SPACE
TELESCOPE
SCIENCE
INSTITUTE

Technical Details of HST for Amateur Astronomers (exerpted from "Cycle 2 Call for Professional Proposals")

PART II: THE HUBBLE SPACE TELESCOPE

9. System Overview

9.1 Telescope Description

The Hubble Space Telescope (HST) is a 2.4-meter Ritchey-Chrétien reflector (see Fig. 9-1). Following its successful deployment into low Earth orbit on April 25, 1990, it is expected to become a long-lived, versatile astronomical observatory in space.

As shown in Fig. 9-1, the Scientific Instruments (SIs) are mounted in bays behind the primary mirror. The Wide Field and Planetary Camera occupies one of the radial bays, with an attached 45° pickoff mirror that allows it to receive the on-axis beam. Four SIs (Faint Object Camera, Faint Object Spectrograph, Goddard High Resolution Spectrograph, and High Speed Photometer) are mounted in the axial bays and receive images several arcminutes off-axis.

The Fine Guidance Sensors (FGSs) occupy the other three radial bays and receive light 10-14 arcminutes off-axis. Since only two FGSs are required to guide the telescope, it will be possible to conduct astrometric observations using a third FGS. Hence the FGS may be thought of as a sixth SI.

All of the SIs are designed to be replaceable in orbit (by a suited astronaut).

For an overview of the SIs, see §11. Detailed information about each SI is contained in six separate *Instrument Handbooks* (see §2.2).

The Ritchey-Chrétien design produces images that are virtually free of coma and spherical aberration over a large field of view, and the secondary mirror is fully articulated to provide for adjustment of tilt, centering, and focus. Some residual wave-front errors may be corrected by a set of 24 actuators that exert pressure on the primary mirror from behind. Table 9-1 lists some properties of the HST optical system. The optical performance of the telescope is described more fully below (§10), and in detail in the *OTA Handbook*.

Table 9-1
Optical Characteristics of HST

Aperture	2.4 m
Wavelength coverage (MgF_2-overcoated aluminum)	1150 Å to 1 mm
Focal ratio	$f/24$
Plate scale (on axis)	3.58 arcsec mm^{-1}
Predicted FWHM of on-axis images,	
including $0\farcs007$ rms pointing jitter—	
1220 Å	0.023 arcsec
2000 Å	0.025 arcsec
3500 Å	0.035 arcsec
4500 Å	0.041 arcsec
6328 Å	0.056 arcsec
Predicted radius of 70% encircled energy (at 6328 Å)	0.10 arcsec

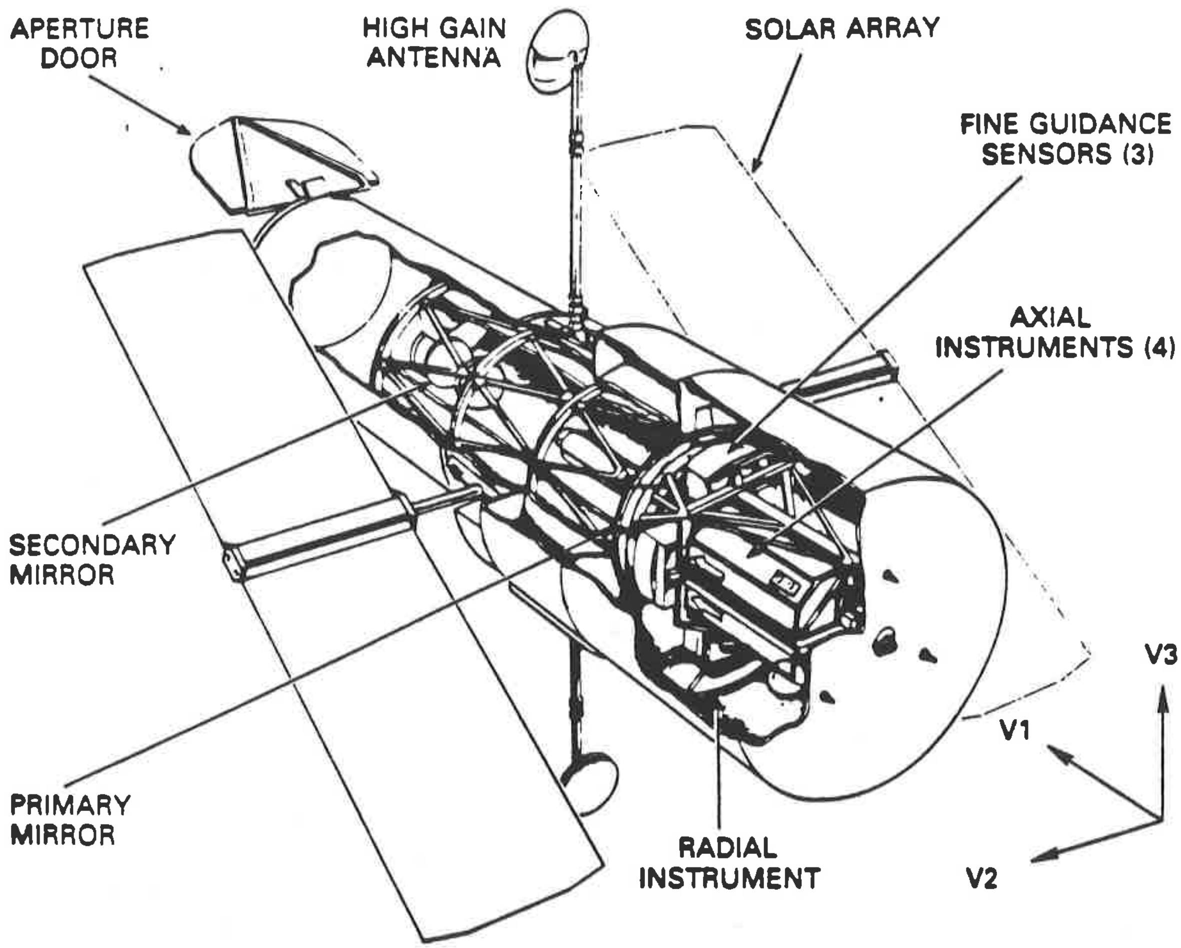


Figure 9-1
The Hubble Space Telescope
Major components are labelled, and definitions of V1,V2,V3 spacecraft axes are indicated

HST receives electrical power from two solar arrays (see Fig. 9-1), which can be turned (and the spacecraft rolled about its optical axis) so that the panels face the incident sunlight. Nickel-hydrogen batteries provide power during orbital night. The two high-gain antennas shown in Fig. 9-1 provide communications with the ground (via the Tracking and Data Relay Satellite System). Power, control, and communications functions are carried out by the Support Systems Module (SSM), which encircles the primary mirror.

9.2 HST Maneuvering and Pointing

HST is, in principle, free to roll about its optical axis. However, this freedom is limited by the need to keep sunlight shining on the solar arrays, and by a thermal design that assumes that the Sun always heats the same side of the telescope.

To discuss HST pointing, it is useful to define a coordinate system that is fixed to the telescope. This system consists of three orthogonal axes: V1, V2, and V3. V1 lies along the optical axis, V2 is parallel to the solar-array rotation axis, and V3 is perpendicular to the solar-array axis (see Fig. 9-1). Power and thermal constraints are satisfied when the telescope is oriented such that the Sun is in the half-plane defined by the V1 axis and the positive V3 axis. The roll angle that optimizes the solar-array positioning with respect to the Sun is called the "nominal roll."

The primary implication of this constraint for observers is that the nominal roll angle required for a particular observation depends on the location of the target and *the date of the observation.* Observations of the same target made at different dates will, in general, be made at different roll angles.

Some departures from nominal roll are permitted during HST observing. The following restrictions will apply to the deviation of the Sun out of the V1,+V3 plane (and they apply whether or not the Sun is actually visible from the spacecraft):

- Deviations of up to $\pm 5^\circ$ are always permissible.
- When pointing to less than than 90° from the Sun, roll deviations larger than $\pm 5^\circ$ are never allowed.
- When pointing between 90° and 178° from the Sun, roll deviations of up to $\pm 30^\circ$ are allowed within restrictions imposed by spacecraft power requirements. Factors restricting such deviations include the duration of the off-nominal roll operation, the size of the deviation, and the length of the orbital day. Large roll deviations may be restricted in length, and may require a subsequent recovery period.
- When pointing to within 2° of the antisun direction, rolls are unrestricted.

As a rule, observations will be scheduled such that the spacecraft is at nominal roll. Thus, observers need not concern themselves with the above restrictions, unless their observations require a specific roll orientation (*e.g.*, if a specific roll is required at a specific time, or if the same roll is required for observations made at different times).

Appendix A3 provides instructions for calculating the nominal roll angle for a given target on a given date. Note that the $\pm 5^\circ$ and $\pm 30^\circ$ restrictions outlined above apply specifically to the deviation of the Sun out of the V1,+V3 plane, not to the permissible range in the V3 position angle.

HST utilizes electrically driven reaction wheels (contained in the SSM) to perform all maneuvering required for target acquisition and pointing control. The slew rate is limited to approximately 6° per minute of time. Thus, about one hour is needed to go full circle in pitch, yaw, or roll. Upon arrival at a new target, up to 10–22 additional minutes (depending on the guiding mode chosen) must be allowed for the FGS to acquire a new pair of guide stars, and for solar-panel vibrations to damp. As a result, large maneuvers are costly in time and will generally be scheduled for periods of Earth occultation or crossing of the South Atlantic Anomaly (see §12.2). In order to reduce total slew time, targets from various scientific programs will be interleaved when planning the observing schedule (§7.2).

The telescope will not observe targets within 50° of the unocculted Sun, 20° of any illuminated portion of the Earth, nor 11° of the limb of the Earth. Observations that require the darkest background should not be made within 80° of the bright limb of the Earth nor 30° of the full Moon.

There are exceptions to these rules for HST pointing in certain cases. For instance, it is anticipated that the bright Earth will be a useful flat-field calibration source. However, there are onboard safety features that cannot be overridden. The most important of these is that the aperture door shown in Fig. 9-1 will close automatically whenever HST is pointed within 20° of the Sun, in order to prevent direct sunlight from reaching the optics and focal plane.

Objects in the inner solar system, such as Venus or comets near perihelion, will unfortunately be difficult or impossible to observe with HST, because of the 50° solar limit. When the scientific justification is compelling, observations of Venus and time-critical observations of other solar-system objects lying between approximately 45° and 50° of the Sun may be possible, provided they are made while HST is in Earth shadow. However, such programs would be limited to exposures short enough to allow the spacecraft to be maneuvered to more than 50° from the Sun before the beginning of orbital daylight.

9.3 Data Storage and Transmission

The HST observing schedule will be constructed at STScI (see §7.2) and forwarded to the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, for transmission to the HST. The HST will be controlled from the Space Telescope Operations Control Center (STOCC), located at GSFC. Communication with the spacecraft is via the Tracking and Data Relay Satellite System (TDRSS), which consists of two satellites in geosynchronous orbit, located 130° apart (at 41° and 171° west longitude).

Commands to HST will originate at the STOCC and be sent via land-line or communications satellites to the TDRSS ground station at White Sands, New Mexico. From White Sands, the commands will be sent via the appropriate TDRS to HST. Both HST and the TDRS will steer their high-gain antennas to maintain the link as their relative positions change due to orbital motion. Scientific data will be sent from HST to the STOCC via the reverse path, and then from the STOCC to the STScI via dedicated high-speed links.

The TDRSS network supports many spacecraft in addition to HST. Therefore, use of the network, either to send commands or return data, must be scheduled weeks in advance. Because of limited TDRSS availability, command sequences for HST observations will normally be uplinked periodically and stored in the onboard computers. HST will then execute the observations automatically.

It will be possible for observers at STScI (or at STOCC) to interact in real time with HST for specific purposes, such as certain target acquisitions. However, because of the TDRSS scheduling difficulties, these real-time interactions will be limited to no more than about 20% of the observations. See §14 for further discussion.

HST has two basic data-transmission rates, 4 kilobits per second (kbps) and 1 megabit per second (Mbps). Each TDRS can service at most 19 satellites at 4 kbps and two satellites at 1 Mbps. Currently, it is anticipated that HST will have a 4-kbps downlink continuously, except for the approximately 10% of the time when HST cannot see either TDRS. The 4-kbps link can be used for many observations with the spectrographs, photometer, and fine-guidance sensors. However, the cameras and certain observing modes of the other SIs generate too much data for the 4-kbps link, and therefore must use the 1-Mbps link. It is expected that about 20 min per orbit, on average, of 1-Mbps link time will be available. There is also a 32-kbps rate available for astrometric observations.

In general, STScI will request real-time TDRSS coverage for all 4-kbps SI data readouts. However, there are three onboard tape recorders that can be used to store data.

One tape recorder will be used to record science data if TDRSS coverage cannot be obtained at the time the readout is planned. In such events, the data will be played back at the next time a TDRSS link is obtained, typically within one orbit. The tape recorder will hold about 20 min of data at 1 Mbps, or about 10 hours of data at 4 kbps; with overheads, the tape recorder can hold 12 WF/PC images. In situations where the data are needed in real time (*e.g.*, for target acquisition), every attempt will be made to schedule the observation in a manner that will result in TDRSS granting the link.

In addition to the TDRSS constraints on data volume, there are limits to the amount of data that can be handled by the ground system supporting HST. The current ground system is designed to receive up to about $2.5\text{–}3 \times 10^9$ bits of science data per day, equivalent to about 70 WF/PC frames. The data-storage and -transmission constraints discussed in this section imply that some scientific programs requiring very high data-acquisition rates cannot be accommodated, because the SIs would generate more data than either the links or ground system can handle.

10. Telescope Performance

10.1 Optical Performance

On axis, the Ritchey-Chrétien optics of the HST will provide essentially diffraction-limited performance in the visual region. The design specification for the image quality, including pointing jitter, is that 70% of the total energy of an on-axis stellar image must be contained within a radius of $0\overset{''}{.}10$ at 6328 Å. Off-axis astigmatism will be the dominant aberration; the off-axis SIs have correcting optics where necessary.

Both image quality and effective throughput of the telescope optics will be degraded by mirror roughness on small scales, and by accumulated dust on the primary and secondary mirrors. Both effects are significant only below 3000 Å, with a loss of up to 40% from the central core of the stellar image at 1200 Å compared to visual wavelengths. The redistributed light creates broad, faint wings (on scales of up to arcminutes) at the shortest wavelengths. Detailed simulations of HST images, including all of the known effects, have been developed at STScI; see the *OTA Handbook* for details.

10.2 Pointing Performance

The Pointing Control System is designed to keep telescope jitter to below $\pm 0\overset{''}{.}007$ rms (under FGS Fine Lock, as described in §13.1), which should be negligible for most scientific investigations. However, long exposures with the FOC in the *f*/288 mode should be broken into shorter intervals (30-35 minutes) and "restacked" during data reduction, in order to remove slow drifts of several milliarcseconds due to thermal effects following large slews.

10.3 Background Light

Several sources of "background" light should be considered by proposers who plan to carry out observations at very low light levels or at certain wavelengths or positions in the sky. A detailed model of the background light (including diffuse galactic light and unresolved stellar background as well as the variable sources mentioned below) has been developed at STScI; potential observers may contact STScI for assistance if the information below is insufficient. There is also a more detailed discussion in the Faint Object Camera *Instrument Handbook*.

The SIs will also suffer detector noise due to particle radiation. The *Instrument Handbooks* should be consulted for details.

10.3.1 Zodiacal Light

Zodiacal light (and Gegenschein), which are due to scattering of solar radiation within the solar system, vary in visual surface brightness from 21 to 23 mag arcsec^{-2}. Potential observers should consider both the degree and location of this radiation in choosing targets and requesting special scheduling requirements. The spectral energy distribution is very similar to that of direct solar radiation. The dependence of zodiacal-light brightness upon ecliptic coordinates has been discussed by A. C. Levasseur-Regourd and R. Dumont (*Astron. Astrophys.*, **84**, 277, 1980).

10.3.2 Scattered Light

The aperture door and baffling system of HST are designed to prevent scattered light from the Sun, Moon, Earth, and bright stars from reaching the focal plane. This design, along with the pointing restrictions outlined in §9.2, is intended to limit the visual stray-light background to 23 mag arcsec^{-2}.

10.3.3 Airglow and Geocoronal Emission

For both imaging and spectroscopic observations in the ultraviolet, the residual O I airglow lines at 1304 and 1356 Å are expected to be significant contaminants only on the daytime side of the Earth. The geocoronal Lyman-α line at 1216 Å is expected to vary in intensity from 2.5 kiloRayleighs on the nighttime side of the Earth to 30 kiloRayleighs on the daytime side.

10.3.4 Shuttle Glow

A spacecraft moving in low Earth orbit creates a diffuse glow, possibly due to the interaction with the residual oxygen atmosphere. Indications are that this "shuttle glow" will result in an additional visual diffuse background of 24 mag arcsec^{-2} for observations "into the wind" (*i.e.*, with the telescope pointing in the direction of orbital motion). The observed continuous spectrum appears to be climbing above 7000 Å, and declines rapidly into the ultraviolet. Analysis of the shuttle-glow effect will be done in the first eight months following HST launch.

10.4 Interstellar Extinction

Proposers should be aware that interstellar extinction can be very significant in the ultraviolet. A detailed discussion is given in the Faint Object Spectrograph *Instrument Handbook.*

10.5 Observing and Program Efficiencies

"Observing efficiency" may be defined as the ratio of HST spacecraft time that is spent actually acquiring and observing targets (see §6.3) to total elapsed time. The main factors that will affect HST observing efficiency are (1) the low orbit, with attendant frequent Earth occultation of most targets; (2) interruptions by passages through the South Atlantic Anomaly (see §12.2); (3) the relatively slow slew rate; (4) telemetry constraints; and (5) the performance of the scheduling algorithm. The observing efficiency will probably be low early in the HST mission; approximate estimates are that it will be ~25% at the beginning of GO observing, and will ultimately increase to ~35%; during Cycle 2, it is estimated that the efficiency will be about 30%. If these estimates prove accurate, ~2750 hours of spacecraft time will ultimately be available to GOs per year; during Cycle 2, the estimated GO spacecraft time is about 1700 hours, because of the lower observing efficiency and the allocation of some of the time to GTOs (see §3.5).

An algorithm for calculating the amount of spacecraft time required for a given set of exposures is provided in the *Phase I Proposal Instructions* (and is also available as software from STScI, as discussed in the *Instructions*). In addition to the on-target exposure time, the algorithm takes into account guide-star and target acquisition, typical instrument overheads, and additional time required for real-time observations. As described in the *Instructions*, proposers will use this algorithm to calculate their "program efficiencies," *i.e.*, the ratios of total on-target exposure time to total spacecraft time for their programs.

The highest program efficiency will generally be attained with pointings that are comparable to or greater than the orbital period in duration. Although scientific merit is the primary criterion in the evaluation of proposals (as discussed in §6.2.3), the TAC will also consider the efficiency with which HST is used.

11. Scientific Instrument Overview

The following six Scientific Instruments (SIs) will be available on HST:

HRS ?

- Wide Field and Planetary Camera (WF/PC)
- Faint Object Camera (FOC)
- Faint Object Spectrograph (FOS)
- Goddard High Resolution Spectrograph (GHRS)
- High Speed Photometer (HSP)
- Fine Guidance Sensors (FGS)

The FGS can be used for astrometric measurements, in addition to their function of providing guiding information for HST. All of the instruments are permanently mounted at the HST focal plane, so that all except the WF/PC receive light that is slightly off-axis. A schematic diagram of the telescope focal plane is given below (Fig. 11-1 in §11.8.1).

Tables 11-1(a)-(e) provide a summary of the capabilities of the SIs. For many applications, more than one instrument can accomplish a given task, but not necessarily with equal quality or speed.

The following subsections contain brief descriptions of the six SIs. After examining Tables 11-1(a)-(e), prospective proposers should read these descriptions in order to determine which SIs are likely to be most suitable for their programs. Six *Instrument Handbooks,* which discuss the SIs in detail, have been distributed to institutional libraries, and are available from STScI as described in §2.2. The appropriate *Handbooks* must be consulted before actual preparation of observing proposals.

Proposers who are contemplating long-term usage of an SI should be aware that it is possible that one or more of the instruments may be retired and replaced with "second-generation" SIs.

11.1 Wide Field and Planetary Camera (WF/PC)

The WF/PC, which is HST's only on-axis instrument, is designed to provide high-quality, nearly diffraction-limited digital images over a wide field of view (FOV). The

Table 11-1
HST Instrument Capabilities

(a) Direct Imaging[1]

Instrument	Field of View	Projected Pixel Spacing on Sky	Wavelength Range (Å)	Magnitude Limit[2]
WFC	$154'' \times 154''$	$0''.10$	1150-11,000	28
PC	$66'' \times 66''$	$0''.043$	1150-11,000	28
FOC $f/48$	$44'' \times 44''$	$0''.043$	1150-6500	27
$f/96$	$22'' \times 22''$	$0''.022$	1150-6500	27
$f/288$	$7''.3 \times 7''.3$	$0''.0072$	1150-6500	26

(b) Astrometry

Instrument	Field of View	Positional Accuracy	Wavelength Range (Å)	Magnitude Limit[3]
FGS	69 arcmin^2	$\pm 0''.002$[4]	4700-7100	17

(c) Photometry

Instrument	Aperture Diameters	Time Resolution	Wavelength Range (Å)	Magnitude Limit[5]
HSP[6]	$0''.4, 0''.65, 1''.0$	10 μs	1200-8000	25

(d) Slitless Spectroscopy[7]

Instrument	Projected Pixel Spacing on Sky	Resolving Power ($\lambda/\Delta\lambda$)	Wavelength Range (Å)	Magnitude Limit
WFC	$0''.10$	100	1600-4000	22[8]
		40	1300-2000	21[8]
		45	3000-6000	23[2]
		35	6000-10,000	23[2]
FOC $f/48$	$0''.043$	50 at 1500 Å	1150-6000	22[9]
$f/96$	$0''.022$	50 at 1500 Å	1150-6000	22[9]

Table 11-1 (continued)
HST Instrument Capabilities

(e) Slit Spectroscopy

Instrument	Projected Aperture Size	Resolving Power ($\lambda/\Delta\lambda$)	Time Resolution	Wavelength Range (Å)	Magnitude Limit[2]
FOC $f/48$[10]	0″.1 × 20″	1150		1150-1325	18
		1150		1200-1800	18
		1150		1800-2700	20
		1150		3600-5400	21
FOS[11]	0″.1-4″.3	1300	20 ms	1150-8500	18- 22-22
		250	20 ms	1150-8500	21-26-23
GHRS	0″.25, 2″.0	100,000	50 ms	1150-3200	11- 14
		20,000	50 ms	1150-3200	13-16
		2000	50 ms	1150-1800	17

Notes to Tables 11-1(a)-(e):

1. The FOC also has coronographic, and both cameras have polarimetric, imaging capabilities.
2. Predicted limiting V magnitude for an unreddened A0 V star in order to achieve a S/N ratio of 5 in an exposure time of 1 hour. Single entries refer to wavelengths near the center of the indicated wavelength range. For FOC direct imaging, the F342W filter was assumed. When two values are given, the first refers to wavelengths near the short-wavelength limit, and the second to those near the long-wavelength limit. For FOS spectroscopy, three values are given, corresponding to 1300, 3200, and 6000 Å, respectively.
3. For S/N = 1 in Fine Lock.
4. In-orbit performance for astrometry is uncertain; figure quoted is design goal.
5. Predicted limiting V magnitude for a 1-hour exposure (half on star, half on sky) on an A0 V star at S/N = 5 with the F450W filter.
6. The HSP can also perform polarimetry.
7. Using "objective" gratings or prisms.
8. Predicted limiting V magnitude for an unreddened B0 V star in order to achieve a S/N ratio of 5 in an exposure time of 1 hour.
9. Predicted limiting V magnitude for a QSO with a ν^{-2} spectrum in order to achieve a S/N ratio of 10 in an exposure time of 1 hour with the far-UV objective prism (PRISM2).
10. Two-dimensional spectroscopy with the long slit and grating.
11. The FOS can also perform spectropolarimetry.

WA

WF/PC has two configurations; in both, the FOV is covered by a mosaic of four charge-coupled devices (CCDs). Each CCD has 800 × 800 pixels and is sensitive from 1150 to 11,000 Å. In the Wide Field Camera (low-resolution) configuration, the FOV is 2.′6 × 2.′6, with a pixel size of 0.″10. In the Planetary Camera (high-resolution) configuration, the FOV is 1.′1 × 1.′1, and the pixel size is 0.″043. A variety of filters may be inserted into the optical path. Moreover, both configurations may be used for slitless spectroscopy ($R = \lambda/\Delta\lambda \simeq 100$) or polarimetry by placing gratings or polarizers into the beam.

The optics of both the WFC and PC contain a low-reflectance spot of diameter 1.″23, which may be used to suppress light from a bright point source in order to examine its immediate surroundings.

The WFC configuration provides the largest FOV available on HST, but undersamples stellar images; the PC configuration will more nearly attain the full resolution of the optics, particularly in the red. The low readout noise of the CCDs is expected to permit WF/PC to detect very faint stellar objects ($m_V \simeq 28$ in a one-hour exposure). The wide FOV will also permit the WF/PC to be used effectively for deep surveys, including those in parallel mode (while another SI is making a different observation of an adjacent target—see §16).

11.2 Faint Object Camera (FOC)

The FOC is intended to provide very high-resolution images of small fields, in order to exploit fully the optical capabilities of HST. The FOC reimages the HST focal plane to provide three different scales (*f*/48, *f*/96, and *f*/288), and optics within the FOC correct for the off-axis astigmatism. A variety of filters, prisms (for slitless spectroscopy), polarizers, and a grating (for long-slit spectroscopy) may be placed in the optical beam.

In the standard 512 × 512 pixel format, the *f*/48 camera has a usable FOV of 22″ × 22″ with a pixel size of 0.″043 × 0.″043. A field of 44″ × 44″ can be used with a 512 × 1024 pixel format and a pixel size of 0.″086 × 0.″043. A long slit (0.″1 × 20″) may also be used with the *f*/48 camera and the grating to provide spectroscopy at $R \simeq 1150$; this is the only two-dimensional slit-spectroscopic capability on HST. A prism may be inserted into the *f*/48 beam to separate overlapping orders in the direction perpendicular to the grating dispersion axis, thereby providing an efficient cross-dispersed mode for point-like sources.

The *f*/96 camera has a FOV of 11″ × 11″ and a pixel size of 0.″022 × 0.″022 in the standard 512 × 512 format; a field of 22″ × 22″ can be used with the 512 × 1024 pixel format with a pixel size of 0.″044 × 0.″022. This camera provides two occulting fingers (0.″4 and 0.″8 wide) at the entrance aperture, in order to block light from bright objects. The *f*/96 camera also has three polarization analyzers for polarimetric imaging. An *f*/288 reimager can be inserted into the *f*/96 system, in order to yield a FOV of 3.″7 × 3.″7 at a pixel size of 0.″0072 in the standard 512 × 512 format.

Both FOC detectors are three-stage image intensifiers, optically coupled to a television tube. Software centroids the individual photons. A variety of options is available for the size and shape of the area that is scanned and the spatial resolution. The dynamic range and limiting magnitude of the FOC depend on the readout format and the desired signal-to-noise ratio, but the FOC is expected to detect stellar objects as faint as $m_U = 28$ to 29 in a broad bandpass, with linear response to sources as bright as $m_U = 21$ or a U surface brightness of 15 mag arcsec^{-2}.

In comparing the FOC and WF/PC, proposers should note the following: (1) the FOC provides the higher angular resolution at all wavelengths, and the WF/PC provides the larger field of view; (2) the FOC is faster below about 4500 Å, while the WF/PC is faster above 4500 Å.

+8500 Angstroms

11.3 Faint Object Spectrograph (FOS)

The FOS performs low-resolution ($R \simeq 250$ and 1300) spectroscopy of faint sources in the wavelength range 1150 to 8500 Å. A variety of single and paired apertures of different sizes and shapes is available to support special applications, including beam-switched sky measurements and occultation of a bright central source. Linear and circular spectropolarimetry are also available.

In the $R = 250$ mode the dispersers are two gratings and a prism, while in the $R = 1300$ mode six gratings are available to cover the full wavelength range. The detectors are two 512-element Digicons, one operating from 1150 to 5500 Å ("blue"), and the other from 1800 to 8500 Å ("red").

The FOS can acquire data in accumulation, rapid-readout, and periodic modes. Time resolution as short as 20 ms can be achieved. The electron image is magnetically stepped through a programmed pattern during the observations, in order to provide for oversampling, compensation of sensitivity variations along the Digicon array, sky measurements, and/or measurement of orthogonally polarized images. Normally the data are read out at intervals that are short compared to the exposure time.

The FOS is expected to reach the following approximate visual magnitudes with S/N = 5 in one hour: 22 at "high" resolution, and 26 with the low-resolution prism.

11.4 Goddard High Resolution Spectrograph (GHRS)

+3200 Angstroms

?

The GHRS may be used for spectroscopy at resolving powers of $R = 2000$, 20,000 and 100,000 in the wavelength range 1150 to 3200 Å. Two entrance apertures are available, which are 0$''$.25 square and 2$''$ square projected on the sky. There is one grating used at the lowest resolution (1150–1800 Å only), and there are four gratings used at medium resolution. The highest resolution is provided by an echelle combined with either of two cross dispersers, depending upon the desired wavelength range. The detectors are two 512-element Digicons, one sensitive from 1150 to 1700 Å, and the other from 1150 to 3200 Å. The wavelength coverage per exposure ranges from 6 Å at the highest resolution and shortest wavelengths to 285 Å at the lowest resolution.

The GHRS acquires data in either an accumulation or a rapid-readout mode. In the accumulation mode, the electron image is magnetically stepped through a programmed pattern to allow for oversampling, compensation of sensitivity variations along the Digicon array, and instrumental background measurements. In addition, there is automatic Doppler compensation for the orbital motion of HST, and an optional exposure-meter function that can make onboard decisions about termination of exposures. None of these functions is available in the rapid-readout mode, but time-resolved spectra may be obtained with integrations as short as 50 ms.

The GHRS is expected to attain S/N = 10 at 1200–1500 Å in 1000 s, for lightly reddened B0 V stars of visual magnitudes 19, 16, and 14, in the low-, medium-, and high-resolution configurations, respectively.

11.5 High Speed Photometer (HSP)

The HSP is designed to take advantage of the lack of atmospheric scintillation for a telescope in orbit, as well as to provide good ultraviolet performance. Integrations as short as 10 μs are possible, over a broad wavelength range (1200 to 8000 Å), and polarimetry is also possible. Observations may be carried out through aperture diameters of $0''.4$ or $1''.0$ with the visual (VIS) and ultraviolet (UV) detectors, and $0''.65$ with the polarimetry (POL) detector. There are also $6''$ and $10''$ apertures that are used for target acquisition.

HSP is unique among the SIs aboard HST in having no internal moving parts. Instead, a large variety of fixed aperture/filter combinations is distributed in the focal plane; selection is accomplished by moving the telescope so as to place the target in the desired aperture behind the desired filter.

The HSP detectors are four image-dissector tubes (IDTs) and one photomultiplier tube (PMT). The limiting magnitude (through the "B" filter) is approximately $V = 24$, for a 2000-sec exposure and S/N = 10; the count rate is about 50,000 per second at $V = 10$. The dead time is only 40 ns, allowing the accurate determination of counting rates up to 10^6 per second. Brighter stars (up to $V = 0$) can be observed by measuring the current from the detectors, rather than using pulse counting.

A variety of ultraviolet and visual filters and polarizers is available. The HSP also has modes in which a beam splitter allows simultaneous high-speed photometry at 3200 Å (with one of the IDTs) and 7500 Å (with the PMT), and in which observations alternating rapidly between two colors are possible.

11.6 Fine Guidance Sensors (FGS)

Each of the three FGSs is capable of measuring the relative positions of stars (or slowly moving asteroids) within its FOV. The total usable magnitude range is $m_V = 4.0$ to 18.0. In normal operation, two of the sensors are used for spacecraft attitude control, allowing the third one (the "prime" FGS) to be used for astrometric measurements.

Generally, a target star and 5 to 10 reference stars within the FOV annulus will be observed at a given epoch and compared to results from other epochs to yield relative proper motions and parallaxes. The effective FOV is reduced for parallax observations to about $4' \times 5'$, since for observations 6 months apart the telescope's roll angles will differ by 180° (see §9.2 and Appendix A3).

The FGS can be used to (1) measure the relative positions of fixed and moving sources to a precision of a few milli-arc seconds (most likely 3 mas); (2) measure the separation, position angle, brightness ratio, and total brightness of binary systems with separations larger than 5 mas and brightness difference less than 3 mag; (3) measure the apparent diameters of stars in the 5–50 mas range; and (4) roughly measure the color indices of stars (± 0.1 mag). Many of these measurements can be performed on non-stellar objects.

11.7 Calibration Overview

Calibration information will be required in order to interpret the raw scientific data from the SIs. Such information may be obtained via laboratory measurements before launch, internal measurements in the SI in orbit, or observations of calibration sources in the sky. A Calibration Data Base (CDB) will be maintained at STScI as part of the Space Telescope Science Data Analysis Software (STSDAS), so that calibration information will be readily available to observers.

As a service to HST users, STScI will carry out calibrations of the SIs in their standard modes; therefore, most GOs will not have to request their own calibration observations. The calibrations that are planned for Cycle 1 are described in the *Cycle 1 Calibration Plan* (see §2.2). Examples of these calibration measurements are the following:

- Wavelength scales for spectroscopic modes, determined from spectra of calibration lamps and astronomical emission-line sources.
- Dark signals in the SIs as functions of geomagnetic coordinates.
- Plate scales and spatial distortions of all imaging SIs, via observations of standard astrometric fields.
- Spatial flat fields for the cameras.
- Spectral flat fields for the spectrographs, from observations of featureless stellar spectra.
- Absolute sensitivities of the SIs, via observations of standard stars, for all standard instrument modes.
- Point-spread functions.

Standard astronomical calibration sources for use by HST in orbit are specified in documents that are available from the calibration-targets staff contact listed in Appendix A1 (see also D. A. Turnshek *et al.*, *Astron. J.*, **99**, 1243, 1990). Prospective proposers are encouraged to contact the appropriate instrument scientist to discuss SI calibration, especially if they have demanding calibration requirements that will require allocation of additional telescope time by the TAC.

Proposers should note that understanding of SI performance will improve during the HST mission; the CDB will be updated periodically to reflect this. As calibration data become available, they will be documented in the *STScI Newsletter*, in the astronomical literature, and in the user-accessible CDB.

Data from all standard observing modes will be automatically calibrated by RSDP (see §8.1), and both raw and calibrated data will be provided to GOs. GOs may recalibrate their data using STSDAS, if desired. Data taken in non-standard modes will usually not be calibrated automatically; in such cases, calibration is left to the GO.

As discussed in §7.5, there will not be a 12-month proprietary period for calibration observations made by STScI.

11.8 The HST Field of View

11.8.1 FOV Diagram

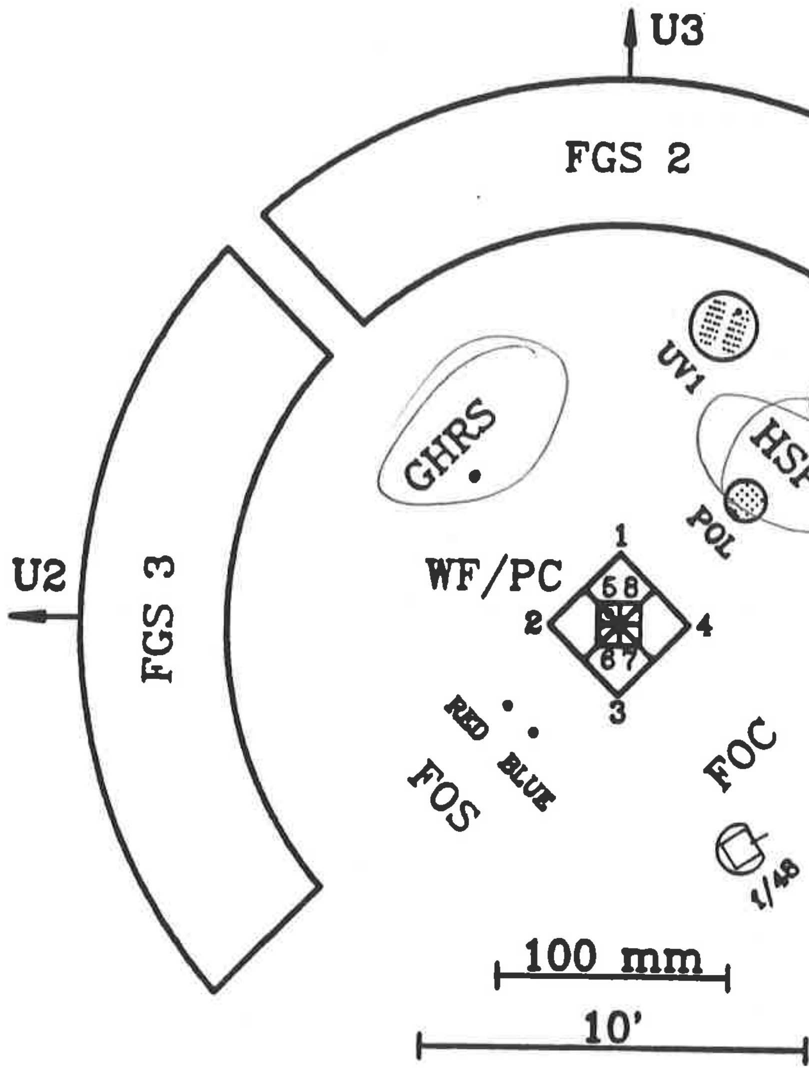
Fig. 11-1 shows the layout of the instrument entrance apertures in the telescope focal plane. The layout is shown as projected onto the sky. The *Instrument Handbooks* should be consulted for details of each instrument's aperture sizes and orientations.

In order to avoid confusion with the spacecraft's V2 and V3 axes, we define two new axes, U2 and U3, which are fixed in the focal plane as projected onto the sky. At nominal roll (see §9.2 and Appendix A3), the U3 axis will point toward the antisun.

11.8.2 Aperture Locations

Table 11-3 lists the relative locations of the SI apertures; the U2,U3 coordinate system of Fig. 11-1 is used, and the linear dimensions have been converted to seconds of arc using a plate scale of 3.58 arcsec mm^{-1}. This information may be needed, for example, by proposers planning coordinated parallel observations (§4.2).

Because of the large number of apertures (HSP, for example, has 174), it is impractical to give the positions for all of them. Instead, Table 11-3 gives the nominal U2 and U3 coordinates of the centers of the camera and FGS FOVs, the FOS and GHRS apertures,



HST Field of View
(As projected onto the sky)

Figure 11-1

and the HSP aperture plates. (For the FOC, the centers of the detector formats, not the apertures, are given.) The column labelled "Maximum Variation" gives the largest possible target offsets from these centers.

It should be noted that the locations listed in Table 11-3 have not been corrected for field curvature; however, this is a small effect, amounting to 5″ at the outer edge of the HST FOV. The aperture locations may also have shifted by up to a few seconds of arc now that HST is in orbit, due to the release of gravitational forces. The entries should therefore be regarded only as nominal values.

11.9 Bright-Object Constraints

Several of the SIs must be protected against over-illumination; these constraints

Table 11-3
Nominal Relative Aperture Locations

Instrument	Aperture	U2	U3	Maximum Variation
		(arcsec)	(arcsec)	(arcsec)
WF/PC	WFC	0	0	109
	PC	0	0	46
FOC	$f/48$	−197	−341	32
	Long slit	−228	−323	10
	$f/96$	−339	−196	16
	$f/288$	−330	−198	5
FOS	Blue	130	−170	3.0
	Red	170	−130	3.0
GHRS		228	228	1.4
HSP	POL	−193	193	26
	UV1	−154	460	42
	VIS	−343	343	42
	UV2	−460	154	42
FGS	FGS-1	−726	0	
	FGS-2	0	726	
	FGS-3	726	0	

are discussed below. Observations that violate these constraints should not be proposed. Note that there may be non-linearity, saturation, or residual-image effects that set in at substantially fainter limits than the safety limits discussed below; the *Instrument Handbooks* should be consulted for details.

1. *WF/PC.* No safety-related brightness limits.
2. *FOC.* May be damaged by continuous illumination by a star of V magnitude 8 anywhere in the FOC field of view, or by an extended source with V surface brightness of 13 mag arcsec^{-2}.
3. *FOS.* V-magnitude limits of −1.3 to 12.3, depending on the grating or mirror used.
4. *GHRS.* Limit of $V \simeq 3$ for some acquisition observations.
5. *HSP.* No safety-related brightness limits.
6. *FGS.* May not observe stars brighter than $V = 1.8$.

12. Orbital Constraints

HST is in a relatively low orbit, so that it can be retrieved or serviced using the Space Shuttle Orbiter. Table 12-1 presents a summary of the nominal orbital parameters. The low orbit imposes a number of constraints upon scientific programs, which will be discussed in this section.

Table 12-1
HST Nominal Orbital Parameters

Altitude	613 km (331 naut. mi.)
Inclination	28°.5
Orbital period	96.7 min
Orbital precession period	56.4 days

12.1 Target Viewing Times

As seen from HST, the Earth occults most of the sky for varying lengths of time during each 97-min orbit. Therefore, many exposures will have to be broken into shorter sub-exposures in order to accommodate the occultations and guide-star reacquisitions. For photon-counting instruments (FOC, FOS, GHRS, HSP, and FGS), this restriction creates mainly a sampling problem. For the WF/PC, which integrates, continuous long exposures accumulate dark signal and particle background, even with the shutter closed; however, breaking the exposure into shorter segments will increase the readout noise.

Targets lying in the orbital plane are unobservable the longest, about 36 min per orbit. However, this is a purely geometric limit and does not include any time lost to Earth-limb avoidance limits (see §9.2), guide-star acquisition or reacquisition, instrument setup, and SAA avoidance (§12.2).

The length of target occultation decreases with distance from the spacecraft orbital plane. Targets lying within 24° of the orbital poles are not occulted at all during the HST orbit. However, the size of the resulting "continuous viewing zones" is substantially reduced by the 11° and 20° Earth-limb avoidance angles, such that the continuous viewing zones extend only 13° from the orbital pole in the direction toward the Sun, and 4° from the pole in the direction away from the Sun. Note also that scattered Earth light may be excessive during some portions of the HST orbit. As an example, for targets in the continuous viewing zones, the scattered Earth light (in the V band) will rise to at least 20 mag arcsec^{-2} and can reach 11 mag arcsec^{-2}.

Since the orbital poles lie 28°.5 from the celestial poles, and precess with a period of about 56 days, any target located in the declination zones $48^\circ.5 \leq |\delta| \leq 74^\circ.5$ will be in a continuous viewing zone at some time during the 56-day precessional cycle. However, targets will remain in the continuous viewing zone for intervals of only a few days, and observations of them may be difficult to schedule. Observers are therefore advised not to rely on the apparent advantages of the continuous viewing zones, unless their programs absolutely require long, uninterrupted observations and can tolerate significant background light.

2

When observations are made under the pointing constraints outlined in §9.2 (*i.e.*, with the telescope pointing more than 50° from the unocculted Sun, 80° from the bright limb of the Earth, and 30° from the full Moon), the sky background will be limited only by zodiacal light. The maximum uninterrupted length of such "dark time" is about 48 min (which occurs for a target in the antisun direction with the Sun lying in the orbital plane of the spacecraft).

12.2 South Atlantic Anomaly

Above South America and the South Atlantic Ocean lies a lower extension of the

Van Allen radiation belts called the South Atlantic Anomaly (SAA). HST passes through the SAA during about six of its orbits per day.

It is expected that no astronomical or calibration observations will be possible during passages through the most intense parts of the SAA, because the high particle radiation will produce excessive noise in the detectors. Moreover, following the emergence of HST from the SAA the detectors may be slightly noisier than average because of radiation-induced phosphorescence. SAA passages will limit the longest possible single exposures, even in the continuous viewing zones, to about 10-12 hours.

12.3 Spacecraft Position in Orbit

Because the HST's orbit is low, atmospheric drag is significant. Moreover, the amount of drag will vary, depending on the orientation of the telescope and the density of the atmosphere, which is determined by the level of solar activity. The chief manifestation of this effect is that it will be difficult to predict in advance where HST will be in its orbit at a given time. The position error may become as large as 30 km within two days of a determination of the position of the spacecraft in its orbit. A predicted position 44 days in the future may be up to ~4000 km (95% confidence level) in error.

This positional uncertainty will affect observers of time-critical phenomena (see §4.1), who will not know at the time of proposal preparation whether or not the target will be behind the Earth at the time of the event. In the worst case, the observer will not know if a given event is observable until the scheduling process is completed a few days before the event.

13. Target Acquisition and Guiding

The optical performance of HST requires a guidance system capable of milliarcsecond stability, in order to avoid significant degradation of the optical image. As with most ground-based telescopes, HST will use guide stars located at the edge of its field of view (FOV). Unlike ground-based telescopes, however, HST requires two guide stars in order to control the pitch, yaw, and roll axes of the telescope. STScI will select guide-star pairs in advance for all observations.

13.1 The Fine Guidance Sensors

Rate gyros are the principal guidance sensors for large maneuvers and high-frequency (> 1 Hz) pointing control. At lower frequencies, the optical guiders, called Fine Guidance Sensors (FGSs), provide for pointing stability, as well as for precision maneuvers such as moving-target tracking (see §13.5) and offsets and spatial scans (§13.6).

Each of the three FGSs covers a 90° sector in the outer portion of the HST FOV (see Fig. 11-1). Optics within the FGS correct for the field astigmatism and, using precision motor-encoder combinations, select a $5'' \times 5''$ portion of the FGS FOV into an x, y interferometer system. Once an FGS is locked onto a star, the motor-encoders are driven to track the guide star. The encoder positions are used by the pointing-control software to update the current telescope attitude and correct the pointing.

The FGS has two guiding modes, called Coarse Track and Fine Lock, the latter of which provides more precise guiding of the telescope but takes longer to establish following a slew to a new target. Estimated acquisition times are 10-12 minutes for Coarse Track, and an additional 8-10 minutes to establish Fine Lock. Because of the desire to maximize scientific usage of the HST, Coarse Track is the default guiding mode for many instrument observing modes. Coarse Track also has the ~~advantage of not being~~ susceptible to lock-on failure owing to stellar duplicity.

The predicted rms guiding precision for Coarse Track is 0''.010–0''.012. For Fine Lock the precision is predicted to improve to 0''.007. ~~It is also~~ possible to obtain short exposures with less overhead time using only the gyros, if a drift rate of about 0''.010/sec can be tolerated.

Table 13-1 lists the default guiding modes that are currently established for the various Scientific Instruments. Additional guiding modes are under study, and could be implemented at a later time; moreover, the actual guiding performance in orbit may differ from that discussed above. Observers may override the defaults in their Phase II specifications.

Table 13-1
Default Guiding Modes

Instrument	Type of Observation	Default Guiding Mode
WF/PC	Wide Field Camera	Coarse Track
	Planetary Camera	Fine Lock
FOC	*f*/48 imaging	Coarse Track
	All other observations	Fine Lock
FOS	0''.1 apertures	~~Fine Lock~~
	All other observations	Coarse Track
GHRS	All observations	~~Coarse Track~~
~~HSP~~	Polarization observations	Fine Lock
	Observations requiring S/N > 200	Fine Lock
	0''.4 apertures	Fine Lock
	All other observations	Coarse Track
FGS	All observations	Fine Lock

13.2 Guide Stars

The selection of guide stars (GSs) for HST observations will be carried out by the Guide Star Selection System (GSSS) at STScI; hence most GOs will only need to supply accurate coordinates for their targets, as described in §13.3. However, an understanding of the GSSS will be useful to observers.

13.2.1 Overview

For each scheduled HST observation, GSSS will provide positions and magnitudes for pairs of GSs in the range $9.0 \leq m_V \leq 14.5$, determined from Schmidt survey plates (or occasionally from other standard astronomical survey plates). The following specific data will be provided by GSSS (quoted errors are 1σ):

- Relative positions of GSs with an accuracy of ±0''.5 in the northern hemisphere and ±0''.8 in the southern hemisphere
- GS magnitudes with an accuracy of ±0.4 mag in the FGS magnitude system (based on the spectral response, 4600 to 7000 Å, of the FGS optics and detector)

Some targets will prove impossible to observe because suitable GSs do not exist and telescope drift (on gyros) during an unguided exposure would be unacceptable. It is estimated that about 15% of targets near the galactic poles will not have a suitable pair of GSs (if the telescope roll angle is fixed; the percentage decreases rapidly if the roll angle is allowed to vary, and with decreasing galactic latitude). Some GSs will prove to be previously unrecognized close visual binaries, and will be unsuitable for Fine Lock guidance. (The FGS will be unable to establish Fine Lock on binaries with $\Delta m < 3$ and separations of $0\overset{''}{.}015$ to $0\overset{''}{.}25$, and, in general, many such binaries will not be recognized until the FGS attempts to lock onto them.)

13.2.2 The Guide Star Catalog

The required whole-sky coverage made it necessary for STScI to assemble a collection of survey plates as the basis for construction of a catalog of GS candidates. For the northern hemisphere (for which proper motions have now outdated the *Palomar Sky Atlas*), a special "Quick-V" survey was conducted for STScI with the 1.2-m Schmidt telescope at Palomar Observatory. The equatorial region and the southern hemisphere are covered by the SERC-J survey and its equatorial extension. Table 13-2 gives details of the survey plates used by GSSS.

Table 13-2
GSSS Survey Plate Collection

	SERC-J	SERC-J Extension	Quick V
Declinations covered	$-90°$ to $-17\overset{\circ}{.}5$	$-17\overset{\circ}{.}5$ to $+3°$	$+3°$ to $+90°$
Mean epoch	1976	1981	1982
Filter	GG395	GG395	Wr 12 or GG495
Emulsion	IIIa-J	IIIa-J	IIa-D
Magnitude limit	22.5 to 23.0	22.5 to 23.0	19.0
Scale (arcsec mm^{-1})	67.2	67.2	67.2

In addition to the survey plates, supplemental plates (usually short exposures) are used for the vicinities of bright stars and for certain very crowded regions, where GS information could not be obtained from the standard survey plate material. Examples of such areas are the Andromeda Nebula, the Magellanic Clouds, and the galactic-center region.

The *Guide Star Catalog* (GSC), which resulted from the digitization and analysis of the plate collection, contains information on about 18 million objects to 14.5 mag. The stellar positions in the GSC are on the system of the AGK3 in the northern hemisphere, the *SAO Catalog* in the southern hemisphere north of $-65°$, and the *Cape Photographic Catalog* south of $-65°$.

13.3 Target Coordinates and GASP

The Observation Summary Form submitted with Phase I observing proposals must specify coordinates for all fixed targets, but these coordinates need only be of sufficient accuracy for the internal and scientific reviews described in §6 (*i.e.*, $\pm 1\overset{'}{.}0$ or better). (For solar-system targets, see §13.5.)

As part of the Phase II information that will be required from all successful proposers (see §7.1), GOs will be asked to provide target coordinates that are sufficiently accurate for the actual HST acquisitions and observations. Table 13-3 lists the acquisition-aperture sizes and the required Phase II coordinate accuracies for the various instruments. Note that in many cases the target coordinates will have to be accurate to about $\pm 1''$.

Table 13-3
Acquisition-Aperture Sizes and Coordinate Accuracies

Instrument	Aperture Size	Remarks	Required Coordinate Accuracy (1σ)
WFC	$154'' \times 154''$		$15''$
PC	$66'' \times 66''$		$6''$
FOC $f/48$	$22'' \times 22''$	512×512 format	$4''$
$f/96$	$11'' \times 11''$	512×512 format	$2''$
$f/288$	$3''.7 \times 3''.7$	512×512 format	$1''$
FOS	$4''.3 \times 4''.3$		$1''$
GHRS	$10'' \times 10''$	using spiral search	$1''$
HSP	$10''$ diameter	Photometry	$1''$
	$6''$ diameter	Polarimetry	$1''$
FGS	$\sim 20''$ diameter	using nominal spiral search	$5''$

The coordinates for stellar targets that are contained in the GSC and in standard positional catalogs (SAO, AGK3, etc.) are, of course, sufficiently accurate for HST observations. For fainter objects, GOs should plan to use the resources of the GSSS Astrometric Support Package (GASP) software that is available at STScI for determining coordinates of any objects visible on the plate collection in the reference frame of the GSC.

Details on usage of the GSC and GASP will be provided as part of the Phase II information package to successful proposers.

Stellar proper motions (and parallaxes) will also be requested during Phase II, since even relatively small stellar motions may be surprisingly significant. For example, a proper motion of $\sim 0''.06$ yr^{-1} would be sufficient to move a target out of the FOS acquisition aperture for an epoch difference of ~ 35 years. Since GASP is presently not capable of providing proper motions and parallaxes, Phase II proposers should be prepared to supply such information themselves.

13.4 Target-Acquisition Methods

In general, an astronomical target must be "acquired" (*i.e.*, precisely centered in the appropriate instrument aperture) before HST can make any scientific observations of it.

Proposers should determine the appropriate acquisition strategies for their scientific observations. The acquisition method(s) should be specified in Phase I proposals (on the Observation Summary Form), as discussed in the *Phase I Proposal Instructions*.

Four different methods are available for target acquisition, depending on the SI used, its aperture sizes, and the accuracy with which the target coordinates are known. The following subsections give an overview of target-acquisition techniques; special considerations that arise for solar-system targets are discussed in §13.5.2. Details are discussed in the *Instrument Handbooks* and the *Target Acquisition Handbooks*; these documents are available from STScI (see §2.2).

13.4.1 Interactive Acquisition

For an interactive acquisition, HST will be moved to a nominal position near the target, an acquisition image will be obtained and transmitted to the ground, and the field will be displayed for the observer (who must be present at STScI). The displayed image could be from the WF/PC or FOC, or could be a "pseudoimage" from the FOS, GHRS, or HSP. The observer will then select the desired target or position.

When the selection has been made, offsets to center the target in the desired SI aperture are calculated, the telescope is moved, and observations begin. (The scientific observation could possibly involve a different SI from the acquisition observation, if the WF/PC or FOC were used to generate acquisition images for one of the other SIs. Such "SI-assisted" acquisitions may be limited by availability of guide stars that will remain in the FGS field of view during both the acquisition and the observation with a second SI.)

Interactive target acquisition places substantial demands on scheduling and data transmission, so that use of this method should be made only when absolutely necessary. This method is intended primarily for moving targets, variable objects, and targets of opportunity. Non-transient objects can usually be acquired with one of the other less demanding methods discussed below.

13.4.2 Early Acquisition

In many cases it will be possible to avoid an interactive acquisition by requesting an "early acquisition." In this case, an acquisition image of the target is taken several months before the actual observation, permitting the GO to identify, and measure coordinates for, the desired target on the image. STSDAS tools will be available for these purposes. An early acquisition will normally be appropriate for very faint objects or objects that are unresolved from the ground; it should not be requested in cases where the information could be obtained from ground-based observations.

It may occasionally happen that a proposer requests an acquisition image that is already contained in a GTO program, which would be protected according to the NASA policies outlined in §7.5; if an early-acquisition image is determined to be in conflict with a protected GTO image, the GO-requested image may still be permitted, but may only be used for acquisition purposes.

13.4.3 Onboard Acquisition

Onboard acquisition is the only acquisition method available for the FGS, and is the preferred method for FOC, FOS, GHRS, and HSP. It is not available for the WF/PC. The telescope will be pointed so as to place the specified target position within the appropriate acquisition aperture of the relevant instrument. Onboard software will determine the precise position of the object and then center it in the acquisition aperture. This centering could, if desired, be followed by an offset to another aperture or to another object.

13.4.4 *Blind Acquisition*

When this method is used, the telescope is pointed to the target coordinates provided by the observer, and the observations begin without any further telescope maneuvers. This method is appropriate only when the target coordinates are known to ~10% of the size of the instrument aperture. It is the preferred method with the WF/PC and FOC, except when the observer wishes to place a target precisely on the WF/PC neutral-density spot or on the FOC long slit or occulting fingers, in which case an interactive or onboard acquisition (if available) should be used.

13.5 Solar-System Targets

Objects within the solar system have apparent motions with respect to the fixed stars. HST will have extensive capabilities to point at and track moving targets, including planets, their satellites, and surface features on them, with sub-arcsecond accuracy.

HST's unprecedented spatial resolution will force planetary scientists to consider their pointing requirements at new levels of detail. Two specific aspects of solar-system observations are discussed below: the initial acquisition of a moving target, and the subsequent tracking of the target during the scientific observations. Only an overview of the current moving-target capabilities is given here. Updates will be available from the sources described in §2.

13.5.1 *Tracking Capabilities*

Provided that the orbital elements of the target are sufficiently well known, and the apparent motion of the target relative to the fixed stars is less than 0.2 arcsec s^{-1}, HST will be capable of tracking moving targets with the same precision as for fixed targets (see §13.1). This is accomplished by maintaining FGS Coarse Track or Fine Lock on the guide stars, and driving the FGS star sensors in the appropriate path, thus moving HST so as to track the target. If the apparent motion exceeds 0.2 arcsec s^{-1}, then the observations can only be done under gyro control, with a potential loss in precision that depends on the length of the observation.

The track for a moving target is derived from its orbital elements. Orbital elements for all of the planets and most of their satellites are available at STScI. Moreover, STScI has access to the ASTCOM data base, maintained by the Jet Propulsion Laboratory (JPL), which includes orbital elements for all of the numbered asteroids and many periodic comets. For other objects, the GO must provide orbital elements for the target in Phase II.

13.5.2 *Acquisition Techniques*

The most difficult aspect of HST observations of moving targets is the acquisition of the target prior to the scientific observations. The choice of acquisition strategy can have a very large impact on the observing efficiency of a given program. Blind acquisitions (§13.4.1) will be the most efficient method, but can result in pointing errors of ~1–3 arcseconds. Observations made with apertures of this size (or smaller) will therefore require use of an onboard or interactive acquisition. Of these two, onboard acquisition is preferred because it takes less time. However, the onboard acquisition capabilities vary significantly depending upon the SI being used and the size of the target. Generally, accurate onboard acquisitions are possible if the target diameter is smaller than 2″. The bright optocenters of comets can be acquired with onboard acquisition, but only with the FOS and (possibly) the HSP.

Onboard acquisitions of a giant planet are best done by first acquiring one of its satellites, and then offsetting to the planet. The technique of last resort (which provides the most flexibility) is an interactive (real-time) target acquisition. This method has the greatest demands on spacecraft time, and thus should be used sparingly.

The only major capability that is not yet supported is the ability to select and track a planetary surface feature identified in real-time (*e.g.*, a short-lived cloud feature found on Jupiter during an interactive acquisition).

Phase I proposers are encouraged to investigate their acquisition strategies carefully, and to consult the moving-target programs contact person at STScI (see Appendix A1) for more detailed information.

13.6 Offsets and Spatial Scans

It is anticipated that offsets (using the same guide stars) can be performed to an accuracy of about $\pm 0\overset{''}{.}01$. The sizes of offsets are limited by the requirement that both guide stars remain within the respective FOVs of their FGSs.

It will also be possible to obtain data while HST scans across a small region of the sky. In all cases the region scanned must be a parallelogram (or a single scan line). Two types of "spatial scans" (*i.e.* raster scans) may be requested:

1. *Continuous scan.* In this case, data are continually obtained while the telescope is in motion.

2. *Dwell scan.* In this case, the telescope stops its motion periodically during the scan, and data are obtained only when the telescope is not in motion.

GOs who have requested spatial scans will be asked to provide the following information as part of the Phase II specifications (see §7.1): number of scan lines (1–99), length and position angle of each scan line, offset between scan lines, scan rate, and angle between sides of the scan parallelogram. For dwell scans, the number of dwells per scan line and the time per dwell must also be provided. The possible scan area will be limited by the requirement that the same guide stars be used throughout the scan, and the maximum possible scan rate for continuous scans is 5 arcsec s^{-1}. Spatial scans cannot be interrupted and must therefore be completed within one orbital target-visibility period. For early planning stages, spatial scans requiring more than 45 minutes of spacecraft time should be avoided.

14. Real-Time Observing

A limited capability for real-time interactions during HST observing will be available.

Interactive acquisitions (§13.4.1) and small maneuvers will be permitted in real time. Slews larger than $\sim 2'$ are not permitted in real time, but maneuvers between different apertures of an SI, or to alternate nearby targets, will be permitted. Such maneuvers will be limited by the requirement that the same pair of guide stars be used to accomplish all such pointings.

Real-time interactions with HST will make use of the Observation Support System (OSS) at STScI. The science data to be used for evaluation will arrive in the OSS within seconds of transmission from HST. The OSS will have image- and graphics-display stations and basic data-manipulation capabilities. The GO will make a reconfiguration or maneuver decision based on evaluation of the data, and the appropriate command request will be sent from OSS to the control center at Goddard Space Flight Center. As described in §7.4, STScI

OAs and SOSs will be present to assist the GO in the use of OSS capabilities and to execute the command requests.

15. Target-of-Opportunity Observations

Some target-of-opportunity programs (see §3.1.2) will require that observations begin as soon as possible upon notification of the occurrence of an event. This section addresses the time delay that will occur between notification and the actual start of observations. Because of the major disruption of the HST observing schedule, such interruptions will usually be limited to a maximum of once per month.

When notifying STScI of the appearance of the target of opportunity, the GO will supply all parameters that were unspecified in the original proposal, and these will be entered into the proposal system. A review of the completed proposal will be made to assure the safety of the observations, to verify that the program complies with the original observing-time allocation, and to identify a breakpoint in the presently executing Science Mission Specification (SMS). After approval by the Director, the program will be entered into the scheduling system, the previous SMS will be re-planned to contain the new observations, and the commands will be generated to conduct the observations. The beginning of the observations of the target of opportunity must be delayed sufficiently to allow the new commands to be generated, to uplink the commands to the spacecraft at an available opportunity, to bring the required SIs from hold to operate mode (if necessary), and to slew the telescope to the target of opportunity.

The time necessary to conduct these activities will vary with the particular circumstances, but it is likely that at least 48 hours will elapse between the time of the original notification and the beginning of observations of the target.

16. Parallel Observations

Parallel observations (see §4.2) provide another mechanism for increasing the efficiency of the HST observatory. This section discusses various technical aspects of parallel observing. A discussion of designation of generic targets for parallel observations is given in the *Phase I Proposal Instructions.* The relative aperture locations are listed in Table 11-3.

Parallel observations will not be permitted to interfere significantly with primary observations; this restriction applies both to concurrent and subsequent observations. Some examples of this policy are the following:

- The parallel observation will not be made if its inclusion would shorten the primary observation.
- Long wide-band exposures by the WF/PC or the FOC at low galactic latitudes, which will probably leave residual images from "bright" stars in the FOV that will contaminate following observations, will not be scheduled as parallel science.
- Parallel observations will have lower priority on stored command capacity and on telemetry data volume.

There are no known power or thermal-control constraints that will prevent any two SIs from operating simultaneously (but simultaneous operation of three SIs is not permitted by spacecraft power requirements). However, telemetry does place some restrictions on the volume of parallel science data. The average data rate is not to exceed 3×10^9 bits/day and peaks may not exceed 10^{10} bits/day. These figures correspond to approximately 70 and

218 WF/PC observations per day, respectively. However, the realities of TDRSS access will usually limit the daily data volume to not much more than the average data rate.