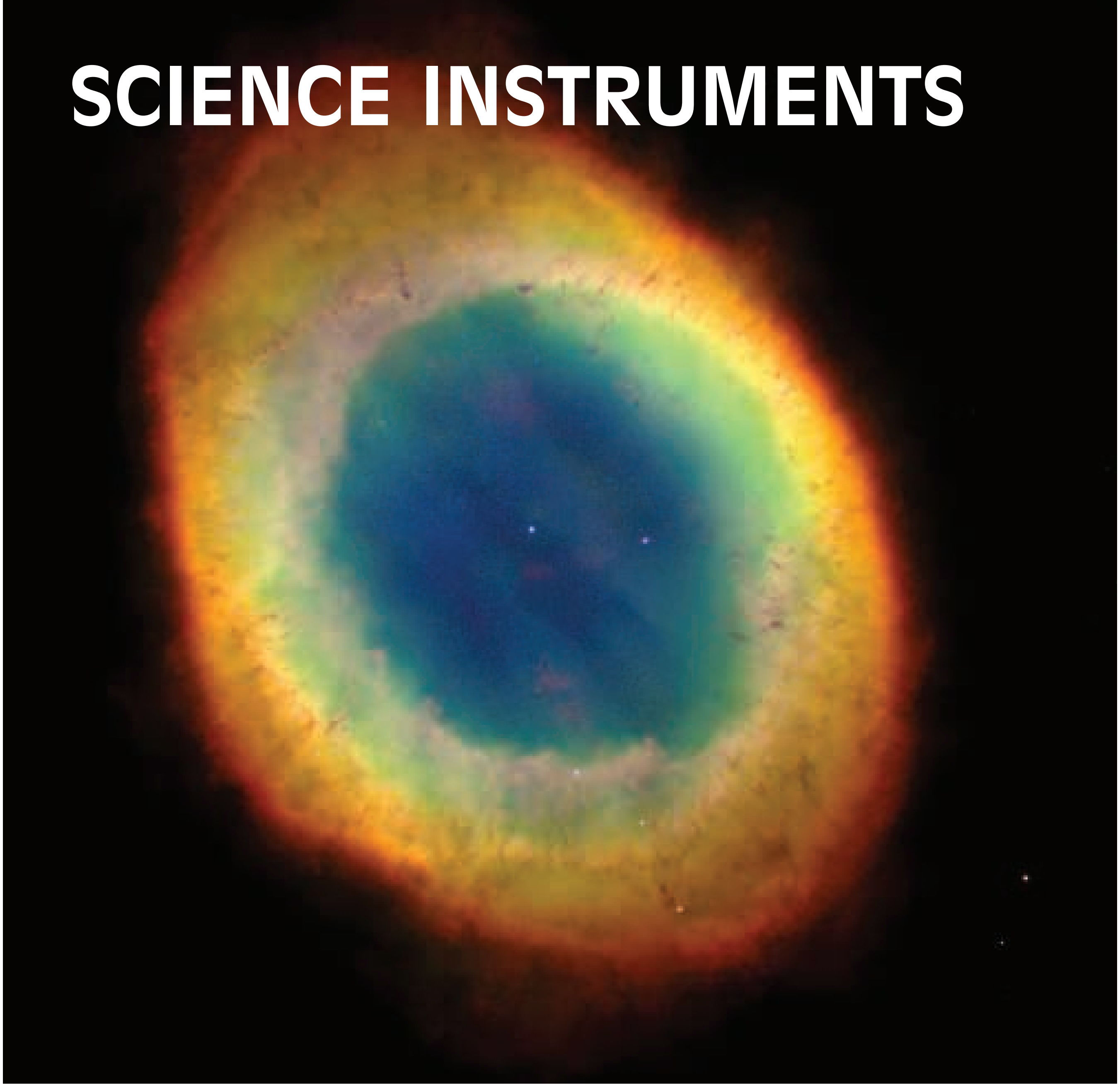
SCIENCE INSTRUMENTS



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

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

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

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

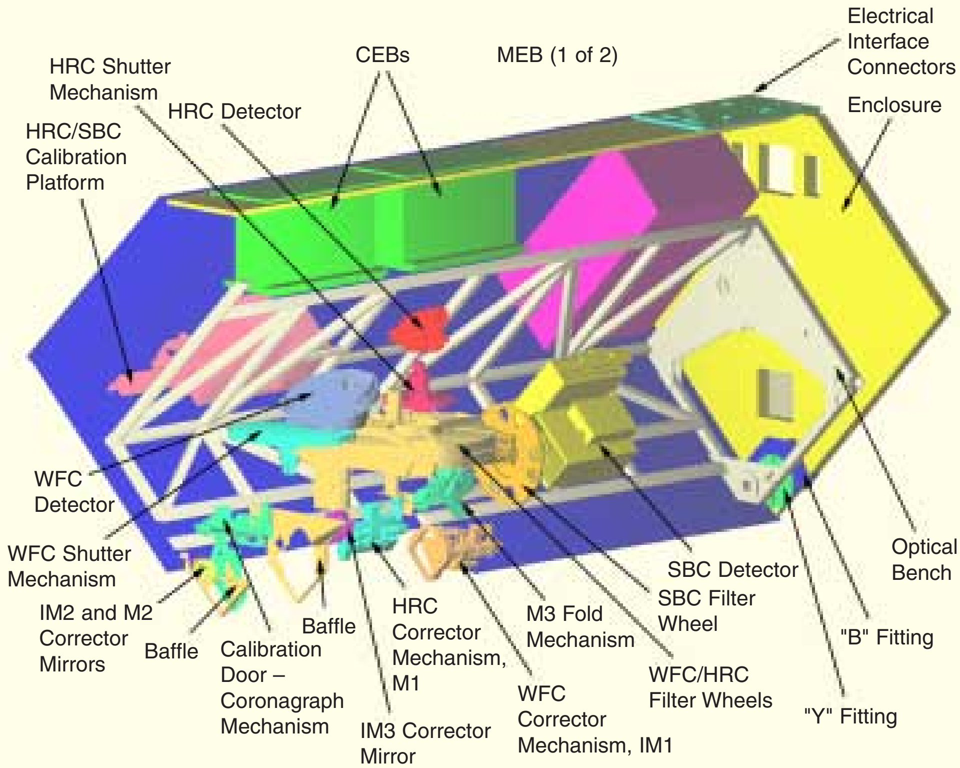
Hubble's three FGSs are undergoing a systematic program of refurbishment and upgrading. On each servicing mission, one FGS is being replaced, returned to the ground, disassembled and refurbished, then taken back to HST to become the replacement unit for the next FGS to be serviced. The final refurbished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

Advanced Camera for Surveys

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

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

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



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

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

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

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

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

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

Physical Description

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

In addition, ACS also provides:

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

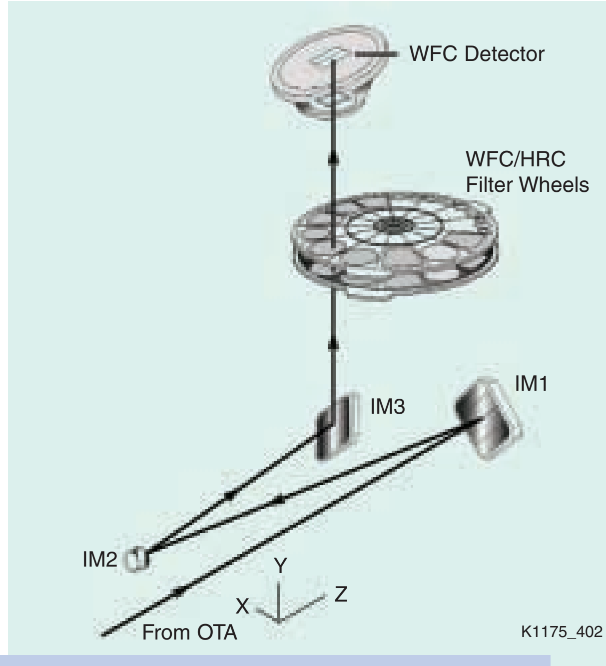

Fig. 4-2 ACS Wide Field Channel optical design

ACS Optical Design

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

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

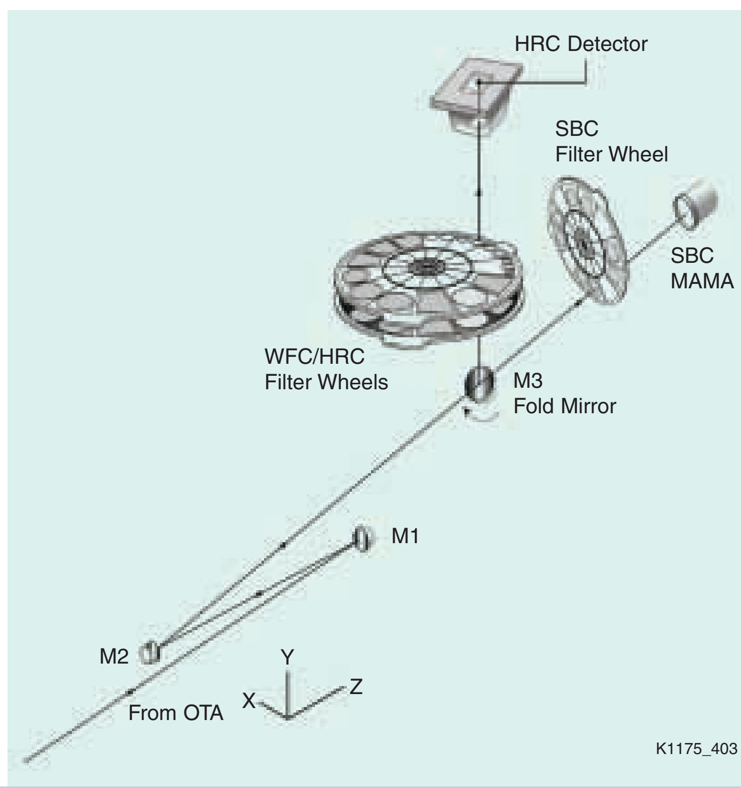

Fig. 4-3 ACS High Resolution/Solar Blind Channels optical design

Filter Wheels

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

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

*Limited field of view for filters using WFC

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Fig. 4-4 ACS CCD filters

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

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Fig. 4-5 SBC filters

Observations

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

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

Near Infrared Camera and Multi-Object Spectrometer

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

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

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

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

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

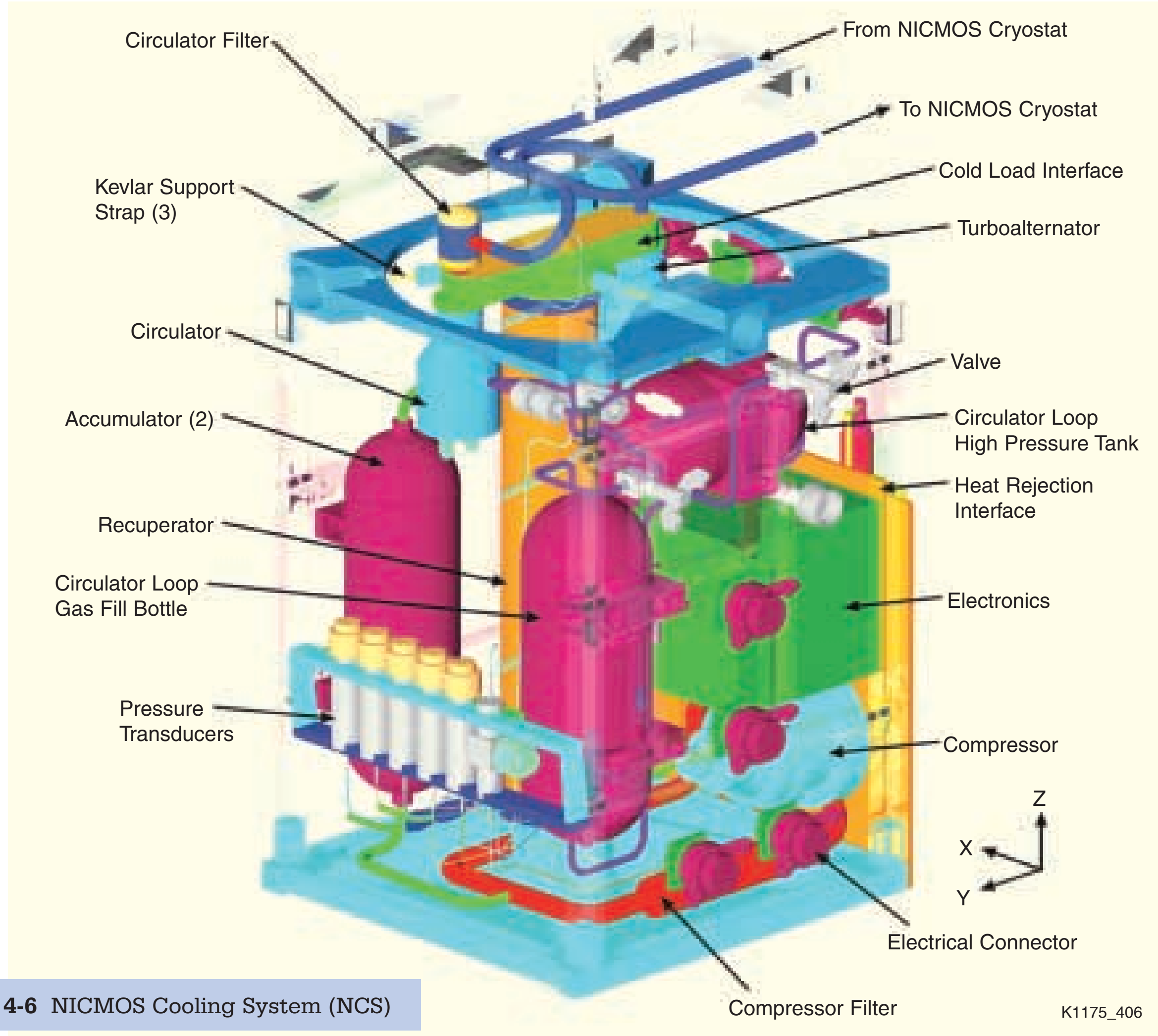

Fig. 4-6 NICMOS Cooling System (NCS)

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

Instrument Description

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

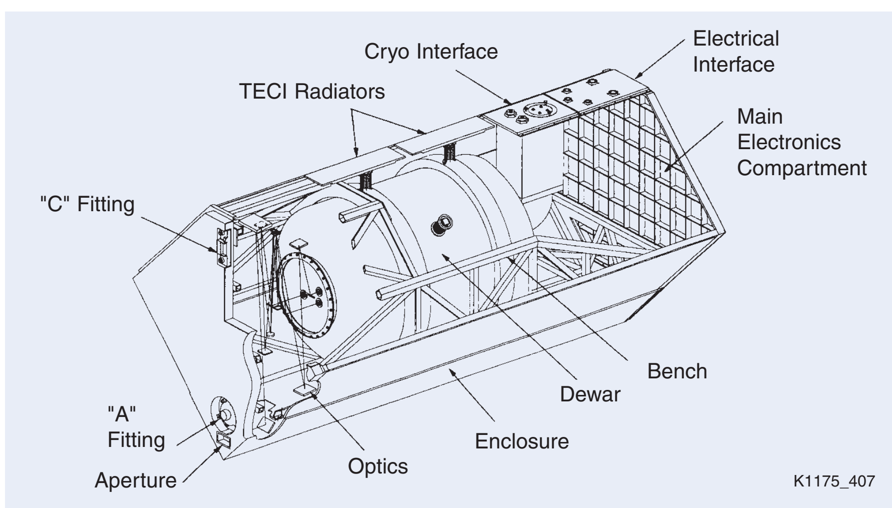

Fig. 4-7 Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

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

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Fig. 4-8 NICMOS optical characteristics

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

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

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

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

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

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

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

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

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

NICMOS Specifications

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

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

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Fig. 4-9 NICMOS specifications

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

Observations

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

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

Space Telescope Imaging Spectrograph

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

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

Physical Description

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

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

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

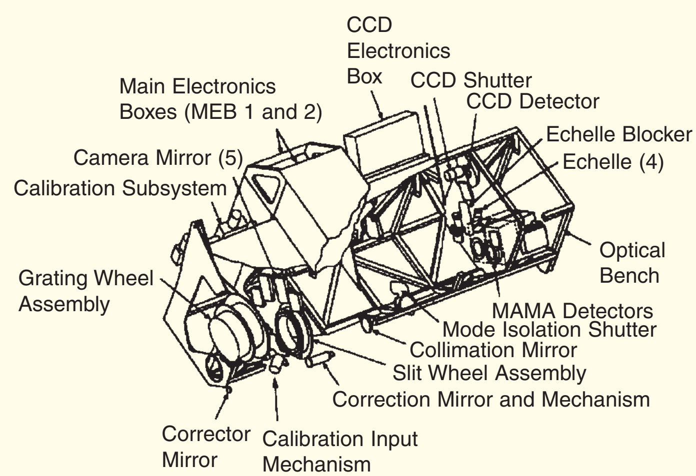

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Fig. 4-10 Space Telescope Imaging Spectrograph

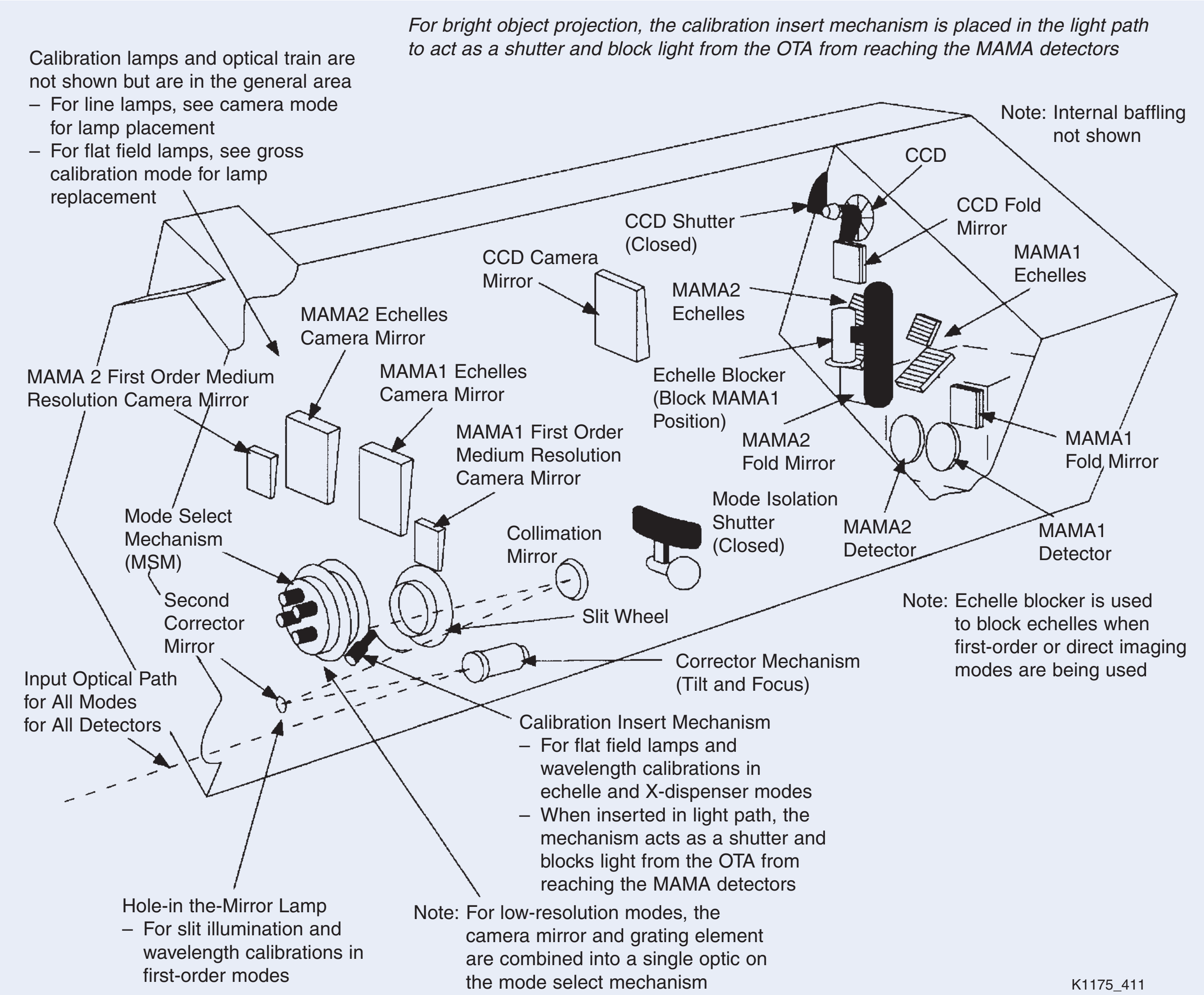

Fig. 4-11 STIS components and detectors

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

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

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

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

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

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

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

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

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

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

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

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

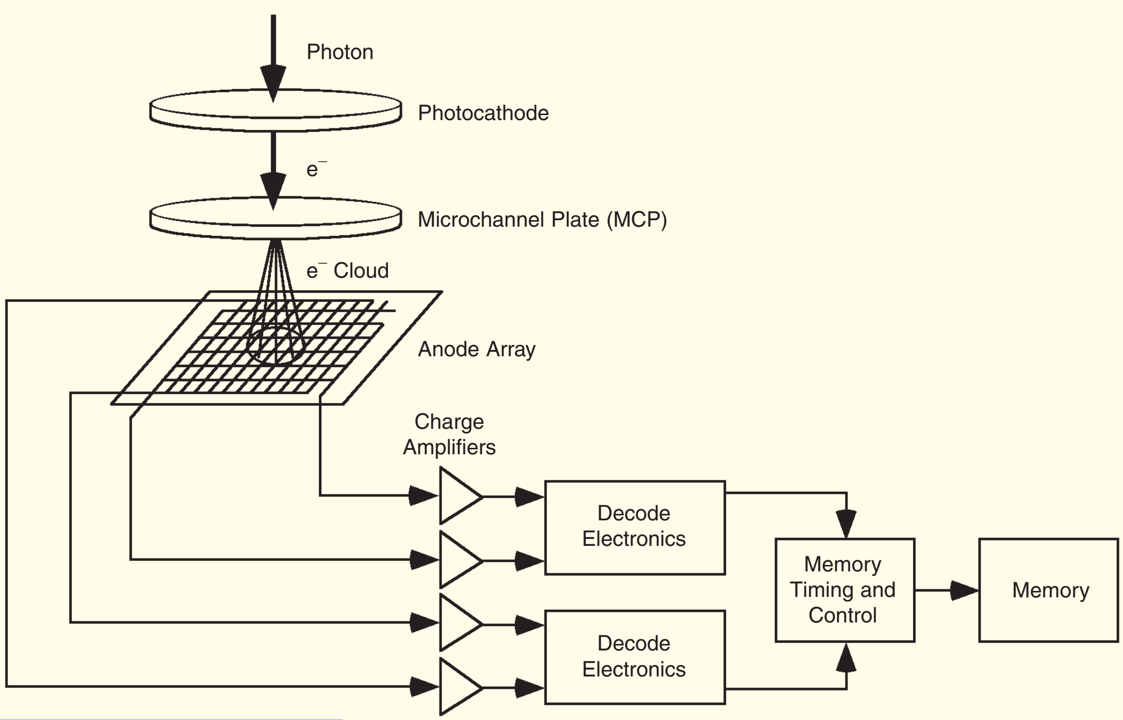

Fig. 4-12 Simplified MAMA system

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

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

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

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

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

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

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

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

STIS Specifications

Fig. 4-13 shows STIS specifications.

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

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Fig. 4-13 STIS specifications

Observations

Scientists use STIS in many areas:

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

Wide Field and Planetary Camera 2

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

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

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

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

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

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

Physical Description

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

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

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

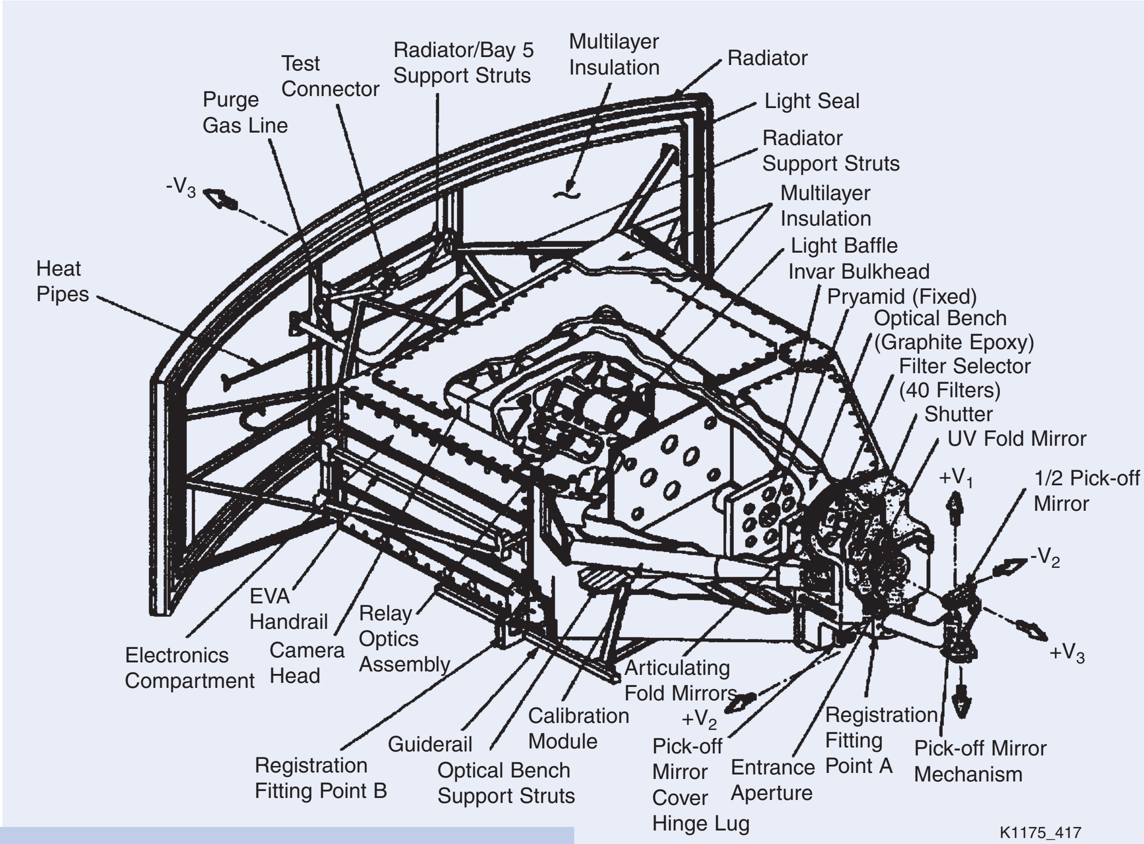

Fig. 4-14 Wide Field and Planetary Camera (WFPC) overall configuration

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

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

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

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

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

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

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

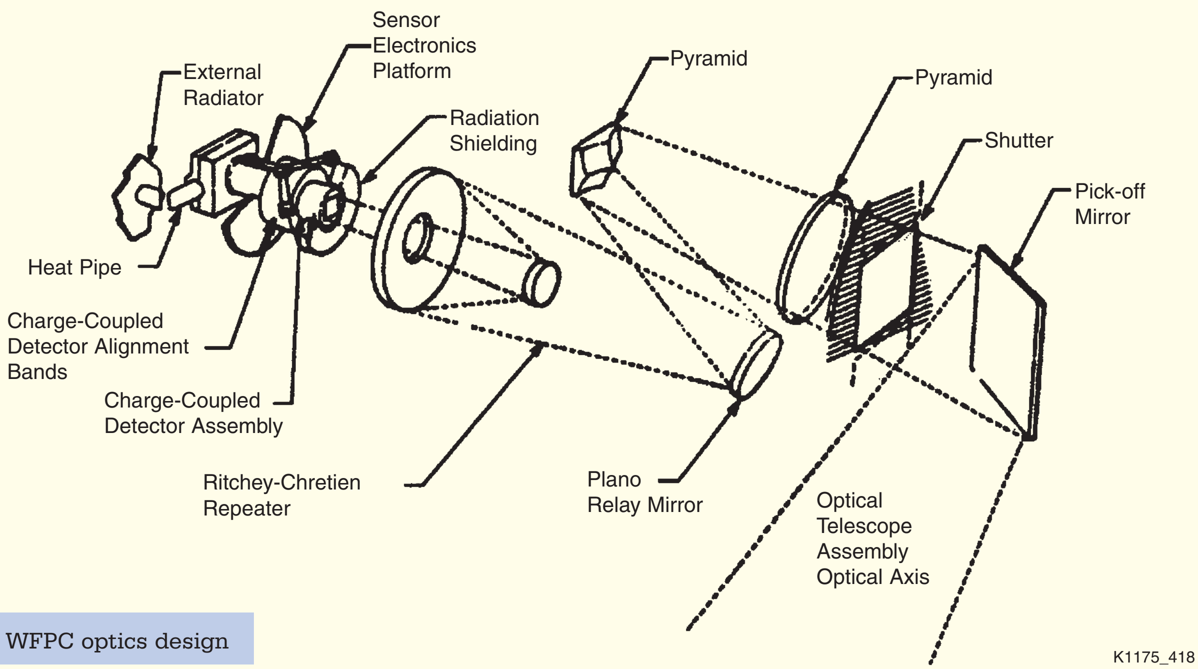

Fig. 4-15 WFPC optics design

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

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

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

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

WFPC2 Specifications

Figure 4-16 shows the WFPC2 specifications.

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

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Fig. 4-16 WFPC2 specifications

Observations

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

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

Astrometry (Fine Guidance Sensors)

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

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

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

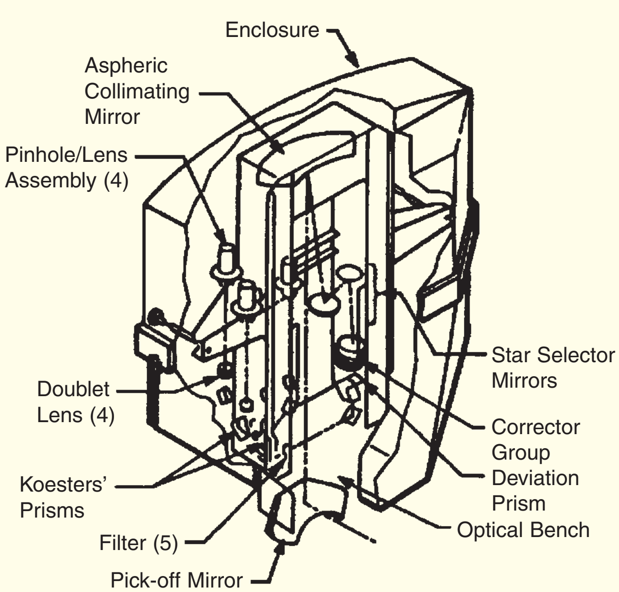

Fig. 4-17 Fine Guidance Sensor (FGS)

Fine Guidance Sensor Specifications

Figure 4-18 shows FGS specifications.

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

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Fig. 4-18 FGS specifications

Operational Modes for Astrometry

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

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

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

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

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

Fine Guidance Sensor Filter Wheel

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

Astrometric Observations

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

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

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

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

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