Three instruments are currently in active scientific use on HST – the Wide Field and Planetary Camera 2 (WFPC2), the Space Telescope Imaging Spectrograph (STIS) and Fine Guidance Sensor 1R (FGS1R), which has been designated as the prime FGS for astrometric science. Other instrument bays are occupied by the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), which is now dormant due to the depletion of its solid nitrogen cryogen; the Faint Object Camera (FOC), which is obsolete and has been decommissioned; and the corrective optical device called COSTAR, which is no longer needed.

During HST Servicing Mission 3B (SM3B) an experimental mechanical cooling system will be attached to NICMOS to determine if it can be brought back into operation. During the same mission the FOC will be replaced by the Advanced Camera for Surveys (ACS). COSTAR will be removed during the final HST servicing mission (SM4) to make room for the Cosmic Origins Spectrograph (COS).

The Fine Guidance Sensors (FGSs) are undergoing a systematic program of refurbishment and upgrading. In "round-robin" fashion, one FGS per servicing mission is being replaced, returned to the ground, disassembled and refurbished, and then taken back to HST on the next servicing mission to become the replacement unit for the next FGS to be serviced. In this manner, by the conclusion of SM4, all three FGSs will have been brought up to optimum condition.

4.1 Space Telescope Imaging Spectrograph

STIS was developed under the direction of the principal investigator, Dr. Bruce E. Woodgate, jointly with Ball Aerospace (see Fig. 4-1). The

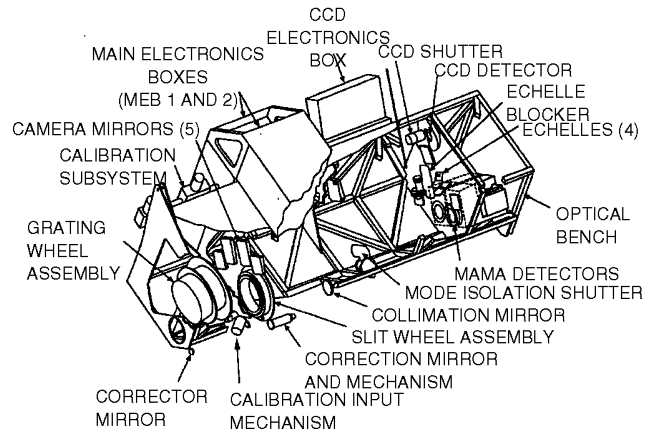

Fig. 4-1 Space Telescope Imaging Spectrograph

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.

STIS was designed to replace many of the capabilities of the instruments it succeeded on SM2 – the Goddard High Resolution Spectrograph and the Faint Object Spectrograph. However, it has additional enhanced capabilities. STIS covers a broader wavelength range with two-dimensional capability, adds a coronagraph capability, and has a high time-resolution capability in the UV. It also can image and can provide objective prism spectra in the intermediate UV. STIS carries its own aberration-correcting optics.

4.1.1 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 ft (2.2 x 0.98 x 0.98 m) 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. An onboard computer controls the detectors and mechanisms.

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 4-2 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 x 50 and 25 x 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 examination of any faint material nearby.

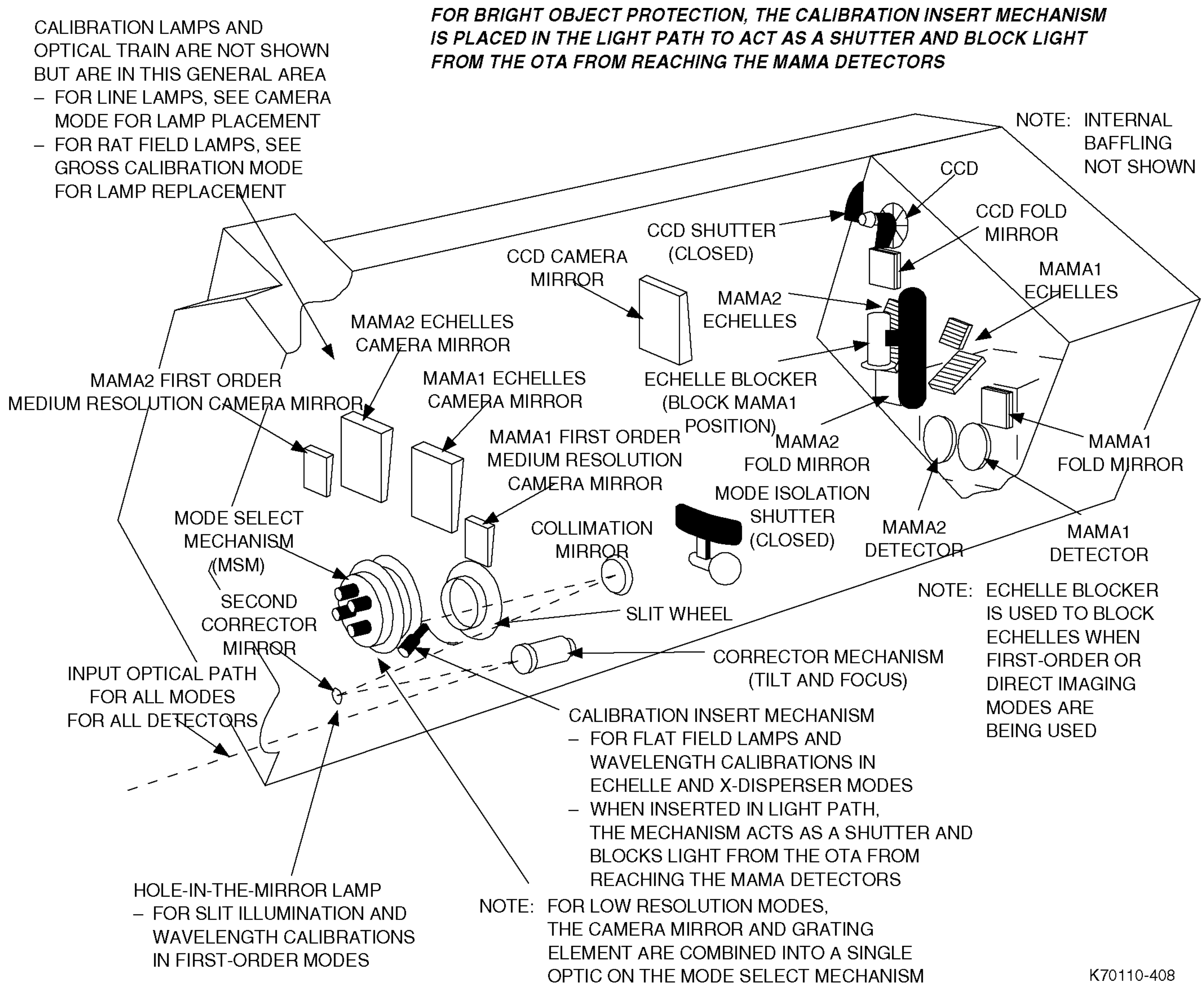

Fig. 4-2 STIS components and detectors

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. 4-3). 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 region. Each detector's photocathode

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	—	—

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Fig. 4-3 STIS spectroscopic modes

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. 4-4, 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 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 4-5 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

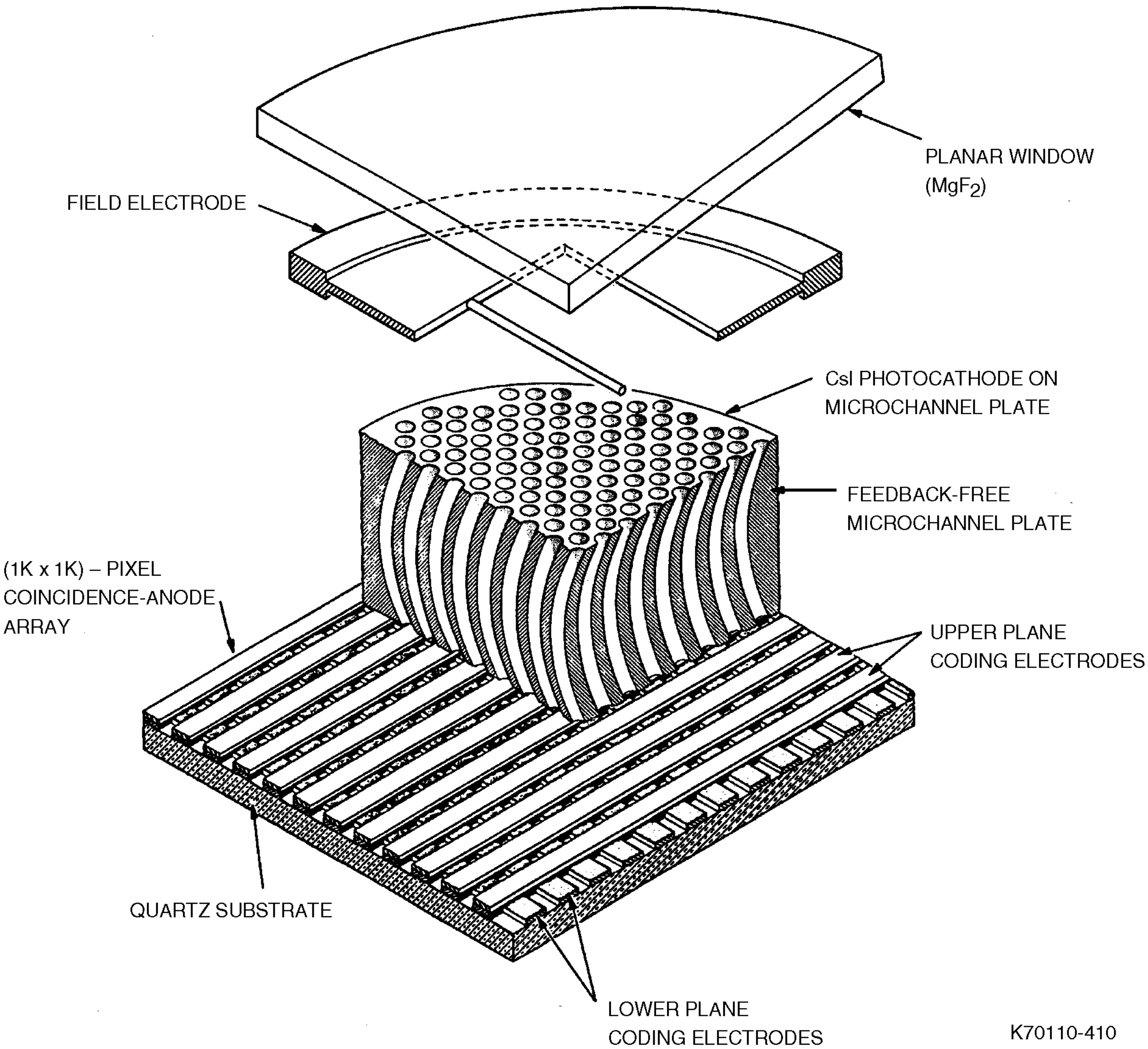

Fig. 4-4 Multi-Anode Microchannel Plate Array (MAMA) detector

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 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; 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).

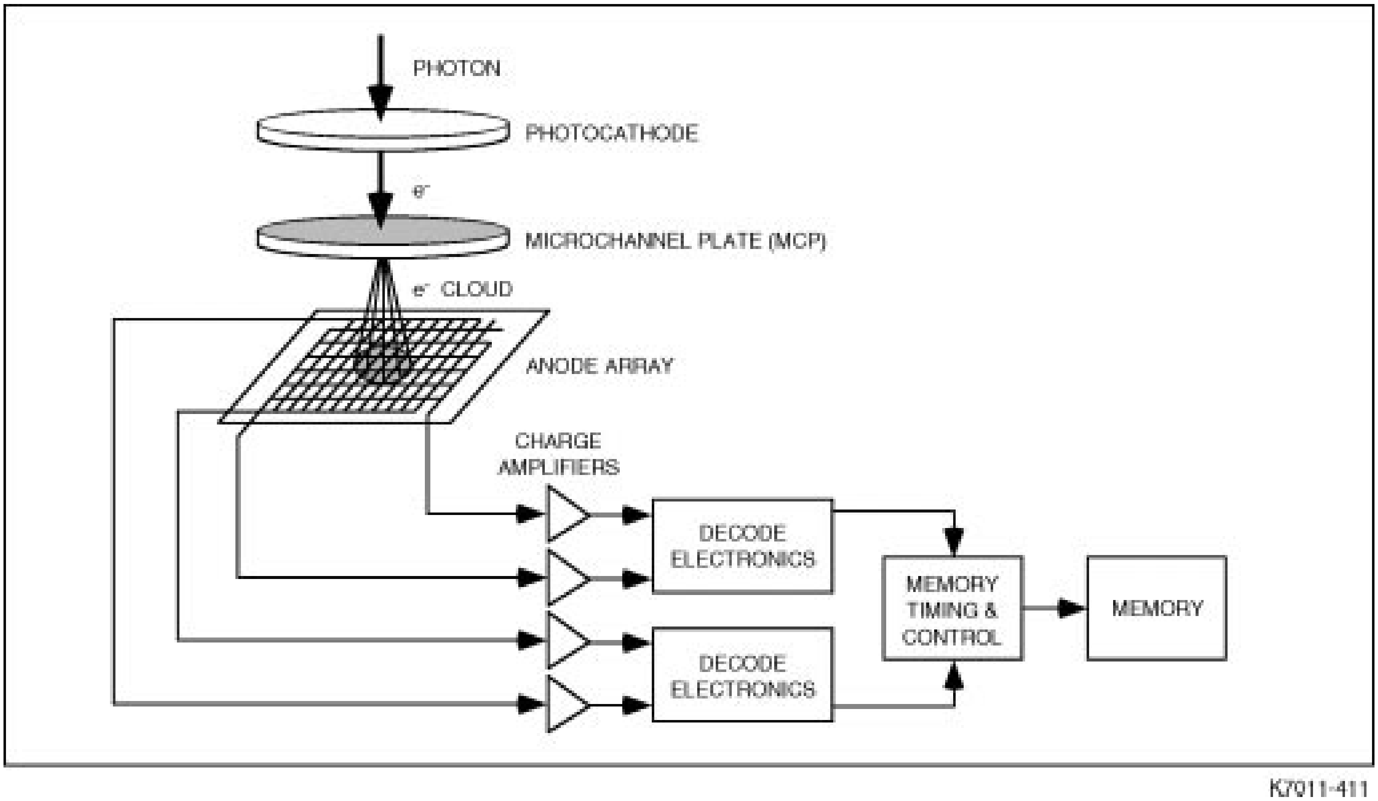

Fig. 4-5 Simplified MAMA system

Fabricated using integrated circuit technology, the detector consists of light-sensitive picture elements (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. The 1024 x 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 -80°C. 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 20°C, 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. Changing the gain can further extend the dynamic range. 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 x 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 x 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.

4.1.2 Spectra Operational Modes

Figure 4-3 shows the spectral operational modes. Two numbers, W and R, describe each instrument mode, 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 4-3 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 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. 4-6). 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.

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

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Fig. 4-6 STIS filter set

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, and 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.

4.1.3 STIS Specifications

Figure 4-7 shows STIS specifications.

4.1.4 Observations

Scientists using STIS 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, and velocity of rotation or internal mass motions in planets, comets, stars, interstellar gas, nebulae, stellar ejecta, galaxies, and quasars.

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

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Fig. 4-7 STIS specifications

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 provide complementary data to NICMOS, which was to peer through the thick dust around young stars. These observations shed light on how planets form, what type of stars have planetary disks, and how quickly the disks evolve into planets.

4.2 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-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 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. The second-generation instrument, WFPC2, was already under construction when the Hubble Telescope 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 so as to achieve the originally specified imaging performance of the Telescope in the WFPC2 field of view.

WFPC2 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 29th magnitude are detectable in the longest exposures (29th magnitude is over one billion 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, WFPC2 can resolve the fine details and pick out bright stellar populations of distant galaxies. It can 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 WFPC1 because of the aberration. WFPC2's high-resolution imagery 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.

4.2.1 Physical Description

The WFPC2 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 WFPC2's field of view 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, WFPC2 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 WFPC's precisely located optical bench. The pickoff mirror reflects the portion of the Telescope's focal plane belonging to WFPC2 into a nearly radial direction, from which it enters the front of the instrument, allowing light falling on other portions of the focal plane to proceed without interference.

WFPC2 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 WFPC'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.

WFPC2 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 4-8 shows the overall configuration of the instrument.

Optical System. The WFPC2 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

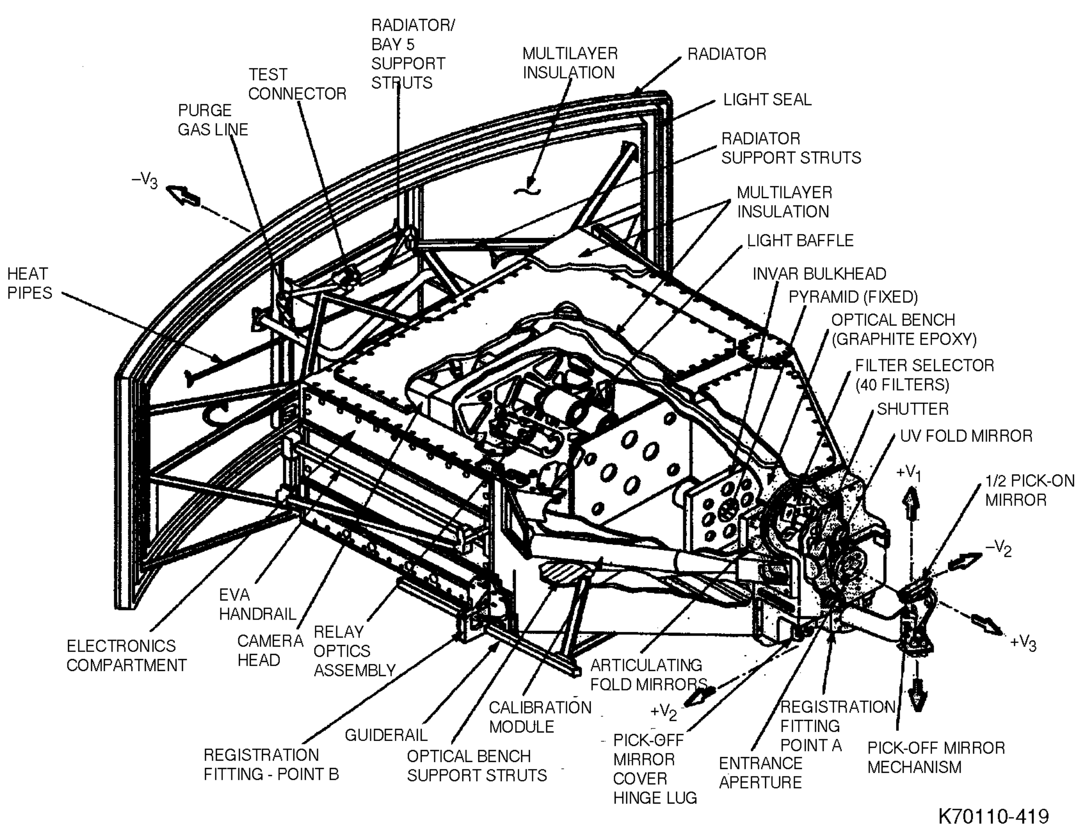

Fig. 4-8 Wide Field and Planetary Camera (WFPC) overall configuration

primary mirror. Figure 4-9 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.

WFPC2'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 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, for 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 the measurement of 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 picture elements (pixels) built upon 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 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

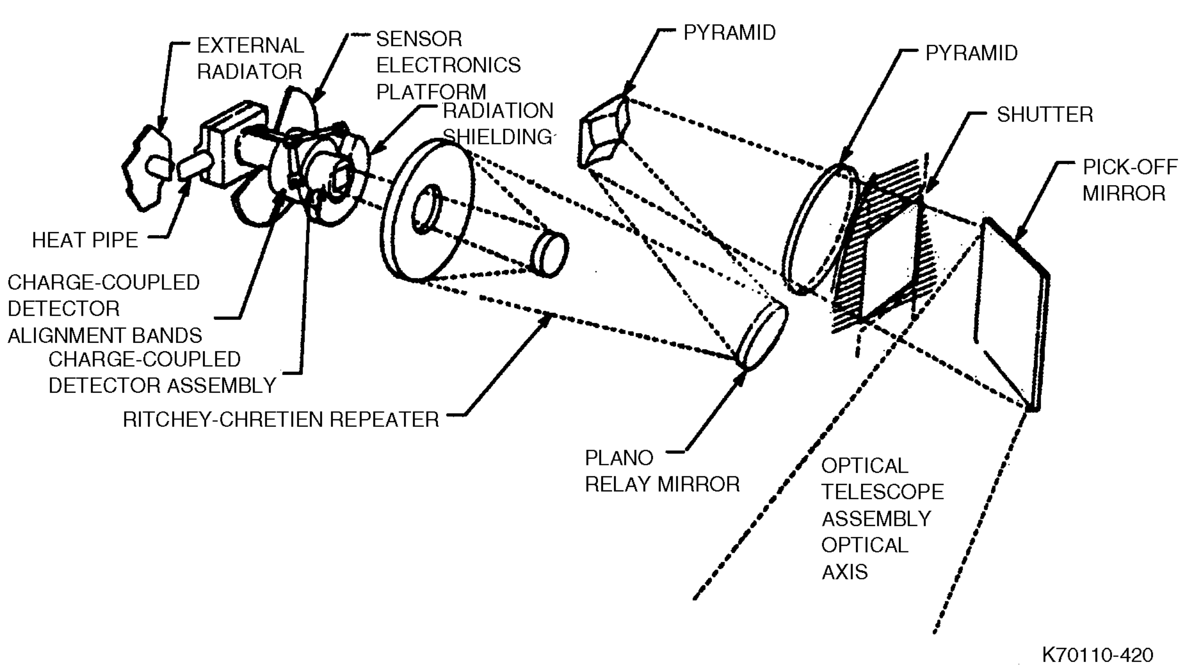

Fig. 4-9 WFPC optics design

reconstruction of the pattern of incoming light on the array. Figure 4-10 illustrates the process.

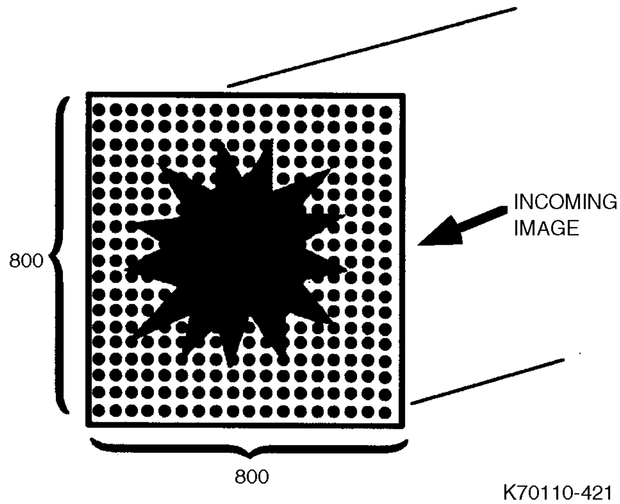

Fig. 4-10 WFPC2 imaging

The CCDs used in WFPC2 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 WFPC2 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 -70°C (-8 to -130°F). 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 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 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.

4.2.2 WFPC2 Specifications

Figure 4-11 shows the WFPC2 specifications.

Wide Field and Planetary Camera 2	
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 arcmin² (WP), 0.3 arcmin² (PC)
Magnitude range	9 to 28 m_v
Wavelength range	1200 to 10,000 angstroms

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Fig. 4-11 WFPC2 specifications

4.2.3 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.

4.3 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 Raytheon 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. 4-12. (See para 5.3 for more 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 Servicing Mission 2, FGS 1 was removed from HST and replaced with FGS 1R, the first FGS to feature this active alignment capability. Now with its optical

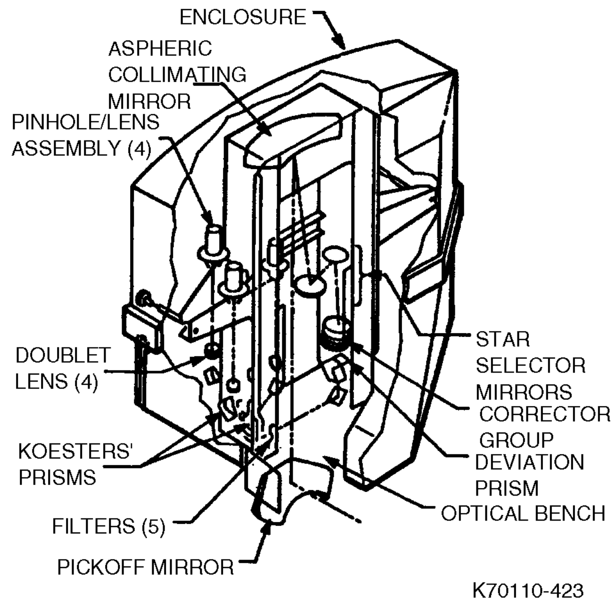

Fig. 4-12 Fine Guidance Sensor (FGS)

system properly aligned, FGS1R performs superbly and is the prime instrument on HST for astrometric science observations.

4.3.1 Fine Guidance Sensor Specifications

Figure 4-13 shows FGS specifications.

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	Raytheon Optical Systems Inc.
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

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Fig. 4-13 FGS specifications

4.3.2 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.

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 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.

Astrometric observations of binary stars provide information about stellar masses which is important to understanding the evolution of stars.

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.

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

4.3.4 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 that around our 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.