The optical designs of the HST scientific instruments

The primary optics of the Hubble Space Telescope provide a 39,000 cm^2 clear light collecting area and a useful spectral bandpass ranging from 110 to at least 4,000 nm. Above the turbulence of the Earth's atmosphere, the telescope's image quality will be limited only by its 2.4 m aperture and by residual aberrations, primarily astigmatism and field curvature. On-axis point source images will achieve 60% encircled energy within a radius of 0.05 to 0.09 seconds of arc from red wavelengths to the vacuum ultraviolet.

Only one of the HST's scientific instruments has access to the on-axis field. The remaining instruments have been designed to compensate within their own optical systems for the astigmatism and field curvature encountered at the off-axis positions of their entrance apertures. Each instrument's optical design also reflects the need to match the format and pixel size of its detectors to the image scale of the telescope.

The HST's scientific payload[6,9] consists of five instruments—two cameras, two spectrographs, and a photometer. Additionally, one of the HST Fine Guidance Sensors has been optimized for the precise positional measurements needed for astrometric science. Taken together, these instruments constitute a complementary and nearly complete set. Only a capability to exploit the HST's infrared throughput is missing, and this will be rectified by a second-generation instrument currently being designed.

The *Wide Field and Planetary Camera* (WFPC), illustrated in Fig. 2, provides relatively wide fields-of-view at a slight sacrifice in angular resolution, with peak sensitivity in the 500–700 nm range. The WFPC, in its "wide field" mode, views a full 2.6×2.6 minutes of arc field using four separate CCD detectors, each an 800×800 array of 15 μm pixels. With a pick-off mirror centered on the telescope's optical axis, this camera diverts the f/24 beam of the telescope through an entrance aperture and a filter wheel assembly onto a four-sided pyramid, each face of which is a concave spherical surface. The pyramid breaks the telescope's image of the sky into four quandrants and each quadrant is relayed by an optical flat to a small Ritchey-Chretien repeater, which images it onto the surface of a CCD. The CCD housing is sealed by a MgF_2 window, which flattens the field.

This optical train reduces the telescope's beam to f/12.9. The resultant image scale at the detector is 0.1 seconds of arc per pixel. To achieve better resolution, while retaining a field of view large enough to encompass Jupiter, for example, the WFPC contains a separate set of four f/30 optical trains and CCDs. This "planetary camera" mode is accessed by means of a 45° rotation of the pyramid. It provides an image scale of 0.04 seconds per pixel over a field of 66 seconds of arc.

The *Faint Object Camera* (FOC), on the other hand, is designed to achieve the highest possible angular resolution, while sacrificing field-of-view. It is most sensitive in the 200–400 nm interval, where the telescope is expected to achieve its finest image quality. The FOC design incorporates two similar optical trains, providing focal ratios f/96 and f/48. In the f/96 mode, the 25 μm pixels of the FOC's two-dimensional, pulse-counting detector subtend 0.022 seconds of arc, sufficient to fully sample the point spread function of the telescope at blue to near-ultraviolet wavelengths.

Its field of view at full resolution in this mode is only 11×11 seconds of arc. The f/48 train provides a wider field, but with undersampled images. The entrance apertures for these trains are located about 6.5 minutes off-axis in the telescope focal surface, and each is accessed by pointing the entire HST. To compensate for aberrations, the optical trains incorporate spherical concave primary mirrors, elliptical convex secondaries, and cylindrical concave relays to focus the image onto the detector photocathodes. Selectable filters are located near the exit pupil.

Of particular interest is a very high magnification f/288 capability, which involves the insertion into the f/96 train of a small, removable Cassegrain telescope onto the relay exit pupil. This device contains an apodizing mask to reduce scattered light diffracted by the HST's secondary mirror spider and primary mirror mounting pads. Used in conjunction with an occulting "finger" protruding into the entrance aperture, the f/288 system provides a coronographic capability, allowing the detection of very faint objects lying close by very bright ones. It will be used, for example, in a

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search for planets associated with nearby stars.

The *Faint Object Spectrograph* (FOS) provides good signal-to-noise ratios on very faint objects at modest spectral resolution. Its useful sensitivity extends from the far ultraviolet through the red. At optical wavelengths, the primary benefit of the FOS over ground-based instruments is in allowing spectroscopy of objects or structures that cannot be spatially resolved from the ground. The FOS delimits its fields-of-view with entrance apertures as small as 0.1 seconds of arc. The optical design of the FOS contains two separate optical paths, selectable by telescope pointing, one of which provides images to an ultraviolet and blue-sensitive detector, and one for a detector with extended red response.

The major optical innovation involves the use of a roof mirror (with one facet for each optical train) to deflect the post-aperture beam about 23° upward into the body of the instrument. This solved the problem of how to place the entrance apertures of the FOS as close as possible to the telescope axis (about 3.5 minutes off axis) to minimize astigmatism and field curvature, while still packaging the larger components of the instrument. The instrument directs a collimated beam to selectable concave gratings operating in first order, concave mirrors for target acquisition, or a mirror/prism combination, which focus the dispersed or reflected image onto the photocathode of a 512-diode, one-dimensional Digicon detector. In this way, resolving powers $\lambda/\delta\lambda \simeq 250$ and 1200 are obtained in overlapping spectral intervals covering the range 115 to 800 nm.

In contrast, the *Goddard High Resolution Spectrograph* (GHRS) disperses light from relatively bright targets to achieve a resolving power unprecedented in space astronomy missions. The GHRS is sensitive only at ultraviolet wavelengths, from 110 to 330 nm. It incorporates both first order and echelle spectrographs in a cleverly packaged layout that reduces to one the number of moving parts needed to access the various modes of the instrument. This is a carousel on which are mounted planar first order gratings, an echelle grating and a selection of flat mirrors used for target acquisition. The target object is positioned by telescope pointing in an entrance aperture, 5.5 minutes away from the telescope axis. Rotation of the carousel brings the desired grating or mirror into the collimated beam, and the alignment of the element then determines the direction the diffracted or reflected beam will take. First order spectra, with resolving powers $\lambda/\delta\lambda \simeq 2{,}000$ and 20,000, are directed to one of two camera mirrors oriented to focus the beam on the photocathode of one of two Digicon detectors.

Similarly, two concave cross-dispersers focus the echelle orders onto these same two detectors. The nominal resolving power in the echelle mode is $\simeq 90{,}000$. Because the spectra are detected by 512-element linear diode arrays, the wavelength interval that can be viewed at one time is limited. For example, at $\lambda/\delta\lambda \simeq 90{,}000$, the observed interval ranges from 0.5 to 1.7 nm. Thus, observing efficiency with the GHRS will be low if one's objective is broad spectral coverage. However, the instrument will be unsurpassed in providing high resolution observations of individual spectral lines with outstanding photometric quality.

The *High Speed Photometer* (HSP) is simple in design, but provides a number of unique capabilities. Its response is linear over about six decades of relative brightness. Thus, it will provide very accurate relative photometry and polarimetry at ultraviolet wavelengths. In both the optical and the ultraviolet, its high speed circuitry will allow the measurement of time variations in the brightness of astronomical sources with a resolution of 20 μsec. The HSP's complement of detectors consists of four image dissector tubes and one photomultiplier. Each image dissector is associated with a filter plate, containing up to 13 filter segments, and an aperture plate containing up to four apertures per filter segment. In total there are 23 unique filter bandpasses for ultraviolet and visual photometry and 4 bandpasses for ultraviolet polarimetry. There are in excess of 150 filter-aperture combinations, any of which may be selected by telescope pointing.

Simultaneous two-color photometry is possible using the photomultiplier and one image dissector in conjunction with a beam splitter, for example to observe the occultation of a distant star by the atmosphere of one of the giant planets in our solar system. It was not possible to design an optical layout for the HSP that allowed all five detectors to directly view the telescope's focal surface. Three optical relays, off-axis ellipsoids, were included to solve this packaging problem. They also correct for astigmatism.

The five scientific instruments contain numerous ancillary modes that enhance their power and versatility—modes for imaging spectroscopy, spectropolarimetry, time-resolved spectroscopy, coronography, astrometry, and so on. The HST's scientific payload will give astronomers a complete set of tools with which to expand our perception of the universe over the next 15 years.