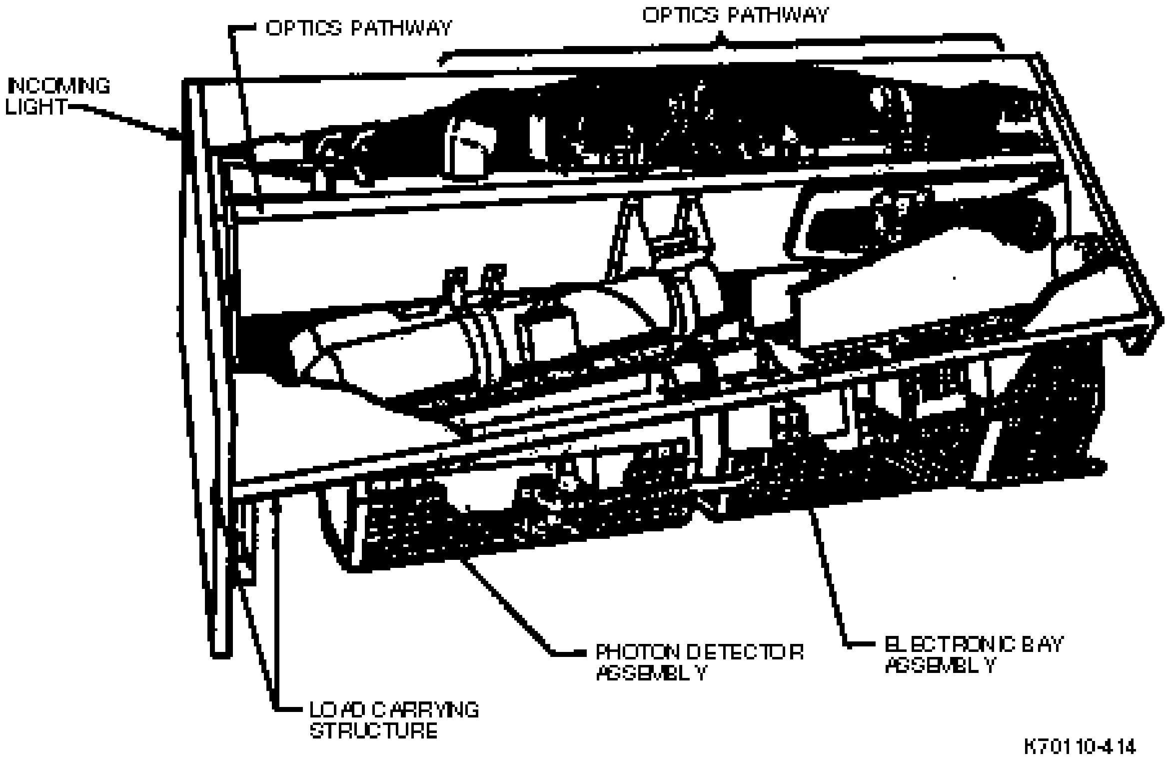


Fig. 4-14 Faint Object Camera (FOC) major subsystems

As shown in Fig. 4-15, light is reflected from a primary concave mirror to a secondary convex mirror on a different plane, then onto a folding mirror, and finally onto the detector tube for enhancing and processing. Both optical pathways have filter wheels to isolate critical wavelength beams for specific studies. The folding mirrors increase the focal length without increasing physical length, move to adjust the focus, and correct for astigmatism in the Telescope optic mechanism.

Each optic system aperture has a shutter that remains closed, completely blocking out light until the camera is needed for astronomical observations.

The f/151 Optics System. This system produces the Telescope's best resolution by increasing its focal ratio of f/37 fourfold. There is a tradeoff, however. The f/151 optical system has a narrow field of view at best (22 arcsec^2), but it allows the FOC to distinguish between two objects only 0.05 arcsec apart. This is a crucial requirement for studying stars within a distant globular cluster; they appear so close together that ground instruments cannot distinguish between them.

The f/151 relay has a special feature to block unwanted light from the field of view – two coronagraphic fingers in the aperture. The fingers can block the light of a bright star so that a faint target close to a bright one can be detected with less intrusive light. This is useful when observing a bright star that has a faint companion suspected of being a planet.

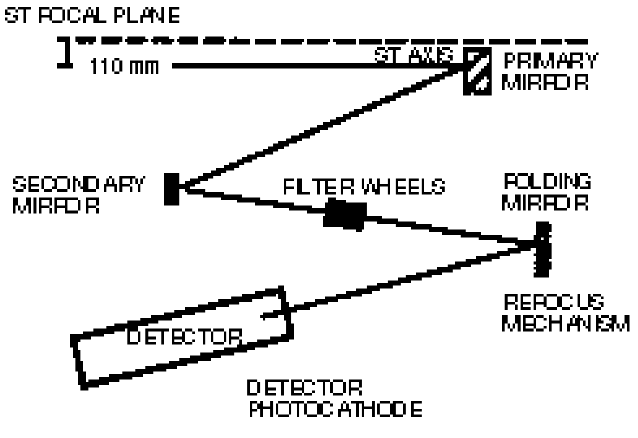


Fig. 4-15 FOC optical relay system layout

Another feature in the f/151 optical path is a series of four filter wheels, which contain 48 filters, prisms, and other optical devices. For example, astronomers can send the beam through a magnesium-fluoride prism to emphasize the far-ultraviolet end of the spectrum. Figure 4-16 shows the complete f/151 optical layout.

The f/75.5 Optics System. This system has a wider field of view – 28 arcsec^2 – but less resolution than the f/151 optics system. The f/75.5 can be used for imaging and spectrography. The f/75.5 optics system has an overall structure identical to that of the f/151 and shares the same calibration device. The separate components of the f/75.5 system are the reflecting optics, the two filter wheels, and a detector like the f/151 detector.

The f/75.5 system also has a 12.5-arcsec-long spectroscopic slit in its aperture. A mirror rotated into the optical path diverts light coming through the slit onto a diffraction grating. This grating breaks the light into a spectrum of the composite wavelengths. The dispersed light reflects into the detector.

The spectrographic slit has a limited spectral range: from 3600 to 5400 angstroms for the first order to 1200 to 1800 angstroms for the third order. The detectors can resolve spectral lines five angstroms apart. This spectral resolution quality falls between that of the FOS and the GHRS. The FOC spectrograph's value is in making spectrographic observations across spatially extended objects, such as galaxies, with the full angular resolution of the FOC.

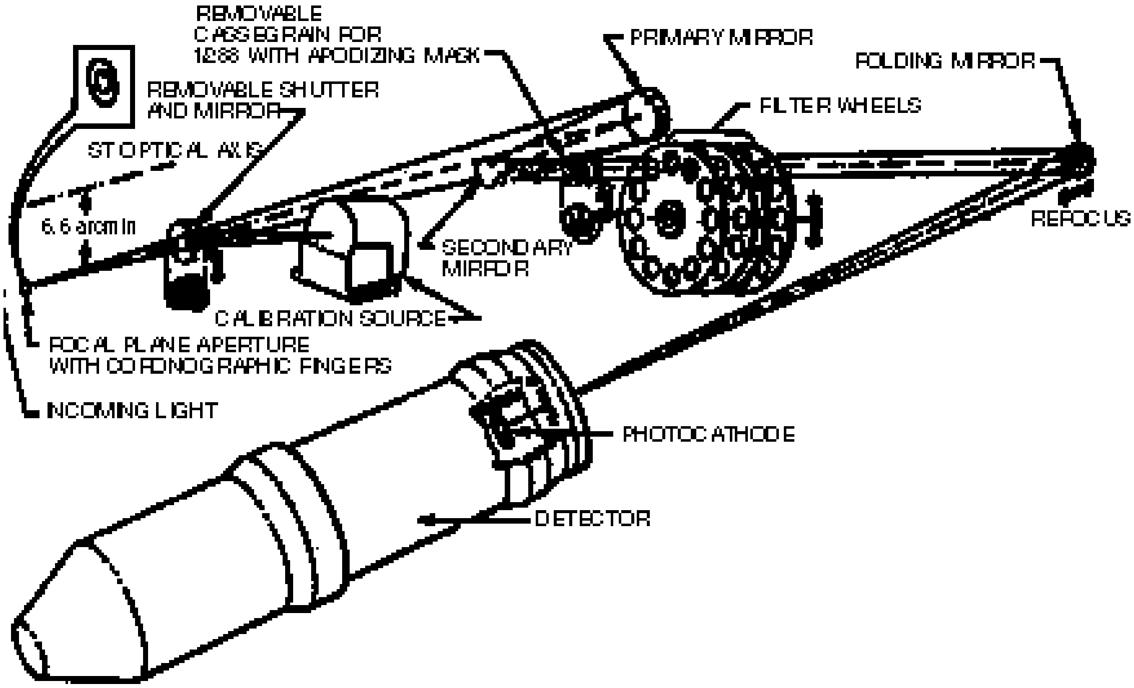


Fig. 4-16 Optical relay system layout at f/151

The f/75.5 optics (see Fig. 4-17) also include two filter wheels, which can be used with either the main optics or the spectrographic optics for specialized viewing. For example, the filters can block out certain wavelengths or select very specific wavelength ranges.

4.3.2 Observation Modes

The FOC has four observation modes: acquisition, imaging, occultation, and spectrographic.

The acquisition mode precedes any observations using the camera’s coronagraphic or spectrographic devices. A special exposure of a target is processed by the Science Instrument Command and Data Handling (SI C&DH) unit to find the target within the camera’s field of view. Then the Telescope is repointed to place the light onto the coronagraphic finger or spectrographic slit.

Imaging mode uses either of the optics systems to take a direct-image measurement of a target. Various formats and filters can change the wavelength range. Occultation mode uses the coronagraphic fingers to block light from a bright object so astronomers can study the surrounding faint background.

4.3.3 Faint Object Camera Specifications

Figure 4-18 shows specifications for the FOC. Note:

- Focal ratio can be selected as commanded from the ground.
- Fields of view listed are the maximum for each focal ratio.
- The wavelengths studied usually are a band within the maximum range. For example, one study may concentrate on the band from 1200 to 1800 angstroms.
- Specific signal-to-noise ratios depend on observation ranges and exposure times, but indicate the camera’s limits.

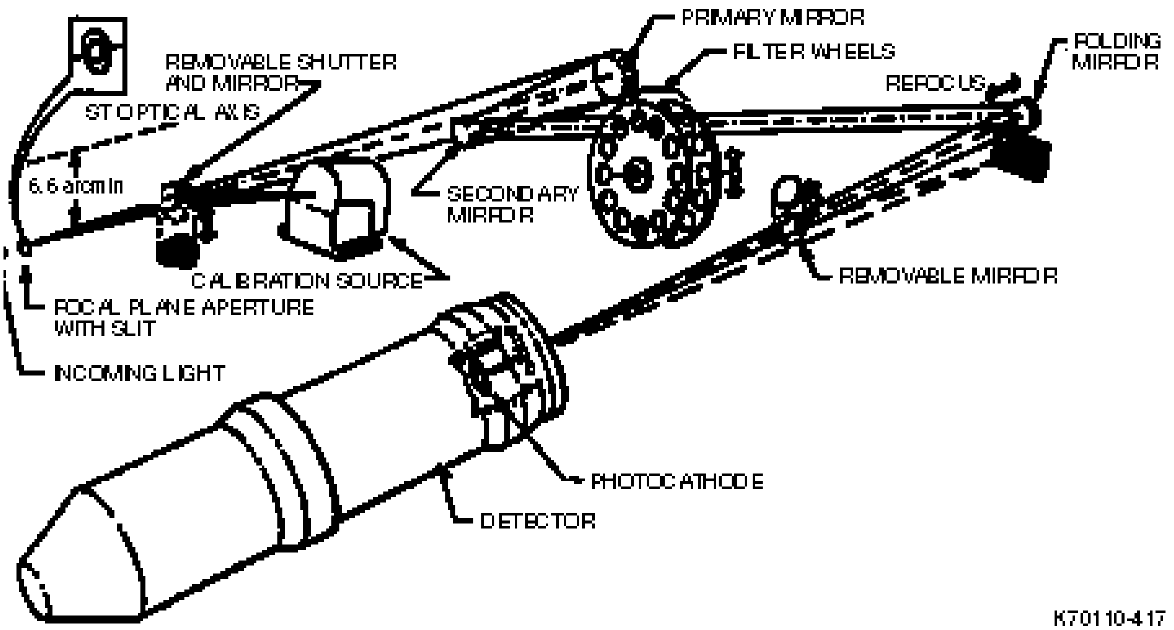


Fig. 4-17 Optical relay system layout at f/75.5

4.3.4 Observations

The FOC can be used by itself or with other Telescope science instruments for important observations, including:

- Studying interstellar gas clouds for evidence relating to star formation and evolution
- Measuring the distance of the farthest galaxies and quasars
- Examining globular clusters and galaxies, normal and irregular
- Providing high-resolution observations of various solar system phenomena.

Stellar Evolution. Stellar formation begins when gas clouds, formed by microscopic dust and gas, are buffeted by shock waves from nearby newly formed and internally combusting stars; from supernova explosions; or from the whirling movement of the arms of spiral galaxies. This violent motion collapses the gas clouds onto themselves. Growing hotter and heavier, the clouds increasingly compress to higher density and temperatures, ignite in sustained nuclear reactions, and become protostars.

Faint Object Camera	
Weight	700 lb (318 kg)
Dimensions	3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m)
Principal investigator	F. D. Macchetto, ESA/STScI
Contractor	Dornier Systems and Matra Espace Corp
Optical modes	f/151, f/75.5
Field of view	14, 28 arcsec^2
Magnitude range	5 to 28 m_v
Wavelength range	1150 to 6500 angstroms

K70110-418

Fig. 4-18 FOC specifications

Galaxies and Quasars. Galaxies fill the universe. Many questions arise when studying galaxies; for example, are the bright centers filled with clumps of stars massed together? The centers of some galaxies radiate more energy than the surrounding galaxy itself. Of particular interest is the center of elliptical galaxy NGC4486, also known as Messier 87. Scientists have found what appears to be a massive black hole at its center.

The FOC also will concentrate on known quasars to see if surrounding galaxies are hidden by the quasars' tremendous luminosity. The masking ability of the camera may help discover these faint galaxies. Because many quasars may have formed shortly after the Big Bang, they and their galaxies may reveal information about the early composition and development of the universe.

Examining Solar System Objects. With the FOC, astronomers can observe planets, moons, asteroids, and other bodies in the solar system more clearly than from ground-based observatories. Scientists obtain data similar in detail to that obtained by the Voyager spacecraft when it was 5 days from encounter. However, the FOC enables astronomers to examine a planetary object for years instead of the brief time dictated by Voyager's flyby trajectories.

Direct observation of Mars, for example, will advance scientific understanding of the planet's geography and weather, such as wind patterns, dust storm velocities, white-cloud formation, and seasonal polar-cap movement. Close-up views of Jupiter, Saturn, Neptune, Uranus, and Pluto will expand our knowledge of the atmospheric composition and the dynamics on these outer planets. The camera's angular resolution allows examination of small asteroids and planetary moons in greater detail than ever before to determine accurate dimensions, axis orientation, orbits, and composition. The FOC also studies comets using its spectrographic optics and a variety of filters.

4.4 Wide Field/Planetary Camera II

The most often used science instrument is the WF/PC. It records two-dimensional images at two magnifications through a selection of 48 color filters covering a spectral range from far-ultraviolet to visible and near-infrared wavelengths. It provides pictorial views of the celestial universe on a grander scale than any other instrument flown to date. Like its predecessor WF/PC I, WF/PC II 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 WF/PC I. Dr. John T. Trauger of JPL is the principal investigator for WF/PC II.

WF/PC I, the first-generation instrument, was launched with the Telescope in 1990 and functioned flawlessly. The second-generation instrument, WF/PC II, was already under construction when the Hubble Telescope was launched. Its original purpose was to provide a backup for WF/PC I with certain enhancements, including an upgraded set of filters, advanced detectors, and improved UV performance. With modifications introduced since 1990, WF/PC II also provided built-in compensation for the improper curvature of the Telescope's primary mirror so as to achieve the originally specified imaging performance of the Telescope in the WF/PC II field of view.

WF/PC II has four CCD cameras arranged to record simultaneous images in four separate fields of view at two magnifications.

In three Wide Field Camera fields, each detector picture element (pixel) occupies 1/10th arcsec, and each of the three detector arrays covers a square 800 pixels on a side (or 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 (or two Wide Field Camera pixels) in diameter. This three-field camera (which operates at a focal ratio of f/12.9) provides the greatest sensitivity for the detection of faint objects. Stars as faint as 28th magnitude are detectable in the longest anticipated exposures of about 28 hours (22nd magnitude is almost 1,000 million times fainter than can be seen with the naked eye).

The Planetary Camera provides a magnification about 2.2 times larger, in which each pixel occupies only 0.046 arcsec, and the single square field of view 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 and is used (brightness permitting) whenever the finest possible spatial resolution is needed, even for stars, stellar systems, gaseous nebulae, and galaxies.

With its two magnifications and its built-in correction for the Telescope's spherical aberration, WF/PC II can resolve the fine details and pick out bright stellar populations of distant galaxies, perform precise measurements of 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 – that could not be studied effectively with WF/PC I because of the aberration. WF/PC II's high-resolution photography of the planets within our solar system allows continued studies of their atmospheric composition as well as discovery and study of time-varying processes on their surfaces.

4.4.1 Comparison of WF/PC II and Faint Object Camera

For the same reasons that a photographer benefits from having a selection of lenses of different focal lengths, or possibly a zoom lens with an adjustable focal length, astronomers using the HST benefit from having the choice of several different magnifications offered by WF/PC II and the FOC. This selection allows astronomers to choose the instrumental characteristics best suited to a particular observational task.

For example, in the quest to measure the rate of expansion of the universe, it is crucial to discover as many Cepheid variable stars in clusters of galaxies as possible. Because Cepheids are rare and randomly scattered over the sky, this task calls for the largest possible field of view if it is to be completed efficiently. Therefore, such studies will utilize the Wide Field Camera, with its focal ratio of f/12.9.

The 0.1-arc second resolution of the Wide Field Camera is too coarse for some purposes because the finest details cannot be resolved with it or because the positions of star images cannot be pinpointed with sufficient accuracy. An example arises in the study of stars gravitationally bound to each other in orbits about their common center of mass. Such studies enable astronomers to determine the relative masses of the orbiting stars, which are of fundamental importance in studying the physics of stars. In many instances, positional accuracies approaching 1/1,000th arcsec are needed. In this case, the high magnification of the f/28.3 Planetary Camera or the even greater magnifications of the f/75.5 or f/151 cameras would be used.

The price paid for high magnification is that the field of view, in terms of area, varies inversely as the square of the magnification. Similarly, the exposure time required to reach a given limiting magnitude or faintness varies directly as the square of the magnification. It would be necessary to use a longer focal length if the object being studied is too bright for the Wide Field Camera. Because of these various factors, the astronomer's choice of which magnification to use often is a compromise.

4.4.2 Physical Description

The WF/PC occupies one of four radial bays in the focal plane structure of the HST. The other three radial bays support the FGSs, which are used primarily for controlling the pointing of the Telescope. The three other science instruments and COSTAR occupy axial bays.

The WF/PC II's field of view of is located at the center of the Telescope's field of view, where the telescopic images are nearly on axis and least affected by residual aberrations (field curvature and astigmatism) that are inherent in the Ritchey-Chretien design.

Because the focal plane is shared by the other instruments, WF/PC II is equipped with a flat pickoff mirror located about 18 in. ahead of the focal plane and tipped at almost 45 degrees to the axis of the Telescope. The pickoff mirror is attached to the end of a stiff truss, which is rigidly fastened to WF/PC's precisely located optical bench. The pickoff mirror reflects the portion of the Telescope's focal plane belonging to WF/PC II into a nearly radial direction in which it enters the front of the instrument, allowing light falling on other portions of the focal plane to proceed without interference.

WF/PC II is shaped somewhat like a piece of pie, the pickoff mirror lying at the point of the wedge, with a large, white-painted cylindrical panel 2.6 ft (0.8 m) high and 7 ft (2.2 m) wide at the wide end. The panel forms part of the curved outer skin of the Support Systems Module (SSM) and radiates away the heat generated by WF/PC's electronics. The instrument 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.

WF/PC II weighs 619 lb (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 SI C&DH unit. Figure 4-19 shows the overall configuration of the instrument.

Optical System. The WF/PC II optical system consists of the pickoff 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 each of 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 Telescope's primary mirror. Figure 4-20 shows the light path from the Telescope to the detectors.

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

WF/PC II's pickoff mirror and three of its four 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 WF/PC II 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, for a total of 48 filters. These can be used singly

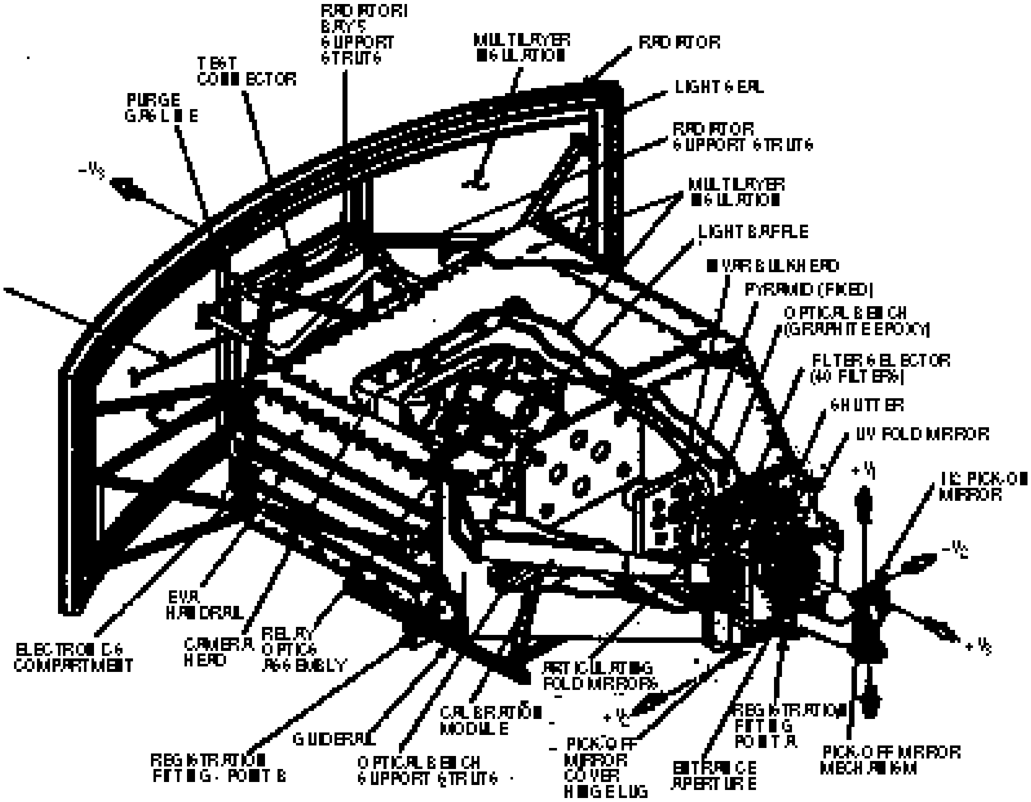


Fig. 4-19 Wide Field/Planetary Camera (WF/PC) overall configuration

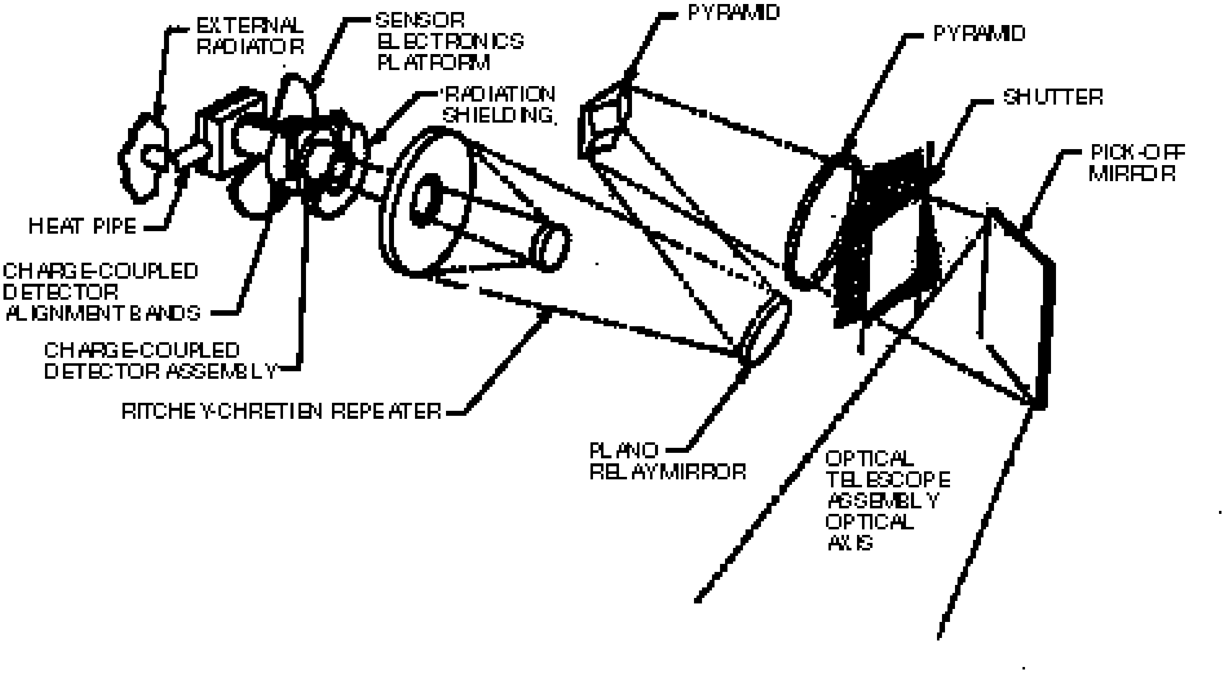


Fig. 4-20 WF/PC optics design

or in certain pairs. Some of the WF/PC II's filters have a patchwork of areas with differing properties to provide versatility in the measurement of spectral characteristics of sources.

WF/PC II 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 picture elements (pixels) built upon a thin wafer of crystalline silicon. The light-sensitive elements are controlled by complex electronic circuits also built onto the wafer. The circuits include low-noise amplifiers to strengthen signals that originate at the light sensors. As light falls upon the array, photons of light interact with the sensor material to create small electrical charges (electrons) in the material. The charge is very 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. Figure 4-21 illustrates the process.

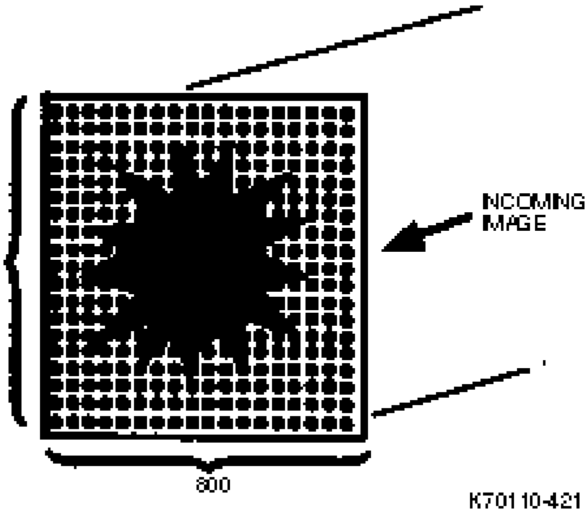


Fig. 4-21 WF/PC II imaging

The CCDs used in WF/PC II consist of 800 rows and 800 columns of pixels, 640,000 pixels in each array. The pixels can be thought of as tiny squares side by side, 15 microns (about 6/10,000 in.) on a side. Their sensitivity to light is greatest at near-infrared and visible wavelengths, but in WF/PC it is extended to the UV by coating them 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 -70YC (-8 to -130YF). This is accomplished by an electrically operated solid-state cooling system that 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 effectively 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 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 WF/PC I.

Processing System. A microprocessor controls all of WF/PC II'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 instruments 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 WF/PC II is digitally tape-recorded during the CCD readout. The data then is transmitted at a slower rate via a communications satellite that is simultaneously in Earth orbit.

4.4.3 WF/PC II Specifications

Figure 4-22 shows the WF/PC II specifications.

Wide Field/Planetary Camera II	
Weight	619 lb (281 kg)
Dimensions	Camera: 3.3 x 5 x 1.7 ft (1 x 1.3 x 0.5 m), Radiator: 2.6 x 7 ft (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 to 10,000 angstroms

K70110-422

Fig. 4-22 WF/PC II specifications

4.4.4 Observations

The WF/PC II 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 close-ups of the center. In addition, the WF/PC II 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 will be made for black holes, planets in other star systems, Mars atmospheric storms, and the connection between galaxy collisions and star formation.

4.5 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 Hughes Danbury Optical Systems, Inc., the sensors are in the focal plane structure, at right angles to the optical path of the Telescope and 90 degrees apart. They have pickoff mirrors to deflect incoming light into their apertures, as shown in Fig. 4-23. (See para 5.3 for more details.)

4.5.1 Fine Guidance Sensor Specifications

Figure 4-24 shows FGS specifications.

4.5.2 Operational Modes for Astrometry

Once the two target-acquisition FGSs lock onto guide stars, the third sensor can perform astrometric operations on targets within the field of view set by the guide stars' positions. The sensor should be able to measure stars as faint as 18 apparent visual magnitude.

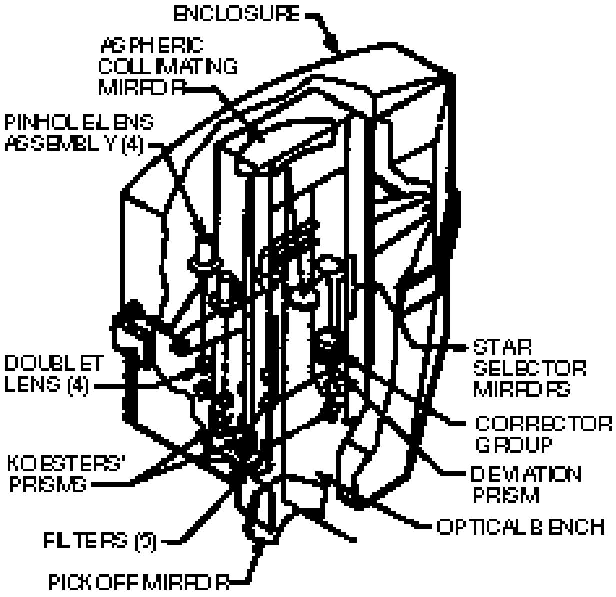


Fig. 4-23 Fine Guidance Sensor (FGS)

Fine Guidance Sensor	
Weight	485 lb (220 kg)
Dimensions	1.6 x 3.3 x 5.4 ft (0.5 x 1 x 1.6 m)
Contractor	Perkin-Elmer Corporation
Principal investigator	William H. Jefferys
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 to 7000 angstroms

K70110-424

Fig. 4-24 FGS specifications

There are three operational modes for astrometric observations: position, transfer-function, and 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 diameter of a stellar target, either through direct analysis of a single-point object or by scanning a diffuse target. Examples of the latter include solar system planets, double stars visually closer together than 0.02 arcsec, and targets surrounded by nebulous gases.

Binary stars visually separated by more than 0.02 arcsec can produce astrometric measurements of stellar masses, leading to information on stellar gravity in the evolution of star and planetary systems.

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.

4.5.3 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; neutral-density filter for observation of nearby bright stars; and two colored filters for estimating a target's color (chemical) index, increasing contrast between close stars of different colors, or reducing background light from star nebulosity.

4.5.4 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 field of view to calculate the angle. Even with the precision of the FGSs, astronomers cannot measure distances by the parallax method beyond nearby stars in our 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. An 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 our sun's. 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 that it is orbiting. Observations of Proxima Centauri (the nearest star to the sun) and Barnard's star now are being conducted in the hope that a planetary companion may be found.

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.

4.6 HST Operations

Space Telescope mission operations are of two types:

- Science operations that observe celestial objects and gather data
- Engineering operations that calibrate, test, and maintain the Telescope's overall performance.

Science and engineering 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 are carried out by the Telescope ground system, which consists of the STScI and Space Telescope Operations Control Center (STOCC). The STScI oversees science operations. It hosts astronomers, evaluates and chooses observation programs, schedules the selected observations, generates an overall mission timeline and command sequences, and stores and analyzes data from the Telescope. Meanwhile, the STOCC makes day-to-day operational decisions through the Payload Operations Control Center (POCC) at GSFC. It interacts with the STScI to receive daily mission schedules, to process quick-look data and displays, and to manage the science data. Figure 4-25 details the ground functions.

4.6.1 Space Telescope Science Institute

Located in Baltimore, Maryland, the STScI is responsible to GSFC for the science programs on the HST. It is operated by the Association of Universities for Research in Astronomy (AURA), a consortium of 20 United States universities that operates several national facilities for astronomy.

The STScI solicits and reviews observation proposals and selects observations to be carried out. It schedules observations and assists guest observers in their work; generates an integrated science and engineering timeline to support all spacecraft activities, including any special engineering tests; and provides the facilities and software to reduce, analyze, archive, and distribute Telescope data.

Additionally, STScI generates an integrated science and engineering timeline to support all spacecraft activities, including any special engineering tests. It also monitors the Telescope and science instruments for characteristics that could affect science data collection, for example, instrument performance quality, pointing inaccuracies, and Telescope focus.

Scientific Goals. The STScI helps conduct the science program to meet the overall scientific

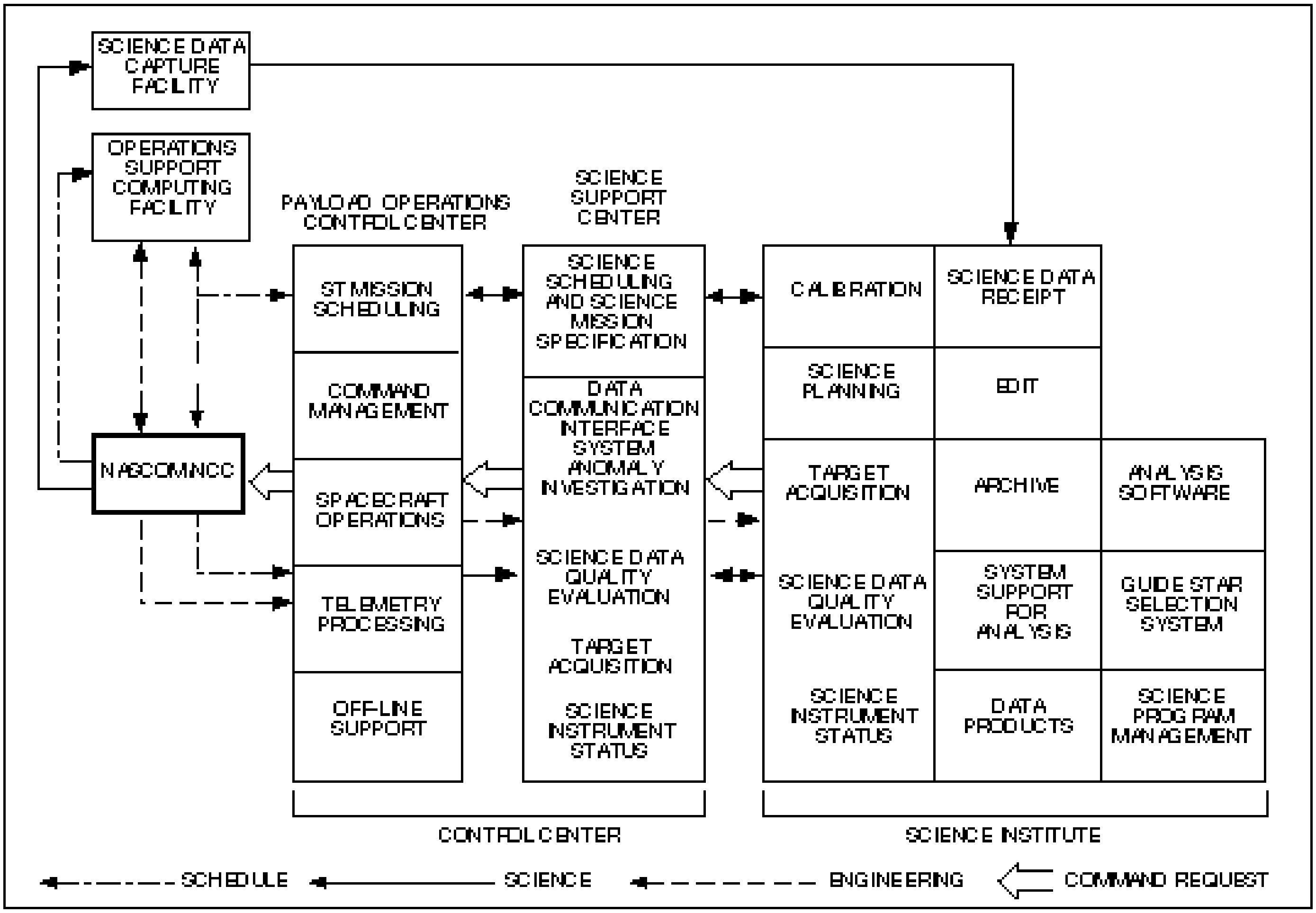


Fig. 4-25 Space Telescope ground systems overview

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.

Institute Software. Computer hardware and software play an important role in STScI work. The Science Operations Ground System (SOGS) is a data-management and scheduling computer system developed by TRW under contract to NASA. The Guide Star Selection System (GSSS) created the guide star catalog used by the pointing control subsystem. Science Data Analysis Software (SDAS) provides analytical tools for astronomers studying processed data. STScI developed the GSSS and SDAS.

SOGS handles mission planning and scheduling, observation support, software support, and routine data processing. Together, these programs perform the computations needed to run the science operations on the Telescope.

GSSS provides reference stars and other bright objects so the FGSs can point the Telescope accurately. This system 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 SOGS 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 the STScI outlining an observing program and describing the scientific objectives and instruments required. The STScI selects observations by evaluating these requests for technical feasibility, conducting peer reviews, and choosing the highest ranked proposals. Because individual astronomers and astronomy teams are expected to submit many more proposals than can possibly be accepted, a team approach is encouraged. The final decision rests with the STScI director, advised by a review committee of astronomers and scientists from many institutions.

First priority for observations goes to principal investigators – the scientists and astronomers who designed the instruments. Principal investigators and their contributions are:

- Rodger Thompson, University of Arizona (NICMOS)
- Bruce E. Woodgate, GSFC (STIS)
- F. Macchetto, ESA/STScI (FOC)
- J. Trauger, NASA JPL (WF/PC II)
- William H. Jeffreys, University of Texas (FGS).

Scheduling Selected Observations. The primary scheduling consideration is availability of a target, limited by environmental and stray-light constraints – for example, a faint object that 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 archives analyzed data. Computer resources include the SDAS and other selected computer facilities.

SOGS data processing receives science data from the Packet Processing Facility (PACOR) at GSFC, then automatically formats it and verifies its quality. It calibrates data to remove instrument interference such as variation in the detector's sensitivity across the data field. Then the software places the data on archive computer tapes from which the data can be formatted into printed reports, printer plots, and photographic prints and negatives. The STScI processes all data within 24 hours after receipt.

The SDAS package is written so that observers can interact to process images received by the SOGS software. In addition, individual observers will be encouraged to bring their own data analysis software and reference data.

STScI is responsible for storing the massive amount of data collected by the Telescope. A database management system 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 to use data manipulation procedures created on STScI computers.

ESA provides approximately 15 percent of the STScI staff and operates its own data analysis facility in Garching, Germany.

In addition to science data, computers store 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.

4.6.2 Space Telescope Operations Control Center

STOCC runs day-to-day spacecraft operations through the POCC and PACOR. In addition, STOCC works with the NASA Communications

Network (NASCOM) and the Tracking and Data Relay Satellite System (TDRSS).

POCC uses mission-control facilities at GSFC built specifically for HST operations.

STOCC has three major operational responsibilities: spacecraft operations, including sending commands to the spacecraft; telemetry processing; and off-line support.

Some commands may pass to the Telescope from POCC, based on specific observation objectives. POCC translates those goals into commands, then passes them along to the Telescope through the communications network. The commands may re-orient the Telescope, open an instrument aperture, turn on the instrument's detectors, request a certain filter or grating setting, or monitor data going from the detector to the instrument's transmission device and out through the SI C&DH unit.

Most specific spacecraft operations are commanded by software embedded in the Telescope's onboard computer. The POCC orders the computer to activate the stored commands.

Telemetry comes into POCC from the communication satellites and provides information that reflects the equipment operation status or spacecraft operation. For example, telemetry can show that voltage going to the Rate Gyro Assembly indicates a power surge, which could disable a gyroscope and affect the stability of the Telescope. POCC defuses the voltage surge or switches to a backup gyro until the problem is solved. In many cases, consultation between POCC and STScI is necessary, particularly if the data affects an ongoing observation.

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

Another important part of STOCC is PACOR processing. When data arrives from NASCOM for science handling, PACOR reformats the data, checks for noise or transmission problems, and passes each packet of data along with a data quality report.

Support for STOCC comes from the Spaceflight Tracking and Data Network (STDN), composed of TDRSS and NASCOM.

TDRSS has two communications relay satellites 130 degrees apart, with a ground terminal at White Sands, New Mexico. There is a small "zone of exclusion" where Earth blocks the Telescope signal to either of the satellites, 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.

NASCOM leases domestic satellites for commercial communications, such as television transmission. These satellites pass data from TDRSs directly to STOCC.

4.6.3 Operational Characteristics

Three major operational factors affect the success of the Telescope: orbital characteristics for the spacecraft, its maneuvering characteristics, and communications characteristics for sending and receiving data and commands.

Orbital Characteristics. The orbit of the Telescope is approximately 320 nmi (593 km). It maintains an orbit between a minimum operating altitude of approximately 200 nmi (368 km) – to keep above altitudes where atmospheric drag comes into noticeable play – and the deployment orbit. The orbit inclines at a 28.5-degree angle from the equator because the Shuttle launch was due east from Kennedy Space Center. The chosen orbit puts the sun in the Telescope orbital plane so that sunlight falls more directly on the Solar Arrays. In addition, the orbit is high enough that aerodynamic drag from the faint atmosphere at that level will not decay the Telescope's orbit to below the minimum operating altitude.

The Telescope completes one orbit every 97 minutes, passing into the shadow of the Earth during each orbit. The time in shadow varies from 28 minutes to 36 minutes. The variation during a nominal 30-day period is between 34.5 and 36 minutes in shadow. If Earth blocks an object from the Telescope, the Telescope re-acquires the object as the spacecraft comes out of Earth's shadow. Faint-object viewing is best while the Telescope is in Earth's shadow. Figure 4-26 shows the nominal orbit.

The Telescope orbit is tracked by the TDRSS, which plots the spacecraft's orbit at least eight times daily and sends the data to the Flight Dynamics Facility at GSFC. This helps predict future orbits, although 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 considerably.

Celestial Viewing. The Telescope is pointed toward celestial targets as a normal orientation to expose instrument detectors for up to 10 hours, if needed. 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. 4-27). 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 in a given period a target will be most visible while the Telescope is in shadow.

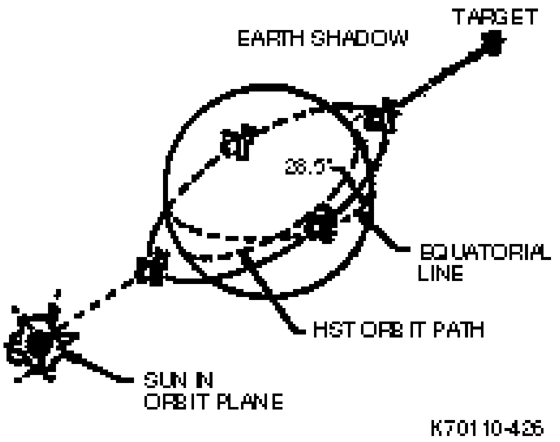


Fig. 4-26 HST nominal orbit

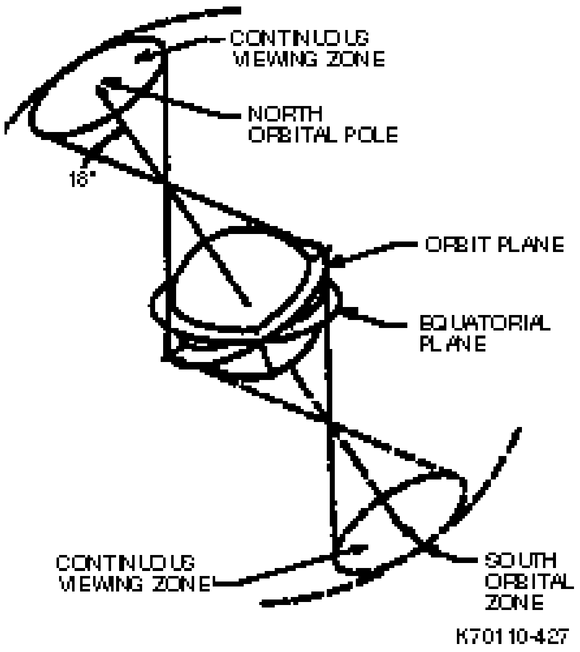


Fig. 4-27 "Continuous-zone" celestial viewing

Other sources affecting celestial viewing are zodiacal light and integrated or background starlight. These affect viewing with certain instruments, such as the light-intensity sensitive FOC.

Solar System Object Viewing. Solar system objects also are affected by the factors mentioned for celestial viewing. 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, which affects the pointing direction toward 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 with long-exposure observations of dim targets.

The Telescope's attitude roll 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. To minimize danger from this exposure, the Telescope views these objects using Earth to block (occult) the sun, that is, after the sunset shadow falls on the Telescope.

Lunar Occultation Viewing. FGSs look away when the Telescope approaches within 10 degrees of the bright moon. By overriding the controls that protect the sensor star selector servos, the ground control team can use the moon as an occulting object for an observation. The moon likely would be between its new-moon and quarter-moon phases so the occulting edge, which is in shadow, precedes the illuminated part of the moon (see Fig. 4-28).

Natural Radiation. Energetic particles from different sources bombard the Telescope continuously 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 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, 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

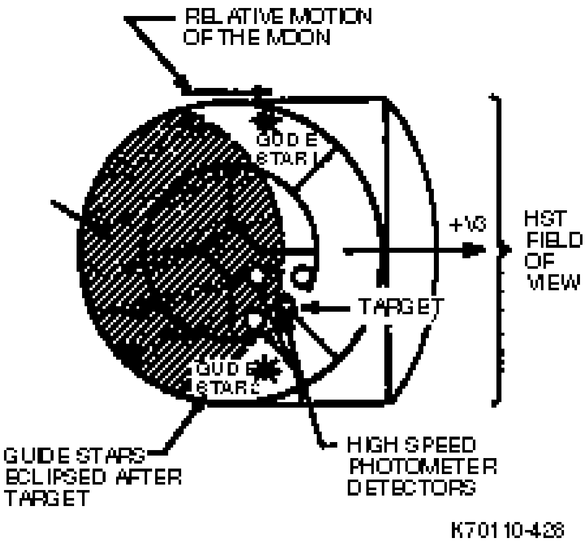


Fig. 4-28 Using the moon as an occulting disk

particles. NASA regularly monitors the flares, and the Telescope can stop an observation until the flares subside. The greatest possible physical danger is to the crew during extravehicular activity, which would be halted until the flares subside.

Maneuver 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 4-29 shows a roll-and-pitch maneuver. When the Telescope maneuvers, it takes a few minutes to lock onto a new target and accumulate 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. Unprotected portions of the SSM aft shroud could be affected thermally. 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. 4-30).

Communication Characteristics. The Telescope 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. 4-31). However, orbital variations by the Telescope and communications satellites affect this ideal situation to widen the zone of exclusion slightly.

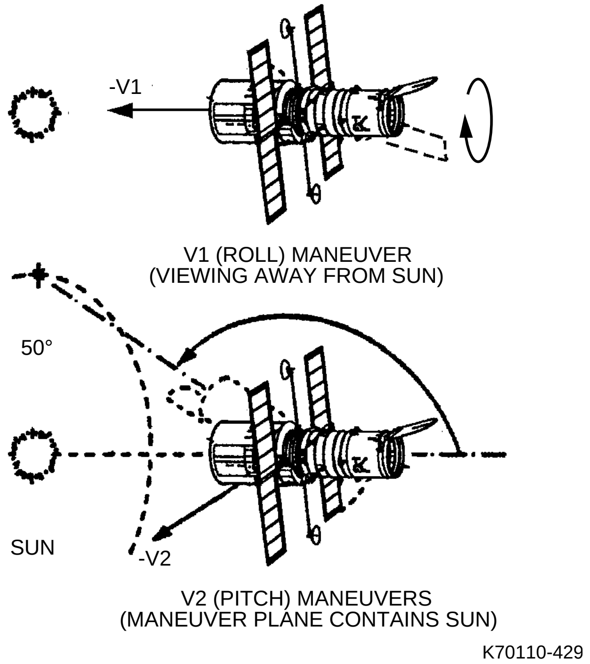


Fig. 4-29 HST single-axis maneuvers

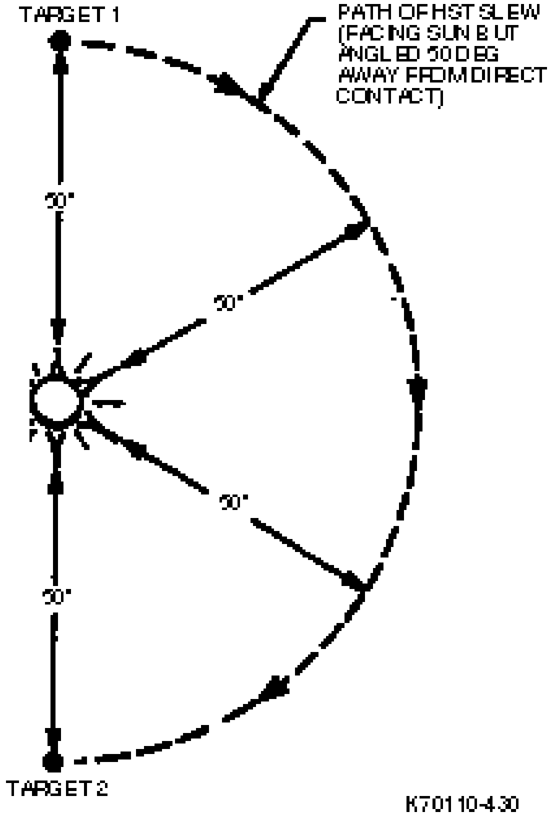


Fig. 4-30 Sun-avoidance maneuver

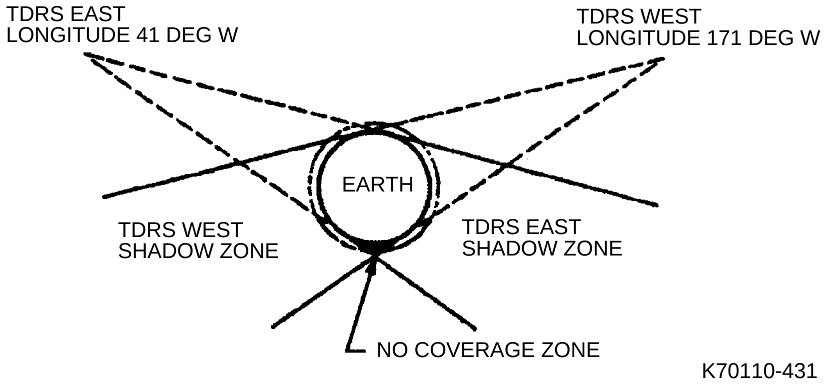


Fig. 4-31 TDRS-HST contact zones

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

The backup communications link is the Ground Spacecraft Tracking and Data Network (GSTDN), 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 GSTDN contacts are required to read data from a filled science tape recorder – with gaps of up to 11 hours between transmissions.

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

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

4.7 Acquisition and Observation

The major steps in the observation process are target acquisition and observation, data collection and transmission, and data analysis.

Each science instrument has an entrance aperture, located in different portions of the Hubble's focal plane (see Fig. 4-32). The different aperture positions make precise

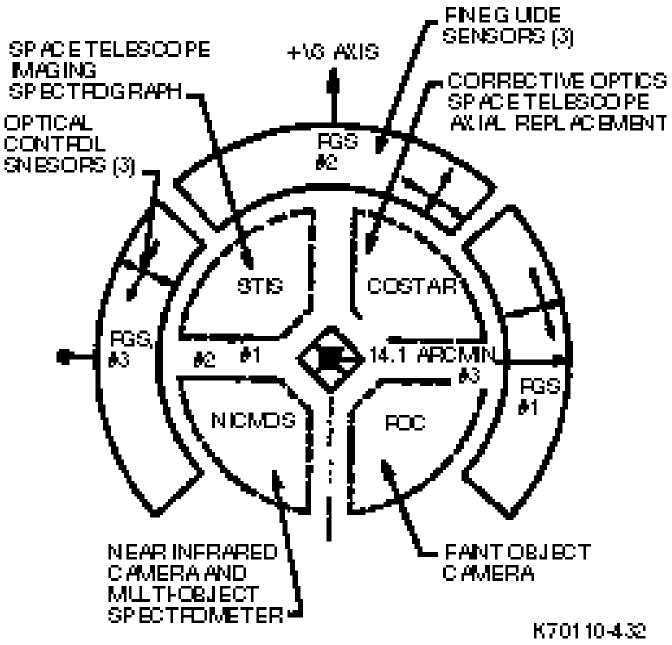


Fig. 4-32 HST instrument apertures

pointing a sometimes-lengthy procedure for the FGSs. In addition to the small apertures in which the FGSs must center the target, 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 DF-224 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 re-acquire a previous target. Called blind pointing, this is used mostly for generalized pointing and for the WF/PC II, 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.

HUBBLE SPACE TELESCOPE SYSTEMS

The Hubble Space Telescope (HST) has three interacting systems:

- The Support Systems Module (SSM), an outer structure that houses the other systems and provides services such as electrical power, data communications, and pointing control and maneuvering
- The Optical Telescope Assembly (OTA), which collects and concentrates the 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. With the exception of the Fine Guidance Sensors (FGS), all are controlled by the Science Instrument Control and Data Handling (SI C&DH) unit.

Additional systems that also support HST operations include two Solar Arrays (SA). These generate electrical power and charge onboard batteries and communications antennas to receive commands and send telemetry data from the HST. Figure 5-1 shows HST configuration.

The Telescope performs much like a ground observatory. The SSM is designed to support functions required by any ground astronomical observatory. It provides power, points the Telescope, and 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.

The Telescope completes one orbit every 97 minutes and maintains its orbital position along three axial planes. The primary axis, V1, runs

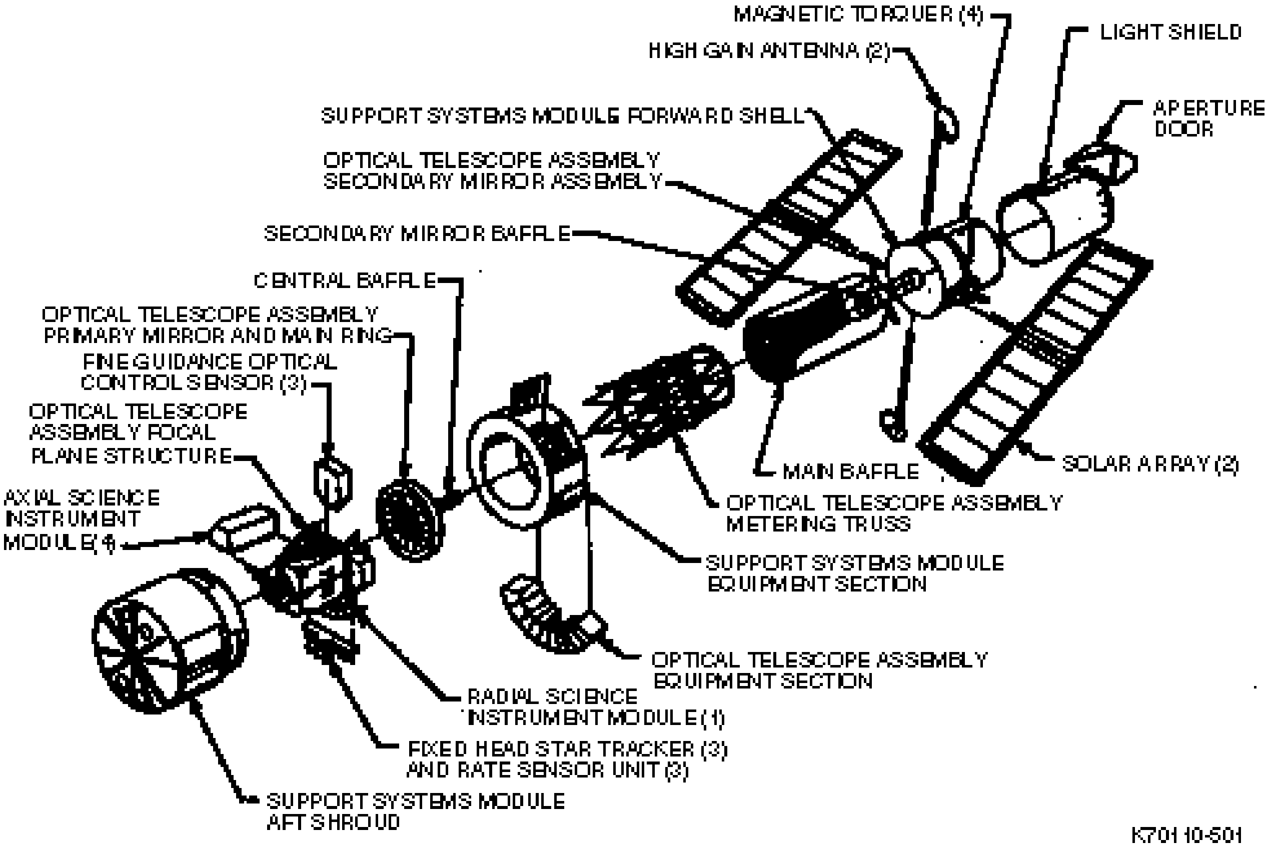


Fig. 5-1 Hubble Space Telescope – exploded view

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.

5.1 Support Systems Module

The 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 in para 5.2.4.)
- Computers to operate the spacecraft systems and handle data

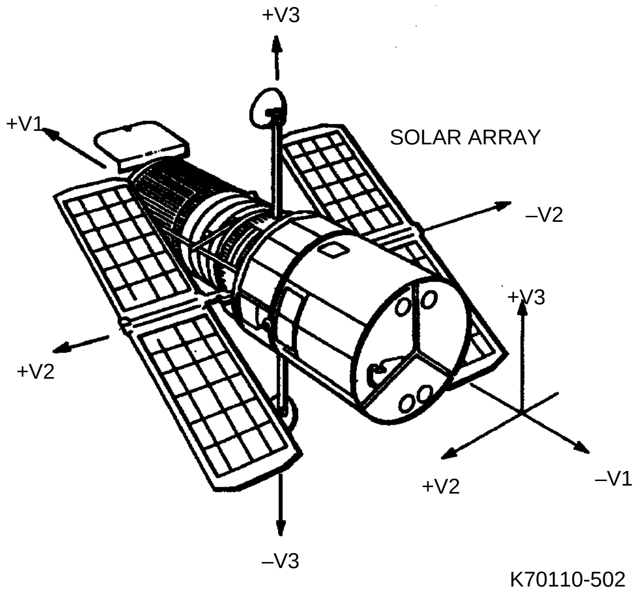


Fig. 5-2 Hubble Space Telescope axes

- 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.

5.1.1 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 Missiles & Space (see Fig. 5-4).

Aperture Door. The aperture door, approximately 10 ft (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

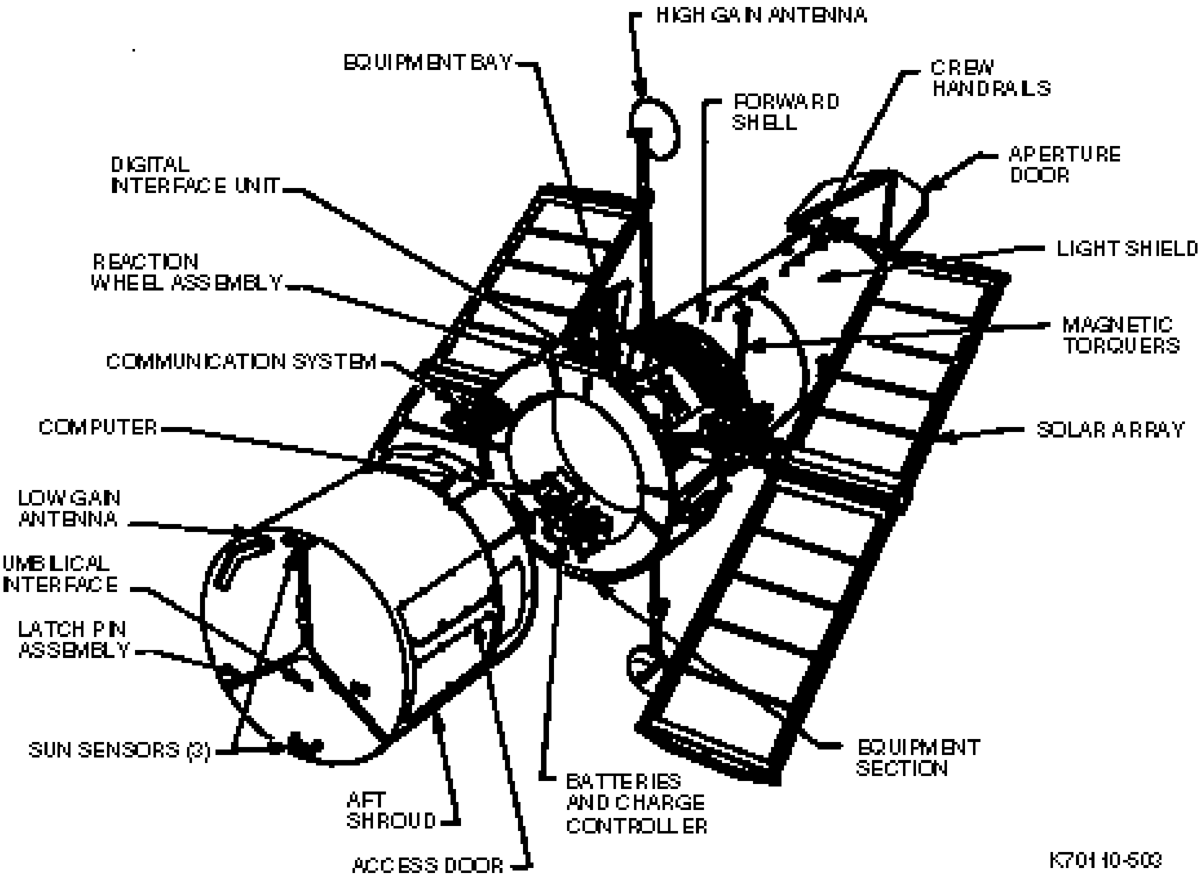


Fig. 5-3 Design features of Support Systems Module

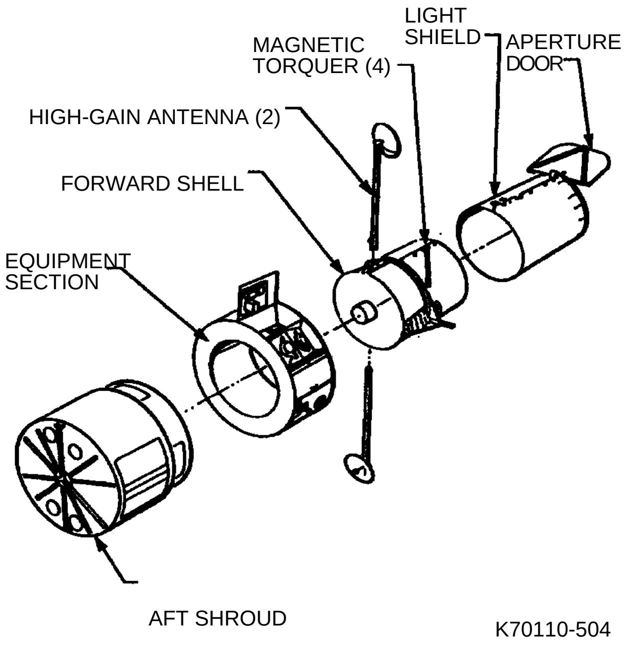


Fig. 5-4 Structural components of Support Systems Module

axis and finishes closing by the time the sun reaches 20 degrees of +V1. This takes no more 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. The light shield (see Fig. 5-4) blocks out stray light. It connects to both the aperture door and the forward shell. On the outer skin of the Telescope on opposite sides are latches to secure the SAs and HGAs when they are stowed. Near the SA latches are scuff plates, large protective metal plates on struts that extend approximately 30 in. 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.

Figure 5-5 shows the aperture door and light shield. The shield is 13 ft (4 m) long, with an internal diameter of 10 ft (3 m). It is machined from magnesium, with a stiffened, corrugated-skin barrel 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.

The forward shell is 13 ft (4 m) long and 10 ft (3 m) in diameter. It is machined from aluminum plating, with external reinforcing rings and internal stiffened panels. The 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. This section contains 10 bays for equipment and two bays to support aft trunnion pins and scuff plates. As shown in Fig. 5-7, going clockwise from the +V3 (top) position, the bays contain:

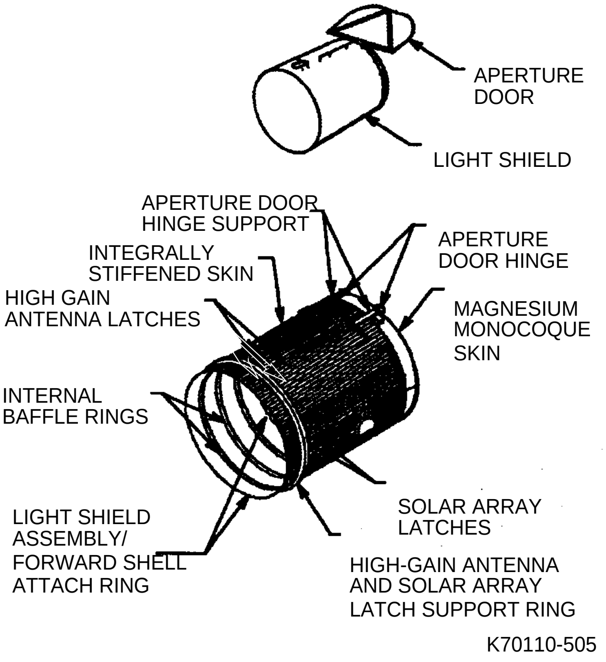


Fig. 5-5 Aperture door and light shield

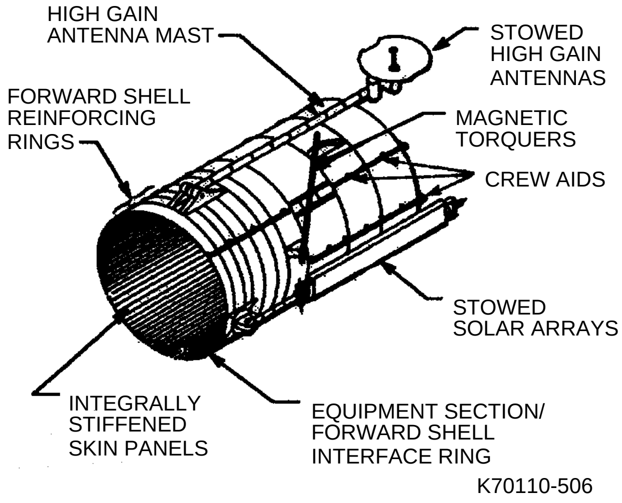


Fig. 5-6 Support Systems Module forward shell

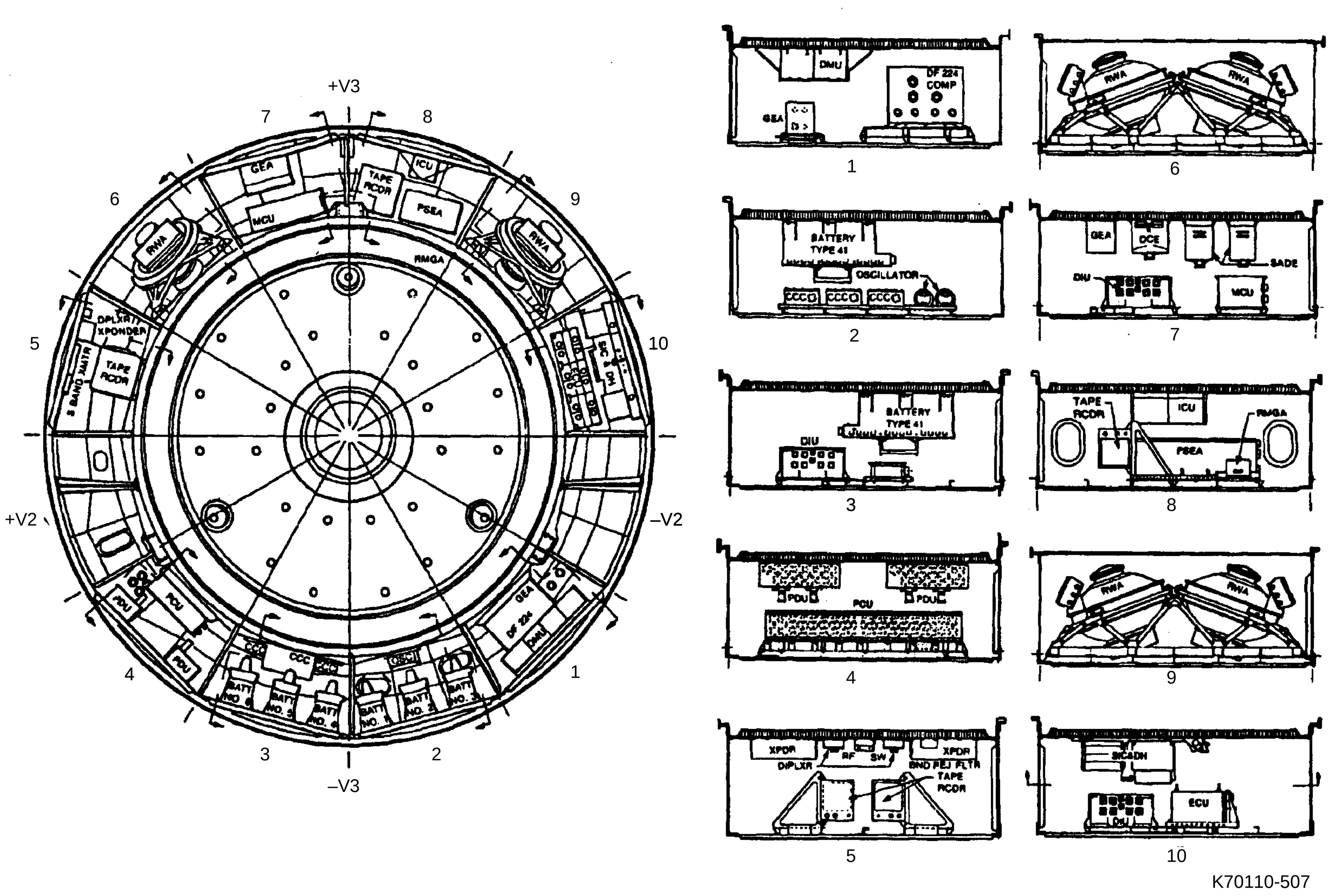


Fig. 5-7 Support Systems Module Equipment Section bays and contents

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
6. Bay 2 through Bay 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, with the outer diameter (the door) – 3.6 ft (1 m) – greater than the inner diameter – 2.6 ft (0.78 m). The bays are 4 ft (1.2 m) wide and 5 ft (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.

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/Planetary Camera II (WF/PC) are housed radially near the connecting point between the aft shroud and SSM Equipment Section. Doors on the outside of the shroud allow shuttle 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 ft (3.5 m) long and 14 ft (4.3 m) in diameter.

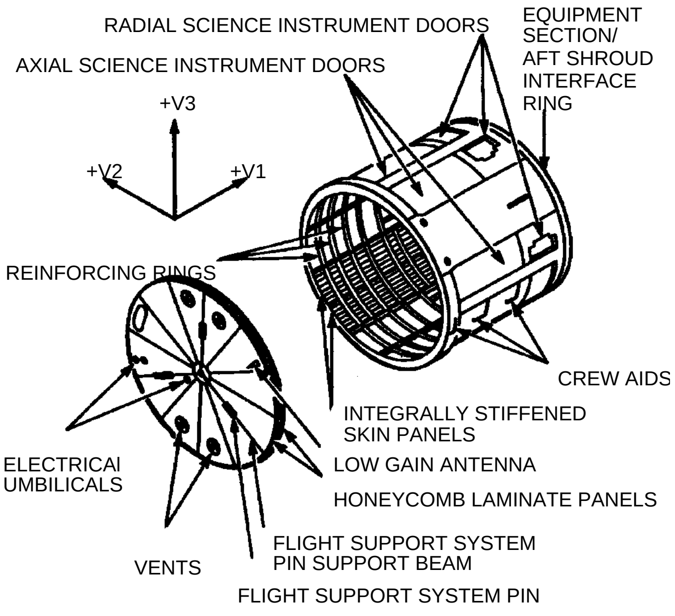


Fig. 5-8 Support Systems Module aft shroud and bulkhead

The aft bulkhead contains the umbilical connections between the Telescope and the shuttle, used during launch/deployment and on-orbit maintenance. The rear LGA attaches 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 used to prevent contamination of the science instruments before launch. All vents used to expel gases are light-tight; that is, no stray light can enter 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 the arrays and antennas

- Gimbals to move the HGA dishes
- Motors to power the hinges and latches and to rotate the arrays and antennas.

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

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.

5.1.2 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 is passed through the Data Management Subsystem (DMS).

The HGAs achieve a much higher RF signal gain, which is required, for example, when transmitting high-data-rate scientific data. These antennas require pointing at the TDRSs because of their characteristically narrow beam widths. On the other hand, the LGAs provide spherical coverage (omnidirectional) but have a much lower signal gain. The LGAs are used for low-rate-data transmission and all commanding of the Telescope.

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 made the antenna dishes. They are manufactured from honeycomb aluminum and graphite-epoxy facesheets.

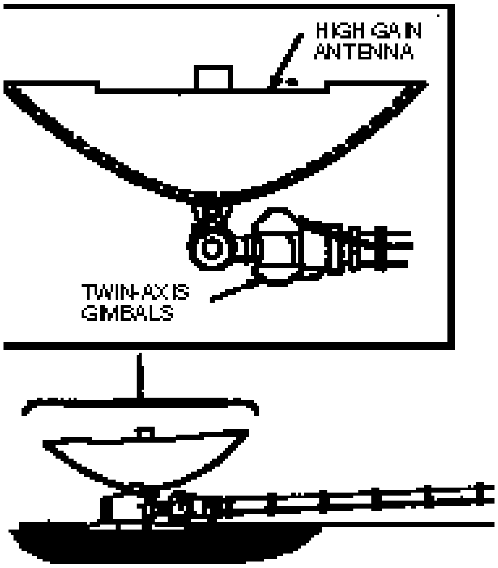


Fig. 5-9 High Gain Antenna

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).

Low Gain Antennas. The LGAs receive ground commands and transmit engineering data. They are on the light shield and aft bulkhead of the spacecraft, set 180 degrees apart. Each antenna is a spiral cone that can operate over a frequency range from 2100 MHz to 2300 MHz. Manufactured by Lockheed Martin, the LGAs are used for all commanding of the Telescope and for low-data-rate telemetry, particularly during Telescope deployment or retrieval on orbit or during safemode operations.

5.1.3 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. Subsystem components are:

- DF-224 computer
- Data Management Unit (DMU)
- Four Data Interface Units (DIU)
- Three engineering/science tape recorders (E/STR)
- 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.

Figure 5-10 is the subsystem functional diagram.

DF-224 Computer. The DF-224 computer is a general-purpose digital computer for onboard engineering computations. It executes stored commands; formats status data (telemetry); performs all Pointing Control Subsystem (PCS) computations to maneuver, point, and attitude stabilize the Telescope; generates onboard commands to orient the SAs toward the sun; evaluates the health status of the Telescope systems; and commands the HGAs.

The DF-224 is configured with three central processing units (CPU), two of which are backups; six memory units, with up to 48K words total; three input/output units, with two as backups; and six power converter units assigned with overlapping functions for reliability. The DF-224 measures 1.5 x 1.5 x 1 ft (0.4 x 0.4 x 0.3 m) and weighs 110 lb (50 kg). It is located in Bay 1 of the SSM Equipment Section (see Fig. 5-11).

During the First Servicing Mission, the DF-224 was augmented with an additional computer

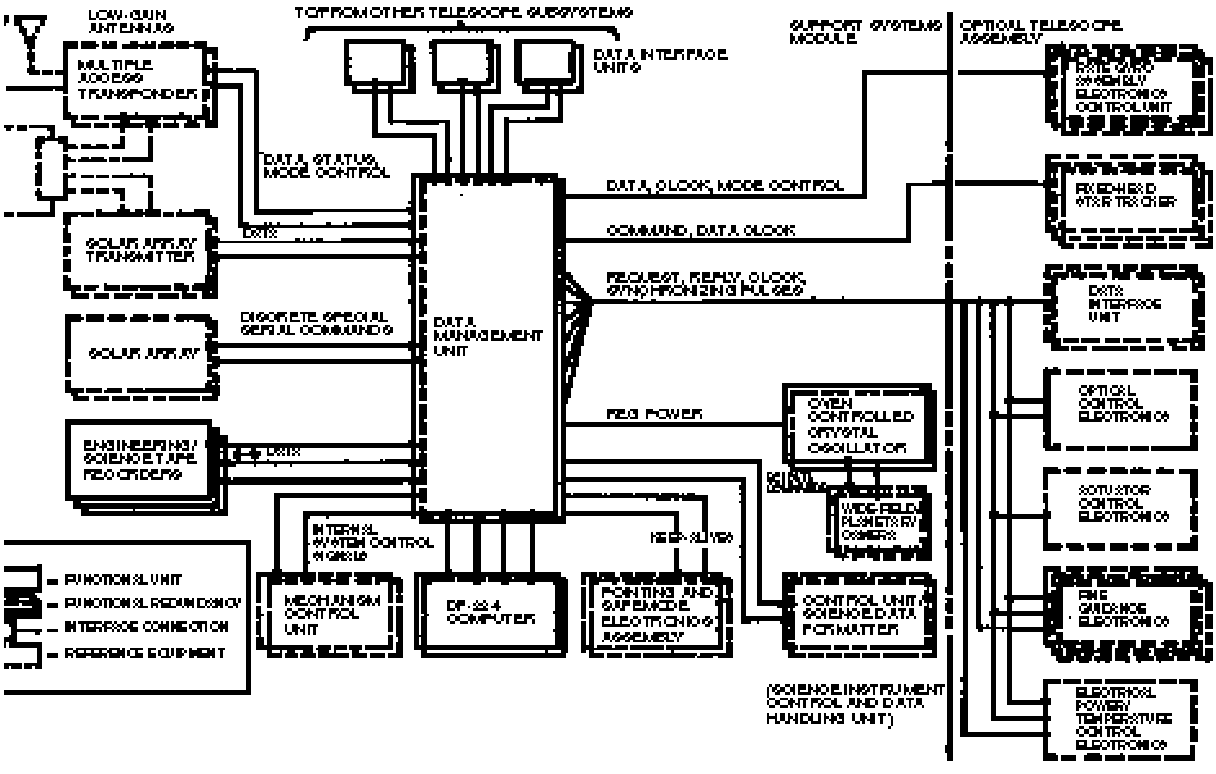


Fig. 5-10 Data Management Subsystem functional block diagram

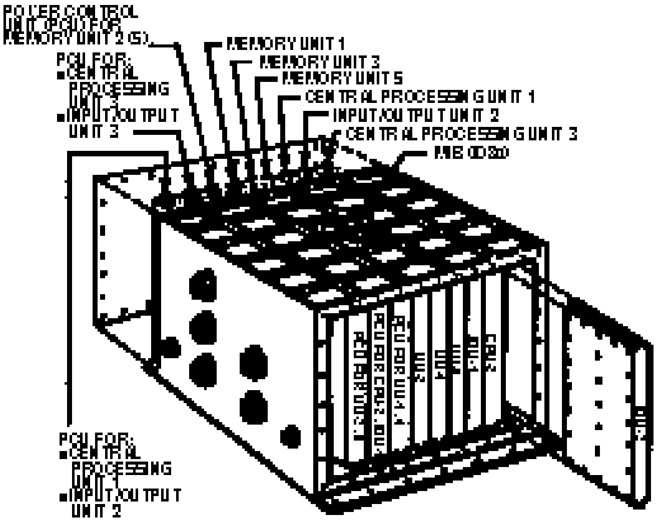


Fig. 5-11 DF-224 computer

called a coprocessor. Its design was based on the Intel 80386 microchip. The coprocessor provided eight new memory units for the DF-224 (with 1 MB of RAM) and a substantial increase in processing power.

Data Management Unit. The DMU links with the DF-224. It encodes data and sends messages to selected Telescope units and all DMS units, powers the oscillators, and is the central timing source. The DMU also receives and decodes all incoming commands, then transmits each processed command to be executed.

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

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 E/STRs if direct telemetry via a TDRS is unavailable.

Data Interface Unit. The four DIUs provide a command and data link between DMS and other Telescope 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 in. (38 x 41 x 18 cm) and weighs 35 lb (16 kg).

Engineering/Science Tape Recorders. The DMS includes three tape recorders that store engineering or science data that cannot be transmitted to the ground in real time. The recorders, which are located in Equipment Section Bays 5 and 8, hold up to 1 billion bits of information. Two recorders are used in normal operations; the third is a backup. Each recorder measures 12 x 9 x 7 in. (30 x 23 x 18 cm) and weighs 20 lb (9 kg).

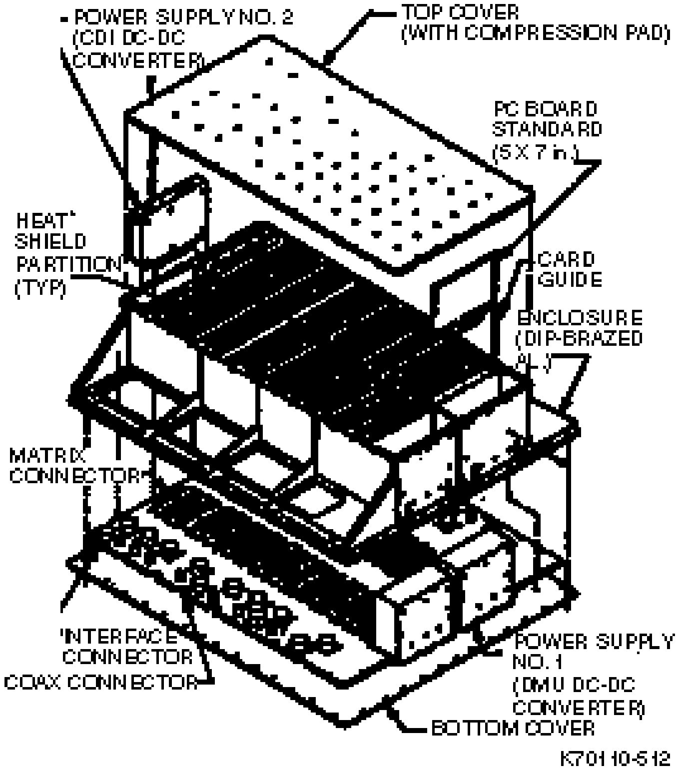


Fig. 5-12 Data Management Unit configuration

Solid State Recorder. A state-of-the-art Solid State Recorder (SSR) will be installed during the Second Servicing Mission in February 1997. This new type of digital recorder will replace one of the current, reel-to-reel recorders on HST. The SSR was developed at Goddard Space Flight Center, Greenbelt, MD. This new recorder has an expected on-orbit life of at least eight years and will add to the efficiency of operations on HST.

Unlike the 1970s-style reel-to-reel recorders, the SSR has no reels, no tape, and no moving parts to wear out and limit lifetime. Data is digitally stored in computer-like memory chips until HST's operators at GSFC command the SSR to play it back.

Although it is about the same size as a reel-to-reel recorder, it can store over 10 times more data. The SSR stores 12 gigabits of data, while the tape recorder it replaces can store only 1.2 gigabits.

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

5.1.4 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 to within 0.01 arcsec and holding the Telescope in that orientation with 0.007-arcsec stability for up to 24 hours while the Telescope continues to orbit the Earth at 17,000 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 into two FGSs and controlling the Telescope to keep it in the same position relative to these stars. When specific target requests require repositioning the spacecraft, the pointing system selects different reference guide stars and moves the Telescope into a new attitude.

The PCS encompasses the DF-224 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), both used by the spacecraft safemode system. See para 5.1.7 for details.

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

The CSSs measure the Telescope's orientation to the sun. They 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. Five CSSs are located on the light shield and aft shroud. CSSs also 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. The system consists of magnetometers and dedicated electronic units that send data to the DF-224 computer and the Safemode Electronic Assembly. Two systems are provided. Both are located on the front end of the light shield.

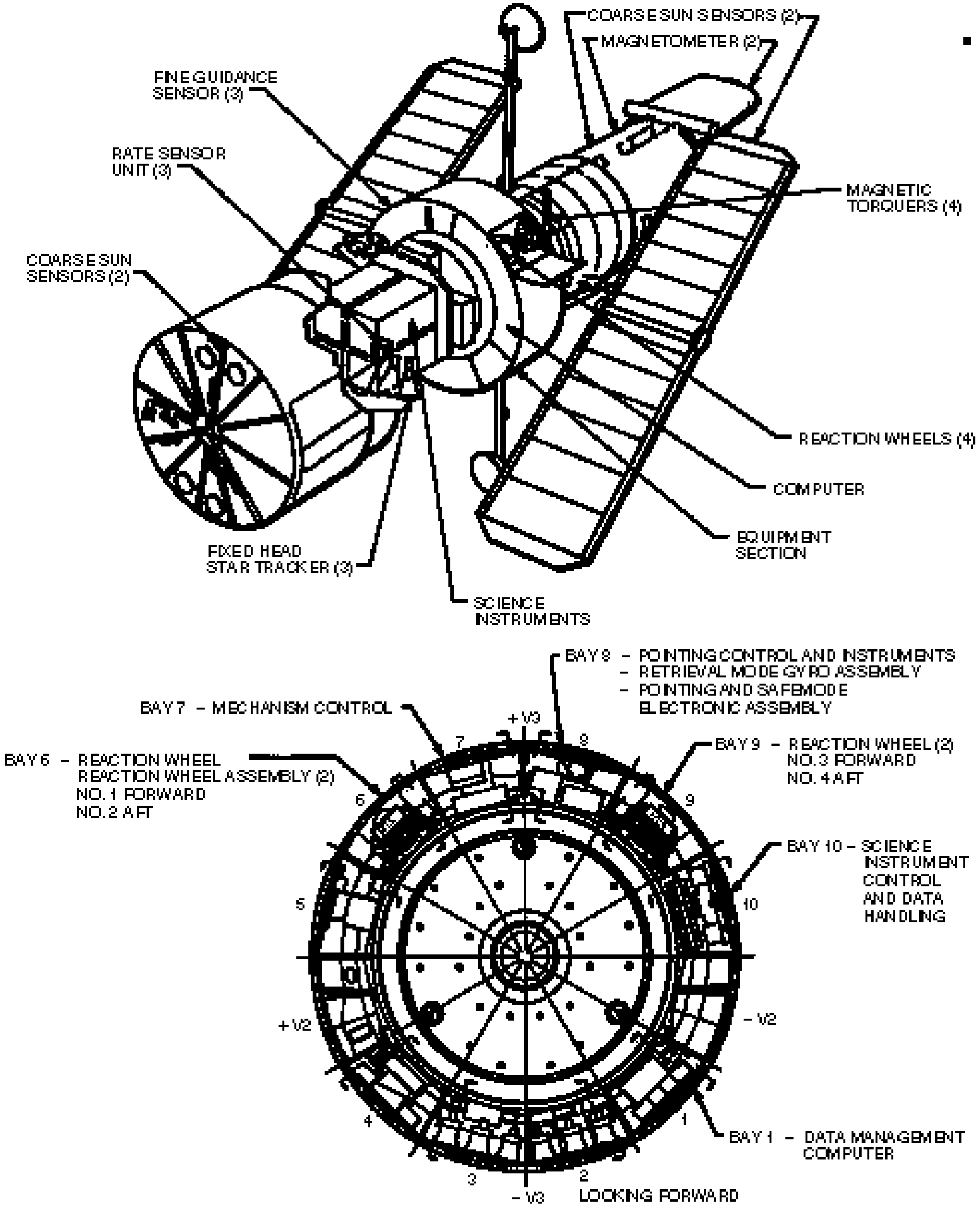


Fig. 5-13 Location of Pointing Control Subsystem equipment

Three RGAs are provided on the Telescope. Each assembly consists of a Rate Sensing Unit (RSU) and an Electronics Control Unit (ECU). An RSU contains two rate sensors, each measuring attitude rate motion about its sensitive axis. This output is processed by its dedicated electronics, which are contained in the ECU. Each unit has two sets of electronics. The RSUs are located behind the SSM Equipment Section, next to the 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 provide the attitude reference when maneuvering the Telescope.

Three of the original six rate gyros were replaced during the First Servicing Mission. Originally, three gyroscopes were required to continue the Telescope mission; however, software that permits science operations to continue with only two gyroscopes operating has been developed and put into service.

An FHST is an electro-optical detector that locates and tracks a specific star within its FOV. Three FHSTs are located in the aft shroud behind the FPS, next to the RSUs. STOCC uses star trackers 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, discussed in more detail in para 5.3, provide angular position with respect to the stars. 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, while the third is available for astrometry, the positional measurement of specific stars.

Pointing Control Subsystem Software. PCS software accounts for approximately 85 percent of the flight code executed by the DF-224 computer. This software translates ground targeting commands into reaction wheel torque profiles that reorient the spacecraft. All motion of the spacecraft is smoothed 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 so that reaction wheel speeds are always minimized. In addition, the software provides various telemetry formats.

Since the Telescope was launched, major modifications have been made to the PCS. A digital filtering scheme, known as Solar Array Gain Augmentation (SAGA), was incorporated to mitigate the effect of any SA vibration or jitter on pointing stability. Software also was used to improve FGS performance when the Telescope is subjected to the same disturbances. This algorithm is referred to as the FGS Re-Centering Algorithm.

Software was used extensively to increase Telescope robustness when hardware failures are experienced. Two additional software safemodes have been provided. The spin-stabilized mode provides 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. This is achieved by maintaining data in the DF-224 plated wire 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 required control torques to stabilize the Telescope's line of sight.

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

Magnetic torquers create torque on the spacecraft and 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.

The magnetic torquers also provide backup control to stabilize the Telescope's orbital attitude during the contingency modes, as described in para 5.1.2. Each torquer, located externally on the forward shell of the SSM, is 8.3 ft (2.5 m) long and 3 in. (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 FGSs 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.

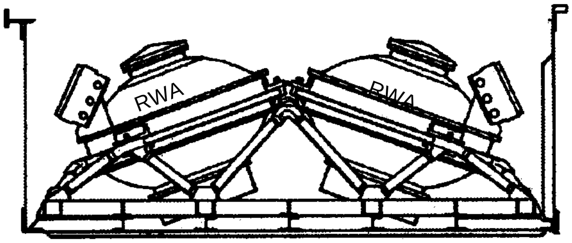


Fig. 5-14 Reaction Wheel Assembly

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 possible pointing the Telescope to 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.

5.1.5 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 are extended and 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. The Telescope 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 a solar cell blanket that converts solar energy into electrical energy. Electricity produced by the solar cells charges the Telescope batteries.

Each array wing has associated electronics. These consist of a Solar Array Drive Electronics (SADE) unit, which transmits positioning commands to the wing assembly; a Deployment Control Electronics Unit, which controls the drive motors extending and retracting the wings; and 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 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 batteries reside in SSM Equipment Section Bays 2 and 3. These units have extensive safety and handling provisions to protect the Shuttle and its astronauts. The design and operation of these batteries, along with special nondestructive inspection of each cell, have allowed these units to be "astronaut rated" for replacement during a servicing mission.

Each battery consists of 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 by 36 by 10 in. (90 x 90 x 25 cm) and weighing about 475 lb

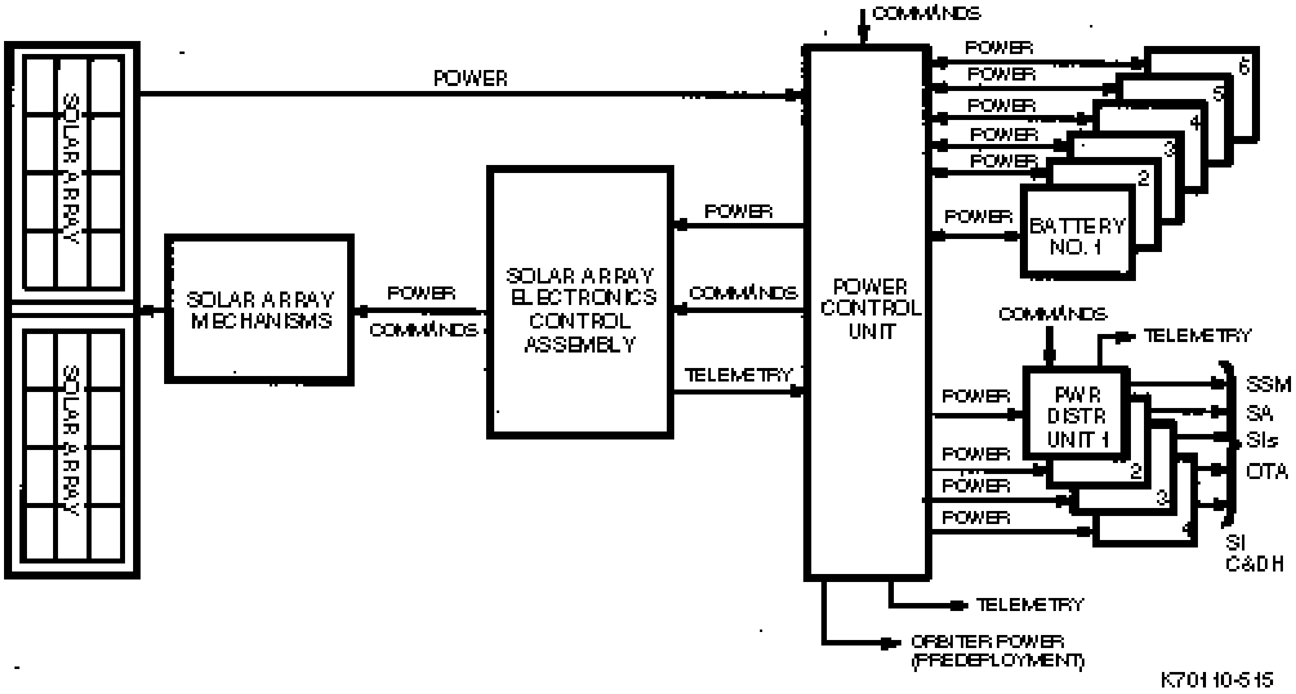


Fig. 5-15 Electrical Power Subsystem functional block diagram

(214 kg). Each module is equipped with two large yellow handles that astronauts use to maneuver the module in and out of the Telescope in space.

The SAs recharge the batteries every orbit following eclipse (the time in the Earth's shadow). The recharge current is controlled by the CCCs. 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 enough 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 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 lb (55 kg) and measures 43 x 12 x 8 in. (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 in. (25 x 12.5 x 45 cm) and weighs 25 lb (11 kg).

5.1.6 Thermal Control

Multilayer insulation (MLI) covers 80 percent of the Telescope's exterior, and supplemental electric heaters maintain its temperatures within safe limits. The insulation blankets are 15 layers of aluminized Kapton, with an outer layer of aluminized Teflon flexible optical solar reflector (FOSR). Aluminized or silverized flexible reflector tape covers most of the remaining exterior. These coverings protect against the cold of space and reflect solar heat. In addition, reflective or absorptive paints are used.

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
- Silverized FOSR tape on the aft shroud and aft bulkhead exteriors
- Radiation shields 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.

5.1.7 Safing (Contingency) System

Overlapping or redundant Telescope equipment safeguards against any breakdown. Nonetheless, a contingency or Safing System exists for emergency operations. It uses many pointing control and data management components as well as dedicated PSEA hardware. 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 is relegated to monitor automatically Telescope onboard functions. The system sends DF-224-generated "keep-alive" signals that indicate all Telescope systems are functioning to the PSEA. Entry into the Safemode is autonomous once a failure is detected.

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 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 any science operations or normal functions can be resumed.

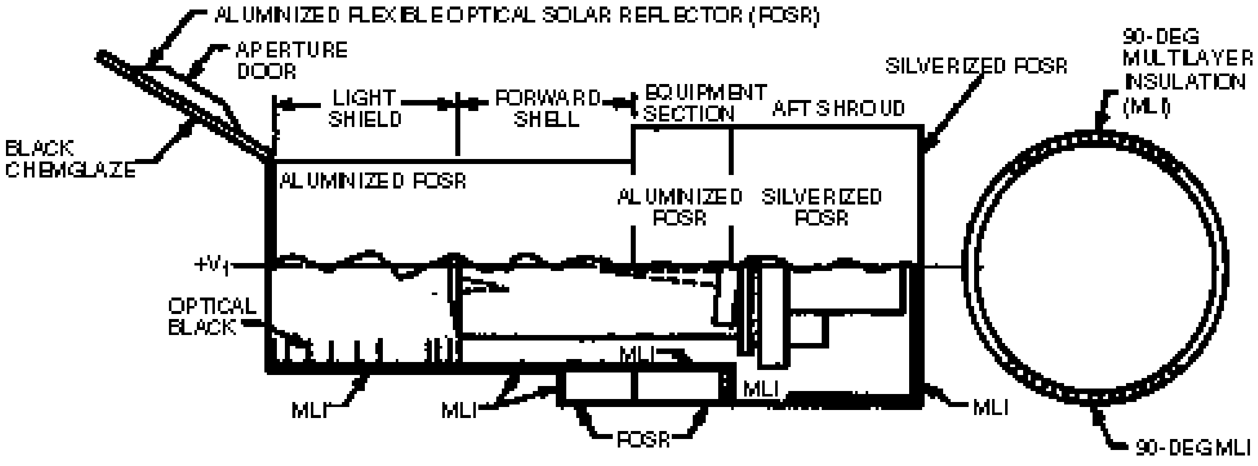


Fig. 5-16 Placement of thermal protection on Support Systems Module

Since deployment of the Telescope in April 1990, the Safing System has seen additional improvements to increase its robustness to survive hardware failures and still protect the Telescope. These additional system features are described in para 5.1.4.

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 any of the following:

- Computer malfunction
- Batteries losing more than 50 percent of their charge
- Two of the three RGAs failing
- DMS failing.

If these conditions occur, the DF-224 stops sending keep-alive signals. This is the "handshake" mechanism between the flight software and the PSEA.

In the Hardware Sun Point Mode, the PSEA computer commands the Telescope and turns off selected equipment to conserve power. Components shut down include the DF-224 computer and, within two hours, the SI C&DH. Before this, 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 upon 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 failure analysis 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. 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) and is installed in the Equipment Section Bay 8. A backup gyroscope package, the RMGA, is dedicated for the PSEA and is also located in Bay 8. The RMGA consists of three gyroscopes. These are lower quality rate sensors than the RGAs because they are not intended for use during observations.

5.2 Optical Telescope Assembly

The OTA was designed and built by the Perkin-Elmer Corporation (now Hughes Danbury Optical Systems). 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 ft (57.6 m) to be packaged into a small telescope length of 21 ft (6.4 m). (Several smaller mirrors in the science instruments are designed similarly to lengthen the light path within the particular science instrument.) This form of telescope is called a Cassegrain, and 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 Telescope 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.

The OTA is a variant of the Cassegrain, called a Ritchey-Chretien, in which both the mirrors are hyperboloidal in shape (having a deeper curvature than a parabolic mirror). This form is completely corrected for coma (an image observation having 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. For example, in the Faint Object Camera (FOC) there is a small telescope designed to remove image astigmatism.

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-in. (2.4-m) primary mirror. Reflecting off the front surface of the concave mirror, the light bounces back up the tube to the 12-in. (0.3-m)-diameter convex secondary mirror. The light is now reflected and converged through a 23.5-in. (60-cm) hole in the primary mirror to the Telescope focus, 3.3 ft (1.5 m) behind the primary mirror.

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

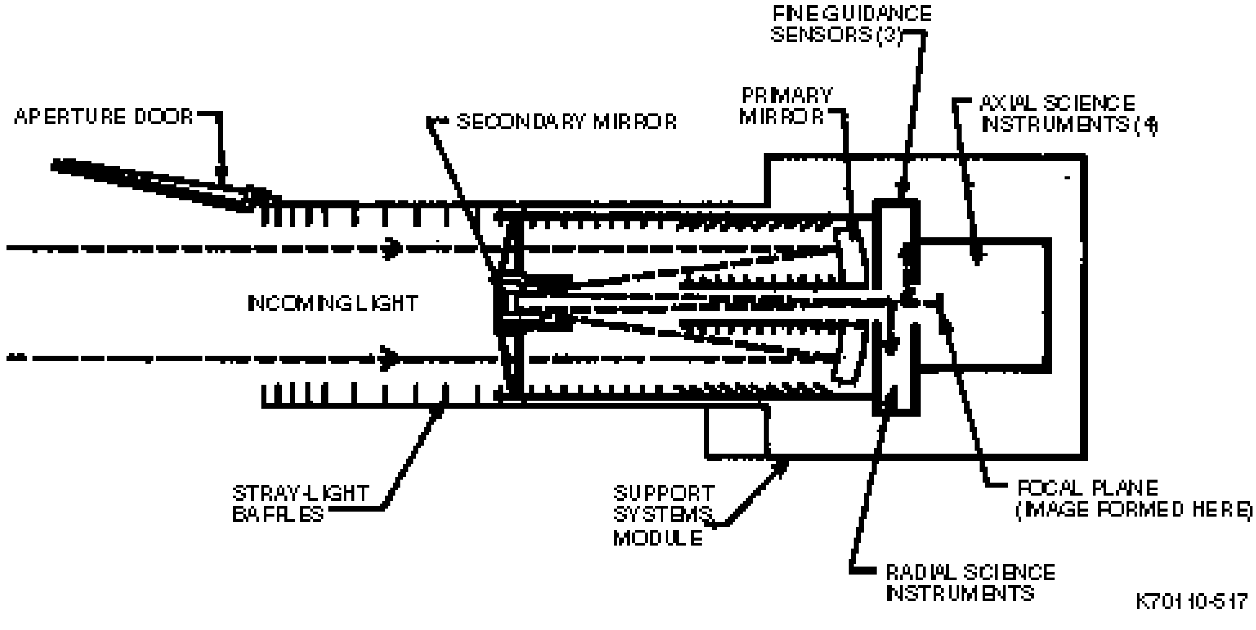


Fig. 5-17 Light path for the main Telescope

light into the WF/PC. 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.

5.2.1 Primary Mirror Assembly and Spherical Aberration

As the Telescope was 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 intensive investigation, the problem was traced to faulty test equipment used to define and measure mirror curvature. The optical component of this test equipment was slightly out of focus and, as a result, had shown the mirror to be ground correctly. After this discovery, Ball Aerospace scientists and engineers built the Corrective Optics Space Telescope Axial Replacement (COSTAR). The COSTAR was installed during the First Servicing Mission in December 1993 and brought the Telescope back to its original specifications.

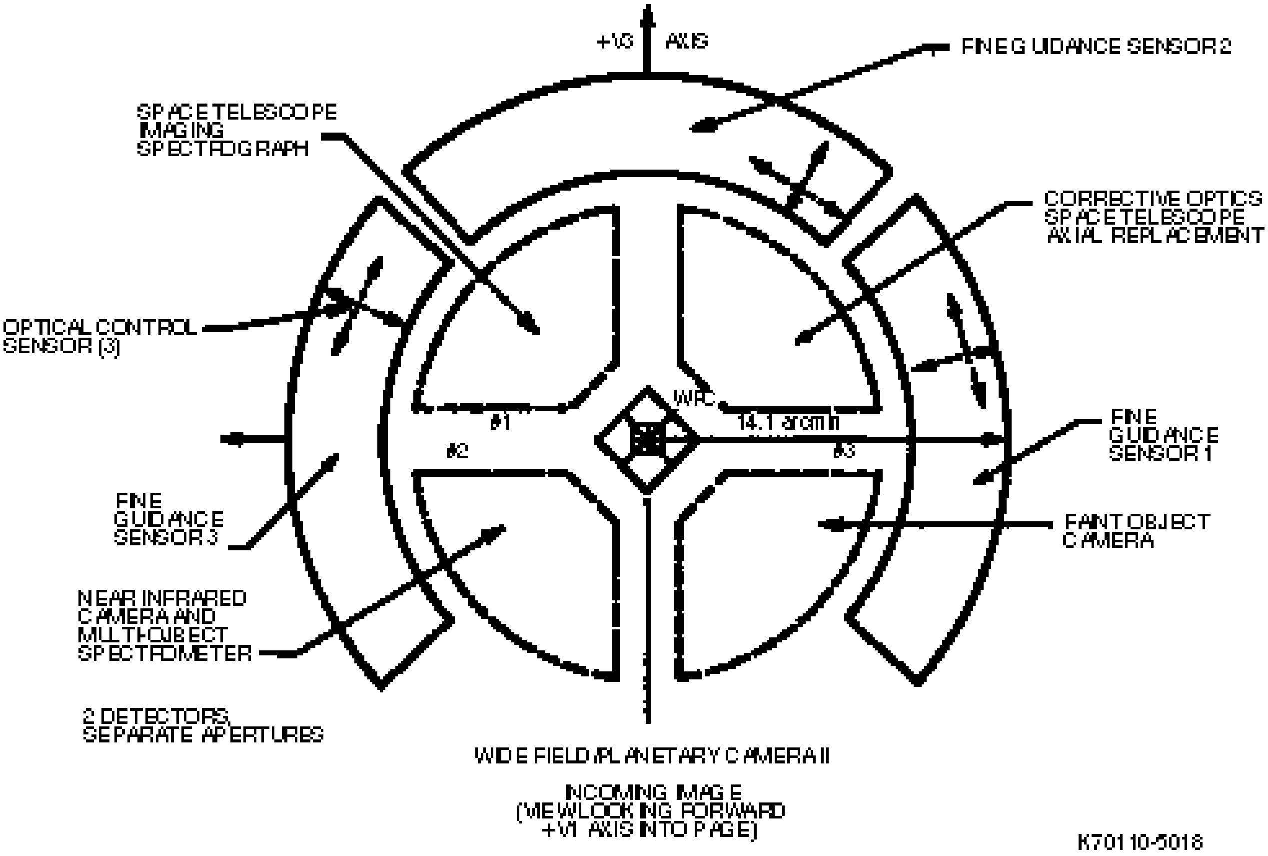


Fig. 5-18 Instrument/sensor field of view

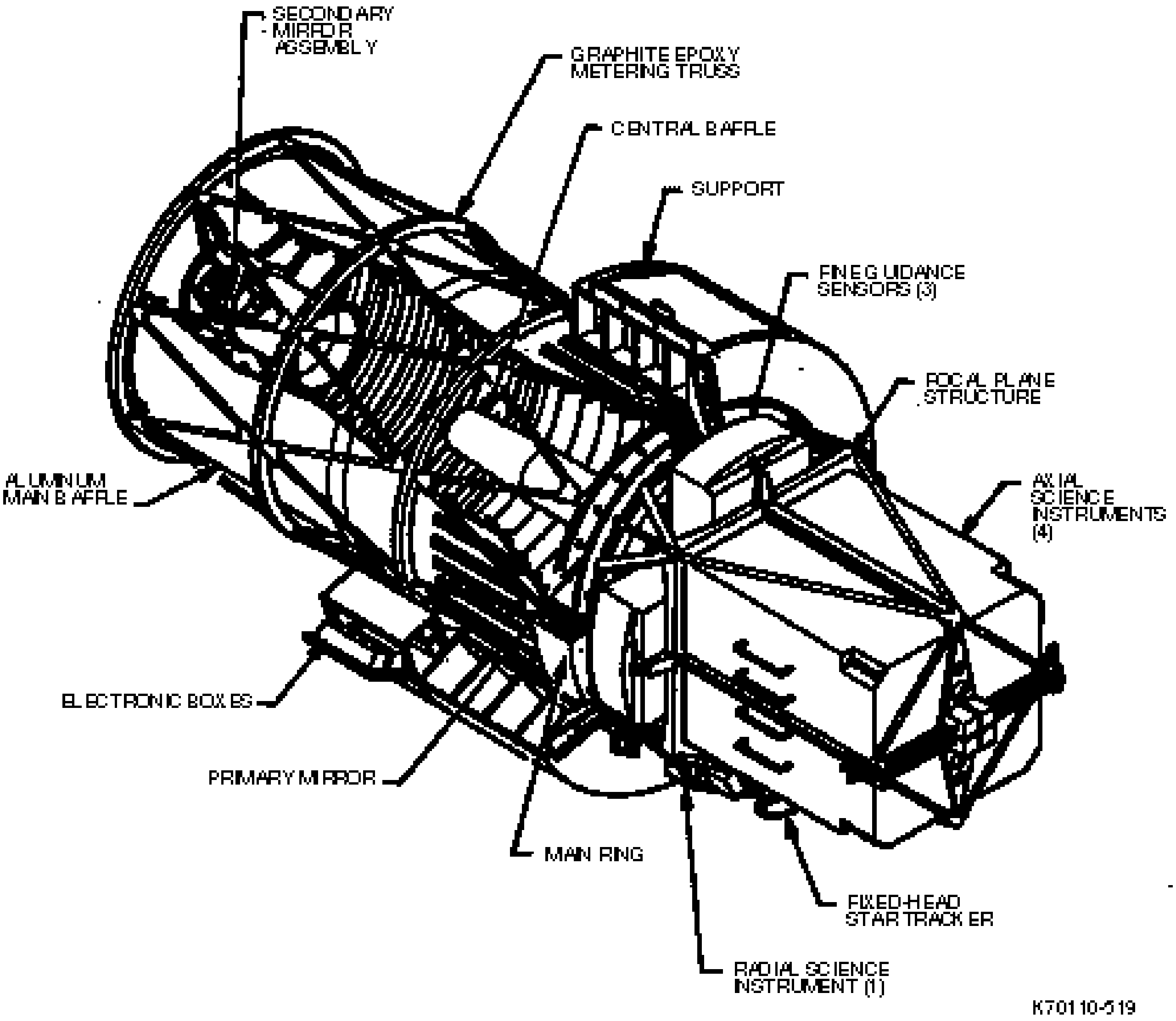


Fig. 5-19 Optical Telescope Assembly components

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 shown in 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.

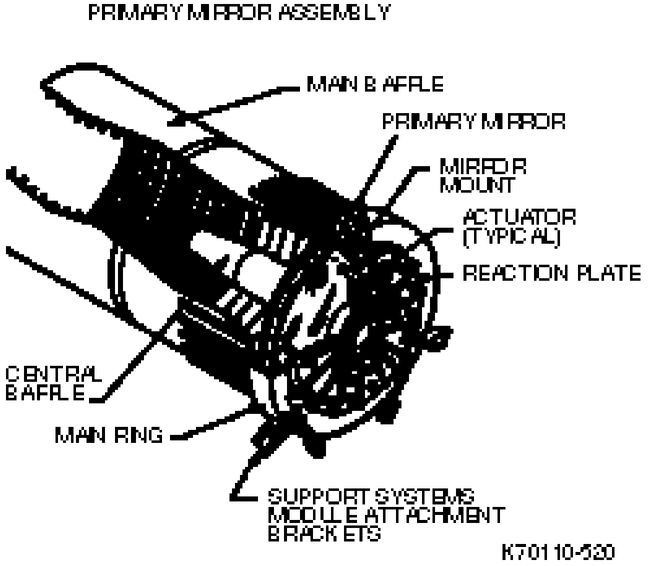


Fig. 5-20 Primary mirror assembly

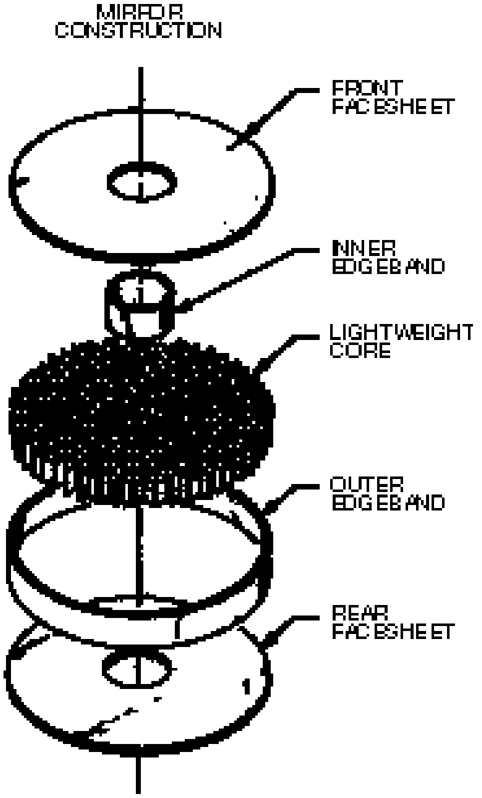
Primary Mirror. The primary mirror blank is a product of Corning Glass Works known as ultralow-expansion (ULE) glass. It was chosen for its very low-expansion coefficient, which ensures the Telescope minimum sensitivity to temperature changes. The mirror is of a "sandwich" construction: two lightweight 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-lb (818-kg) mirror instead of an 8000-lb solid-glass mirror.

The mirror blank, 8 ft (2.4 m) in diameter, was ground to shape by Perkin-Elmer (now Hughes Danbury Optical Systems) in its large optics fabrication facility. When it was close to its final hyperboloidal shape, the mirror was transferred to Perkin-Elmer's computer-controlled polishing facility.

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. The titanium ring is a hollow box beam 15 in. (38 cm) thick, weighing 1200 lb (545.5 kg), with an outside diameter of 9.8 ft (2.9 m) (see Fig. 5-22). It is suspended inside the SSM by a kinematic support.



THE MIRROR IS MADE OF CORNING CODE 7971
ULTRA-LOW EXPANSION (ULE) SILICA GLASS

Fig. 5-21 Primary mirror construction

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

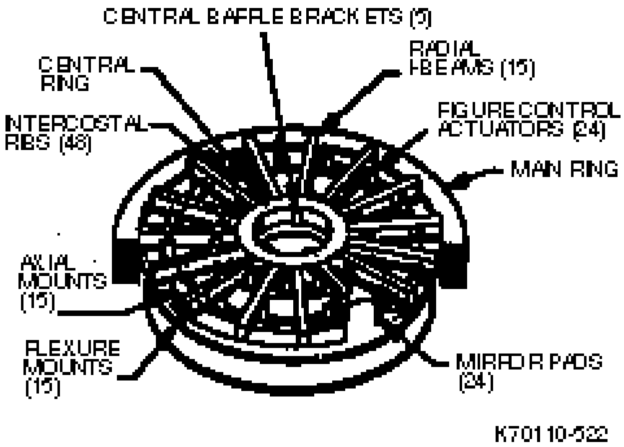


Fig. 5-22 Main ring and reaction plate

Baffles. The baffles of the OTA 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 of the three assembly baffles.

Attached to the front face of the main ring, the outer, main baffle is an aluminum cylinder 9 ft (2.7 m) in diameter and 15.7 ft (4.8 m) long. Internal fins help it attenuate stray light. The central baffle is 10 ft (3 m) long, conical in shape, 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.

5.2.2 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 in. 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, converting the primary-mirror converging rays from f/2.35 to a focal ratio system prime focus of f/24 and sending 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 in. (0.3 m) in diameter and made of Zerodur glass coated with aluminum and magnesium fluoride. Steeply convex, its surface accuracy is even greater than that of the primary mirror.

Ground command adjusts the actuators to align the secondary mirror to provide perfect image quality. The adjustments are calculated from data picked up by the optical control system's tiny 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 ft (4.8 m)

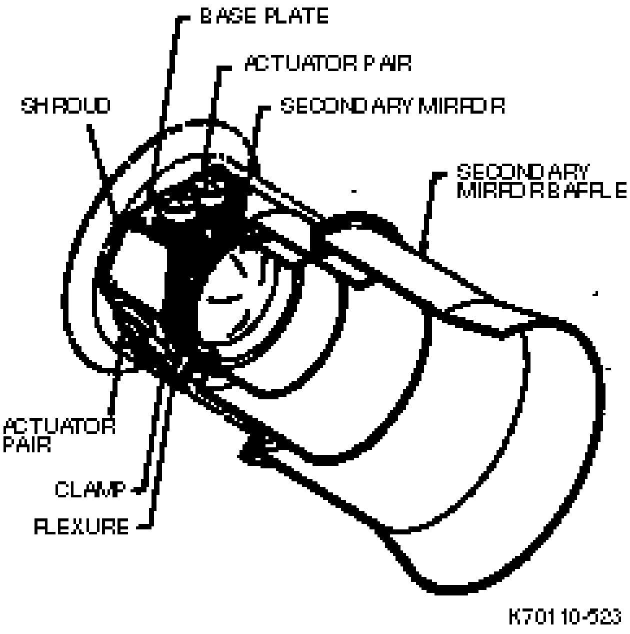


Fig. 5-23 Secondary mirror assembly

long and 9 ft (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 in. (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 the stray bright-object light from sources outside the Telescope FOV.

5.2.3 Focal Plane Structure Assembly

The FPS is a large optical bench that aligns the image focal plane of the Telescope with the science instruments and FGSs and physically supports the science instruments and FGSs. 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 ft^2 (2.1 m) by 10 ft (3.04 m) long and weighs more than 1200 lb (545.5 kg). It is made of graphite-epoxy, augmented with mechanical fasteners and metallic joints at strength-critical locations, because it must have extreme thermal stability and be stiff, lightweight, and strong. The FPS has metallic mounts and supports for Orbital Replacement Units (ORU) used during maintenance.

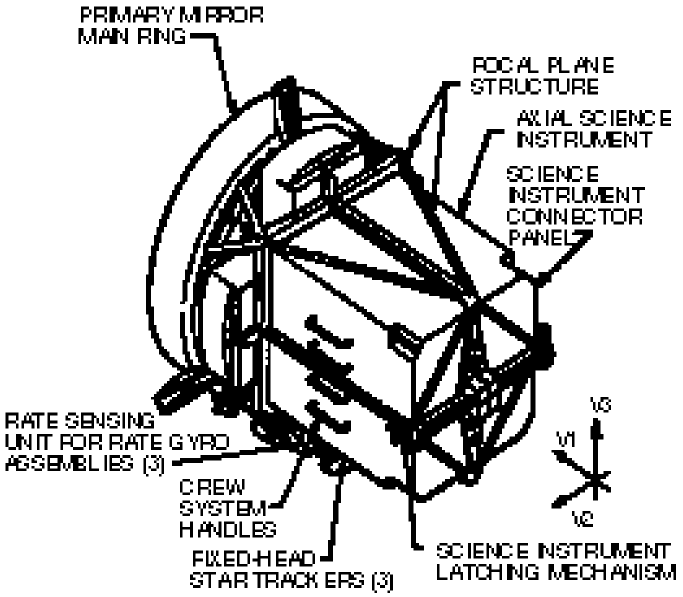


Fig. 5-24 Focal plane structure

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.

5.2.4 OTA Equipment Section

The Equipment Section for the OTA 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.

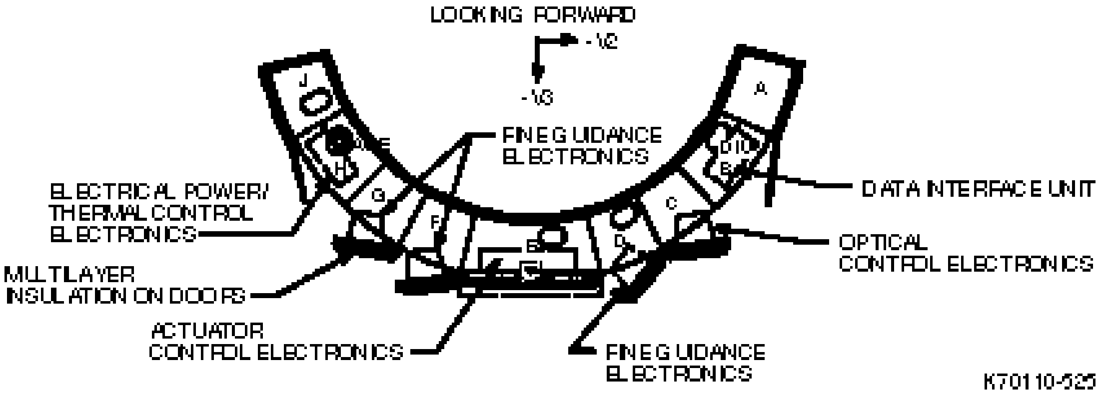


Fig. 5-25 Optical Telescope Assembly Equipment Section

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.

The three FGE units provide power, commands, and telemetry to each FGS. The electronics perform computations for the sensor and interface with the spacecraft pointing system for effective Telescope line-of-sight pointing 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 all control sensors are run by the OCE Unit.

The DIU is an electronic interface between the other OTA electronics units and the Telescope command and telemetry system.

5.3 Fine Guidance Sensor

The 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 is 5.4 ft (1.5 m) long and 3.3 ft (1 m) wide and weighs 485 lb (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.

5.3.1 Fine Guidance Sensor 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, as shown in Fig. 5-26. The entire mechanism adjusts to move the Telescope into precise alignment with a target star. Each FGS has a large (60 arcmin) FOV to search for and track stars and a 5.0 arcsec^2 FOV used by the detector prisms to pinpoint the star.

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. First, 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. The guide stars, once designated and located, keep the image of the observation target in the aperture of the selected science instrument.

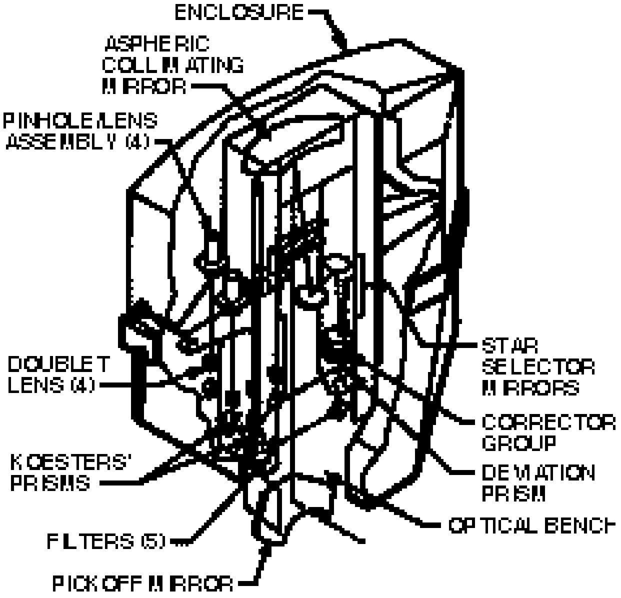


Fig. 5-26 Cutaway view of Fine Guidance Sensor

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, so the FGS will look anywhere in that field to find it. 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.

The FGS can move its line of sight anywhere within its large FOV using a pair of star selector servos. Each can be thought of as an optical gimbal: One servo moves in a north-south direction, the other east and west. They steer the small FOV (5 arcsec) 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 spiraling 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

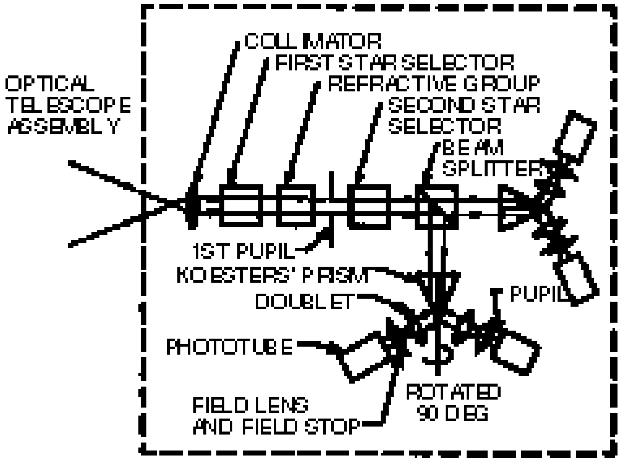


Fig. 5-27 Optical path of Fine Guidance Sensor

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 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.

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.

5.3.2 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 performance of the FGS with this innovative design improvement.

5.4 Solar Array and Jitter Problems

From the beginning, in the late 1970s, the SAs – designed by the European Space Agency and built by British Aerospace, Space Systems – have been scheduled for replacement because of their power loss from radiation exposure in space. However, as engineers put the Telescope through its paces in April 1990, they 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, cause the panels to distort twice during each orbit. As a temporary fix, engineers created software that commanded the PCS to compensate for the jitter automatically. The problem was remedied during the First Servicing Mission by the replacement of the old arrays with new ones that had been modified to alleviate the jitter problem.

5.4.1 Configuration

The SAs 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. For the replacement SAs delivered to the Telescope during the First

Servicing Mission, the spring-loaded roller assembly was replaced by a series of springs connecting the spreader bar to the blanket. This change eliminated the jitter induced into the Telescope as it passed from eclipse (night) into sunlight (day) each orbit.

The wings are on arms that connect to a drive assembly on the SSM forward shell at one end and to the secondary deployment mechanism (blankets and bistems) on the other end. The total length of the cassette, arm, and drive is 15.7ft (4.8 m) (see Fig. 5-28).

Each wing has 10 panels that roll out from the cassette. The panels are made of 2438 solar cells attached to a glass fiber/Kapton surface, with silver mesh wiring underneath, covered by another layer of Kapton. The blankets are less than 500 micrometers thick, so they roll up tightly when the wings are stowed. Each wing weighs 17 lb (7.7 kg) and, at full extension, is 40 ft (12.1m) long and 8.2 ft (2.5 m) wide.

5.4.2 Solar Array Subsystems

The SA subsystems include the primary and secondary deployment mechanisms, their drives, and associated electronics.

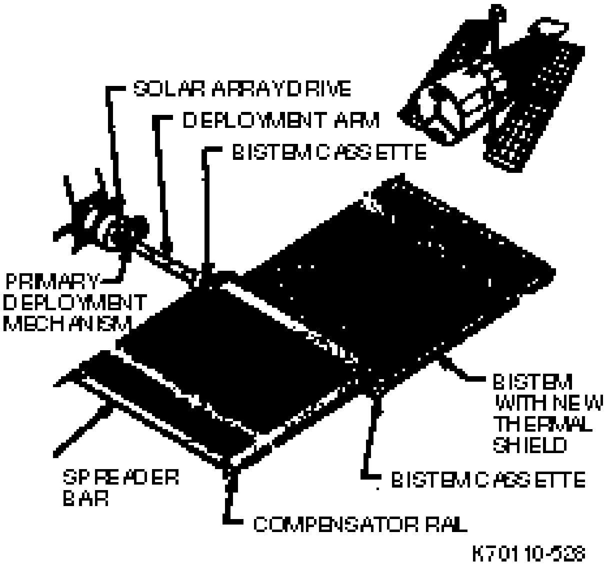


Fig. 5-28 Solar Array wing detail

The primary deployment mechanism raises the SA mast from the side of the SSM to a standing position perpendicular to the Telescope. There are two mechanisms, one for each wing. Each mechanism has motors to raise the mast and supports to hold it in place when erect.

An astronaut can raise the array mast manually if the drive power fails. Using a wrench fitting on the deployment drive, the astronaut hand-cranks the mast after releasing the latches.

Once the SA is raised, the secondary deployment mechanism unfurls the wing blankets. Each wing has a secondary mechanism assembly: a cassette drum to hold solar panels, a cushion to protect the blanket, and motors and subassemblies. The assembly rolls out the blanket, applies tension evenly so the blankets stretch, and transfers data and power along the wing assembly. The blanket can roll out completely or part way. The secondary deployment mechanism also has a manual override (see Fig. 5-29).

A SA drive at the base of each mast rotates the deployed array toward the sun, turning in either direction. Each drive has a motor that rotates the mast on command and a brake to keep the array in a fixed position with respect to the Telescope. The drive can move and lock the SA into any position.

Each drive has a clamp ring that acts as a release mechanism if opened. This allows a crew member to jettison the entire SA if necessary.

Two electronics assemblies (boxes) – the Solar Array Deployment Electronics and the Solar Array Drive Electronics – control and monitor all functions of each SA. They provide the electronic interface to the other Telescope systems and generate the commands for the primary and secondary deployment mechanisms and the SA drive.

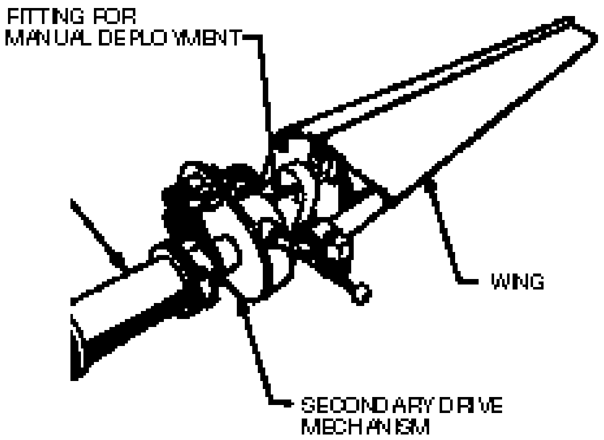


Fig. 5-29 Fitting for Solar Array manual deployment

5.4.3 Solar Array Configuration for Second Servicing Mission

The Solar Array wings will remain deployed during servicing. This will allow the Telescope's batteries to remain fully charged during the mission and will not impact servicing activities.

5.5 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 tape recorders, or transmit all science and engineering data created by the instruments to the ground. Fairchild Camera and Instrument Corporation and IBM built this unit.

5.5.1 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. 5-30). 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 the NASA Standard Spacecraft Computer (NSCC-I), two standard interface circuit boards for the computer, two control units/science data formatter units, two CPU modules, a PCU, two RIUs, and various memory, data, and command communications lines (buses) connected by couplers. The SI C&DH 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 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.

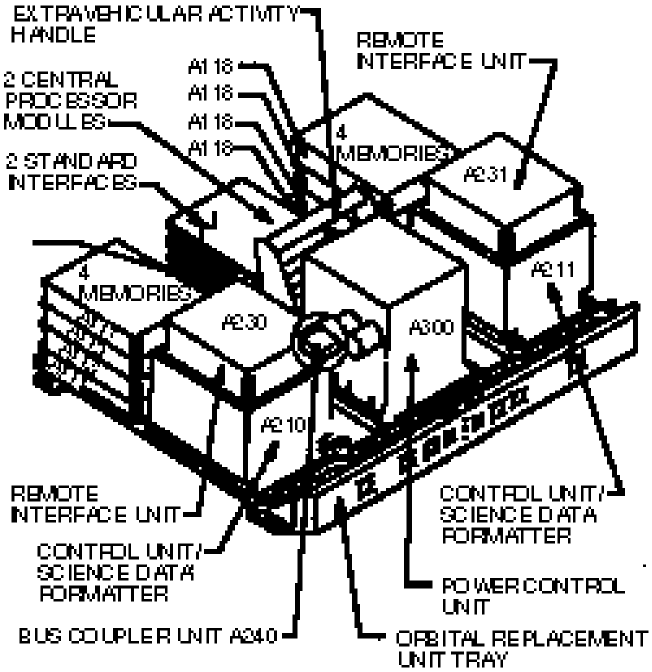


Fig. 5-30 Science Instrument Control and Data Handling unit

Standard Interface Unit. The standard interface 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," or communications codes. The CU/SDF transmits commands and requests after formatting them so that the specific destination unit can read. 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; the CU/SDF, on the other hand, requires +28 volts. The PCU ensures that all voltage requirements are met.

Remote Interface Units. RIUs transmit commands, clock and other system signals, and engineering data between the science instruments and the SI C&DH unit. 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 should fail. The SI C&DH coupler unit is on the ORU tray.

5.5.2 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 (see para 2.1.7) – a suspension of science operations.

Command Processing. Figure 5-31 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"

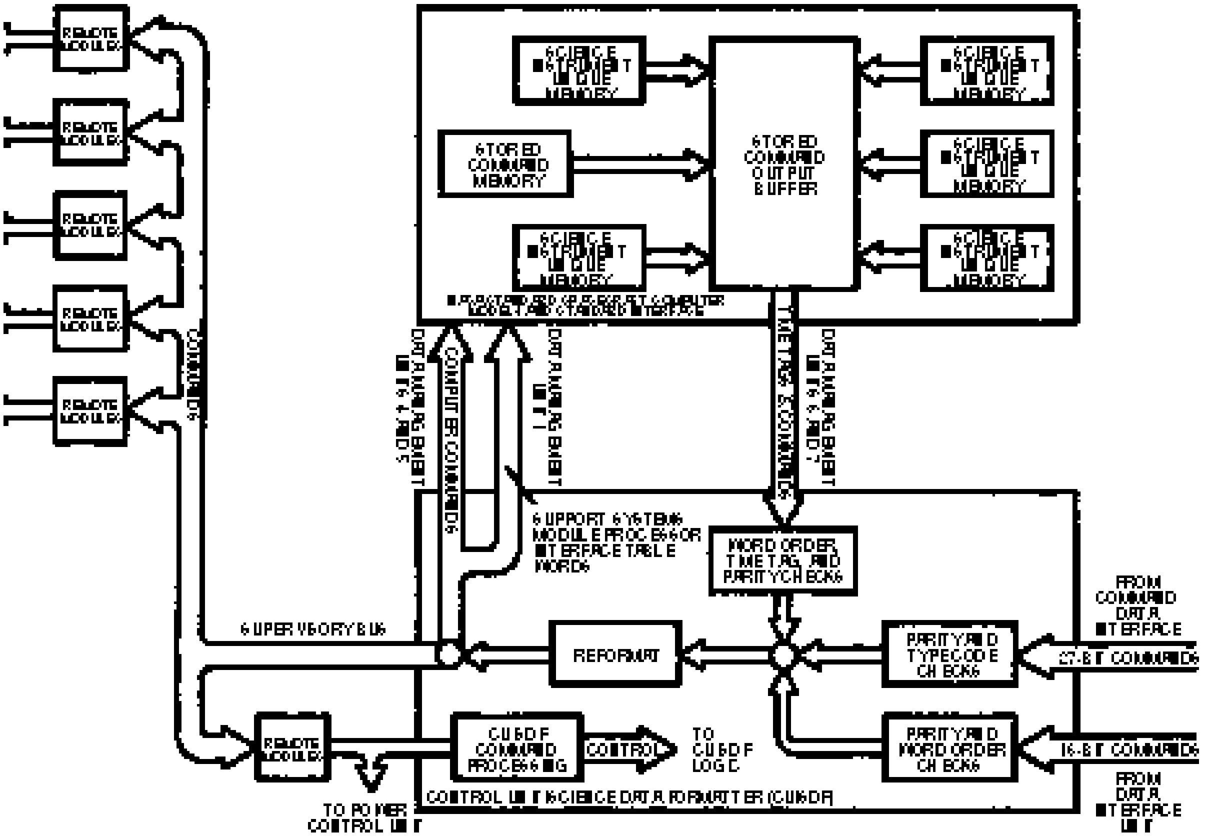


Fig. 5-31 Command flow for Science Instrument Control and Data Handling unit

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 tape 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 pseudorandom noise) can be added to the data as options. Figure 5-32 shows the flow of science data in the Telescope.

5.6 Space Support Equipment

The Hubble Space Telescope 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, and the crew will perform

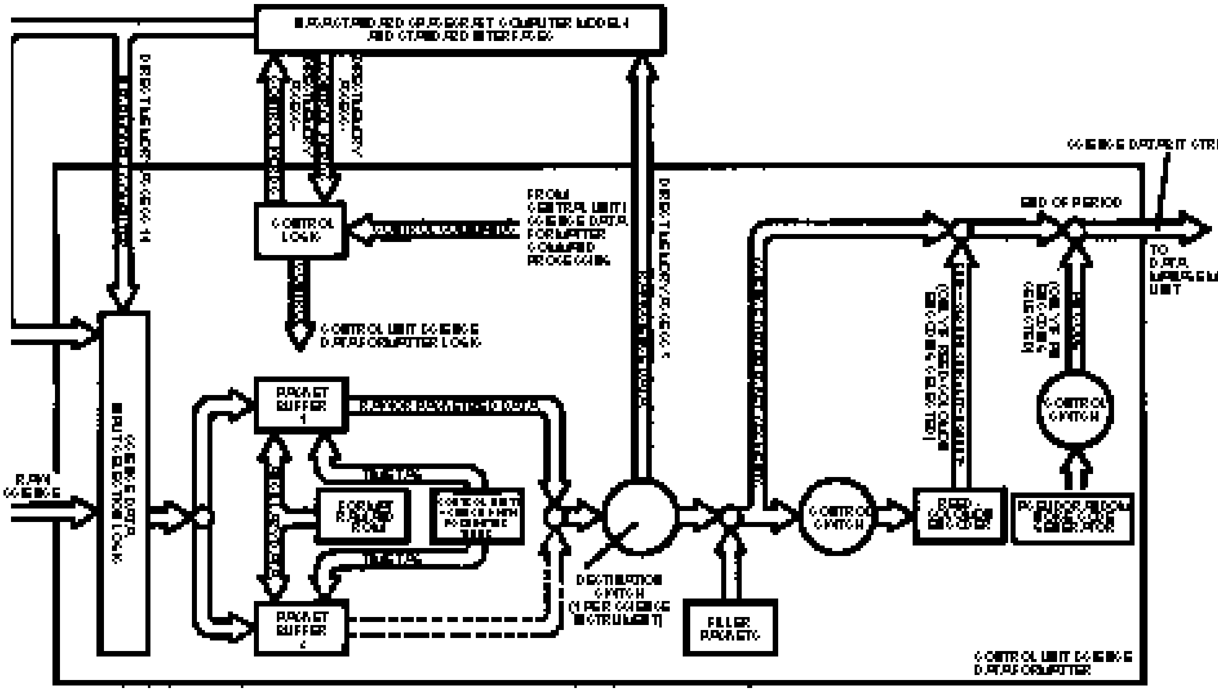


Fig. 5-32 Flow of science data in the Hubble Space Telescope

maintenance and replacement tasks. The Space Support Equipment (SSE) to be used during the mission provides a maintenance platform to hold the Telescope, provides electrical support of the Telescope during servicing, and provides storage for replacement components known as ORUs.

The major SSE items used for the Second Servicing Mission are the Flight Support System (FSS), the ORU Carrier (ORUC), and the Second Axial Carrier (SAC). Additionally, crew aids and tools will be used during servicing.

5.6.1 Flight Support System

The FSS provides the platform that holds the Telescope during servicing (see Fig. 5-33). The FSS has been used in different configurations for the HST First Servicing Mission, the Solar Maximum Repair Mission, and the Upper Atmospheric Research Satellite Deploy Mission. The FSS consists of two major components: a horseshoe-shaped cradle and a supporting latch beam providing a structural and electrical interface with the Shuttle. A circular ring called the Berthing and Positioning System (BAPS) interfaces with the Telescope, allowing it to pivot or rotate during the mission.

The BAPS ring is pivoted down locked for liftoff. During the mission, the ring is pivoted up to a horizontal position. A closed-circuit television camera mounted to the FSS helps astronauts guide the Telescope onto the ring. Three remote-controlled latches on the ring grab and hold three towel-rack-like pins on the rear of the Telescope. A remote-controlled electrical umbilical connector on the FSS engages the Telescope, providing it with orbiter power through the FSS. This power helps relieve the drain on the Telescope's batteries during the mission. Radio communications provide telescope telemetry data and control.

Once the Telescope is berthed to the ring (see Fig. 5-34), the FSS can pivot (tilt) or rotate the Telescope. This positions the appropriate region of the Telescope for access during extravehicular activity. Additionally, the ring can pivot the

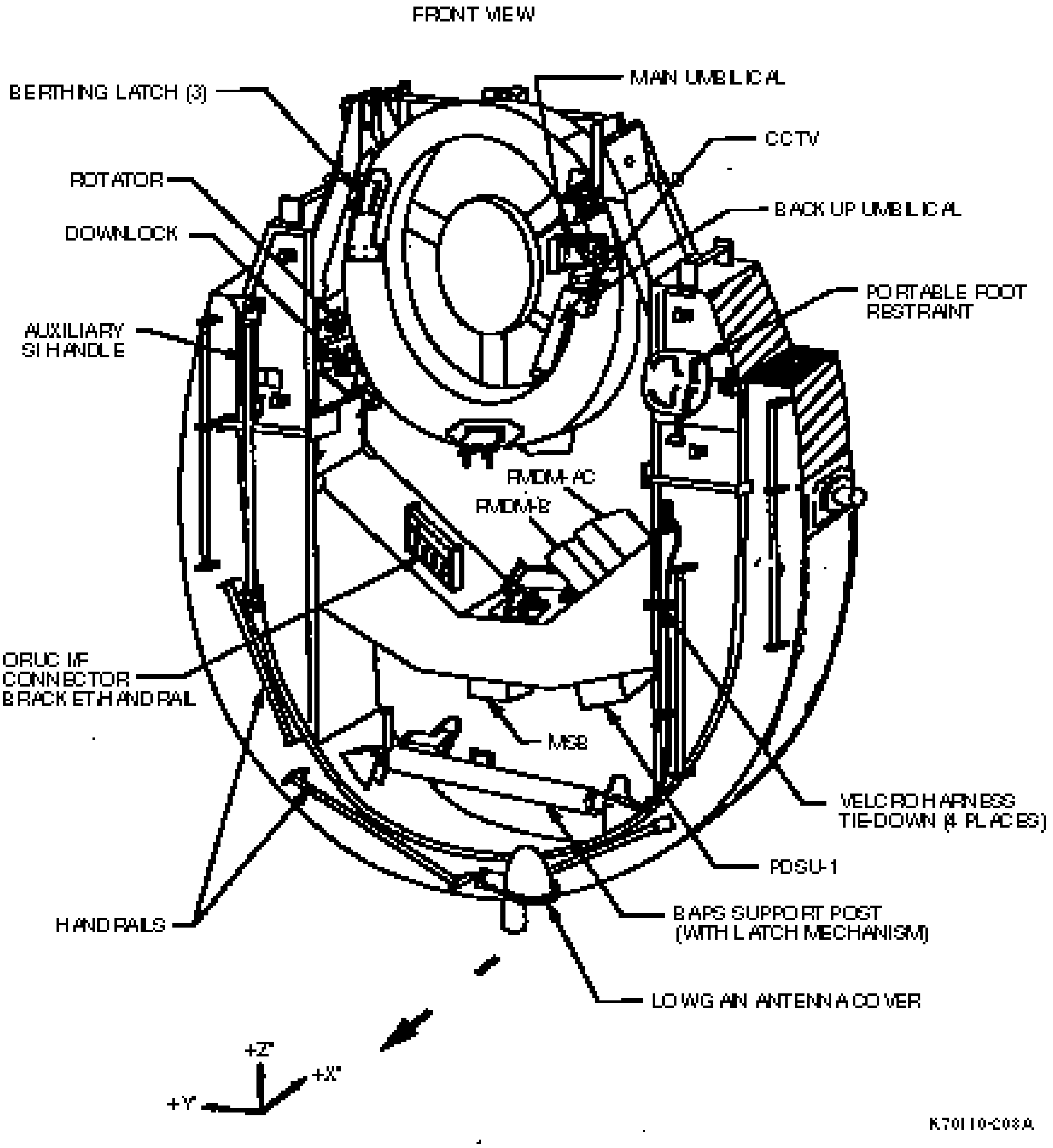


Fig. 5-33 Flight Support System configuration

Telescope to an appropriate attitude for orbiter reboost.

During the first EVA, crew members will install the BAPS Support Post (BSP). The BSP provides an additional linkage to support and isolate the Telescope during EVAs and for any orbital reboosts. The BSP will remain in position for landing.

Astronauts remotely control all FSS mechanisms – berthing latches, umbilical connector, pivoter, BSP lock, rotator, and ring down-lock –

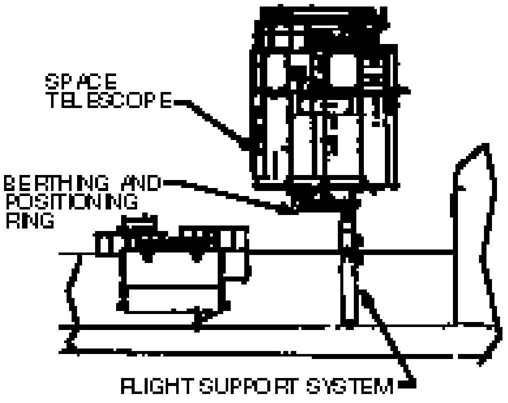


Fig. 5-34 Flight Support System Berthing and Positioning System ring pivoted up with Telescope berthed

from the orbiter's aft flight deck, providing the crew maximum flexibility. Besides being fully electrically redundant, each mechanism contains manual overrides and backups to ensure mission success and astronaut safety.

5.6.2 Orbital Replacement Unit Carrier

An ORUC is used to carry replacements into orbit and to return replaced units to Earth. The carrier consists of a Spacelab pallet outfitted with shelves and protective enclosures to hold the replacement units (see Fig. 5-35). Items on the ORUC for the Second Servicing Mission include a Reaction Wheel Assembly in the LOPE, two Solid State Recorders, one Engineering/Science Tape Recorder, one Solar Array Drive Electronics, and associated flight harnesses in the SOPE. The FGS will be transported in the FGS Scientific Instrument Protective Enclosure (FSIPE) and the Space Telescope Imaging Spectrograph (STIS) in the Axial Scientific Instrument Protective Enclosure (ASIPE). The carrier also will have various aids for the crew during liftoff and landing. 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.

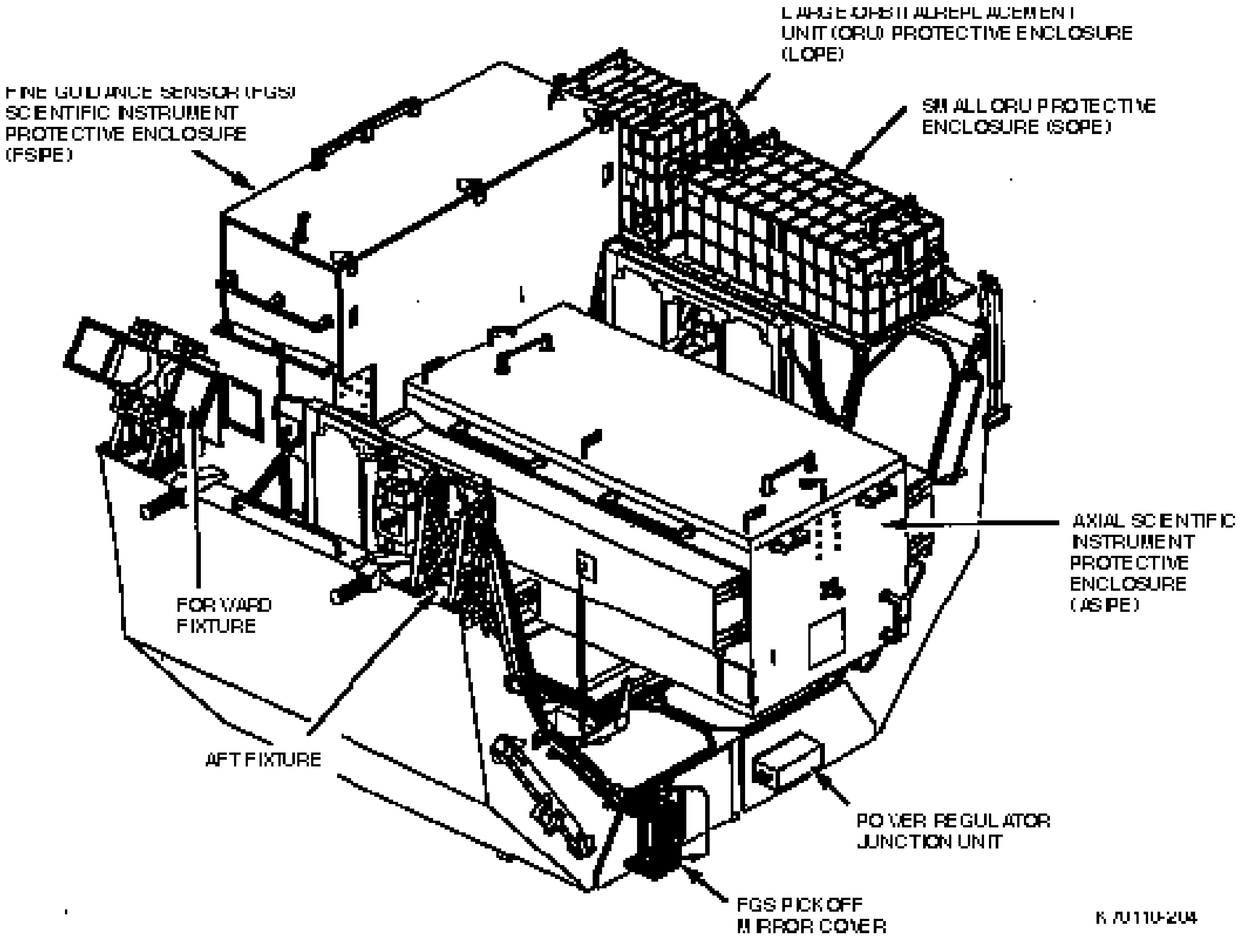


Fig. 5-35 Orbital Replacement Unit Carrier

The instruments are mounted in the enclosures using the same manually driven latch system that holds instruments in the Telescope. The ASIPE and FSIPE are mounted to the pallet on a spring system that reduces the level of vibration the instruments receive, especially during liftoff and landing.

The other ORUs are carried in two additional enclosures called the Small and Large ORU Protective Enclosures (SOPE and LOPE). These enclosures also provide contamination and thermal control, though not to such stringent requirements as the SIPE. The SOPE and LOPE contain Transport Modules that are designed to custom fit each ORU. The transport modules have foam or Visco-Elastic Material that surrounds the ORU and isolates it from launch and landing vibration environments.

During the change-out process, replaced science instruments are stored temporarily in the ORUC. A typical changeout 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.

5.6.3 Second Axial Carrier

The Second Axial Carrier (SAC) is being flown on the HST Second Servicing Mission to transport and protect the NICMOS science instrument and a complement of ORUs (see Fig. 5-36). The SAC structure is based on the Goddard Pallet Assembly.

The Goddard Pallet Assembly is a multimission shuttle payload carrier built to support Shuttle-based HST servicing activities. For the HST First Servicing Mission, the Pallet Assembly was configured as the Solar Array Carrier, with a Solar Array Support Structure designed to transport HST Solar Arrays.

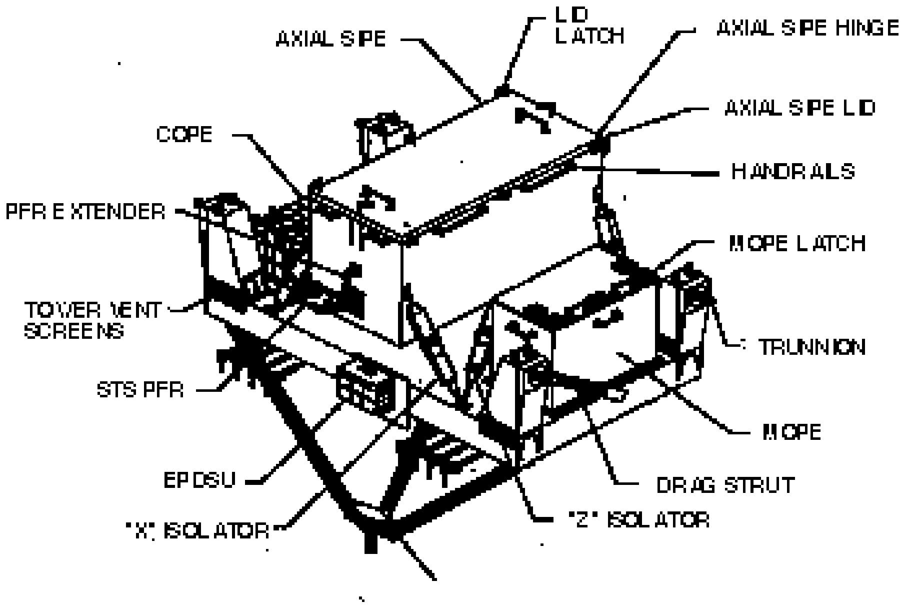


Fig. 5-36 Second Axial Carrier

For the Second Servicing Mission, the Pallet Assembly has been modified and is the base structure of the SAC. The SASS has been replaced with an Axial Scientific Protective Enclosure (ASIPE) to transport onto orbit the new HST NICMOS science instrument. The Contingency ORU Protective Enclosure (COPE) and a new ORU Protective Enclosure, called the Multimission ORU Protective Enclosure (MOPE), are used to house and thermally protect the ORUs, also mounted on the Pallet Assembly.

The SAC spans the cargo bay and structurally ties into the Shuttle at five points, four longeron and one keel trunnion. Active isolators, similar to automobile shock absorbers, reduce launch and landing vibration loads transmitted to the NICMOS. Each isolator consists of a spring and a magnetic damper. The magnetic damper converts the mechanical vibration energy from the launch event into heat energy, reducing the loading on NICMOS. The SAC incorporates eight isolators, configured in four sets of two each. Each isolator is attached to the Pallet Assembly and also to the ASIPE at its base or end plate.

The SAC ASIPE is based on the ORUC ASIPE, with design modifications to be flown as a stand-alone enclosure. Aside from the unique NICMOS/FOS latch configuration, all EVA and instrument interfaces are the same for both ASIPEs. The ASIPE is thermally controlled using a heater system designed to precondition the NICMOS prior to EVA change-out operations.

ORUs transported on the SAC for the Second Servicing Mission are two DIUs in the MOPE, and two RSUs and an ECU in the COPE. The MOPE also will carry electrical harnesses for the DIUs, spare fuse plugs and PIP pins, and crew aids and tools, including the pistol grip tool, power ratchet tool and its controller, a DIU portable handle, and the NICMOS cryo vent line. In addition to the ORUs, the COPE will house the MSS covers, an MLI repair kit, spare electrical harnesses, and a JSC-provided tool called the PFR Attachment Device.

Within the MOPE and COPE, transport modules protect the ORUs from launch and landing vibration loading. These transport modules are designed to custom fit each ORU using foam to surround the ORU. Transport modules for each ORU are integrated into the OPEs as a module unit, simplifying system integration.

The SAC receives power directly from the Orbiter through the Enhanced Power Distribution and Switching Unit (EPDSU). The EPDSU is modular avionics for Shuttle payloads designed to be readily configured for unique payload power, command and telemetry requirements. Custom applications are easily serviced using the EPDSU. An EPDSU, configured for the FSS, is also available for backup to the FSS Power Distribution and Switching Unit.

5.6.4 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 were standardized not only for the Telescope but between the Telescope and the Shuttle. For example, grappling receptacles share common features.

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

The 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), shown in Fig. 5-37.

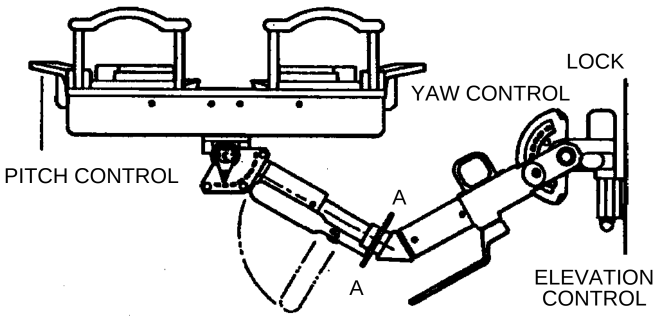


Fig. 5-37 Portable Foot Restraint

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 SA wings so the crew can push the equipment away from the Telescope.

-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
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
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
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 one degree, in the 360-degree "pie" that makes up the sky. An arcminute is 60 seconds; a degree is 60 minutes.
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
attitude	Orientation of the spacecraft's axes relative to Earth

AURA	Association of Universities for Research in Astronomy
axial science instruments	Four instruments – the FOS, FOC, GHRS, and COSTAR – located behind the primary mirror. Their long dimensions run parallel to the optical axis of the HST. The GHRS will be removed and replaced by STIS, and FOS will be removed to make way for NICMOS.

-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.
CAT	Crew Aids and Tools
CCC	Charge Current Controller
CCD	Charge-coupled device
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
COSTAR	Corrective Optics Space Telescope Axial Replacement
CPM	Central Processor Module

CPU	Central Processing Unit
CTVC	Color television camera
CU/SDF	Control Unit/Science Data Formatter
CSS	Coarse Sun Sensor

-D-

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
DOB	Deployable Optical Bench
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
E/STR	engineering/science tape 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
FOS	Faint Object Spectrograph
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-

G/E	Graphite-epoxy
GE	General Electric
GGM	Gravity Gradient Mode
GHRS	Goddard High Resolution Spectrograph
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
HRS	High Resolution Spectrograph

HSP	High Speed Photometer
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.	Inches
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

lb	Pound
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
LMMS	Lockheed Martin Missiles & Space
LOPE	Large ORU Protective Enclosure
LOS	Line of sight
LS	Light Shield
luminosity	Intensity of a star’s brightness

-M-

m	Meter
μm	Micrometer; one 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	Multilayer insulation

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
M	Absolute visual magnitude
m	Apparent visual magnitude

-N-

NASA	National Aeronautics and Space Administration
NBSF	Neutral Buoyancy Simulator Facility
NASCOM	NASA Communications Network
NCC	Network Control Center
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
nova	Star that suddenly becomes explosively bright
NSSC-I	NASA Standard Spacecraft Computer, Model-I

-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
OTA	Optical Telescope Assembly

-P-

PACOR	Packet Processing Facility
parallax	Change in the apparent relative orientations of objects when viewed from different positions
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 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

-Q-

quasar	Quasi-stellar object of unknown origin or composition

-R-

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, it 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 Sensing Unit
RWA	Reaction Wheel Assembly

-S-

SA	Solar Array
SAA	South Atlantic Anomaly
SAC	Second Axial Carrier
SAD	Solar Array Drive
SADE	Solar Array Drive Electronics
SADM	Solar Array Drive Mechanism
SAGA	Solar Array Gain Augmentation
SBA	Secondary Baffle Assembly
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
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.
SSC	Science Support Center
SSE	Space Support Equipment
SSM	Support Systems Module
SSM-ES	SSM Equipment Section
SSR	Solid State Recorder
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
UV	Ultraviolet
USA	United States Army
USAF	United States Air Force
USN	United States Navy

-V-

V	Volt
V1, V2, V3	HST axes
VCS	Vapor-cooled shield

-W-

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