

HIGH SPEED PHOTOMETER INSTRUMENT HANDBOOK

Version 3.0

April 1992

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Chapter 1: Introduction

1.1 How to Use This Manual

This manual is a guide for astronomers who intend to use the High Speed Photometer (HSP), one of the scientific instruments onboard the Hubble Space Telescope (HST). All the information needed for ordinary uses of the HSP is contained in this manual, including:

- (1) an overview of the instrument (Chapter 2),
- (2) a detailed description of some details of the HSP-HST system that may be important for some observations (Chapter 3),
- (3) tables and figures describing the sensitivity and limitations of the HSP (Chapter 4),
- (4) how to go about planning an observation with the HSP (Chapter 4), and
- (5) a description of the standard calibrations to be applied to HSP data and the resulting data products (Chapter 5).

An HSP neophyte should begin by reading Chapters 2 and 4 to get an overview of the instrument and what it can do. Chapter 4 also shows how to plan an observation using the HSP. Chapter 5 describes the data products received by the observer. Skimming through Chapter 3 will give some feeling for the complications that may arise.

The HSP sophisticate will refer mainly to Chapters 3 and 4, and may often find that the careful construction of complicated observing programs is driven by the constraints described in Chapter 3.

Some observing programs will inevitably require more detailed information about the HSP than is given here. For example, it is possible to write special purpose programs for a microprocessor inside the HSP that controls observing sequences, but this manual does not contain enough information to determine precisely what can and cannot be done with such programs. If you require such detailed information, it is available either from the Space Telescope Science Institute or from the documents listed in the bibliography of this manual.

As time passes, there will undoubtedly be changes in this manual. Chapters 3 and 4 are especially vulnerable to changing as our knowledge of the instrument improves. Consequently, users should be wary of using outdated versions of the manual.

Suggestions for improvements are welcome and should be addressed to the authors.

1.2 Acronyms

Acronyms are a necessary, if often overused, aid in reducing the length of NASA documents. The following acronyms may rear their heads in this manual:

Table 1–1: Acronyms

A/D	Analog to Digital
BD	Bus Director
CVZ	Continuous Viewing Zone
D/A	Digital to Analog
FGS	Fine Guidance System
FOC	Faint Object Camera
FOS	Faint Object Spectrograph
GSFC	Goddard Space Flight Center
GHRS	Goddard High Resolution Spectrograph
HSP	High Speed Photometer
HST	Hubble Space Telescope
IDT	Image Dissector Tube
NASA	National Aeronautics and Space Administration
NSSC-1	NASA Standard Spacecraft Computer
ODS	Optical Detector Subsystem
OTA	Optical Telescope Assembly
PAD	Pulse Amplitude Discriminator
PDB	Project Data Base
PMT	Photomultiplier Tube
RAM	Random Access Memory
ROM	Read-Only Memory
SCUM	System Controller User's Manual
SOGS	Science Operations Ground System
STScI	Space Telescope Science Institute
STSDAS	Science Data Analysis System
TAV	Target Acquisition and Verification
TBD	To Be Determined
TDRSS	Tracking and Data Relay Satellite System
UV	Ultraviolet
WF/PC	Wide Field/Planetary Camera

1.3 Acknowledgements

The High Speed Photometer was designed and built at the University of Wisconsin by Robert C. Bless (Principal Investigator) with scientific guidance from the HSP Investigation Definition Team: Joseph F. Dolan, James L. Elliott, Edward L. Robinson, and Wayne van Citters. Among those making major contributions to the design, construction, and testing of the HSP were Evan Richards, Jeff Percival, Fred Best, Dave Birdsall, Gene Buchholtz, Scott Ellington, Don Finegan, Ed Hatter, Sally Laurent-Muehleisen, Matt Nelson, Bill Phillips, Jerry Sitzman, Mark Slovak, Colleen Townsley, Andrea Tuffli, Mark Werner, Doug Whiteley, and others, to whom I apologize for their omission from this list.

Much useful criticism of the HSP Instrument Handbook was provided by Bob Bless, Joe Dolan, Howard Bond, and Lisa Walter; however, any remaining problems are the responsibility of the authors.

Chapter 2: Overview of the HSP

The High Speed Photometer (HSP) exploits the capabilities of the HST by making photometric measurements over visual and ultraviolet (UV) wavelengths at rates up to 10^5 Hz and by measuring very low amplitude variability (especially for hotter stars in the UV). A secondary purpose of the instrument is to measure linear polarization in the near UV. The HSP has several advantages over similar ground-based instruments:

- (1) UV wavelength coverage.
- (2) Smaller apertures, permitting higher spatial resolution and reducing the sky background.
- (3) No atmospheric absorption or scintillation, leading to higher photometric accuracy and the ability to use very short sample times.

In what follows we will present an overview of the HSP, its optics and detectors, its electronics, its mechanical structure, and finally some observational considerations.

2.1 Summary of HSP Characteristics

<i>Quantum Efficiency:</i>	~0.1–3% (throughput for entire HSP-HST system)
<i>Time Resolution:</i>	10.7 μ s (pulse-counting mode, count rate < 10^6 cts/s) ~1 ms (current mode, count rate > 10^6 cts/s)
<i>Photometric Accuracy:</i>	Systematic errors < 2% from V=0 to V=20
<i>Apertures:</i>	1.0 arcsecond diameter for normal observations 6.0, 10.0 arcsecond for target acquisition
<i>Filters:</i>	23 UV and visual filters from 1200 Å to 7500 Å
<i>Polarimetry:</i>	4 UV filters 2% polarimetric accuracy
<i>Operation:</i>	Telescope must slew to move star from one filter to another. Slew time ~30–60 s (limits rate at which multicolor photometry is possible). There are four filter pairs with beam-splitters that can be used for two color photometry without moving telescope; for these filter pairs, can get simultaneous or nearly simultaneous (separated by only 10 milliseconds) two color photometry.

2.2 Detectors and Optics Configurations

The HSP has quite an unusual design, in that it has no moving parts. Figure 2-1 shows a sketch of the arrangement of the detectors and optics in the HSP. There are five detectors in the instrument—four image dissector tubes (IDTs) and one photomultiplier tube. The former are ITT 4012RP Vidissectors, two with CsTe photocathodes on MgF₂ faceplates (sensitive from 1200 Å to 3000 Å) and two with bialkali cathodes on suprasil faceplates (sensitive from 1600 Å to about 7000 Å). Each image dissector tube, its voltage divider network, and its deflection and focus coils are all contained in a double magnetic shield within the housing. The photomultiplier is a Hamamatsu R666S with a GaAs photocathode. Three of the image dissectors—the two CsTe tubes (called *UV1* and *UV2*) and one of the bialkali tubes (*VIS*)—are used for photometry. The second bialkali dissector (*POL*) is used for polarimetry,* and a beamsplitter allows the photomultiplier (*PMT*) along with the bialkali photometry dissector (*VIS*) to be used for simultaneous observations in two

* Note that the polarimeter also has one clear filter that can be used for photometry.

Figure 2–1: *HSP Optics and Detectors*

colors (*e.g.*, for occultations). For convenience, we will refer to the photometric, polarimetric, and PMT “configurations”, but in most respects the operation of the various detectors is identical.

For the purposes of the HST proposal forms, the HSP has the following configurations and modes:

Table 2–1: *HSP Configurations and Modes*

<i>Configuration</i>	<i>Modes</i>
HSP/UV1, UV2, VIS	SINGLE, STAR-SKY, ACQ, IMAGE, PRISM
HSP/POL	SINGLE, STAR-SKY, ACQ, IMAGE
HSP/PMT	SINGLE
HSP/⟨ D_1 ⟩/⟨ D_2 ⟩	STAR-SKY
HSP/PMT/VIS	SPLIT

All these modes are discussed in the following paragraphs. The ACQ mode is used for target acquisition and is also discussed in §2.5.1 and in the *HSP Target Acquisition Handbook*. See the *Hubble Space Telescope Phase II Proposal Instructions* for information about how to specify the various configurations and modes on the proposal forms.

2.2.1 Single-Color Photometry

Consider first photometric observations, which can be carried out using the mode SINGLE. This mode can be used with any of the five HSP detectors. Light from the HST enters the HSP through

Figure 2–2: *HSP Focal Plane Layout*

one of three holes in its forward bulkhead. These holes are all centered on an arc 8.1 arcminutes off-axis; the focal plane layout for the HSP is shown in Figure 2-2. After passing through a filter (which is about 36 mm in front of the HST focal plane) and an aperture (which is in the HST focal plane), the light is brought to a refocus on the dissector photocathode by a relay mirror—a 60 mm diameter off-axis ellipsoid located about 800 mm behind the HST focal surface. The relay mirrors enable a more efficient use to be made of the HST focal plane available to the HSP than would otherwise be possible, *i.e.*, the image dissectors are too large to place more than two directly in the focal plane. The magnification of the relay mirrors is about 0.65, which converts the $f/24$ bundle entering the HSP to $f/15.6$ at the photocathode, with a corresponding change in scale from 3.58 arcseconds/mm to 5.54 arcseconds/mm.

The only unusual feature of the HSP’s optical system is its filter-aperture “mechanism” (see Figures 2-3 through 2-7) mounted behind each forward bulkhead entrance hole. Each filter plate contains thirteen filters mounted in two columns positioned 36 mm ahead of the HST focal plane. At this location the converging bundle of light from the HST is 1.5 mm in diameter, well within the 3 mm width of each filter; however, because the light bundle is out of focus, small variations in filter transmission with position should not be important. For each filter plate there is an aperture plate, located at the HST focal surface, that contains 48 apertures arranged in two columns that are positioned directly behind the corresponding columns of filters. Nine of the filters are associated with four apertures each—two with diameters of 1 arcsecond (280 μm) and two with diameters of 0.4 arcseconds (112 μm). Due to space limitations, one filter is associated with only three apertures, and two other filters are associated with two apertures each. The thirteenth filter, of double width, is a clear window and has five associated apertures, including one of 10 arcsecond diameter for target acquisition. The VIS detector has one additional aperture that also passes light to the PMT (see §2.2.3). *The choice of 1.0 and 0.4 arcsecond apertures was made on the basis of*

the specified performance of the HST image at the HSP location 8 arcminutes off-axis. However, the degraded image caused by spherical aberration severely limits the utility of the 0.4 arcsecond apertures because the amount of energy encircled is only 20% of that expected. Normally, therefore, the 1.0 arcsecond apertures will be used for most observations.

The HST is commanded to point so that the target's position in the HST focal plane coincides with the particular filter-aperture combination desired. Light from the target is then focused on the dissector cathode by the relay mirror. The resulting photoelectrons are magnetically focused and deflected in the forward section of the image dissector so that the photocurrent is directed through a 180 μm aperture (corresponding to 1 arcsecond on the sky). This aperture connects the forward section of the detector to a 12-stage photomultiplier section. Thus with no moving parts, 48 different filter-aperture combinations are available for each photometry detector in the HSP. Not all of these are unique, however, because of duplicate filters and duplicate apertures associated with each filter.

The following series of four charts (Figures 2-3 through 2-7) show the filter and aperture configuration for the four HSP images dissector tubes. On the left side of each filter strip from top to bottom, the following information is provided:

- (1) The filter designation in PDB syntax.
- (2) The (obsolete) original HSP team filter designation, provided for reference to old documentation only.
- (3) The filter designation in current proposal syntax.

For each aperture, the following information is provided from top to bottom:

- (1) The aperture designation in PDB syntax.
- (2) The (obsolete) original HSP team aperture designation, provided for reference to old documentation only.
- (3) The aperture designation in current proposal syntax.

There are three so-called "dark apertures" on each IDT that are labeled D1, D2, and D3. These "apertures" represent the locations on the solid part of the faceplate to where the readbeam is deflected for collection of dark counts. The innermost scale is the physical scale in millimeters of the filters and apertures referenced to the image dissector tube faceplate. The deflection step scale represents the magnetic deflection (in HSP D/A units) required to point the read beam to any location. These are provided as reference only and are not used in proposals. The outermost scale is in arcseconds and is referenced to the focal plane. The V2 and V3 axes are shown relative to the position of the detectors as projected through the optics onto the sky. The order of the scales for the POL diagram (Figure 2-7) is slightly different.

All of the UV filters are multi-layer interference filters of Al and MgF_2 evaporated on MgF_2 substrates for the far ultraviolet, or on suprasil for the near UV. The visual filters consist of Ag and cryolite layers deposited on glass. The substrates are 1/16 inch (± 0.002 inch) thick. The general filter characteristics are listed below in Tables 4-1 and 4-2. Some filters are common to two or more photometry image dissectors for the sake of redundancy and to enable all three channels to be tied together photometrically. Some filters define bandpasses similar to those flown on previous space observatories, while others are similar to some in the Wide Field and Faint Object Cameras.

There is one filter on the *POL* IDT (F160LP, see Fig. 2-7) with two 0.65 arcsecond apertures that can be used for photometry. The other filters on *POL* have polarizers and can be used only for polarimetry (§2.2.4).

Figure 2-2 shows the *X* and *Y* reference axes that are used if it is necessary to specify a particular orientation for an HSP observation (using the *ORIENT* special requirement) or a special position for a target in an aperture (using the *POS TARG* special requirement). For example, the acceptable range of orientations may be restricted to insure that an aperture to be used for mea-

Figure 2–3: *HSP Filter/Aperture Tube Configuration*

surement of the sky brightness will not be contaminated by field star. (See §2.5.2 for discussion of sky subtraction using the HSP.)

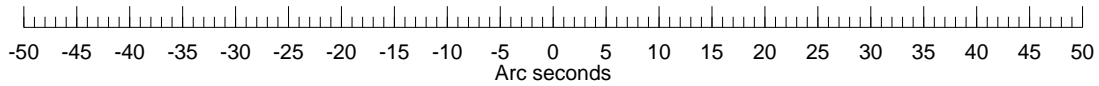
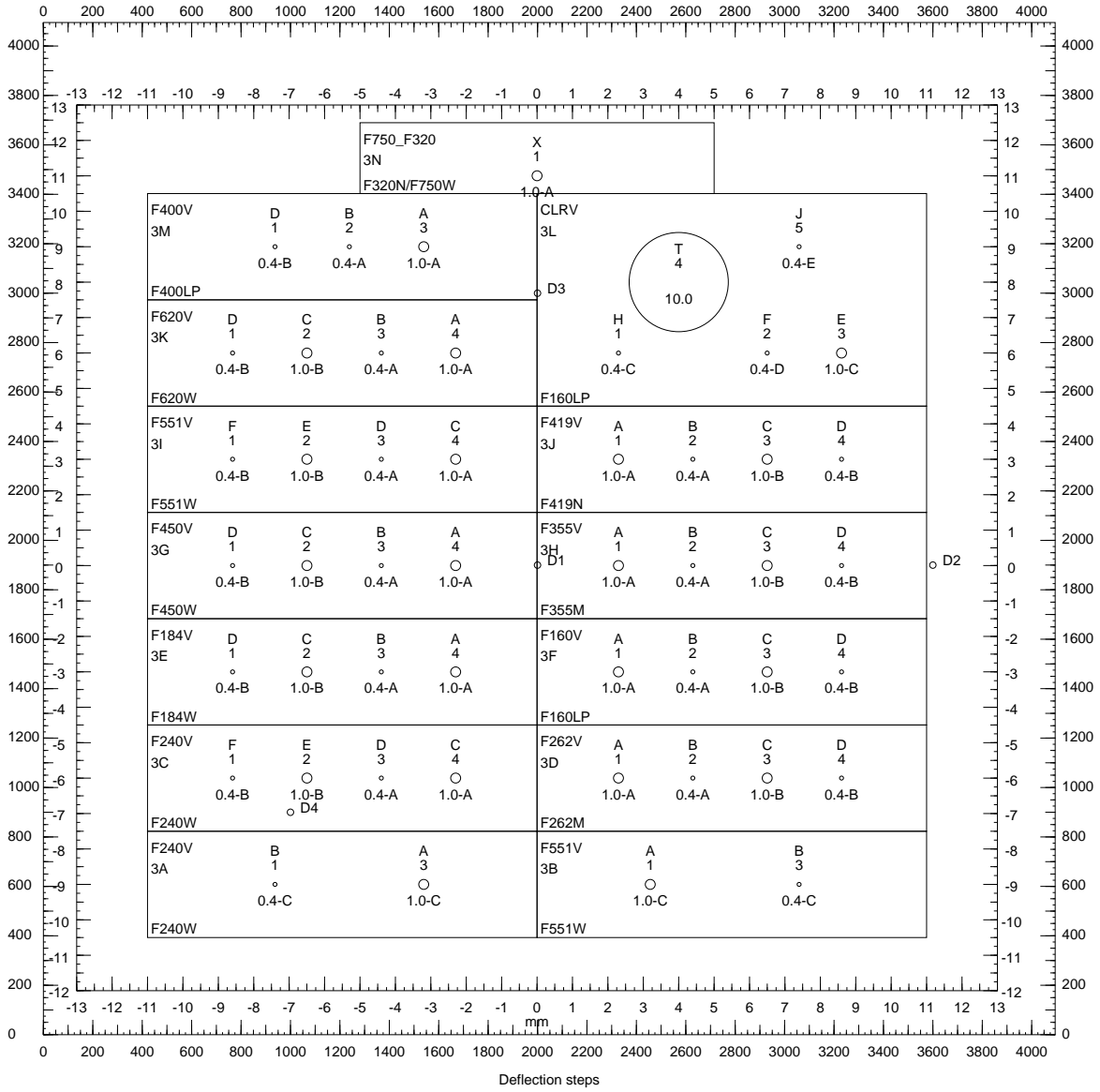
Notice that filter changes generally require the HST to slew from one aperture to another; this requires about 30 seconds for two apertures on the same IDT and about 60 seconds for two apertures on different IDTs. The slew time determines how rapidly multicolor photometry can be done. There are two exceptions to this restriction: rapid two-color observations can be made either in **PRISM** mode with detectors VIS, UV1, and UV2, or in **SPLIT** mode using PMT and VIS.

2.2.2 Two-Color Photometry with Prisms

On each photometry IDT, there is a beamsplitter/prism combination that divides the light of an appropriately placed target between two 1 arcsecond apertures that have different filters (see Figures 2-4 through 2-6). A partially reflecting MgF₂ plate mounted at 45° to the incoming beam transmits part of the incident light to a filter and 1 arcsecond aperture. The reflected beam is totally internally reflected by a right angle prism made of suprasil; it then passes through another filter, a suprasil rod (which compensates for the longer path followed by the reflected beam), and another 1 arcsecond aperture. In all cases, the transmitted beam passes through the short wavelength filter and the reflected beam goes through the long wavelength filter of the pair.

Using this prism beamsplitter (mode **PRISM** on the proposal forms), it is possible to measure an target's brightness in two colors merely by moving the IDT beam from one aperture to the other rather than by slewing the HST, permitting observations in the two bandpasses separated by only about 10 milliseconds rather than by the thirty seconds required for an HST slew. Thus, the prisms permit nearly simultaneous observations in two colors.

Figure 2-4: VIS IDT Apertures and Filters



IDT3/VIS
Proposal names
 Chart version 1.4 (11/10/90)
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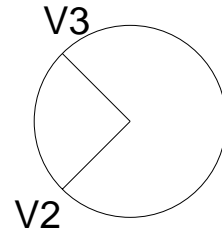
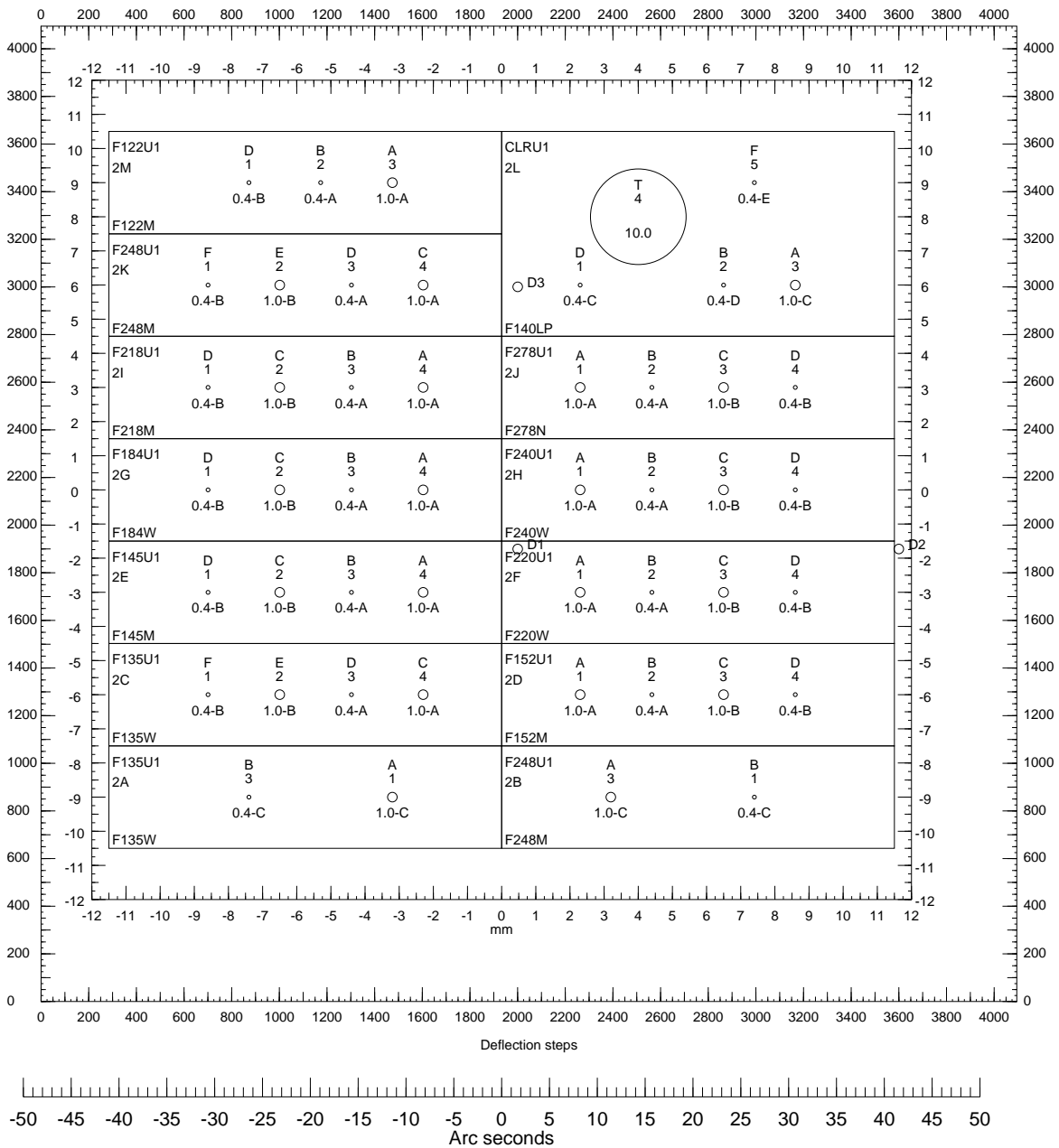


Figure 2-5: UV1 IDT Apertures and Filters



IDT2/UV1
 Proposal names
 Chart version 1.4 (11/10/90)
 Jeffrey W Percival

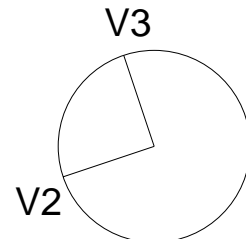
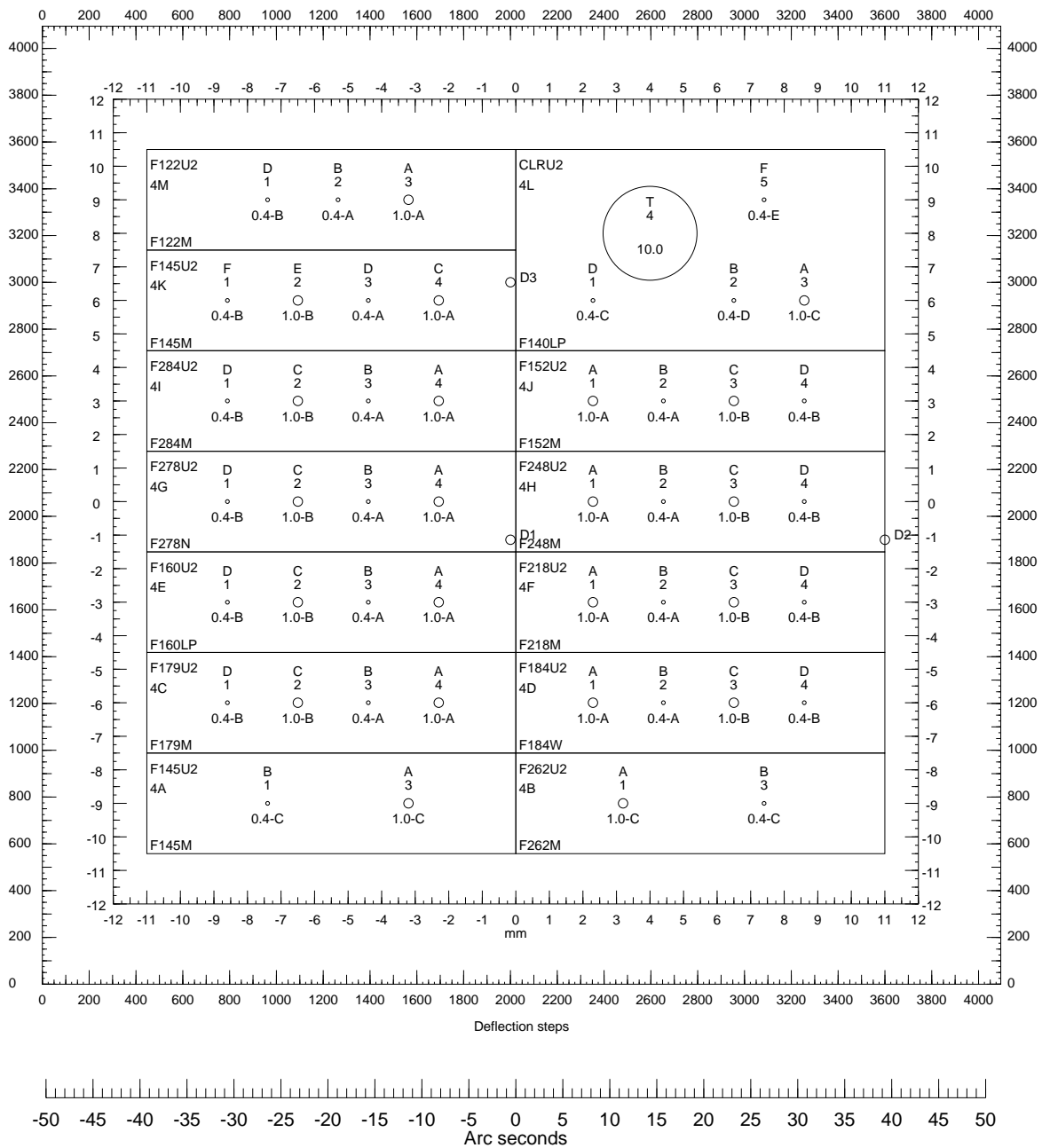


Figure 2-6: UV2 IDT Apertures and Filters



IDT4/UV2
Proposal names
 Chart version 1.6 (11/10/90)
 Jeffrey W Percival

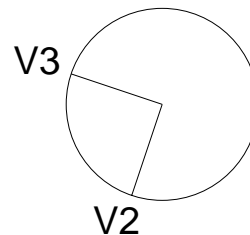
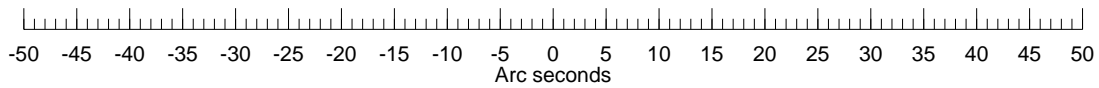
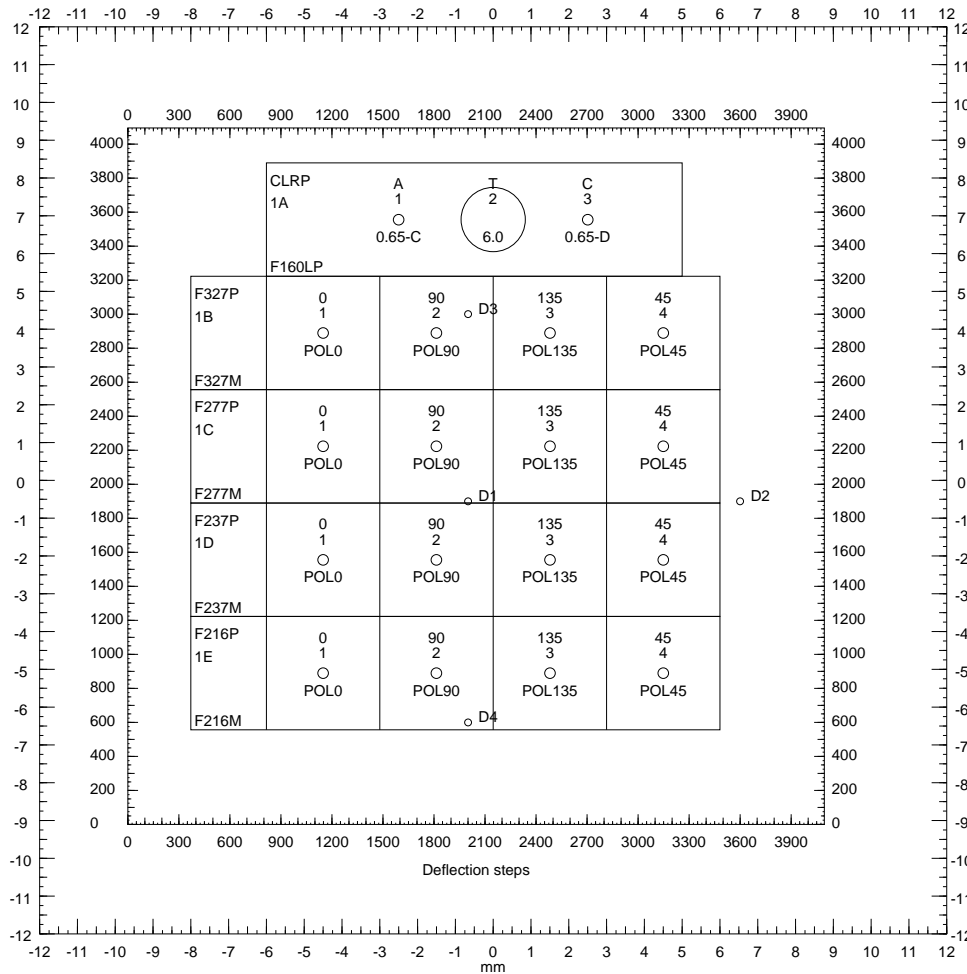
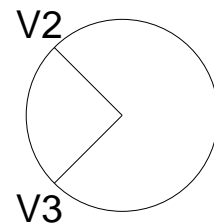


Figure 2-7: Polarimetry IDT (POL) Apertures and Filters



IDT1/POL
 Proposal names
 Chart version 1.5 (11/10/90)
 Jeffrey W Percival



Only one pair of filters on each of the three photometry IDTs can be used with a prism; Table 4-3 lists the three pairs of prism filters. Duplicates of all prism filters are also available as normal (straight through) filters without the intervening prism.

The prism mode is still being calibrated. Contact the STScI for the current status of the prism mode.

2.2.3 Two-Color Photometry with the PMT

In the SPLIT mode, light from the target passes through a filter (in this case clear suprasil, Fig. 2-4) and on through a 1 arcsecond aperture, after which it strikes a Ag-Cryolite beamsplitter at 45° to the incident beam. The mirror reflects red light to the photomultiplier (PMT) via a red glass filter and a Fabry lens. The beamsplitter passes a spectral band in the blue on to a relay mirror and to the VIS image dissector. Truly simultaneous observations can therefore be made at about 7500 Å and 3200 Å.

The PMT detector and the F320N filter on the VIS detector can also be used independently for single-color photometry (§2.2.1). However, there is ordinarily no advantage in doing so because taking data through both filters requires no additional observing time or overhead.

Note that the 45° reflection in both the PMT beamsplitter and the prism beamsplitters introduces significant instrumental polarization in the transmitted beam, so that the count rates for a 10% polarized source will vary by about 2% with the HST roll angle.

2.2.4 Polarimetry

In the HSP/POL configuration, light from the target passes through a filter-aperture assembly (which is only about 4 arcminutes off-axis) directly to the image dissector; no relay mirror is used. The filter assembly (Figure 2-7) contains four near UV filters (see Table 4-2) across which are four strips of 3M Polacoat with polarizing axes oriented at 0°, 45°, 90°, and 135°. The aperture plate contains a single aperture for each filter-polarizer combination. There is also a clear window with two small apertures, which can be used for photometry, and a 6 arcsecond diameter finding aperture. Linear polarization for a particular bandpass is measured by deriving the Stokes parameters Q and U from observations through each of the four polaroids in succession.

The internal IDT aperture for the polarimetric IDT is 180 μm in diameter, the same as for the photometric IDTs; however, because there is no relay mirror to change the plate scale, this corresponds to 0.65 arcseconds on the sky. Thus, the internal aperture is slightly smaller than the 1 arcsecond focal plane apertures, and the effective aperture diameter for the polarimeter is 0.65 arcseconds. This affects the accuracy of polarimetry because the degraded HST image puts more energy near the aperture edge, and the smaller effective aperture diameter exacerbates the effects of pointing errors and jitter.

For some observations, the polarimeter on the Faint Object Spectrograph might be better than that on the HSP. For example, the FOS would usually be preferable for a source that has a polarized continuum contaminated by unpolarized line emission. On the other hand, the FOS polarimeter may not be as well-calibrated as the HSP polarimeter during the initial phases of the HST mission. See the *FOS Instrument Handbook* for details on the FOS polarimeter. Observers planning to do polarimetry are encouraged to contact the STScI for advice on which instrument is best for their proposal.

2.2.5 Images with the HSP

The light paths for the IMAGE and ACQ modes are identical to those for the other HSP modes. These modes differ from ordinary photometry only because the data are collected in a different sequence. An *Image* (sometimes called an *Area Scan*) is a series of integrations in which the IDT beam is moved to cover a rectangular grid on the photocathode. The number and separations of the rows and columns, and the sample time at each point are all adjustable. The number of

samples taken at each point in the image and the delay time between samples are also adjustable using optional parameters on the Phase II observing forms.

Targets are located in the 10 arcsecond finding aperture by commanding the HSP to take an image covering the aperture (§2.5.1). Images will not often be used by observers except for target acquisition, in which case the instrument mode can be specified as ACQ, and all parameters except the exposure time are set to default values. However, HSP images may also have some other uses; *e.g.*, an image could be taken after a target acquisition to confirm the success of the acquisition.

An image may be acquired using any of the IDTs, including the polarimeter. There is an overhead of about 25 ms per point in the image, so that a 20×20 target acquisition scan requires at least 10 s. This overhead time is not included when specifying the exposure time for the image, but is charged to the observer.

2.3 Electronics

Figure 2-8 shows a block diagram of the HSP electronics. All five detectors have identical electronic subsystems with the exception of the photomultiplier, which does not have the amplifiers needed in the image dissectors to drive focus and deflection coils. The horizontal and vertical deflections and focus settings are 12-bit programmable quantities. A change of 1 in the deflection corresponds to a beam motion of about $4 \mu\text{m}$ (0.014 arcseconds for the POL detector, 0.02 arcseconds for the others). The 8-bit programmable high voltage power supplies provide negative DC voltages between 1400 and 2600 volts for the detectors.

The settings of all internal HSP quantities will usually be handled automatically by STScI, although there may be rare observations that require changing the high voltage, discriminator settings, etc., to get the best performance from the HSP.

The output of the detectors can be measured by counting pulses, by measuring the photocurrent, or by doing both simultaneously. In the current (analog) data format*, a current-to-voltage converter measures detector current outputs over a range of 1 nA to 10 μA full scale in five decade gain settings selectable by discrete command inputs. The amplifier output is converted to a 12-bit digital value by an A/D converter. The analog data format will be used for stars that are too bright for the pulse-counting data formats. One benefit of the programmability of the high voltage is that it provides a means of extending the dynamic range of the detectors in their analog data format. The minimum sample time in the analog data format is set by the analog-to-digital conversion time of 128 μs . The true time resolution in analog data format is somewhat larger than this; it is determined by the time constant of the current amplifier, which ranges from 4 ms in the 1 nA range to 0.4 ms in the 10 μA range.

It should be emphasized that the effective integration time when collecting data with the analog format is always very short. For example even if the sample time is specified to be 1 sec, the effective integration time is only ~ 1 ms. Thus, decreasing the sampling rate leads to widely spaced, short samples of the brightness of the star, but does not increase the accuracy of measurement for each sample. The number of samples required to achieve a specified accuracy using the analog format is essentially independent of the sample time (and may be very large for faint targets).

In the pulse-counting (digital) data format, the output of the preamplifiers, which provide a voltage gain of about 7, is received by pulse amplifier/discriminators (PADs). The PADs amplify and detect pulses above a threshold set by an 8-bit binary control input, enabling the signal-to-noise ratio to be optimized for any high voltage setting. The PAD thresholds are usually set by STScI and will rarely be of concern to the observer. Digital format data can be taken with sample times as short as 10.7 μs . Pulses separated by about 40 ns or more can be separately detected so that count rates of up to 2.5×10^5 Hz can be accommodated with a dead-time correction of no more

* For a detailed description of data format selections, see §3.1.2.

Figure 2–8: *HSP Electronics Block Diagram*

than one percent.

The sample times for both digital and analog data formats are commandable in 1 μ s intervals up to 16.384 s. Between successive samples there can be a delay time of zero to ~ 16 s, again in 1 μ s steps. This delay time will usually be set to zero except in cases where a delay is necessary for some reason (*e.g.*, in 1-detector STAR-SKY mode, see below). Use optional parameters **SAMPLE-TIME** and **DELAY-TIME** to specify these values on the exposure logsheet. By default the sample time is 1 second and the delay time is its minimum possible value.

The five identical detector controllers perform those functions that relate to a specific detector, *i.e.*, they receive a sequence of parameters and instructions from the system controller necessary for an observation and science data collection. Each contains an I/O port, a storage latch, two 24-bit pulse counters, and a multiplexer. Detector parameters are received from the system controller through the I/O port and are stored in eight one-byte latches. These latch outputs are used to control focus and deflection amplifiers, high voltage power supplies, discriminator thresholds, analog gain settings, etc. A 1.024 MHz clock signal, received through the I/O port, supplies a signal to the A/D converter and synchronizes sampling start and stop control signals to the two pulse counters. It can also be used as a test input to the counters. The outputs of the two pulse counters, the A/D converter, and the eight one-byte latches are multiplexed and transmitted through the detector controller bus I/O port to the system controller.

As its name implies, the system controller's functions have to do with the instrument as a whole rather than with a specific detector. These functions include serial command decoding and distribution, detector controller programming, science data acquisition and formatting, serial digital engineering data acquisition and formatting, and interfacing with the HST command and data handling system through redundant remote modules and redundant science data interfaces. The system controller consists of an Intel 8080 microprocessor, memory, and various I/O ports. Direct memory access is provided to allow rapid data transfer through the science and engineering data ports and to allow science data acquired from the detector controllers to be stored in memory quickly. An 8K byte ROM block is provided for the microprocessor program storage. The remaining memory is composed of six 4K blocks of RAM, which may be configured in any order. 4K of the RAM are allocated for the microprocessor system, 16K as a buffer for science data storage, and 4K as a spare block. The spare block may be used to replace any other 4K block that becomes defective. In contrast to the detector controllers, the system controller is dual standby redundant.

The power converter and distribution system converts the input +28V DC bus power from the HST to secondary DC outputs required by all other subsystems and provides power input switching and load switching for independent operation of individual detector electronics and heaters. The DC-DC converters essential to overall instrument operation are dual standby redundant. Converters that power electronics associated with only one detector are not redundant. With three detectors and their electronics on simultaneously the power consumption is about 135 W.

2.4 Mechanical Structure and Thermal Characteristics

The HSP is aligned and supported in the HST at three registration points. Two of these (one forward and one aft) have ball-in-socket fittings, and the third point (in the forward bulkhead) provides tangential (rotational) restraint. The mechanical loads (including a pre-load to keep the HSP in alignment) are transmitted from the instrument to the telescope structure through the three registration points. The two ball-in-socket fittings, the electronics boxes, and the optical and detector system are all mounted directly to a box beam and baseplate, the main structural elements of the HSP. The box beam runs the length of the instrument thereby connecting the two forward and aft fittings and carries the pre-load. The baseplate (actually a milled-out lattice structure) is attached to the box beam and provides stiffness to the structure. Four internal bulkheads on each side of the box-beam and baseplate form ten bays for the electronic boxes, which are mounted on

the baseplate. In addition to giving mechanical support to the electronics and to the wire harness, the baseplate provides a high conductance path between electronic modules as well as a radiating surface. The optics and detectors are mounted to (but thermally isolated from) the box-beam on the side opposite the baseplate, and at the forward end of the instrument.

Detectors are not actively cooled and are expected to range in temperature between -15°C and 0°C for “cold” and “hot” orbits, respectively. Over an orbit their temperatures will change by no more than 0.1°C , and will change by no more than 8°C during an extended observation.

2.5 Observing with the HSP

2.5.1 Target Acquisition

An observation with the HSP begins with the acquisition of the target. As for most of the other HST instruments, the HSP has four target acquisition strategies: *Blind*, *Onboard*, *Interactive*, and *Early*. These schemes are described in detail in the *HSP Target Acquisition Handbook*; this section briefly summarizes that document.

In a *Blind* target acquisition, the target is put directly in the desired 1.0 arcsecond aperture. This is equivalent to doing no acquisition at all. However, it usually will be necessary to determine the target position very accurately before going to a small aperture. Neither the target position nor the guide star positions will generally be known accurately enough for a Blind acquisition except when the target has been observed previously.

For the other target acquisition methods, the HST will acquire guide stars in such a way that the program star falls within the large finding aperture of the specified image dissector. The finding aperture has a diameter of 10 arcseconds for the photometry IDTs and 6 arcseconds for the polarimetry IDT. Target positions must be accurate enough that the target will never fall outside the finding aperture. A 20×20 raster scan covering the finding aperture is then performed by the dissector to form a pseudo-image (the *Acquisition* image). Acquisitions are requested on the proposal forms with the ACQ mode and must be listed as separate exposures on the exposure logsheet. The type of acquisition must be specified using the ONBOARD (or INTERACTIVE or EARLY) ACQ FOR $\langle lines \rangle$ special requirement. Typical times required to collect the target acquisition image are given in Table 4-7.

Note: The degraded images produced by the HST affect the accuracy of the HSP onboard centroid calculation. The centering is improved by doing the acquisition twice in a row. This double acquisition is now embedded in the scheduling software so that two are performed for every one requested. *Do not request two consecutive acquisitions on the exposure log sheet unless you want four to be performed!*

If the star field is simple so that the program star is easily identifiable, the target may be suitable for an *Onboard* target acquisition. Software in the HST computer examines the pseudo-image and makes a list of up to 20 targets within a specified brightness range. The program star can be specified to be the only candidate on the list (in which case it is an error if there is more than one candidate) or the n -th brightest star on the list, where n is 1, 2, etc. The centroid location of the selected star is then found automatically and the correct telescope offset to the desired filter-aperture is calculated. This offset is passed to the HST pointing control system and the small maneuver is carried out. The program star is now in the correct aperture with the detector parameters properly set, and the observation begins.

If the program star is in a crowded field or is highly variable, it may not be possible to acquire it by means of the automatic finding routine described above. Instead, an *Interactive* or *Early* target acquisition is necessary. In an *Interactive* acquisition, the pseudo-image is displayed on the ground where the observer indicates the target with a cursor; then its position is transmitted to HST. Obviously the observer must be present at the STScI if an Interactive acquisition is necessary.

In many cases the target acquisition image can be taken in advance of the actual observation (an *Early* acquisition), making real-time interaction with HST unnecessary. This avoids both the necessity that the observer be present for the observations and difficulties with real-time interactions with HST. Early acquisitions may also make use of the imaging instruments onboard HST, the WF/PC and the FOC.* If the field is very complicated, the target faint, or the target's ultraviolet magnitude very uncertain, then it may prove useful (or necessary) to get a Wide Field Camera image of the field before the HSP observation. The pointing requirements for target acquisition by the WF/PC are obviously much less stringent than those of the HSP. Unfortunately, the long slews required to move a target from the WF/PC to the HSP will often preclude the use of the same guide stars for the two instruments; this will mean that it will still be necessary to perform some sort of target acquisition with the HSP before observing the target, though it may be possible to use a nearby star that is suitable for an Onboard acquisition. See the *Target Acquisition Handbooks* for the HSP and the other instruments for more information on various strategies for difficult cases.

For faint targets ($m_V > 20$, depending on the color of the star), the time to acquire a 20×20 HSP image may become prohibitive. Then it becomes necessary to adopt a somewhat different target acquisition strategy. There are several possibilities:

- (1) Use the WF/PC (discussed above).
- (2) Reduce the size of the HSP image. For example, a 10×10 image will still usually be large enough to include the target, but requires only 1/4 the time of a 20×20 image.
- (3) Choose a brighter star nearby for offset pointing. For offset target acquisition, the bright offset star is acquired (using any of the usual techniques, including Onboard acquisition); then the telescope is slewed to place the position corresponding to the real target in the desired aperture.

The brightness of the target and the availability of offset stars will determine which of these techniques will be best for a particular target.

Proper motion of the target must be specified or removed when filling in the coordinates in the target list. Proper motion is particularly important for: (1) solar system targets that are moving rapidly, (2) Blind acquisitions in which the target either has not been previously observed or in which the target has moved significantly since the last observation, or (3) targets acquired via offset pointing. In any case, target motions of less than about 0.1 arcseconds during the course of a series of exposures are not important for HSP observations.

2.5.2 Sky Subtraction Modes

If a measurement of the sky background is required, it usually can be made through the other 1.0 arcsecond aperture on the same filter. Apertures in a given row are 15 arcseconds apart, so generally the other aperture should be suitably located for a background measurement. The HST pointing need not be changed; the dissector simply is commanded to collect photoelectrons from the point on the photocathode corresponding to the selected sky aperture. This section discusses the various operating modes that can be used for sky subtraction with the HSP. See §2.2 for a list of which modes can be used with the various HSP configurations. The *HST Phase II Proposal Instructions* give the precise format that must be used.

The HSP will most commonly be used in **SINGLE** mode, in which an exposure consists of a series of measurements of the star's brightness made through some filter/aperture combination. Multi-color photometry is simply a series of **SINGLE** exposures. Measurements of the sky brightness can also be made as **SINGLE** exposures (requiring a separate line on the Exposure Logsheet).

* The FOC will not be used as often as the WF/PC because its field of view is only twice the diameter of the HSP finding apertures.

If the background brightness is expected to vary significantly during the exposure, then the HSP can be commanded to measure alternately the star brightness and the sky brightness from 2 different apertures on the same IDT (STAR-SKY mode). For STAR-SKY mode, the sample times for the star and the sky can be set independently (using the SAMPLE-TIME and SKY-SAMPLE optional parameters).

The minimum time required for the image dissector beam to be deflected from one location to another is 10 milliseconds. Should measurements of the star's brightness be required at intervals shorter than that, two alternatives are available: either background exposures can be taken before and after the high speed data run (requiring three SINGLE mode exposures, two on the sky and one on the star), or if a second dissector contains a filter identical with or relatable to the filter used for the program star, two dissectors can collect data simultaneously, one from the star, one from the sky (also STAR-SKY mode, but with the two different detectors specified in the configuration as HSP/⟨ D_1 ⟩/⟨ D_2 ⟩). In this mode, the sample times for each detector must be identical but can be as short as 28 μ s. This is slightly more than twice the shortest possible sample time (10.7 μ s) when only one detector is collecting data. In principle this sample time could be reduced by using a special "bus director" program (see §3.1.1).

The SPLIT configuration, in which a beamsplitter sends part of a star's light to two different detectors, uses the same technique as two-detector STAR-SKY mode to get simultaneous measurements of a star in two colors. On the other hand, two-color photometry using the PRISM mode is accomplished using the equivalent of one-detector STAR-SKY mode, switching the beam of a single IDT between the two apertures associated with a particular prism. Thus, prism mode measurements are not truly simultaneous but are separated by at least 10 milliseconds, just as are all one-detector STAR-SKY measurements.

2.5.3 Occultation Observations with the HSP

The HSP has many advantages over ground-based telescopes for occultation observations:

- (1) Shorter sample times allow greater resolution.
- (2) UV observations and smaller apertures greatly reduce the scattered light from the occulting body.
- (3) "Stationary" occultations occur when the motion of HST nearly compensates for the motion of the occulting body.

The most difficult part of planning an occultation observation is probably calculating which occultations are favorable for observations with the HST. The STScI can supply orbital elements to those who would like to do occultation predictions; however, STScI will not be able to do such predictions for GOs. Another difficulty is that atmospheric drag causes the orbit to change on relatively short time scales, making it difficult to predict the location of HST accurately more than a short time (about a month) in advance. This means that it will often be impossible to determine at the time of proposal whether the HST will be suitably placed to observe a particular candidate occultation. As a result, many occultation observations will have to be proposed as targets of opportunity.

2.5.4 Other Useful Information

The 10^5 Hz data collection rate (in which a data word is 8 bits long rather than the usual 16) would fill the HSP buffers in only 0.16 s. However, data at this rate can be transferred continuously to the on-board tape recorder for about 10 minutes, where it will be stored until its contents are transmitted to the ground. More details on the transmission and storage of data are given in Chapter 3.

The HSP contains no calibration lamps; its final radiometric calibration will be established by observing stars with known spectral energy distributions. The instrument's sensitivity can be

estimated from the specification that in 2400 seconds it be able to measure a 24th magnitude star in the *B* band with a signal-to-noise ratio of 10. Typical image dissector dark counts and currents are less than 0.1/sec and 1 pA, respectively. Chapter 4 gives a detailed description of the HSP sensitivity.

Chapter 3: Details of the HSP-HST System

Chapter 2 describes the general characteristics of the HSP in enough detail for most observing programs. However, sometimes more information will be needed in order to use the HSP as efficiently as possible. This chapter has sections on some internal details of the HSP's operation, on some quirks and limitations of the HSP-HST system, and on sources of noise in measurements made with the HSP.

3.1 Internal Details of the HSP

3.1.1 The Bus Director

Individual observing sequences in the HSP are carried out by a “nanoprocessor” called the Bus Director (BD). The BD executes a very limited set of 16 instructions that do things like load the latches of a particular detector with deflection settings, cause the contents of a counter or an A/D converter to be placed into the science data buffer, loop a specified number of times, or wait a specified number of clock cycles. (One clock cycle is $1/(1.024 \text{ MHz})$; for convenience this usually is referred to as 1 tick.) Thus, a sequence of 100 1 sec samples on a star is executed by a BD program that loops 100 times through instructions that start a counter, wait 1 sec, then stop the counter and put its contents in the science data buffer. All of the different data formats and modes that are described below are the result of “standard” BD programs; however, it is also possible to write non-standard programs to produce new modes or formats (*e.g.*, a Star/Sky/Dark sequence that measures the dark counting rate separately from the sky background rate, or a data format in which only the *top* two bytes of the three byte digital counter are read out.) It is far beyond the scope of this manual to give enough information for the reader to write his or her own BD programs. The HSP team has designed a language and produced a compiler for special Bus Director programs. Contact the HSP team for details.

3.1.2 Standard Data Formats

There are five standard data formats (and a default) for HSP data. They are:

Table 3–1: HSP Data Formats

<i>Format</i>	<i>Description</i>	<i>Restrictions</i>
BYTE	one byte digital	$Ct < 256 \text{ cts}, C < \sim 2 \times 10^6 \text{ cts/s}$
WORD	two byte digital	$Ct < 65,536 \text{ cts}, C < \sim 2 \times 10^6 \text{ cts/s}$
LONGWORD	three byte digital	$Ct < 16,777,216 \text{ cts}, C < \sim 2 \times 10^6 \text{ cts/s}$
ANALOG	12 bit analog (in two bytes)	$C > \sim 10^5 \text{ cts/s}$
ALL	three byte digital plus two byte analog	$C > \sim 10^5 \text{ cts/s}$
DEF	Default: Format selected by STScI	

Here C is the count rate from the target and t is the sample time for the observation (specified by optional parameter `SAMPLE-TIME`). Chapter 2 distinguishes only between digital and analog data formats because it will often be unnecessary for the observer to specify which particular format is to be used. In that case the sixth entry in the table, `DEF`, is selected (by default) on the observing forms; then the data format is set to the STScI default for the source's counting rate (as specified by the flux data in the target list) and integration time. The brightness of the source determines

whether pulses can be counted or whether the IDT current must be measured; if the count rate is low enough for pulse-counting, the sample time determines whether one, two, or three bytes of digital output will be necessary. The shorter digital formats (BYTE and WORD) are used to reduce the data rate out of the HSP when the sample time is short. Except in a few ambiguous cases, the STScI should be able to determine which data format is best for a particular observation. If necessary, the data format can be specified on the observing form using the optional DATA-FORMAT parameter.

Note that the ALL format allows the simultaneous measurement of the IDT output using the pulse-counting and current methods. This is useful for cross-calibration of the two techniques and for observing bright stars with count rates near the limit of the pulse-counting modes (typically between 10^5 and 2×10^6 cts/s).

Any data format may be used with any observing mode, though only the WORD and ANALOG formats are permitted for onboard target acquisitions.

3.2 The HSP-HST System

This section describes aspects of the interaction of the HSP and the HST, some of which are obvious and some of which are quite subtle.

3.2.1 Changing Filters with the HSP

The HSP's filter/aperture "mechanism" requires the HST to execute small slews to move the target from one filter to another. This means that the time to change filters is determined by the time for HST to do a small angle maneuver, which turns out to be about 30 seconds for all slews shorter than 1 arcminute. (This may seem surprisingly long; it is necessary to move slowly to avoid setting up long-lived oscillations in HST's solar panels.) Consequently, when doing multicolor photometry with the HSP, it is inefficient to integrate less than ~ 30 seconds between filter changes, because then most of the HST time will be spent slewing from filter to filter instead of collecting photons.

For two filters on different IDTs, the slew time is about 60 seconds, so the exposure times through each filter must be even longer for efficient use of HST time.

If a program requires multicolor observations at shorter intervals, a pair of filters that is accessible through one of the beamsplitters must be used (Table 4-3).

3.2.2 Limits to the Length of Uninterrupted Observations

It will often be difficult or impossible to acquire an uninterrupted series of integrations lasting more than about 30 minutes. The *Call for Proposals* discusses HST's orbital constraints. The HST will be in a low orbit so that almost half of the sky is occulted by the earth. Thus, most objects will be unobservable for about half of each orbit, and each orbit requires only 95 minutes. Furthermore, it will not be possible to point HST closer than 50° from the sun, and the sky background will be high when looking at a target close to the earth's bright limb.

Data are transmitted from HST to the ground or stored on the onboard tape recorder at either 4×10^3 or 1.024×10^6 bits/sec (4 kbs or 1 Mbs). There is also an internal 32 kbs link to the tape recorder. The data rate from the HSP, R , is determined by the sample time, t , and the number of bits per sample, n : $R = n/t$. The data rate from HST to the ground is always at least 14% larger than this because of data added by the spacecraft computer (*e.g.*, error correction bits). The bandwidth available to the HSP is reduced even more if other HST instruments are being used at the same time, as will often be the case.

There are various restrictions that arise for the three different link rates. When the HSP is producing data more slowly than 4 kbs, the data rate generally places no restrictions on the total length of the observation time. If the 1 Mbs link is required, then the length of the observation will be limited to the tape recorder capacity (about 10 minutes of continuous data) or to the duration

of the 1 Mbs downlink (~ 20 minutes on the average). Between 4 kbs and 32 kbs the length of the observation may also be limited: if the tape recorder is not available, the data will have to be sent to the ground at 1 Mbs.

To determine whether these restrictions are important for a particular observation, you need to know the following information:

- (1) Is the target in the continuous viewing zone (CVZ)? Targets in the CVZ are continuously visible for several days during certain phases of HST's 56-day orbital precession. Targets not in the CVZ are occulted by the earth on every orbit.
- (2) What is the required data rate? $R \geq 1.14n/t$, where t is the sample time (determined by your scientific objectives) and n is the number of bits per sample (determined from t and from the target count rate C — see Table 3-1.)
 - (a) $R \leq 4$ kbs: no limit on observing time.
 - (b) $4 \leq R \leq 32$ kbs: observations may be up to 8 hours long if data are stored on onboard tape recorder.
 - (c) $32 \text{ kbs} \leq R \leq 1 \text{ Mbs}$: observations may usually last only 10–20 minutes, depending on the availability of the 1 Mbs TDRSS link to the ground.

All of these restrictions mean that most observations that require more than 20 or 30 minutes will probably have gaps in their time coverage. These gaps will obviously lead to some difficulties in the data analysis (*e.g.*, aliases of the 95 minute orbital period will show up in periodic analyses). Observers should try to anticipate how these problems will affect their projects; if gaps in the data will make it impossible to achieve the goal of the program, they should be sure to ask for continuous observations in the proposal. For some programs it may be necessary to choose targets in the “continuous viewing zones”, small regions near the orbital poles that are visible throughout the orbit because they are not occulted by the earth. Note that the continuous viewing zones are always near the limb of the earth, so sky subtraction may be more critical for such observations than for targets far from the limb.

3.2.3 Unequally Spaced Data

Most high speed photometrists are accustomed to using mathematical tools such as fast Fourier transforms and autocorrelation functions to analyze their data; these tools require that the data be equally spaced. However, another consequence of the HST's low orbit is that data from the HSP often will *not* be equally spaced in time. The light travel time from one side of the HST orbit to the other is about 40 msec. Consequently, observations that have sample times shorter than this and that last a significant fraction of an orbit will not be equally spaced in the heliocentric rest frame. The STSDAS system at STScI will provide software to calculate the time of each sample in the solar rest frame (see the *timeseries* package in STSDAS); however, the observer should be prepared to analyze the resulting unevenly spaced data. Consult the *STSDAS Users Guide* for more information.

3.2.4 Absolute Timing of Observations

Although the HSP can make observations with sample times as short as $10.7 \mu\text{sec}$, the absolute time of an observation can only be established to within a few milliseconds. This happens because the phase of the HST onboard clock is only known to a few milliseconds compared to the time on the ground. The HST clock is calibrated daily, with regressions performed to establish clock rates and clock drift rates. Observations of the Crab pulsar have been performed, and comparisons to ground-based radio observations show that the HST clock is well within the 10 msec specification, and is probably good to within a millisecond of UTC. Reducing HSP data to absolute time at this

level of accuracy requires the merging of several data sources not typically available to observers, so interested parties should contact the HSP team for details.

3.3 Sources of Noise and Systematic Errors

There are many sources of noise and/or possible systematic errors for the HSP. This section discusses those that are currently judged to be of possible significance.

3.3.1 Noise

“Noise” is here taken to mean random variations in the measured counting rates that would average to zero in a long series of observations. The noise in most HSP observations will be determined by the Poisson statistics for the star, sky, and detector dark counts. The star counting rate obviously depends on the color and magnitude of the star and on the filter used. The sky counting rate has the same dependencies; it also depends in a complicated way on the angle to the sun, the moon, and the limb of the earth.

Dark counts in the HSP may be produced either by emission of thermal electrons from the photocathode (~ 0.1 counts/sec for the IDTs, ~ 200 counts/sec for the PMT) or by impacts of high energy particles on the photocathode and the first dynode. Large particle fluxes like those encountered in the South Atlantic Anomaly may also cause the MgF_2 in the HSP filters and faceplates to fluoresce for a period of time. The particle background and its effect on the HSP will vary with the position of the HST in its orbit. This effect is small, and has yet to be quantified for the HSP.

Very bright sources will have to be measured using analog (current) data format because their counting rates will be too high for the pulse counting electronics. The statistics of noise for the current data format will be determined by the counting rate, the time constant of the current amplifier, and the sample time. The noise will consequently be somewhat more complicated than simple Poisson statistics.

Only when the number of photons counted is very large ($> 10^6$) will other sources of noise become noticeable. One such noise source is the imperfect guiding of the HST pointing system. Guiding errors move the source away from the center of the aperture, decreasing the fraction of the source’s flux that reaches the HSP detector. Spatial variations in the quantum efficiency of the photocathodes may also lead to small variations in the count rate as the image of the star moves. The spherical aberration increases the effect of the former, putting more energy at the edge of the aperture, and decreases the latter, by smearing the light out over a larger piece of the photocathode. The fluctuations can be large (5% over an orbit) and vary from pointing to pointing.

Fluctuations in the high voltage can change the gain of the photomultiplier sections of the IDTs. This will have little effect on the pulse counting rate, but may change the current out of the tube. The HSP high voltage power supplies have been designed so fluctuations will lead to IDT current variations smaller than 0.1%.

Fluctuations in the low voltages could also affect the performance of the HSP by changing the deflections and focus of the IDTs, the threshold of the pulse amplitude discriminator, the output voltage of the current-to-voltage converter, etc. However, all of these effects have been found to be negligibly small in laboratory testing.

3.3.2 Systematic Errors

The accuracy of the measured brightness will be determined for many sources by systematic errors, which do not average to zero after many measurements. The sizes of systematic errors are inherently more difficult to determine from observations than are noise amplitudes; this problem is made even harder by the fact that the HSP is capable of making more accurate measurements than any ground-based photometer; consequently, the systematic errors of the HSP photometric system probably will not be measurable by comparison to observations using other instruments. It

is hoped that the sum of all systematic errors that cannot be removed will be less than 1% of the signal.

Small-scale spatial variations in the filters and photocathodes cause errors in the measured fluxes because the calibration targets and program targets may not be placed in exactly the same locations within any given aperture. These errors should not be large because the beam is not in focus at the filters and the photocathodes are quite uniform on small scales. The degree to which target positioning is reproducible depends on the performance of the HST pointing control system, which is still experiencing some repeatability and stability problems.

Non-linearities in the A/D conversion may limit the accuracy of analog (current) mode measurements. Because the A/D converter has 12 bits, even a perfect device cannot measure the current to an accuracy better than $\sim 0.03\%$.

Fluctuations from guiding errors, discussed above with reference to noise, can also produce systematic errors. It is likely that the guiding errors will be different for objects with different guide stars. Consequently, two objects with identical fluxes may have different average counting rates: the one with larger guiding errors will appear to have a smaller flux. It may be possible to remove this effect by analyzing the engineering telemetry from the HST to determine how large the guiding errors were for a particular observation. Recent observations with the HSP show an unexplained variation in stellar flux whose period matches that of the HST orbit. An orbital variation has appeared in observations with one other instrument. This is an area being actively investigated, and the user should contact the STScI for information on this effect.

The IDTs inside the HSP must warm up for some time before they can be used for accurate photometry. This warm-up time will be a function of the accuracy that is desired; for example, a few seconds will probably suffice for 10% photometry. The current scheduling procedures appear to be adequate in achieving thermal stability in the detectors.

The changing temperature of the HSP can lead to systematic variations in the counting rate. The photocathode efficiency can vary as a function of temperature; this will be important for the PMT and possibly the alkali IDTs (VIS and POL), but should not affect the CsTe IDTs (UV1 and UV2), which have photocathodes with much larger work functions. All voltages produced by electronic power supplies will also vary with temperature. Most of these effects will be removed by STScI through calibration observations at different temperatures.

3.3.3 Reducing Systematic Errors

Many of the systematic errors can be reduced greatly by observing a calibration target before and after observing program targets. The STScI will eventually determine how often such calibration observations must be done to achieve a given level of accuracy. Note, however, that very critical observations probably will always require extra calibrations (which will count as part of your observing time and which must be requested as separate exposures in your proposal.) Chapter 5 describes the standard calibrations that STScI expects to supply for the HSP.

Chapter 4: Instrument Performance

4.1 Sensitivity of the HSP

This section consists mainly of figures and tables describing the sensitivity of the HSP. The filter transmission data are all based on pre-launch data, but the throughput data include the effect of the spherical aberration. During the Orbital and Science Verification periods after launch, the HSP VIS detector has exhibited some loss of sensitivity. STScI can be contacted for more current information as it becomes available.

Some of the data included in this chapter are:

- (1) Transmission and/or reflectivity as a function of wavelength for all optical elements: filters, mirrors, polarizers, and beamsplitters.
- (2) Tables giving nominal descriptions of all filters (name, central wavelength, FWHM, transmission, etc.)
- (3) Quantum efficiency as a function of wavelength and dark count rates for detectors.
- (4) Figures giving time to reach S/N 100 for a star of a given magnitude and effective temperature.
- (5) Nominal background counting rates through various filters.
- (6) The time required for target acquisition as a function of magnitude and color of the target.

Several explanatory comments apply to all the tables and figures:

- (1) Filter names are all of the form Fxxxw where xxx is the central wavelength of the filter in nm and w is a measure of the width of the filter bandpass with the following approximate ranges:
 - N = narrow (FWHM < 5% of central wavelength)
 - M = medium (5% < FWHM < 15%)
 - W = wide (FWHM > 15%)
 - LP = longpass (filter passes all wavelengths longward of xxx)
- (2) “Throughput” means the peak efficiency for the entire HSP-HST system, including reflectivity of mirrors, filter, polarizer, and beamsplitter transmission, and detector efficiency. These values were calculated using the portable HSP simulator software, and *include* the spherical aberration. Comparison with observations show that these numbers are accurate (~10%) for most apertures. The hpsim program appears to be *underestimating* the throughput for the shortest wavelength filters, and those below about 150 nm (excluding the POL filters) can be estimated to be about a factor of two or three above the tabular values.
- (3) “Transmission” means the peak value for the given optical element (filter, polarizer, etc.) alone, not including any other elements in system.

At the end of the chapter is an example that demonstrates how to use the information in the tables and figures to estimate exposure times for HSP observations.

Table 4–1: HSP Photometry Filters

Name	λ (\AA)	FWHM (\AA)	Transmission (%)	Throughput (%)	Remarks
F122M	1220	130	7	0.005	
F135W	1350	230	12	0.015	
F145M	1450	200	13	0.032	
F152M	1520	180	13	0.043	
F179M	1790	220	30	0.31	
F184W	1840	370	31	0.37	
F218M	2180	170	35	0.48	
F220W	2200	350	35	0.49	
F240W	2400	550	48	0.64	
F248M	2480	370	35	0.46	
F262M	2620	290	33	0.1	UV2 IDT
				0.5	VIS IDT
F278N	2780	140	33	0.18	
F284M	2840	380	31	0.33	
F320N ¹	3200	160	26	0.32	PMT beamsplitter (VIS)
F355M	3550	310	19	0.29	u
F419N	4190	190	31	0.66	v
F450W	4500	1400	65	1.4	B
F551W	5510	850	38	0.54	V
F620W ²	6200	1300	–	0.72	R
F750W ²	7000–9000		–	2.7	PMT beamsplitter (PMT)
F140LP	1400–3000		90	1.7	
F160LP ³	1600–3000		90	1.7	UV2 IDT
	1600–7000		90	2.0	VIS IDT
	1600–7000		90	1.8	POL IDT
F400LP	4000–7000		90	1.8	

NOTES:

- (1) Shape of F320N is determined by band passed by PMT beamsplitter rather than by focal plane filter. Transmission is for beamsplitter bandpass.
- (2) Shapes of R filter (F620W) and PMT filter (F750W) are defined by the photocathode efficiency, so transmissions for filters alone are not given.
- (3) F160LP occurs on both CsTe and Bialkali IDTs. The red cutoff is determined by the photocathode response in both cases.
- (4) Unless listed separately, filters that occur on two or three different IDTs have same throughput on all IDTs.

Table 4–2: HSP Polarimetry Filters

Name	λ (\AA)	FWHM (\AA)	Transmission (%)	Throughput (%)
F216M	2160	300	34	0.028
F237M	2370	280	35	0.054
F277M	2770	340	38	0.14
F327M	3270	410	31	0.11

NOTE: All filters on polarimeter are available with 4 polarizers oriented at 45° intervals. On the observing forms, these are specified as *POL0*, *POL45*, *POL90*, and *POL135*.

Table 4–3: HSP Beamsplitter Filters

IDT	Name	λ (\AA)	FWHM (\AA)	Throughput %
UV1 Prism	F135W	1350	230	0.009
	F248M	2480	370	0.1
UV2 Prism	F145M	1450	200	0.02
	F262M	2620	290	0.1
VIS Prism	F240W	2400	550	0.62
	F551W	5510	850 (V)	0.27
PMT	F320N	3200	100	0.32
	F750W	7500	1600	2.7

Table 4-4: Locations of HSP Filters

<i>Filter Name</i>	<i>IDT Name</i>				<i>Substrate</i>	<i>Remarks</i>
	<i>UV1</i>	<i>UV2</i>	<i>VIS</i>	<i>POL</i>		
F122M	1	1			MgF ₂	Lyman α
F135W	2				MgF ₂	
F145M	1	2			MgF ₂	
F152M	1	1			Crystal Quartz	
F179M		1			Suprasil	
F184W	1	1	1		Suprasil	
F216M				1	Suprasil	
F218M	1	1			Suprasil	
F220W	1				Suprasil	
F237M				1	Suprasil	
F240W	1		2		Suprasil	
F248M	2	1			Suprasil	
F262M		1	1		Suprasil	
F277M				1	Suprasil	
F278N	1	1			WG 280	
F284M		1			Suprasil	
F327M				1	WG 280	
F355M			1		WG 280	u
F419N			1		GG 395	v
F450W			1		BG 28	B
F551W			2		GG 395	V
F620W			1		RG 610	R (red cutoff from IDT)
F140LP	1	1			Crystal quartz	Clear
F160LP		1	3	1	Suprasil	Clear (PMT window)
F400LP			1		GG 395	Clear
F320N			1			PMT beamsplitter (VIS)
F750W			1		RG 695	PMT beamsplitter (PMT) (red cutoff from PMT)

- NOTES: (1) Numbers in IDT columns indicate how many slots are occupied by the filter on that IDT.
- (2) Locations are also given in Figures 2-4 through 2-7.
- (3) All substrates are 1/16 inch thick.
- (4) All substrates are coated to produce multi-layer interference filters except for F450W (B), F620W (R), F750W (PMT), and those indicated to be clear.
- (5) For several filters (marked "Cutoff from IDT"), one edge of the wavelength response is determined by the cutoff of the photocathode response.

Table 4–5: HSP Detectors

Detector	Photocathode	Dark Count Rate (cts/s)	
		0° C.	–15° C.
VIS	Bialkali	0.03	0.01
POL	Bialkali	0.05	0.01
PMT	GaAs	400	200
UV1	CsTe	0.05	0.05
UV2	CsTe	0.1	0.1

Table 4–6: Sky Background Counting Rates for 1" Apertures

Filter	Detector	Sky (cts/s)	Remarks
F240W	VIS, UV	0.008	(without prism)
F240W	VIS	0.005	(with prism)
F248M	UV	0.004	
F262M	VIS, UV	0.005	
F284M	UV	0.005	
F320N	VIS	0.015	IDT/PMT beamsplitter
F355M	VIS	0.019	u
F419N	VIS	0.044	v
F450W	VIS	0.61	B
F551W	VIS	0.26	V (without prism)
F551W	VIS	0.13	V (with prism)
F620W	VIS	0.63	R
F750W	PMT	2.6	IDT/PMT beamsplitter
F140LP	UV	0.031	Crystal Quartz
F160LP	VIS	2.3	Suprasil
F160LP	POL	0.46	Suprasil
F160LP	UV	0.030	Suprasil
F400LP	VIS	1.9	GG 395

- NOTES: (1) The sky brightness is modeled as a dilute 4700 K black body distribution with $m_{5556} = 22.7$ magnitudes per square arcsecond (see *Faint Object Spectrograph Instrument Handbook*.)
- (2) Sky counting rates for filters at and near Lyman α (F122M, F135W, F145M) are strongly affected by the geocoronal $\text{L}\alpha$ line, which varies greatly depending on the position in orbit and the viewing angle.
- (3) For all other filters not listed, the counting rate from the sky is expected to be smaller than the dark count rate from the detector (≤ 0.002 cts/s for VIS, POL and ≤ 0.006 cts/s for UV1, UV2).

Table 4–7: Target Acquisition Time (minutes)**UV1, UV2 IDTs**

m_V	<i>Effective Temperature</i>			
	5000 K	10000 K	20000 K	40000 K
15	4	0.4	0.2	0.2
16	10	0.6	0.3	0.2
17	25	1.4	0.4	0.3
18	70	3.5	0.8	0.4
19	–	8	1.6	0.8
20	–	20	4	1.8
21	–	50	10	5
22	–	–	25	11
23	–	–	70	30
24	–	–	–	75

VIS IDT

m_V	<i>Effective Temperature</i>			
	5000 K	10000 K	20000 K	40000 K
15	0.3	0.2	0.2	0.2
16	0.4	0.3	0.2	0.2
17	0.6	0.4	0.3	0.3
18	1.2	0.7	0.4	0.4
19	3	1.6	0.8	0.6
20	9	4	2	1.2
21	30	12	5	3
22	–	40	15	9
23	–	–	50	25
24	–	–	–	–

POL IDT

m_V	<i>Effective Temperature</i>			
	5000 K	10000 K	20000 K	40000 K
15	0.2	0.2	0.2	0.2
16	0.3	0.3	0.2	0.2
17	0.6	0.4	0.3	0.3
18	1.1	0.7	0.4	0.4
19	3	1.4	0.8	0.5
20	7	4	1.7	1.1
21	20	9	4	3
22	60	25	11	7
23	–	90	30	20
24	–	–	–	60

- NOTES: (1) Time was calculated for a 20×20 image with a signal-to-noise ratio of 6 for the target, including noise from the sky background and dark counts.
(2) An overhead of 25 ms per point is included (10 s for the 20×20 image).
(3) Times longer than 100 minutes are marked “–”.

Figure 4-1: *HSP Filters: 1000–2500 Å*

Figure 4-2: *HSP Filters: 2000–3500 Å*

Figure 4-3: *HSP Filters: 2500–7500 Å*

Figure 4-4: *HSP Filters: Polarimetry*

Figure 4–5: *HSP Beamsplitter Filters: Throughput*

Figure 4–6: *HSP Longpass Filters*

Figure 4-7: *HSP Detector Quantum Efficiencies*

Figure 4-8: *HSP Prism Beamsplitter Characteristics*

Figure 4–9: *HSP PMT Beamsplitter Characteristics*

Figure 4–10: *HSP Polarizer Characteristics*

Figure 4–11: *Reflectivity of HST and HSP Mirrors*

Figure 4–12: *Time to Reach $V=15$ with $S/N=100$: UV Filters*

Figure 4–13: *Time to Reach $V=15$ with $S/N=100$: UV, VIS Filters 1*

Figure 4–14: *Time to Reach $V=15$ with $S/N=100$: UV, VIS Filters 2*

Figure 4–15: *Time to Reach $V=15$ with $S/N=100$: Polarimetry Filters*

Figure 4–16: *Time to Reach $V=15$ with $S/N=100$: Beamsplitter Filters*

Figure 4–17: *Time to Reach V=15 with S/N=100: Longpass Filters*

4.2 Planning a Typical Observation with the HSP

This section shows how to calculate exposure times, etc., using the information given above and in Chapter 3. The example has a relatively simple goal, but it demonstrates some of the complications that can arise in planning an observation and shows that the considerations discussed in Chapter 3 are often important.

4.2.1 How to Calculate Exposure Times

The exposure time (which must be specified on the exposure logsheet) is the total time HST spends pointing at the target from the beginning to the end of the observation. The exact relation between the exposure time (t_{exp}) and the other times (sample time, delay time, etc.) specified for the observations depends on the mode used:

Configuration	Mode	Exposure Time
HSP/⟨D⟩	SINGLE	$t_{exp} = N_{samp}(t_{samp} + t_{delay})$, where N_{samp} is the number of samples desired, t_{samp} is the time for each sample, and t_{delay} is the delay time between samples. t_{delay} is usually zero for these modes.
HSP/PMT/VIS	SPLIT	$t_{exp} = N_{samp}(t_{samp} + t_{delay})$
HSP/⟨D ₁ ⟩/⟨D ₂ ⟩	STAR-SKY	$t_{exp} = N_{samp}(t_{samp} + t_{delay})$
HSP/⟨D⟩	PRISM, STAR-SKY	$t_{exp} = N_{samp}(t_{samp,tot} + t_{delay,tot})$, where $t_{samp,tot}$ is the sum of the sample times for the two apertures and $t_{delay,tot}$ is the sum of the delay times for the two apertures. t_{delay} is usually 10 milliseconds for each aperture in these modes, so $t_{delay,tot}$ is usually 20 milliseconds.

If a sequence containing a number of exposures is defined, then the total exposure time for the sequence is simply the sum of the individual exposure times.

The sample time and number of samples needed for a particular observation are determined by the scientific objectives of the program: the brightness of the target, the filter used, the time resolution needed, the signal-to-noise required, etc. The next section shows how to calculate the sample time and number of samples for a typical HSP observation.

4.2.2 Photometry of the Crab Pulsar

The Crab pulsar is a classic object for high speed photometry. The scientific goal of this sample program is to measure the width of the ultraviolet pulse from the Crab pulsar.

The (time-averaged) de-reddened spectrum of the Crab pulsar in the UV is approximately

$$F_\nu = 5 \times 10^{-29} \left(\frac{\nu}{10^{15} \text{ Hz}} \right)^{-0.5} \text{ W m}^{-2} \text{ Hz}^{-1}$$

or

$$F_\lambda = 1.5 \times 10^{-14} \left(\frac{\lambda}{3000 \text{ \AA}} \right)^{-1.5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$$

(*e.g.*, see *Pulsars* by Manchester and Taylor). The extinction to the Crab pulsar is $A_V = 1.6^m$; from the standard interstellar reddening curve (tabulated in the *Faint Object Spectrograph Instrument Handbook*), we can calculate the reddened flux at the wavelengths of the filters we are going to use. Then the counting rate in each filter can be estimated from the data for the polarimetry filters given in Table 4-2:

Filter	λ (\AA)	A_λ (mag)	F_λ (photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$)	FWHM (\AA)	Throughput (%)	Count Rate (cts/s)
F240W	2400	4.07	6.0×10^{-5}	550	0.17	8.2
F278N	2780	3.12	1.3×10^{-4}	140	0.39	1.3
F355M	3550	2.45	2.2×10^{-4}	310	0.29	7.7
F140LP	2000	4.51	4.4×10^{-5}	1200	0.29	25

The counting rate is the product of the photon flux density, the collecting area of HST ($0.86\pi[120 \text{ cm}]^2$), the FWHM of the filter, and the throughput of the system. This includes the 14% loss of light due to the secondary mirror.

For comparison, the HSP simulator predicted a time-averaged count rate of 55 per second for the F140LP UV2 filter, and the actual observation yielded 43 counts per second.

The sky brightness is relatively small compared to the brightness of the Crab pulsar, so we will not bother to measure or subtract the sky background. This means that we will use **SINGLE** mode.

The sample time should be somewhat shorter than a millisecond to make the rebinning of the data into 1 msec bins easier (see §3.2.3); 0.5 msec is a good choice because then the data rate will be about 16 kilobits per sec, which is comfortably under the 32 kbs rate at which the tape recorder stores data (see §3.2.2). (There is no way to get the data rate under 4 kbs.) There will inevitably be gaps in the time coverage due to occultations by the earth (§3.2.2), but the period of the Crab pulsar is so well known that the gaps should not pose any data analysis problems. If there are unexpected problems, the pulsar is bright enough to determine the phase of a short segment of data from the data itself.

Finally, it is necessary to specify how the target will be acquired. It is possible to use the Onboard target acquisition method, in which an HSP image is automatically analyzed to identify and locate the target (§2.5.1). Remember that the points in an HSP image are accumulated one at a time, so a target that varies during the target acquisition data collection may be misidentified or missed entirely. The Crab pulsar's period is about 33 ms, so we want the sample time for each pixel in the image to be a lot longer than this. We chose 750 ms. The total target acquisition time for the Crab Pulsar (including the 25 ms per point overhead) is then $400 \times (25 + 750)$ ms = 5 minutes.

Chapter 5: Standard Calibrations and Data Products

This chapter describes the way HSP data are usually calibrated and what data products result.

5.1 “Pipeline” Calibrations

The raw data received from the HST pass through an automatic calibration procedure called the “pipeline” before it is received by the observer. For the HSP the pipeline performs 6 steps:

- (1) *Reformatting.* The data are put in a standard form that is independent of the particular way it was collected. Interleaved data taken in **STAR-SKY** mode are divided into two files; data taken with the **ALL** data format is split into separate digital and analog files. Each data sample (which may be from 8 bits to 24 bits long) is converted to a 32-bit floating point number. The data is written to a FITS-like format called “GEIS” format which can be read directly by the STSDAS analysis routines.
- (2) *Convert counts to count rates and apply deadtime correction.* For pulse-counting (digital) data, the raw counts are divided by the sample time to yield count rates, which are then corrected for the non-linearities caused by the deadtime of the counting electronics. This correction is 1% for counting rates of about 2.5×10^5 counts/s. The deadtime is known from laboratory measurements to be a weak function of temperature, so it should be possible to make accurate deadtime corrections for count rates up to at least 10^6 counts/s.
- (3) *Subtract dark counts or currents.* The standard dark contribution from the phototube is subtracted. Nominal dark counts and currents are known as a function of both the position on the IDT cathode and the detector temperature. Notice that if a special dark calibration is requested by the observer (via the **DARK** internal calibration target request described in the *Phase II Proposal Instructions*), it will not be subtracted in the pipeline; instead, it will have to be subtracted using the general purpose data analysis system, STSDAS (see below).
- (4) *Convert currents to equivalent count rates.* For current (analog) data, the photocurrents that were measured are converted to the effective count rates that would have been measured by a pulse-counting system with zero deadtime.
- (5) *Correct for the instrumental efficiency.* The instrumental efficiency is measured by observing a standard star through the same aperture-filter combination. Comparison of observations of the same standard star taken at different times allows the removal of changes in the HSP sensitivity as a function of time. The pipeline calibration program computes the HSP count rate the target would have had if the HSP sensitivity had not changed.
- (6) *Divide observations of extended objects by aperture area.* Note that this applies to sky observations as well as to observations of extended targets.

5.2 Data Products

The results of the pipeline calibration are files containing the HSP count rates as a function of time for the star+sky and (if it was measured) the sky. In addition, the reformatted data (produced by step 1 above) are readily available to the observer. A single observation can generate up to 8 separate data files: a **STAR-SKY** observation using the **ALL** data format will generate an uncalibrated data file and a calibrated data file for each of the star/digital, star/analog, sky/digital, and sky/analog data.

The pipeline calibration products will probably be sufficient for most observers. However, if an observer wishes to recalibrate her data, perhaps using a different calibration table, the pipeline software is available in STSDAS. Refer to the *STSDAS Calibration Guide* for more information.

Note that the sky background is not subtracted from the star+sky measurement. It was decided that sky subtraction is sufficiently complicated that it is not reasonable to include it in the automated pipeline. Instead, it will be the observer's responsibility to decide how the sky measurements are to be averaged and interpolated before they are subtracted from the star measurements.

Note also that the HSP count rates are not translated either to absolute fluxes or to a standard magnitude system. Both of these conversions depend on knowing the spectral energy distribution of the target star. Keywords in the header of the data will allow conversion to fluxes; the Science Data Analysis System (STSDAS) at STScI will include the tools that are necessary to convert HSP count rates to a standard magnitude system if the target star's color is known or if some shape for the spectrum is assumed. STSDAS will also have access to the calibration data that are required for these translations (*e.g.*, color terms for standard filters and the absolute flux distribution for calibration stars.) Consult the *STSDAS Users Guide* for more information.

An advantage of supplying the data in the form of HSP count rates rather than absolute fluxes is that the former are independent of the flux distribution assumed for the standard stars. Thus, if the flux scale of the standard spectra is revised, the HSP count rates will not change.

5.3 Special Calibrations

Calibration observations made as a service by the STScI will be sufficient to calibrate most HSP observations. However, there will inevitably be some observations that require special calibrations. For example, a special calibration may be required to measure the strongly varying sky background that is seen during a lunar occultation. As another example, it may be desirable to observe a standard star before and after the target is observed in order to remove small systematic effects (see Chapter 3 for more discussion of this).

Any special calibration observations must be requested as part of the observing proposal. The observer is responsible for applying the calibration to the data. Attempts to derive standard calibrations have been thwarted by the repeatability problems in the FGS and the unexplained instabilities. It is impossible to say at this time what the accuracy of the standard calibrations will be, but ultimately the goal will be to remove all systematic effects larger than 0.1% of the signal. Smaller effects will probably always be the responsibility of the observer, and larger effects will almost certainly be present during the year following launch.

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6.1 Further Reading

Several resources deserve a little further description. *Science Mission Schedules* contain the HSP commanding. Each instrument team put together procedures for decoding the dense SMS files, but many were based on a syntactical attack: scanning for well-known lexical features in the SMS. The HSP team produced a program that attacks the SMS *semantically*. It is a real compiler,

produced using modern compiler production tools, that is capable of logically dismantling any SMS that conforms to ICD-11. A full HST data model is maintained by this program, allowing the user to follow SMS-directed interactions between any HST subsystems. This tool produces readable digests of HSP activity, including data collection summaries, error reports, guide star usage, and even sky maps showing the HST movements for a given week. In addition, a post-processing tool called *optime* produces an accurate accounting of HSP hardware usage. Total on time, number of cycles, and so on are extracted from past SMS files. The HSP team keeps online the complete history of SMS files, allowing the user (probably the instrument engineer) to obtain quickly the flight history of any given component in the HSP.

Another resource is the Bus Director Compiler. The HSP data collection processor is programmable. Standard data collection programs, such as Single Color Photometry, have been loaded in advance and are used in an “off the shelf” fashion. It is possible, however, to load a special Bus Director program of your own. Three Color Photometry or rapid readout area scans are examples of what can be considered. The Bus Director Compiler (BDC) is a program that reads in a program specification in the form of simple words (start counter, stop counter, etc.) and produces the opcodes that implement this program. In addition, we have simulated the operation of the Bus Director in a second program, which can read in any bus director program and execute it, with a printout giving actual timestamps when counters are started and stopped, and so on.

Finally, a few words should be said about the various HSP simulator programs. The original *hpsim* was written at the STScI and is still available there. The HSP team also has a simulator program that uses the same data files, but has a little different look and feel. The HSP team version is written in portable C, contains no site-dependent graphics code, and has been compiled and run on several different computers and operating systems. It has a simple tabular output, and can be run either interactively, or in batch mode. Another feature is that the user can specify wildcards that can select all the filters on a detector, a given filter on any detector that has it, or even all filters on all detectors. The input spectrum can be a blackbody, a power law, or user-defined. A library of Kurucz model spectra is also available for a more realistic input.

Documentation and programs for these resources are available from the HSP team. Write to jwp@sal.wisc.edu for details.

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