The Hubble Space Telescope

This description of the Hubble Space Telescope is taken from the Cycle 7 Call for proposals, edited by Palle Møller.

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**System Overview**

**Telescope Description**

As shown in Fig. 1, *HST*’s Scientific Instruments (SIs) are mounted in bays behind the primary mirror. The Wide Field Planetary Camera 2 occupies one of the radial bays, with an attached 45 degree pickoff mirror that allows it to receive the on-axis beam. Three SIs (Faint Object Camera, Near Infrared Camera and Multi-Object Spectrometer, and Space Telescope Imaging Spectrograph) are mounted in the axial bays and receive images several arcminutes off-axis.

![Hubble Space Telescope](image)

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

During the servicing mission in December 1993, the astronauts installed the Corrective Optics Space Telescope Axial Replacement (COSTAR) in the fourth axial bay (in place of the High Speed Photometer). COSTAR deployed corrective reflecting optics in the optical paths in front of the Faint Object Camera, thus removing the effects of the primary mirror's spherical aberration. In addition the Wide Field and Planetary Camera (WF/PC) was replaced by the WFPC2, which contains internal optics to correct the spherical aberration.

The Fine Guidance Sensors (FGSs) occupy the other three radial bays and receive light 10-14 arcminutes off-axis. Since at most two FGSs are required to guide the telescope, it is possible to conduct astrometric observations with a third FGS. Their performance is unaffected by the installation of COSTAR.

For an overview of the SIs, see **Scientific Instrument Overview**. Detailed information about each SI is contained in separate **Instrument Handbooks**.

*HST* receives electrical power from two solar arrays (see Fig. 1), which are turned (and the spacecraft rolled about its optical axis) so that the panels face the incident sunlight. During the 1993 servicing mission the astronauts installed new solar arrays, which have significantly reduced the thermally induced vibrations that the old arrays had been producing. Nickel-hydrogen batteries provide power during orbital night. The two high-gain antennas shown in Fig. 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.

In addition to STIS and NICMOS, the second servicing mission will replace several additional pieces of equipment. One of the FGSs (most likely FGS 2) will be replaced. The new FGS will have an adjustable fold flat to recover some of the performance capability lost by spherical aberration. A spare magnetic tape recorder will replace the failed ESTR-2. A solid state recorder (SSR) will replace ESTR-1, and will provide for a factor of 10 greater on-board data storage volume. This extra storage will be necessary to support parallel operations of the WFPC2, STIS, and NICMOS. It will also provide increased flexibility in scheduling *HST* observations, reducing the tight coupling with the TDRSS system.

**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. 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 orientation that optimizes the solar-array positioning with respect to the Sun is called the "nominal orientation."

It should be noted that the nominal orientation 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 times will, in general, be made at different orientations.
Some departures from nominal orientation are permitted during $HST$ observing (e.g., if a specific orientation is required at a specific date, or if the same orientation is required for observations made at different times). Roll is defined as the angle about the V1 axis between a given orientation and nominal orientation. Off-nominal rolls are restricted to approximately 5 degrees when the sun angle is between 50 degrees and 90 degrees, < 30 degrees when the sun angle is between 90 degrees and 178 degrees and is unlimited at anti-sun pointings of 178 degrees to 180 degrees.

$HST$ utilizes electrically driven reaction wheels to perform all maneuvering required for guide-star acquisition and pointing control. A separate set of rate gyroscopes is used to provide attitude information to the pointing control system. The servicing mission restored or replaced three gyros that had failed since the original launch, so that the spacecraft currently has a total of six operational gyros. Any three of these are the minimum required for telescope pointing control.

The slew rate is limited to approximately 6 degrees 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 9 additional minutes must be allowed for the FGSs to acquire a new pair of guide stars. As a result, large maneuvers are costly in time and are generally scheduled for periods of Earth occultation or crossing of the South Atlantic Anomaly.

The telescope does not generally observe targets within 50 degrees of the Sun, 15.5 degrees of any illuminated portion of the Earth, 7.6 degrees of the dark limb of the Earth, nor 9 degrees of the Moon. Following the first servicing mission, the telescope is again allowed to point directly away from the Sun.

There are exceptions to these rules for $HST$ pointing in certain cases. For instance, the bright Earth is 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. 1 will close automatically whenever $HST$ is pointed within 20 degrees 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, are unfortunately difficult or impossible to observe with $HST$, because of the 50 degree solar limit. When the scientific justification is compelling, observations of Venus and time-critical observations of other solar-system objects lying between 45 degrees and 50 degrees of the Sun may be carried out (this capability was successfully demonstrated in Cycle 4).

**Data Storage and Transmission**

The $HST$ observing schedule is constructed at STScI and forwarded to the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The $HST$ is 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 a set of satellites in geosynchronous orbit.

Commands to $HST$ originate at the STOCC and are sent via land-line or communications satellites to the TDRSS ground station at White Sands. From there the commands are sent via the appropriate TDRSS to $HST$. Scientific data are 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. Because of limited TDRSS availability, command
sequences for HST observations are normally uplinked periodically and stored in the onboard computers. 
HST then executes the observations automatically.

It is possible for observers at STScI to interact in real-time with HST for specific purposes, such as
certain target acquisitions. In practice, real-time interactions are difficult to schedule. Historically, during
normal operations, fewer than 50 real-time interactions have been required per year.

HST currently uses two onboard tape recorders to store scientific data. After the second servicing mission
a much larger capacity Solid State Recorder will be available. Except when real-time access is required,
most HST observations are stored to a recorder and read back to the ground several hours later. There are,
however, limits to the amount of data that can be handled by the ground system supporting HST. 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 could handle.

### Telescope Performance

#### Optical Performance

Because the primary mirror has about one-half wave of spherical aberration, the Optical Telescope
Assembly (OTA) did not achieve its design performance until after the December 1993 servicing
mission. Table 2 gives a summary of the excellent optical performance now being achieved.

**Table 2: HST Optical Characteristics and Performance**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Wavelength coverage (MgF2-overcoated aluminum)</td>
<td>1100 Å to 2.6 microns</td>
</tr>
<tr>
<td>Focal ratio (without COSTAR)</td>
<td>f/24</td>
</tr>
<tr>
<td>Plate scale (on axis, without COSTAR)</td>
<td>3.58 arcsec/mm</td>
</tr>
<tr>
<td>FWHM of WFPC2 images (at 6328 Å)</td>
<td>0.053 arcsec</td>
</tr>
<tr>
<td>WFPC2 encircled energy within 0.1” radius (at 6328 Å)</td>
<td>55-65%</td>
</tr>
<tr>
<td>FWHM of FOC images (at 4860 Å)</td>
<td>0.042 arcsec</td>
</tr>
<tr>
<td>FOC encircled energy within 0.1” radius (at 4860 Å)</td>
<td>86%</td>
</tr>
<tr>
<td>FWHM of NICMOS images (at 1.6 micron) [1]</td>
<td>0.14 arcsec</td>
</tr>
<tr>
<td>NICMOS encircled energy within 0.3” radius (at 1.6 micron) [1]</td>
<td>93%</td>
</tr>
</tbody>
</table>


Software has been developed at STScI for detailed simulations of HST images, which agree well with
actually observed (pre- and post-repair) images. This Telescope Image Modelling (TIM) software, with
its point-spread-function (PSF) library, is available for downloading from STEIS. Another set of
software specifically designed to simulate HST camera images, called TINYTIM, is also available.

A figure showing actual measurements of the PSF and encircled energy achieved with the Faint Object
Guiding Performance

HST's Pointing Control System (PCS) has two principal hardware components. Rate gyroscopes are the guidance sensors for large maneuvers and high-frequency (> 1 Hz) pointing control. At lower frequencies, the optical Fine Guidance Sensors (FGSs) provide for pointing stability, as well as for precision maneuvers such as moving-target tracking and offsets and spatial scans.

Each of the three FGSs covers a 90-degree sector in the outer portion of the HST field of view (FOV), as shown in Fig. 2. Optics within the FGS, using precision motor-encoder combinations, select a 5" x 5" region of sky into an x, y interferometer system. Once an FGS is locked onto a star, the motor-encoders are driven to track the interference fringe of the guide star. The encoder positions are used by the PCS software to update the current telescope attitude and correct the pointing.

The FGSs have two guiding modes: Fine Lock and Coarse Track. Fine Lock was designed to keep telescope jitter below 0.007" rms. Previously, there were periods of 2 to 5 minutes each orbit when there was increased jitter (0.020-0.050") due to thermal effects in the Solar Arrays. The combination of the new Solar Arrays and tuning of the pointing control system has successfully eliminated these effects. The telescope jitter is now routinely below the 0.007" rms level. A drift of up to 0.05" may occur over a timescale of 12 hours and is attributed to thermal effects as the spacecraft and FGSs are heated or cooled. Observers planning extended observations in 3 0.1" STIS slits should execute a target peak up maneuver every 4 orbits.

Coarse Track is now believed to cause degradation in mechanical bearings in the FGSs, and accordingly is no longer available as a guiding mode.

Guide-star acquisition times are typically 9 minutes. Reacquisitions following interruptions due to Earth occultations take about 6 minutes. It is also possible to take observations (primarily WFPC2 "snapshot" exposures) without guide stars, using only gyro pointing control. The absolute pointing accuracy using gyroes is about 14" (one sigma), and the pointing drifts at a rate of 1.4 +/- 0.7 mas s**-1.

Observing Time Availability

HST's "observing efficiency" may be defined as the fraction of the total time that is devoted to acquiring guide stars, acquiring astronomical targets, and exposing on them. In other words, the observing efficiency is defined as the ratio of "spacecraft time" to total time.

The main factors that limit the observing efficiency are (1) the low spacecraft orbit, with attendant frequent Earth occultation of most targets; (2) interruptions by passages through the South Atlantic Anomaly; (3) the relatively slow slew rate; (4) telemetry constraints; and (5) the performance of the scheduling algorithm.
Scientific Instrument Overview

The following Scientific Instruments (SIs) will be available on HST during Cycle 7:

- Wide Field Planetary Camera 2 (WFPC2)
- Faint Object Camera (FOC) (f/96), (f/48 for Long Slit Spectroscopy only)
- Space Telescope Imaging Spectrograph (STIS)
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS)
- Fine Guidance Sensors (FGS)

All of the SIs are permanently mounted at the HST focal plane, so that all except the WFPC2 receive light that is slightly off-axis. A schematic diagram of the telescope focal plane is given in Fig. 2.

Tables 3(a)-(e) provide a summary of the capabilities of the SIs. For some 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 five SIs. After examining Tables 3(a)-(e), prospective proposers should read these descriptions in order to determine which SIs are likely to be most suitable for their programs. Revised and updated Instrument Handbooks, which discuss the SIs in detail, have been distributed to institutional libraries, and are available from STScI. The Instrument Handbooks must be consulted before actual preparation of observing proposals. In addition, exposure simulators for the SIs are available to assist in the estimation of exposure times, as described in the Synphot User's Guide; users may contact the STScI Help Desk for more information.

Data from the following four SIs, which were removed from HST during the December 1993 servicing mission (WF/PC, HSP), or are planned for removal in February 1997, are now available only in archival form:

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

Overviews of the capabilities of these four instruments are provided in Appendix D, which should be consulted by persons interested in proposing Archival Research funding with WF/PC, HSP, FOS, and/or GHRS data. Archival data from the WFPC2, FOC and FGS are, of course, also available from past Cycles.

Table 3: HST Instrument Capabilities
### Table 3: HST Instrument Capabilities (continued)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Projected Aperture Size</th>
<th>Resolving Power (\lambda/\Delta\lambda)</th>
<th>Wavelength Range (Å)</th>
<th>Magnitude Limit[2]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(b) Slit Spectroscopy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOC f/48</td>
<td>0.063” x 12.5”</td>
<td>1150</td>
<td>1150-5400</td>
<td>21.5</td>
</tr>
<tr>
<td>STIS[9]</td>
<td>0.06”-2.0” x 25”</td>
<td>~100,000 through ~150</td>
<td>1150-3100</td>
<td>11.8-13.0</td>
</tr>
<tr>
<td></td>
<td>0.06”-2.0” x 51”</td>
<td>~30,000 through ~8000</td>
<td>1150-3100</td>
<td>12.7-15.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~700</td>
<td>1150-11,000</td>
<td>15.2-16.1-19.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.6-20.1-22.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>(c) Slitless Spectroscopy</strong></th>
<th>Projected Pixel Spacing on Sky</th>
<th>Resolving Power (\lambda/\Delta\lambda)</th>
<th>Wavelength Range (Å)</th>
<th>Magnitude Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>WFPC2[7]</td>
<td>0.1”</td>
<td>~100</td>
<td>3700-9800</td>
<td>25</td>
</tr>
<tr>
<td>FOC f/96</td>
<td>0.014”</td>
<td>100 at 1500 Å</td>
<td>1150-6000</td>
<td>20.3</td>
</tr>
<tr>
<td>NICMOS</td>
<td>0.2”</td>
<td>200</td>
<td>8000-25,000</td>
<td>21, 20, 16</td>
</tr>
<tr>
<td>STIS</td>
<td>0.05”</td>
<td>~700-8000</td>
<td>2000-11,000</td>
<td>See slit spectroscopy above</td>
</tr>
<tr>
<td></td>
<td>0.024”</td>
<td>~700-8000</td>
<td>1150-3100</td>
<td></td>
</tr>
</tbody>
</table>
(d) Positional Astrometry

| Instrument | Field of View | Positional Precision | Wavelength Range (Å) | Magnitude Limit[
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FGS</td>
<td>5' x 4'</td>
<td>+/- 0.002”</td>
<td>4700-7100</td>
<td>15</td>
</tr>
</tbody>
</table>

(e) Double-Star Astrometry

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Separation Precision</th>
<th>Wavelength Range (Å)</th>
<th>Magnitude Limit[</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGS</td>
<td>+/- 0.005”</td>
<td>4700-7100</td>
<td>14</td>
</tr>
</tbody>
</table>

Notes to Tables 3(a)-(e):

1. WFPC2, FOC, and NICMOS have polarimetric imaging capabilities. The FOC, NICMOS, and STIS have coronographic 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. STIS direct imaging entries assume use of a clear filter. For this example $V = H$ (relevant for NICMOS), since color terms are zero for an A0 V star. For STIS spectroscopy to achieve the specified S/N per wavelength pixel with a 0.5" slit, multiple values are given corresponding to 1300, 2800, and 6000Å respectively (if in range). For the NICMOS grism spectroscopy the three entries refer to 1.0, 1.4 and 2.0 microns with Grisms A, B, and C respectively.

3. The WFPC2 has four CCD chips that are exposed simultaneously. Three are "wide-field" chips, each covering a 77" x 77" field and arranged in an "L" shape, and the fourth is a "planetary" chip covering a 35" x 35" field.

4. The maximum FOV is 14" x 14", at full resolution it is 7" x 7". The available FOC configuration is referred to by its original $f$-ratio, $f/96$. With COSTAR the effective focal ratio is $f/151$. The $f/288$ configuration is no longer supported. Use of the $f/48$ is limited to LONG SLIT spectroscopy only.

5. The three NICMOS cameras will usually be operated simultaneously and are offset from one another on 33" (1 to 2) and 48" (1 to 3) centers providing nearby, but not contiguous fields of view.

6. The 25" slit is for the MAMA detectors, the 51" slit is for the CCD. The $R \sim 150$ entry for the prism on the near-UV MAMA is given for 2300Å.

7. Slitless spectroscopy can be done using the FOC's "objective" prisms or NICMOS's "objective" grisms. All STIS modes can be operated in a slitless manner by replacing the slit by a clear aperture. WFPC2 has a capability of obtaining low-resolution "spectra" by placing a target successively at various locations in the WFPC2 ramp filter.

8. For S/N = 1 in Fine Lock with default settings.

9. Magnitude limit for primary star.
Wide Field Planetary Camera 2 (WFPC2)

The WFPC2, which is HST's only on-axis instrument, is designed to provide digital imaging over a wide field of view (FOV). It has three "wide-field" charge-coupled devices (CCDs), and one high-resolution (or "planetary") CCD. Each CCD covers 800 x 800 pixels and is sensitive from 1200 to 11,000 Å. All four CCDs are exposed simultaneously, with the target of interest being placed as desired within the FOV.

The three Wide Field Camera (WFC) CCDs are arranged in an "L"-shaped FOV whose long side projects to 2.5', with a projected pixel size of 0.10". The Planetary Camera (PC) CCD has a FOV of 35" x 35", and a projected pixel size of 0.0455". A variety of filters may be inserted into the optical path. Polarimetry may be performed by placing a polarizer into the beam. A ramp filter exists that effectively allows one to image a small 3 10"object in an arbitrary 1-3% bandpass at any wavelength between 3700 and 9800 Å, by appropriately positioning the target within the FOV.

The WFC configuration provides the largest FOV available on HST, but undersamples the cores of stellar images; the PC configuration samples the images better, over its smaller FOV.

Faint Object Camera (FOC)

The FOC is intended to provide high-resolution images of small fields. The camera reimages the HST focal plane to provide two different scales. The focal ratios were originally $f/96$ and $f/48$; to avoid confusion these names are retained, but installation of COSTAR changed the effective focal ratios to $f/151$ and $f/75$, respectively. A variety of filters, prisms (for slitless spectroscopy), and polarizers may be placed in the optical beam.

The $f/96$ camera (plus COSTAR) has a FOV of 7" x 7" and a pixel size of 0.014" x 0.014" in its standard 512 x 512 format; a field of 14" x 14" can be used with the 512 x 1024 pixel format with a (rectangular) pixel size of 0.028" x 0.014". This camera provides two occulting fingers (0.3" and 0.5" wide) at the entrance aperture. The $f/96$ camera also has three polarization analyzers for polarimetric imaging.

Usage of the $f/48$ camera is currently restricted to LONG SLIT spectroscopy only; see the FOC Instrument Handbook for further details.

The FOC detector is a three-stage image intensifier, 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 limiting magnitude in a broad bandpass is about $m_U = 27$.

In comparing the FOC and WFPC2, proposers should note the following: (1) the FOC provides the higher angular resolution at all wavelengths, and the WFPC2 provides the larger field of view; (2) the FOC is faster below about 4500 (Å), while the WFPC2 is faster above 4500 (Å).
Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

The NICMOS provides HST’s only infrared capability. The three 256 x 256 pixel cameras of NICMOS are designed to provide diffraction limited sampling to 1.0 micron (Camera 1), 1.75 micron (Camera 2), and offer via Camera 3 a relatively large field of view. The short wavelength response at 0.8 micron is set by the HgCdTe detector array, while a 2.6 micron cutoff was selected as the longest usable wavelength given HST’s warm optics. The dewar lifetime of NICMOS is expected to be 4.5 years.

Each camera carries 19 independent optical elements providing a wide range of filter options. Cameras 1 and 2 have polarimetric filters, Camera 2 has a 0.3 arcsec radius coronographic spot and optimized cold mask, Camera 3 has three separate grisms providing slitless spectroscopy over the full NICMOS wavelength range. A variety of standard dithering and chopping (for background and sky mapping) sequences are available.

The three cameras are designed to be operated independently and simultaneously. Accordingly, proposers are strongly encouraged to request use of all three cameras in their Phase I submission. In cases where the user has no interest in obtaining multi-camera observations then the user will be expected to specify survey observations through standard filters at the Phase II submission. Details of our proposed survey programs are in the NICMOS Instrument Handbook.

Space Telescope Imaging Spectrograph (STIS)

STIS uses two-dimensional detectors operating from the ultraviolet to the near-infrared (1150-11,000Å) in support of a broad range of spectroscopic capabilities. STIS can be used to obtain spatially resolved, long slit (or slitless) spectroscopy from the full 1150-11,000Å range at low to medium spectral resolutions of R ~ 400 to 14,000 with first order gratings. Echelle spectroscopy at medium and high (R ~ 24,000 and 100,000) resolutions covering broad spectral ranges of Dl ~ 800 or 250Å respectively is available in the ultraviolet (1150-3100Å). STIS can also be used for imaging, although the filter complement is limited.

The three 1024 x 1024 pixel detectors supporting spectroscopy, target acquisitions, and limited imaging applications are:

- A solar blind CsI (FUV-) Multi-Anode Microchannel Array (MAMA) with 0.024" pixels, a nominal 25" x 25" field of view (FOV) operating from 1150-1700Å.
- A Cs2Te (NUV-) MAMA with 0.024" pixels and a nominal 25" x 25" FOV operating from 1650-3100Å.
- A CCD with 0.05" pixels, covering a 51" x 51" FOV operating from ~2500 to 11,000Å.

The MAMA detectors support time resolutions down to 125 micro-sec in TIME-TAG mode, and the CCD can be cycled in <10 sec with use of narrow subarrays. The CCD also provides visible light coronographic imaging.

Fine Guidance Sensors (FGS)

In normal operation, two of the FGSs are used for spacecraft attitude control. The third FGS thus has the potential of carrying out astrometric and photometric observations, including (1) measuring the relative
positions of sources to a precision of a few milliarcseconds; (2) measuring the separations and magnitude differences of binary stars; and (3) measuring stellar angular diameters. Note that the FGSs were unaffected by the installation of COSTAR.

For positional measurements, the useful magnitude range is $m_v = 4$ to 17 mag, and the precision is about +2 mas. Generally, a target star and 5 to 10 reference stars within the FOV annulus would be observed at several epochs to yield relative proper motions and parallaxes. Note that the effective FOV for parallax observations is reduced to about 4" x 5", since for observations six months apart the telescope's roll angle will differ by 180 degrees (see HST Maneuvering and Pointing).

The "TRANS" mode for double-star and angular-diameter measurements is available, and considerable data-reduction and analysis software has been developed at STScI. This mode is nominally capable of measuring (1) separations down to 5 mas and magnitude differences of up to 4 mag, for double stars whose primaries are as faint as about $m_v = 14$ mag, and (2) angular diameters above 20 mas. Similar measurements on non-stellar objects are also possible.

A new FGS is scheduled to be installed during SM97. Its utility as an astrometric device will be evaluated during the post-servicing mission observatory verification period. However, proposals should be based on FGS-3, currently being used for astrometry, which will remain on board the spacecraft.

The HST Field of View

Fig. 2 shows the layout of the instrument entrance apertures in the telescope focal plane, as projected onto the sky. The Instrument Handbooks should be consulted for details of each instrument's aperture sizes and orientations. The figure shows the physical locations of the WFPC2, NICMOS, STIS, and FGS apertures in the focal plane. The effective locations of the apertures for FOC are those of the first mirrors ("M1") in each of the two-mirror light paths provided by COSTAR. These effective locations are shown as open circles in Fig. 2.

In order to avoid confusion with the spacecraft's V2 and V3 axes, we define two new axes in Fig. 2, U2 and U3, which are fixed in the focal plane as projected onto the sky. At nominal roll (see HST Maneuvering and Pointing), the U3 axis points toward the anti-Sun.

Table 4 lists the relative effective locations of the SI apertures; the U2,U3 coordinate system of Fig. 2 is used, and the linear dimensions have been converted to seconds of arc using a plate scale of 3.58 arcsec mm**-1. The locations of the WFPC2, FOC and FGS apertures are accurate to about +/-1", the predicted locations of the STIS and NICMOS apertures could be in error by as much as 10".

Table 4: Nominal Effective Relative Aperture Locations
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Aperture</th>
<th>U2 (arcsec)</th>
<th>U3 (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WFPC2</td>
<td>PC</td>
<td>-2</td>
<td>+31</td>
</tr>
<tr>
<td></td>
<td>WF2</td>
<td>52</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>WF3</td>
<td>+1</td>
<td>-47</td>
</tr>
<tr>
<td></td>
<td>WF4</td>
<td>-55</td>
<td>7</td>
</tr>
<tr>
<td>FOC</td>
<td>f/96</td>
<td>-242</td>
<td>-135</td>
</tr>
<tr>
<td>STIS [1]</td>
<td></td>
<td>218</td>
<td>215</td>
</tr>
<tr>
<td>NIC-MOS[1]</td>
<td>NIC1</td>
<td>312</td>
<td>-309</td>
</tr>
<tr>
<td></td>
<td>NIC2</td>
<td>335</td>
<td>-333</td>
</tr>
<tr>
<td></td>
<td>NIC3</td>
<td>277</td>
<td>-275</td>
</tr>
<tr>
<td>FGS</td>
<td>FGS-1</td>
<td>-726</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FGS-2 [2]</td>
<td>0</td>
<td>726</td>
</tr>
<tr>
<td></td>
<td>FGS-3</td>
<td>726</td>
<td>0</td>
</tr>
</tbody>
</table>

[1] Predicted locations for STIS and NICMOS.
[2] FGS-2 to be replaced during SM97, location will remain unchanged.
Bright-Object Constraints

Several of the SIs must be protected against over-illumination; these constraints 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. **WFPC2**. No safety-related brightness limits.
2. **FOC**. May be damaged by continuous illumination by a star of $V < 9$ through a CLEAR filter anywhere in the field of view, or by an extended source with $V$ surface brightness of $< 12$ mag arcsec$^{-2}$.
3. **STIS**. No safety-related brightness limits for the CCD. The STIS MAMA detectors can be damaged by excessive levels of illumination and are therefore protected by hardware safety mechanisms. In order to avoid triggering these safety mechanisms, absolute limits on the brightest targets which can be observed by STIS will be enforced by proposal screening. It is the GO's responsibility to provide accurate information to facilitate this process. It is STScI policy that observations lost due to MAMA bright object violations not be repeated.

In order to avoid exceeding the MAMA bright object limits, observations must never:
1. exceed a total count rate on either MAMA detector of 300,000 counts/sec.
2. exceed a maximum local count rate of 50 counts/sec/pixel (NUV-MAMA only).
3. exceed a maximum local count rate of 25 counts/sec/pixel (FUV-MAMA only).
4. **NICMOS.** No safety-related brightness limits.
5. **FGS.** Objects as bright as $V = 1.8$ may be observed if the 5-mag neutral-density filter is used. Observations on all objects brighter than $V = 6.8$ should be performed with this filter. There is a hardware limitation which prevents the Spiral Search phase of an FGS target acquisition from succeeding for any target brighter than $V = 8$ (3 with F5ND).

### Orbital Constraints

*HST* is in a relatively low orbit, whose nominal parameters (following the orbital boost in December 1993) are summarized in Table 5. The low orbit imposes a number of constraints upon scientific programs, which will be discussed in the following subsections.

**Table 5: HST Nominal Orbital Parameters (Epoch 1996.3)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimajor axis</td>
<td>6971 km</td>
</tr>
<tr>
<td>Altitude</td>
<td>600 km</td>
</tr>
<tr>
<td>Rate of descent</td>
<td>0.4 km/yr</td>
</tr>
<tr>
<td>Inclination</td>
<td>28.5 degrees</td>
</tr>
<tr>
<td>Nodal period</td>
<td>96.4 min</td>
</tr>
<tr>
<td>Orbital precession period</td>
<td>56.0 days</td>
</tr>
</tbody>
</table>

### Target Viewing Times and Continuous Viewing Zones

As seen from *HST*, targets in most of the sky are occulted by the Earth for varying lengths of time during each 96-min orbit. Targets lying in the orbital plane are occulted for the longest interval, about 36 min per orbit. However, this is a purely geometric limit and does not include the additional time lost due to Earth-limb avoidance limits (see §11.2), guide-star acquisition or reacquisition, instrument setup, and SAA avoidance (see [South Atlantic Anomaly](http://www.stsci.edu/hst/CP7overview.html)). These orbital occultations are analogous to the diurnal cycle for ground-based observing and impose the most serious constraint limiting the efficiency of most *HST* observations.

The length of target occultation decreases with angle from the spacecraft orbital plane. Targets lying within 24 degrees of the orbital poles are not geometrically occulted at all during the *HST* orbit. However, the size of the resulting "Continuous Viewing Zones" (CVZs) is substantially reduced by the Earth-limb avoidance angles. Note also that scattered Earth light may be significant when *HST* observes near the bright Earth limb.

Since the orbital poles lie 285.5 from the celestial poles, any target located in the two declination zones near +/- 615.5 will be in the CVZ at some time during the 56-day *HST* precessional cycle. The maximum
uninterrupted length of an observation may then be up to 7 days, although passages through the SAA (see below) will force gaps in coverage after a maximum of 8 orbits.

A detailed examination of all the observing constraints has shown that there are two distinct CVZ regions. The "heart" of the CVZ are those positions where substantial scheduling opportunities exist, and these observations will be treated as any other observation. The "wings" of the CVZ are those positions where limited scheduling opportunities exist, and so it is possible for those observations to come into conflict with other observations or contingencies. If a proposer elects to request CVZ time in the "wings", and the observations are not obtained in the limited CVZ opportunities, then those observations may NOT BE EXECUTED.

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). No astronomical or calibration observations are possible during passages of the spacecraft through the SAA because of the high background induced in the detectors. SAA passages limit the longest possible uninterrupted exposures, even in the CVZs, to about 12 hours (or 8 orbits).

Spacecraft Position in Orbit

Because *HST*'s orbit is low, atmospheric drag is significant. Moreover, the amount of drag varies, depending on the orientation of the telescope and the density of the atmosphere, which depends on the level of solar activity. The chief manifestation of this effect is that it is difficult to predict in advance where *HST* will be in its orbit at a given time. The position error may be 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 affects observers of time-critical phenomena, since the target could be behind the Earth at the time of the event. In the worst case, it will not be known if a given event will be observable until a few days before the event.

Guide Stars and Target Acquisition

As described in Guiding Performance, *HST* uses guide stars located at the edge of its field of view. Unlike ground-based telescopes, however, *HST* uses two guide stars in order to control the pitch, yaw, and roll axes of the telescope. (It is also possible to control the telescope pointing in pitch and yaw with one guide star, with the rate gyros controlling the roll angle.) The guide star(s) are selected in advance by STScI for each observation.
Guide Stars

Selection of guide stars (GSs) is carried out by the Guide Star Selection System (GSSS) at STScI. 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.

The *Guide Star Catalog* (GSC), which resulted from the digitization and analysis of the plate collection, contains information, including coordinates and magnitudes, on about 18 million objects to 14.5 mag.

The observation summary that is part of each Phase I observing proposal must include celestial coordinates for all fixed targets, but these coordinates need only be of sufficient accuracy for the scientific and technical reviews.

More accurate target coordinates are required in Phase II. Stellar proper motions (and parallaxes) will also be requested during Phase II, since even relatively small stellar motions can be surprisingly significant. Phase II proposers should be prepared to supply such information themselves.

Target Acquisitions

Target acquisition is the method used to assure that the target is in the field of view of the requested aperture to the level of accuracy required by the science. There are several distinct methods of target acquisition; each has a different approach and different accuracy, and will take different amounts of time and resources to complete. The level of accuracy required depends most strongly on the size of the aperture to be used to take the science data and the nature of the scientific program.

**Target Acquisition without the Ground System**

*No acquisition* means that pointing control will be entirely on gyros, and FGSs will not be used. The telescope is slewed on gyro control from the last target. The pointing accuracy depends on the size of the slew from the previous target. The best-case uncertainty is 0.010" for each 30" displacement in the slew to the target.

*Blind acquisition* means that guide stars are acquired and the FGSs are used for pointing control. The pointing is accurate to the guide star position uncertainty, which is about 1".

*Onboard acquisition* means that software onboard the spacecraft specific to the science instrument in use will be used to center the fiducial point onto the target. On-board target acquisitions will be needed for all STIS spectroscopic observations, and for NICMOS coronographic observations. The WFPC2 and FOC do not have onboard acquisition capabilities. For specific information on methods and expected pointing accuracies, see the *Instrument Handbooks* for the instrument to be used.

*Early acquisition* means using an image taken on an earlier visit to provide improved target coordinates for use with subsequent visits. Usually the WFPC is used to make the acquisition image several months in advance of the science observations. The observer will analyze the early acquisition image and provide the improved coordinates to the scheduling system.
Target Acquisition with the Ground System (OPUS)

Target acquisitions that cannot be accomplished reliably or efficiently via one of the above methods may still be possible by transmitting relevant data to the STScI, analyzing it to determine the needed pointing corrections, and then providing those corrections to the telescope. This description covers two kinds of activities, the "interactive acquisition" and the "reuse target offset", both of which are described briefly here. The observer who uses these capabilities will be supported by staff of the OPUS (the Observation Support/Post-Observation Data Processing (OSS/PODPS) Unified System) of the Data Systems Division.

Interactive acquisition, or real-time target acquisition, uses the ground system software to calculate the small angle maneuver to move the aperture onto the target. This method is available for all science instruments except the astrometry FGS. High data rate TDRSS links are required at the time the data is read out of the instrument to transmit the data to the ground, and at a subsequent time to re-point the telescope before the science observations, which adds a difficult constraint to the scheduling. The GO, or a designated representative, must be present at the STScI at the time of the acquisition. The acquisition data, usually an image, is analyzed by OPUS personnel to compute the image coordinates and centering slew for the target identified by the GO.

Reuse target offset means using an offset slew derived from an onboard acquisition done on visit 1 to reduce the amount of onboard acquisition time required for subsequent visits to the same target. The data from the initial visit are analyzed by OPUS personnel to provide the offset slew to be repeated for subsequent visits. All subsequent visits to the target must use the same guide stars as the initial visit, which limits the time span of all visits to a few weeks. There are additional instrument-specific requirements. The GO is advised to contact the STScI Help Desk if this capability is required.

Solar-System Targets

Objects within the solar system have apparent motions with respect to the fixed stars. HST has the capability to point at and track moving targets, including planets, their satellites, and surface features on them, with sub-arcsecond accuracy. However, there are a variety of practical limitations on the use of these capabilities that must be considered before addressing the feasibility of any particular investigation.

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. Phase I proposers are encouraged to consult the STScI Help Desk for more detailed information.

Tracking Capabilities

HST is capable of tracking moving targets with the same precision as for fixed targets (see Guiding Performance). This is accomplished by maintaining FGS Fine Lock on guide stars, and driving the FGS star sensors in the appropriate path, thus moving HST so as to track the target. Tracking under FGS control is technically possible for apparent target motions up to 5 arcsec s**-1. In practice, however, this technique becomes infeasible for targets moving more than a few tenths of an arcsec s**-1. It is currently possible to begin observations under FGS control and then switch over to gyros when the guide stars have moved out of the FGS field of view. If sufficient guide stars are available, it is possible to "hand off" from one pair to another, but this will typically incur an additional pointing error of about 0.3".
Targets moving too fast for FGS control, but slower than 7.8 arcsec s**-1, can be observed under gyro control, with a 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 database, 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.

Offsets and Spatial Scans

Offsets (using the same guide stars and performed under the same guide star acquisition) can be performed to an accuracy of about +/-0.02". The sizes of offsets are limited by the requirement that both guide stars remain within the respective FOVs of their FGSs. Offsets that continue across separate visits (including visits executed with the same guide stars), will typically encounter accuracy of ~0.3".

It is also possible to obtain data while \textit{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" (\textit{i.e.}, raster scans) may be requested:

- \textit{Continuous scan}. In this case, data are continually obtained while the telescope is in motion.
- \textit{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.

The possible scan area is limited by the requirement that the same guide stars be used throughout the scan, and the maximum possible scan rate for continuous scans is 1 arcsec s**-1. Continuous spatial scan lines cannot be interrupted and must therefore be completed within one orbital target-visibility period. Spatial scans requiring more than 45 minutes of spacecraft time should be avoided.