Fine Guidance Sensor Instrument Handbook

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1.0 INTRODUCTION

Since the Hubble Space Telescope's Fine Guidance Sensors work interferometrically, their "resolution" is not limited by the point spread function of the telescope and milli-arc second (mas) level performance can be achieved. The Fine Guidance Sensors should primarily be used for parallax, proper motion, binary star, and angular diameter observations. Since the FGSs will probably be the longest-lived, and the most stable, of all the scientific instruments on the Hubble Space Telescope, and it is exactly this kind of permanence and longevity that are the hallmark of first-rate astrometrical instruments, General Observers who wish to utilize the FGSs are invited to do so in Cycle 5 and beyond. Note too that the FGSs are the only remaining high-speed photometric devices on the spacecraft.

1.1 Overview

This is a revised version of the Hubble Space Telescope Fine Guidance Sensor Instrument Handbook. The main goal of this edition is to help the potential General Observer (GO) learn how to most efficiently use the Fine Guidance Sensors (FGSs). First, the actual performance of the FGSs as scientific instruments is reviewed. Next, each of the available operating modes of the FGSs are reviewed in turn. The status and findings of pertinent calibrations, including Orbital Verification, Science Verification, and Instrument Scientist Calibrations are included as well as the relevant data reduction software. The Phase II Proposal Instructions for the TRANSfer and POSition Modes are explored parameter by parameter. Additionally, complete examples of the General Observer Phase II Proposal Forms for the different observing modes are given in Appendix A. **Note:** the format of the Phase II Proposal forms as well as the procedures for creating the forms are currently being revised; an up-to-date version of the Phase II Proposal template should be available on STEIS. It is strongly recommended that the user checks the available Phase II documentation carefully.

The ST ScI FGS data reduction software, or Astrometry Pipeline, does for astrometric data what the Routine Science Data Processing (RSDP) pipeline does for the observational data gathered by the other scientific instruments onboard the Hubble Space Telescope. Since astrometric data reaches the Institute via the Astrometry and Engineering Data Processing telemetry stream, rather than the main scientific instrument telemetry stream, an entirely separate set of software had to be designed, coded, tested, and debugged merely to obtain access to the data. This software is being transformed so that it can reside in the normal Space Telescope Science Data Analysis Software (STSDAS) IRAF environment. The Space Telescope Astrometry Team (University of Texas) played a significant role in the design and development of the telemetry handling software for which we are grateful — especially to E. O. Nelan.

The Bibliography, which is intended as an index to FGS work, consists of many FGS-related papers including documentation of the technical details behind the Institute's Astrometry Pipeline, the optical system of the Fine Guidance Sensors, and how the Fine Guidance Sensors function.

1.2 Fine Guidance Sensor Performance

As the FGS Instrument Scientists have been reporting via the HST Newsletter, Fine Guidance Sensor scientific observations have only been marginally affected as a consequence of the mis-figuring of the primary mirror by Perkin-Elmer Corp. (See Table 1 for actual and expected performance levels.) The FGSs have lost limiting magnitude for positional astrometry (about 1.0 mag from $V = 17.0$ mag). They have lost "resolution" with respect to double star separations (about 10 milli-arc seconds for separations larger than 10 mas but this depends on both the total magnitude of the binary and the magnitude difference between the components). They have also lost some limiting magnitude with respect to double star magnitude differences, that is in the detection of fainter components. This is about 0.5 mag from an expected sensitivity of $\Delta m = 4.0$ mag (and depends too on the total apparent magnitude of the system). Similarly, the ability to do really small angular diameter measurements (below about 15 mas) has been sacrificed but apparent size determinations were an additional capability of the instrument (Taff 1990). Finally, some ability to detect color index effects via a change in slope of the Transfer Function near its null may have been lost. This too was an additional capability of the instrument and of only a 0.25 mag precision at best (it relied on a second order optical aberration within the FGSs which is now dwarfed by other optical aberrations).

The causes of these performance curtailments are a combination of the mis-figured primary mirror of the Optical Telescope Assembly (OTA), a less than optimal focus, tilt, and decenter for the secondary mirror of the OTA (from the point of view of the FGSs), and the thermally-induced solar array spacecraft jitter.

Some of these goals may be recovered when the astrometry jitter rectification software is implemented. [Because astrometry data is acquired via the Astrometry and Engineering Data Processing (AEDP) telemetry stream rather than the RSDP stream, and full Guide Star pointing information is included at the same frequency (*i.e.*, typically 40 Hz) as the scientific data, the data should be especially well suited to the minimization of the deleterious effects of jitter.]

1.2.1 Some Details

The successful implementation of COSTAR (Corrective Optics Space Telescope Axial Replacement) did not affect either the FGSs or the wave front reaching them. What has been lost to the Fine Guidance Sensors is a coherent wave front properly brought to a diffraction-limited focus; the spherical aberration of the primary mirror of the Optical Telescope Assembly has destroyed the phase coherence of the incoming plane wavefront from the target. For the imaging and spectroscopic instruments, this degradation was usually (before COSTAR) viewed as an increased size of the point spread function. For the Fine Guidance Sensors, which operate in their scientific modes (and some guidance modes) interferometrically, this degradation is manifested as a decrease in the (interferometrically produced) fringe visibility function. A significantly reduced modulation in the fringe visibility function, the appearance of multiple lobes, the presence of multiple nulls, other — and asymmetric — distortions, the development of azimuthally dependent (therefore *not* spherical aberration) distortions, a masking of sensitivity to the input spectrum (*i.e.*, the masking of color index effects by other distortions), and so on are the consequences. Thus, the poor quality wave front being presented to the Fine Guidance Sensors make interferometry more difficult.

Table 1.
Fine Guidance Sensor Science Performance

TRANSfer Function Mode:	
Binary star "resolution" limits	
Separations	5 mas (a)
Magnitude differences	4 mag (a)
Binary star precision estimates	
Separations	1 mas (a)
Magnitude differences	0.05 mag (a)
Angular diameter precision estimates	5 mas (b)
Angular diameter limits	>20 mas (b)
Color index	to be dropped as infeasible
POSition Mode:	
Precision	<5 mas (a)
Limiting magnitude	17 mag (a)
Walkdown Mode: (c)	
Precision	<3 mas
Limiting magnitude	15 mag

(a) Based on GO and GTO observations and data reduction.
(b) Depends on further calibrations and jitter removal.
(c) New mode of operation of FGSs. Currently being upgraded from an engineering only mode. The numbers are estimates.

Most of this "loss of performance" can be regained by moving the secondary mirror of the OTA in tilt, decenter, or focus. However, moving the secondary mirror also has consequences for the point spread function that the other scientific instruments receive. In particular, when the secondary mirror is positioned to maximize the fringe visibility function in as much of the three FGS's fields-of-view as possible — the azimuthal dependence across the three FGSs is pronounced — unacceptable levels of coma, astigmatism, and so on are introduced into both Faint Object Camera and Wide Field/Planetary Camera II images. Thus, the present location and orientation of the secondary mirror is meant to maximize the scientific capabilities of the on-axis instruments, preserving the scientific capabilities of the Fine Guidance Sensors only minimally, while maintaining the engineering functions of the Fine Guidance Sensors (namely Guide Star acquisition and the steady state holding of the spacecraft in Coarse Track and Fine Lock). Since there are placements of the secondary mirror which make each of the Fine Guidance Sensors "perform better", and there are indications in some of the collimation testing that has been executed that all of them can be made "to work" quite well, whatever may be wrong inside each of the Fine Guidance Sensors has not been the dominant problem with their "behavior".

The main piece of evidence that the Fine Guidance Sensors themselves are not primarily responsible for their "performance" is the fact that each of their fringe visibility functions show clear-cut, azimuthally dependent, variations. There are continuous changes in the modulation, presence or absence of multiple lobes and secondary nulls, amplitude of asymmetric features, and so forth which most likely originate in the OTA. Indeed, the moves of the secondary mirror of the OTA for SMOV (Servicing Mission Orbital Verification), after the installation of COSTAR, introduced marked changes in the shapes of the Transfer Functions as viewed in all 3 FGSs. The discontinuities in these features between adjacent Fine Guidance Sensors point to separate, and different, problems within each of the FGSs. Despite many attempts, by Perkin-Elmer Corp. (now Hughes Danbury Optical Systems), by ST ScI personnel, and others, no convincing physical optics model of the combined OTA/FGS optical system can explain these variations (nor most other abnormalities of FGS "behavior"). Therefore, the philosophy of the Instrument Scientist Calibration Plan is to proceed on a totally empirical basis. This approach to FGS science has also been reflected in the robustness and success of the very general TRANSfer Mode data reduction software developed for the Institute's Astrometry Pipeline (Lattanzi, Bucciarelli, Holfeltz, and Taff 1992).

1.2.2 Fixes and Workarounds

How can these problems be minimized? Each FGS has a filter wheel in its optical train. This wheel has positions for five filters (see Table 2), one of which is referred to as a CLEAR filter. Note that the astrometer FGS, which is the one in radial bay #3, and *not* the one in radial bay #2 as originally expected, has instead of the RED filter the ASTROMETRY CLEAR filter. Another position in the filter wheel is occupied by the PUPIL which is an aperture stop. The aperture stop limits, by one-third, the portion of the OTA primary mirror wavefront that is allowed to enter the FGS interferometer. Not surprisingly, if one constructs a fringe visibility function with this filter in place, the modulation is increased, the frequency of multiple lobes lessened, the occurrence of secondary nulls diminished, the size of the asymmetric distortions reduced, and so on. The only drawback is a loss of sensitivity since one-third of the photons collected by the primary mirror are prevented from being detected by the FGS photomultiplier tubes. The loss of one-third of the out of phase photons is usually more than offset by the gain of having the remaining photons more in phase. As can be seen in Fig. 1, the change in the fringe visibility function is dramatic. Thus, the recommended filter wheel element for POSitional and TRANSfer astrometric work with the Fine Guidance Sensors is PUPIL. (The same has been true of Guide Star acquisitions for similar reasons.) This does limit one's ability to search for color index related effects (since all the other filters are full aperture). General Observers who need the additional photon counts or who want to explore spectral aspects should use the filter wheel positions which their scientific purposes demand. The Instrument Scientist Cycle 4 Calibration Plan concentrates on the PUPIL and CLEAR filter wheel positions.

Table 2.
Spectral Elements for the FGS

Name	Comments	Effective Wavelength (Å)	Full Width at Half Maximum (Å)
F583W	"Clear" filter	5830	2340
F5ND	Neutral Density (5 mag)	—	—
F605W[a]	"Astrometry Clear" filter	6050	1900
F650W[b]	"Red" filter	6500	750
F550W	"Yellow" filter	5500	750
PUPIL	Pupil stop	—	—

[a]F605W is to be specified with FGS #3 only.
[b]F650W is to be specified with FGS1 or FGS2 only.

2.0 TRANSFER MODE OBSERVING, CALIBRATION, AND DATA PROCESSING

The scientific purpose of TRANSfer Mode observing can be simply realized by understanding what the Transfer Function reveals. (The fringe visibility function produced by the Koesters prism interferometer inside the FGS is known as a "Transfer Function". Hence, TRANSfer Mode and so on.)

When a star, taken for simplicity to be single, of no apparent angular diameter, and with a monochromatic spectral energy distribution, is far away from the null of the Koesters prism interferometer (say angular distance greater than $\sim$ 75 milli-arc seconds), then the folding over of the OTA focal plane by the prism results in negligible constructive or destructive interference. Therefore, the photon counts in the two channels of the interferometer are roughly equal and the fringe visibility function (= Transfer Function) is approximately zero. As the angular distance between the star and the null of the Koesters prism interferometer decreases, the interference increases. Depending on the direction of approach, the interference is either constructive or destructive, eventually producing a maximum or minimum in the Transfer Function. In between the two extrema there is a complete balance, and hence null, in the fringe visibility function. Finally, before reaching the maximum or minimum of constructive or destructive interference, secondary peaks in the fringe visibility function will be present.

The nominal, perfect optical system Transfer Function for a single, monochromatic point-source is shown in Fig. 2. Its analytical form is

$$S(z) = \frac{\sin^2 z}{z}, \qquad z = 2\pi R\theta/\lambda \tag{1}$$

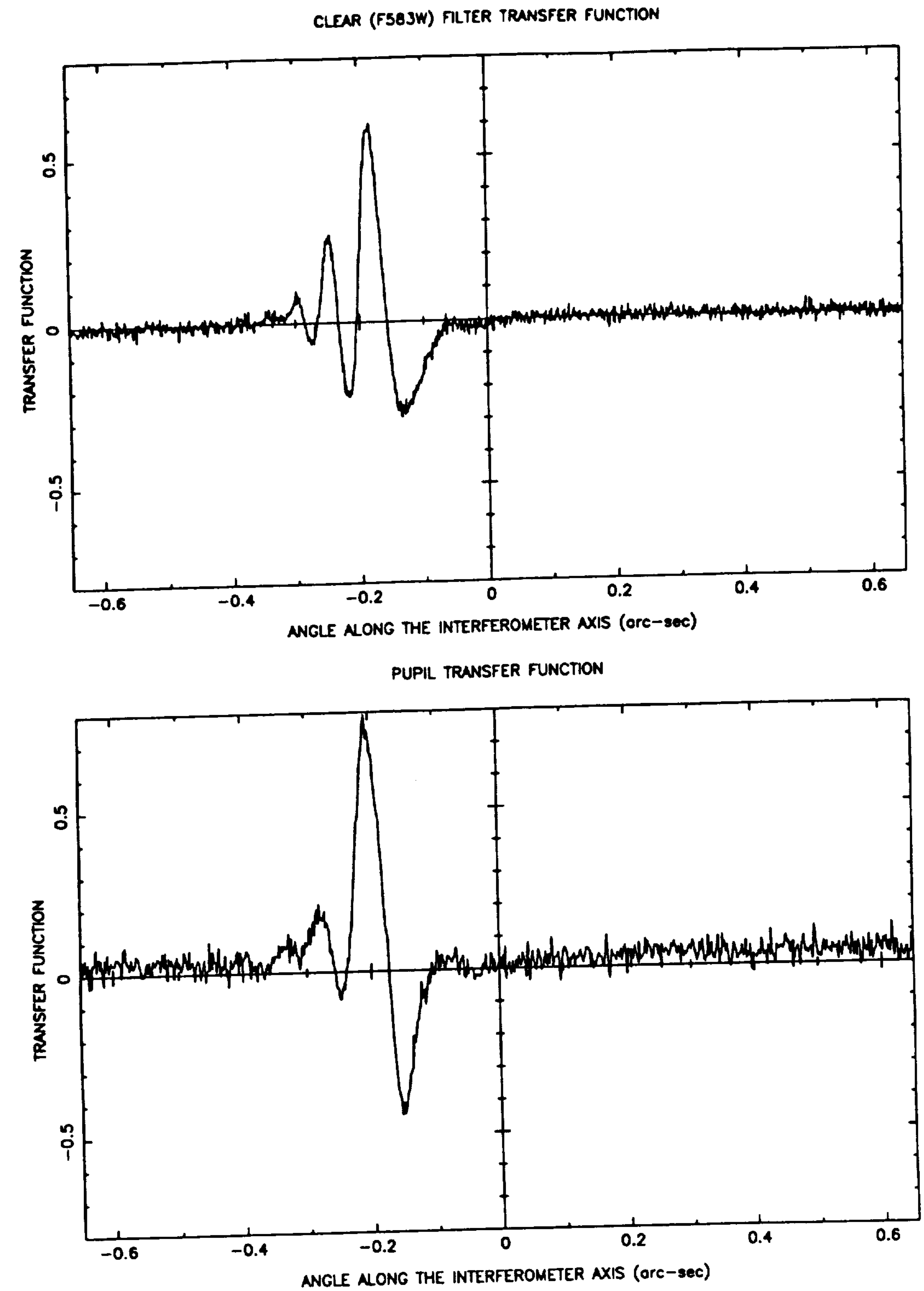

Figure 1. Full aperture (top) and two-thirds aperture (bottom) Transfer Functions from the same place in the FGS field of view. These are good quality, empirical versions of the theoretical expectation shown in Fig. 2.

where R is the radius of the primary mirror of the OTA (120 cm; 80 cm if the PUPIL is in place), λ is the wavelength at which the assumed monochromatic point source is radiating, and θ is the angular distance from the interferometer null.

Transfer Functions for non-monochromatic sources or finite-sized sources can be built up by using the expression in Eq. (1) as the Green's function for the appropriate integrals (see Taff 1991). The effects of color temperature and apparent size on the theoretical Transfer Function are shown in Figs. 3–5. (Remember that this entire discussion and the figures are pre-knowledge of the primary mirror defects.)

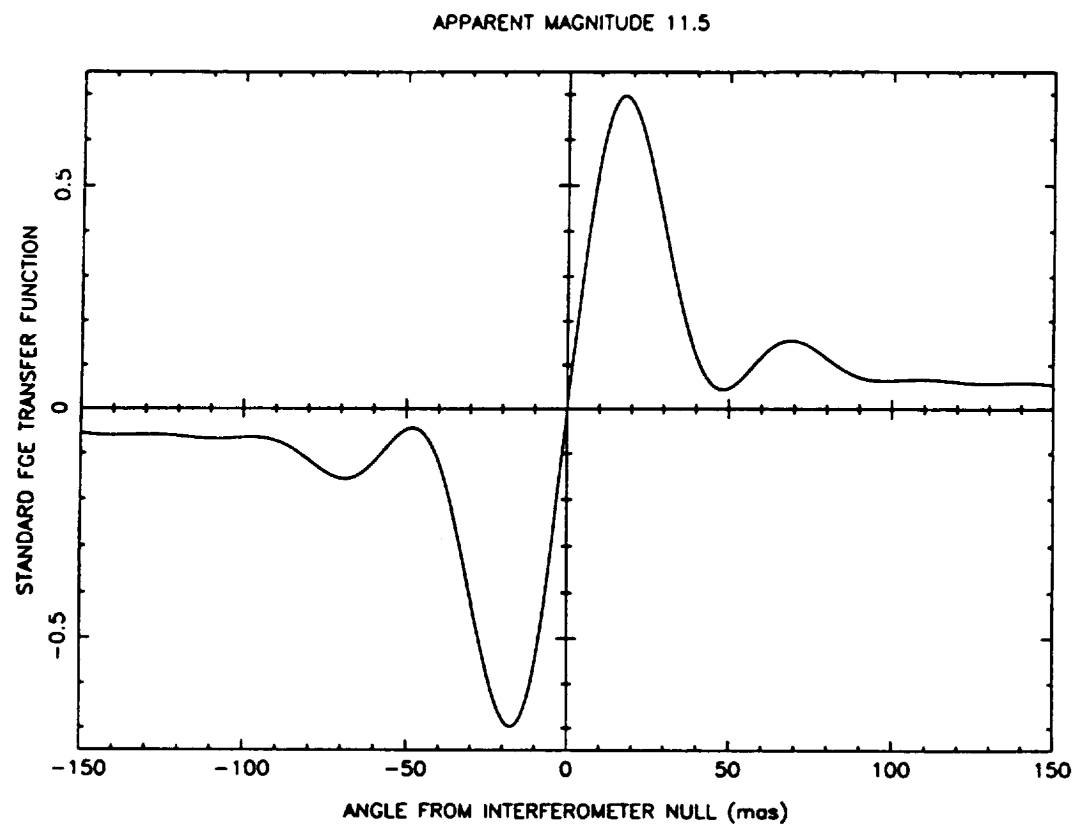

Figure 2. Pre-spherical aberration theoretical expectation for the Transfer Function. Compare with Fig. 1.

Similarly, double star Transfer Functions are constructed by combining single star Transfer Functions plus the assumption that the combined OTA/FGS optical system is linear. Given that the optical processes in the OTA and FGS are linear, if the source were a binary star instead of a single star, the prediction would be that the resulting Transfer Function would show two sets of primary extrema for it would just be a linear combination of two single star Transfer Functions; see Eq. (2) in §2.3.3 and Fig. 6. The separation between the two maxima (or two minimà) provides information about the separation between the stars

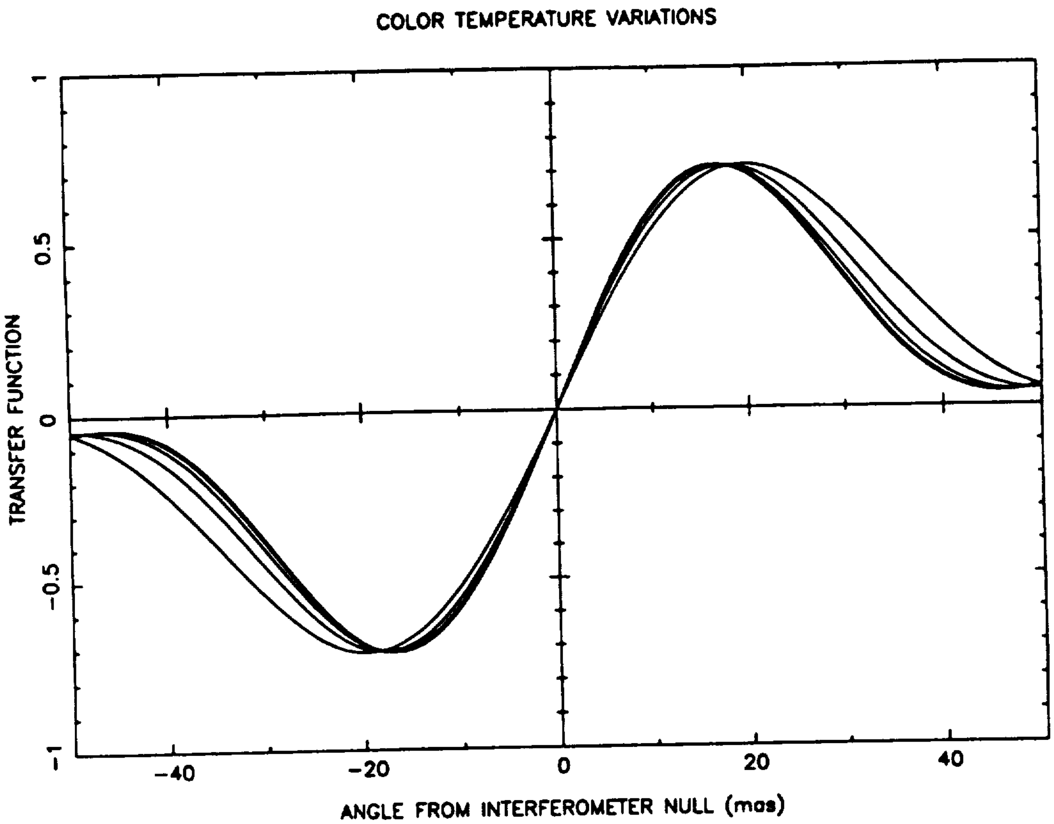

Figure 3. The effects of color temperature on the theoretical Transfer Function. The hottest star (32,000 K) has the greatest inward shift of the extrema of the Transfer Function. Temperatures vary downward by a factor of 2.

as seen projected onto the celestial sphere in the direction of this axis of the interferometer. The difference in amplitude between the main extrema provides information about the magnitude difference between the primary and the secondary star of the binary. (In reality the ST ScI astrometry data reduction software estimates these aspects of a double star by a thorough analysis of the entire Transfer Function, see §2.3.)

In an analogous fashion, if the source were an extended object instead of a point source, then the Transfer Function would again be distorted. This deformation can be computed since it can be viewed as a "sum" of many different Transfer Functions, each one arising from a small piece of the extended source. Transfer Functions from the other axis (see §2.2) will reveal a non-circular symmetry in an extended object or provide separation information in another direction for a binary star (the magnitude difference information is redundant). Adding the complication of limb-darkening it can be seen that de-convolving an extended source Transfer Function will be a challenging task.

Similarly, if the target is embedded in a bright background, the Transfer Function will suffer characteristic distortions. To enable TRANS Mode observing in fields with high background, the FGS Cycle 3 Instrument Scientist Calibration program performed TRANS Mode

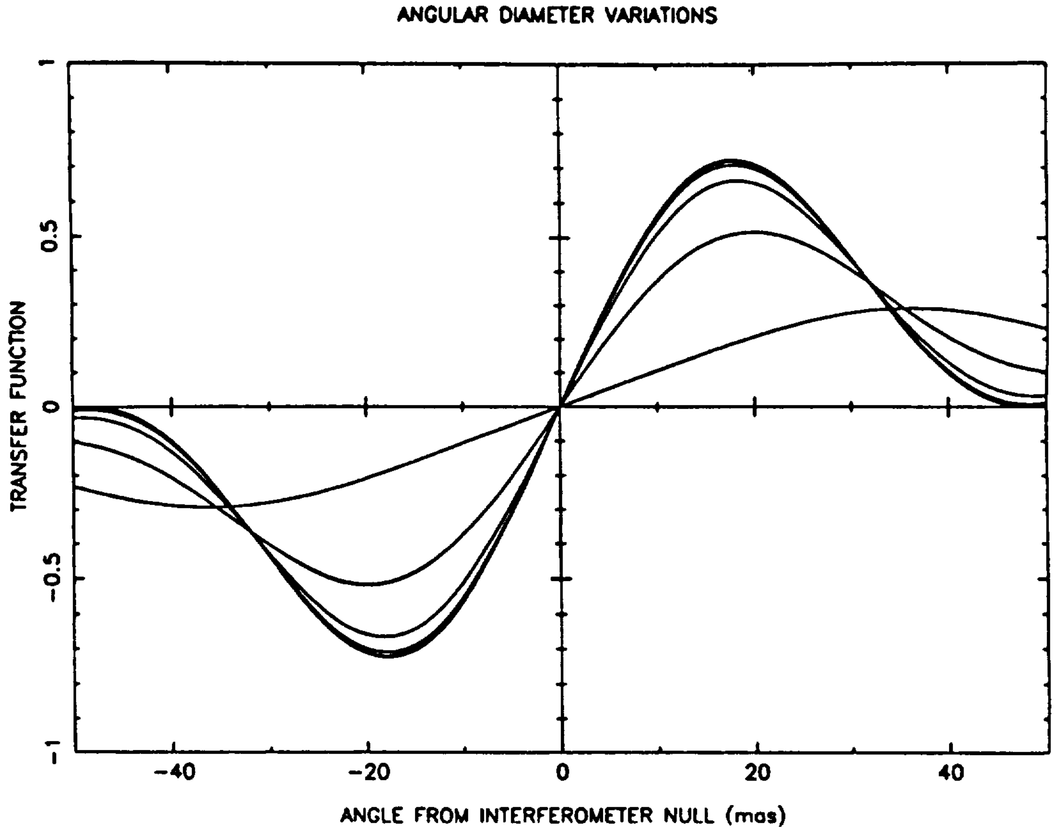

Figure 4. The effects of finite angular size on the theoretical Transfer Function. The largest star (80 mas) has the peak-to-peak of the Transfer Function depressed and shifted outward the most. Angular diameters vary downward by a factor of 2.

observations on the bright core of the massive star cluster R136 within 30 Doradus, R136a, and other O3 supergiant stars within 30" of R136a. The success rate of the Search/Coarse Track/Walkdown acquisition procedure, which locates the position of the target before starting the TRANSfer scans (see §3.0), was 70% for the most crowded part of the cluster and 100% in the less crowded part.

Thanks to the incoherent nature of background light, the strong (and complex) background around the R136 cluster, which is about 15 mag per second of arc^2 in V as measured by the FGS itself, does not prevent the FGS from achieving its angular resolution limit of approximately 0."015 per axis and V photometry to 0.1 magnitude (Lattanzi, Hershey, Burg et al., 1994). The signal-to-noise ratio scales as the square root of the number of consecutive scans taken. For a background of 15 mag per second of arc^2 in V, a single scan of a V $\simeq$ 12.5 mag has a signal-to-noise ratio of about 10 (this goes down if other point-like sources of comparable magnitude are present in the FGS field of view).

Therefore, FGS TRANS Mode is viable for those programs designed to perform astrometry and photometry of sources embedded in strong background. Stellar crowding as well,

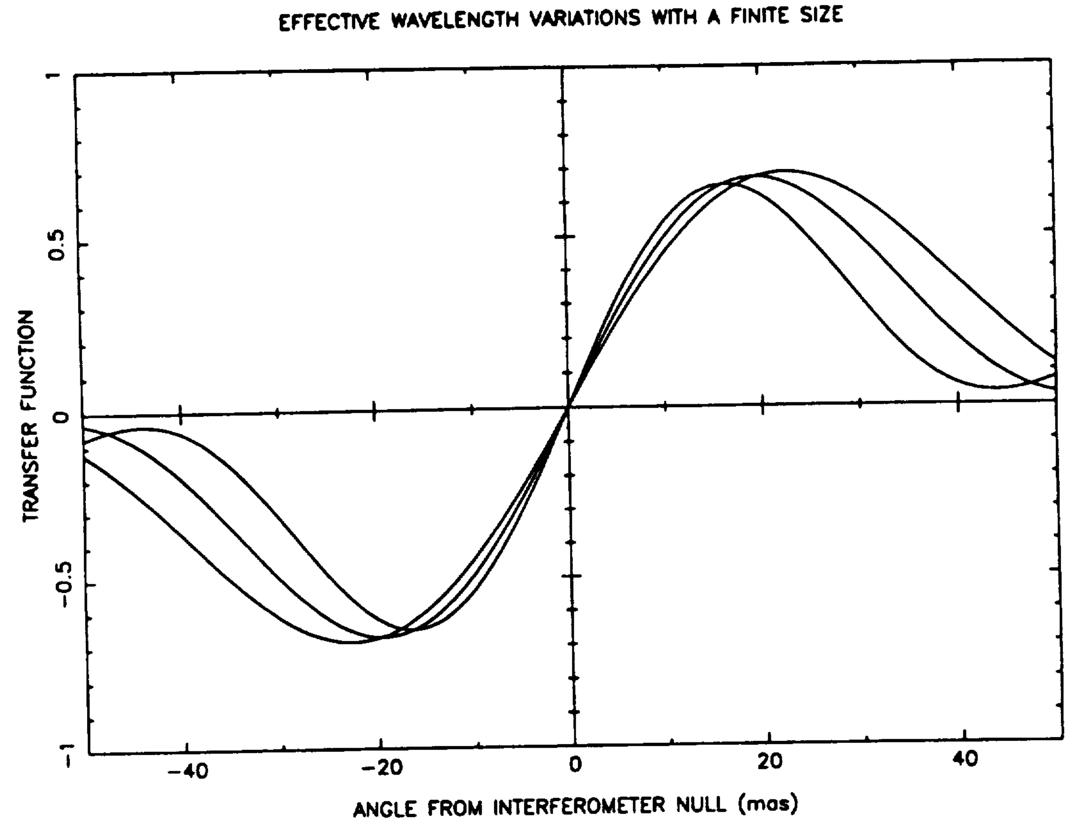

Figure 5. The effects of color temperature compounded by finite angular size on the theoretical Transfer Function. This is for the three hottest stars in Fig. 3 all with an angular diameter of 20 mas.

when not too severe, does not seem to affect the measurements. The measurements appear to be of the same quality as those taken in normal fields with comparable signal-to-noise.

2.1 Phase II Proposal Specifications for TRANS Mode Observing

While reading this section please refer to the re-printed Phase II Proposal Instructions in Appendix B. TRANSfer Mode observing is relatively simple. The instantaneous field-of-view of an FGS (the one designated by the GO as the "astrometer" FGS for this observation) is moved (scanned) across a scientific target. To do this, the instrument and operating mode must be specified by setting the keywords CONFIG: FGS and OPMODE: TRANSfer. The GO must also choose the APERTURE or FOV, that is, choose an FGS to be the astrometer for this observation. This can be done by default (APERTURE: PRIME), in which case it is FGS #3 (the FGS in radial bay #3) or by specifying one of the other (UNCALIBRATED !) FGSs. Using an FGS other than FGS #3 would require a very strong scientific argument because it would require a significant amount of additional overhead to perform the special calibrations. (Given that the other two FGSs are not going to be calibrated for TRANS

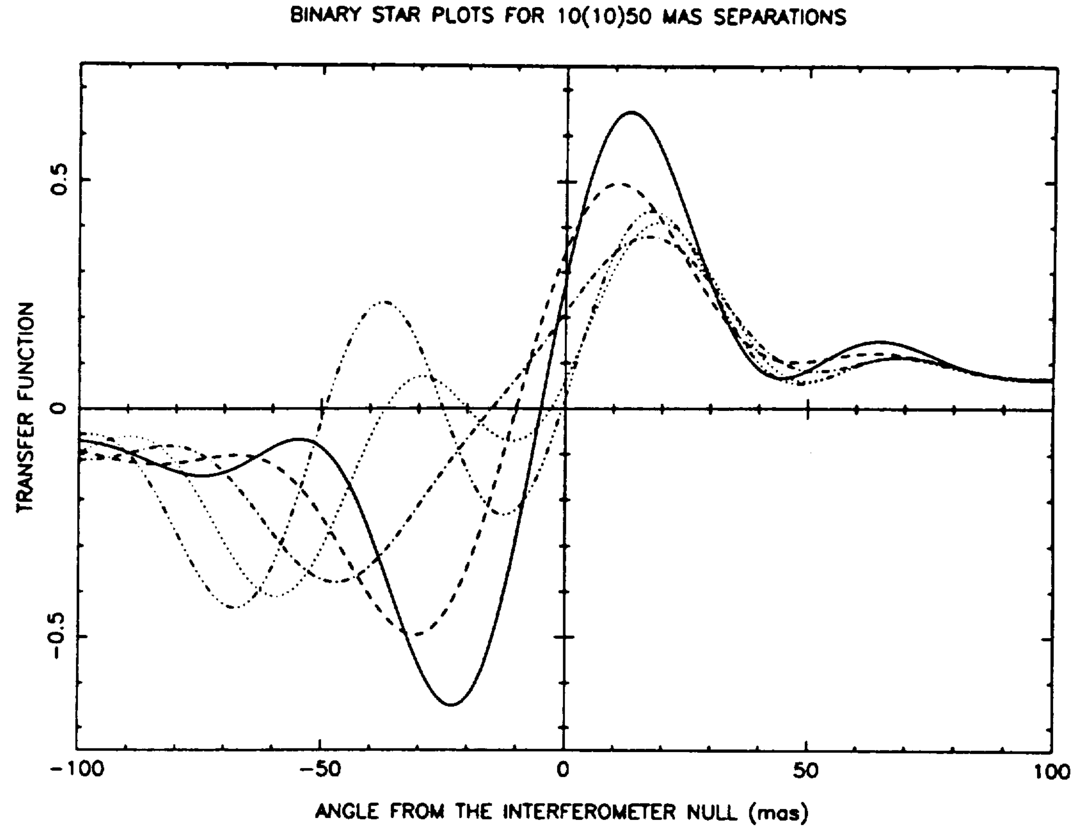

Figure 6. The effects of duplicity on the theoretical Transfer Function. The five curves show separations of 10(10)50 mas for a magnitude difference of 1.5 mag.

Mode observing in Cycle 4, the alternative would be to successfully argue that the scientific purpose can be achieved with uncalibrated data.)

The user must specify the spectral element or filter (keyword SP_ELEMENT) to be used. Each FGS is equipped with a filter wheel that has five apertures (see Table 2). Four of the five filters are the same across the three FGSs while the astrometer FGS has, instead of an intermediate band RED filter (F650W), a wide-band red filter (F605W) referred to as the ASTROMETRY CLEAR filter. The recommended filter for all astrometric observations is the PUPIL (SP_ELEMENT: PUPIL). As discussed earlier (see §1.2.2), use of the PUPIL stop results in a sharper interference pattern. Some General Observer scientific goals will require color information and they should use either the ASTROMETRY CLEAR or the YELLOW (F550W) filter in conjunction with the CLEAR (F583W) filter to meet them. It is the intention of the Instrument Scientist to eventually calibrate all four filters in the astrometer FGS at $\sim$ 15 points within its field-of-view.

DATA-RATE defines the rate at which the telemetry will operate and can be specified by the observer. The higher data rate is recommended (DATA-RATE = 32) unless the target is really quite faint ($V > 16$ mag). Signal-to-noise ratio may be regained by "adding" together subsequent scans (see below).

The term *scan* refers to sweeping the instantaneous field-of-view of the chosen astrometer FGS through and slightly beyond the target once. If we perform this multiple times then there would be multiple scan lines. The SCANS parameter is simply the total number of scan lines to be executed. Specifying a value of SCANS greater than one can be regarded as the equivalent, were one doing photometry, of making multiple exposures, or the equivalent of taking multiple plates were one doing positional astrometry. The fainter the target, the more scan lines one would want, hence the larger SCANS should be. As a rule of thumb, for scientific targets brighter than $V = 13$ mag, 5 to 10 scan lines (SCANS = 10) should be enough and most of this repetition is to provide sufficient information to minimize the deleterious effects of spacecraft jitter.

The scan lines are executed in a forth and back fashion as the Pointing Control System, which controls TRANS Mode observing [not the Fine Guidance Electronics (FGE) within the FGS], attempts to lay them one on top of the other on the celestial sphere. Perfect alignment never occurs, because of spacecraft jitter and other reasons, thus complicating the "adding" together of Transfer Functions obtained from different scan lines. The actual process is not really an addition, as the scans do not exactly line up as seen projected onto the celestial sphere. The process employed in the Institute's Astrometry Data Processing Pipeline is more like a merging of successive scans. Signal-to-noise is only slowly regained; the effective magnitude brightens by $\Delta m = 2.5 \log N^{1/2}$ which is 1.25 mag for $N = 10$ (= SCANS).

To understand this more deeply, realize that because of the spacecraft jitter, the details of the commanding and assorted other problems, even though the successive scan lines in a TRANS observation are supposed to perfectly overlap back to front, they do not. They neither perfectly overlap in Star Selector encoder space within the FGS nor do they overlap in any other coordinate system. Hence, if one literally tried to add several scan lines together (that is add the computed Transfer Functions from individual scans together), the effect would be not be to increase the signal-to-noise ratio but to decrease it because the scan lines (and hence their associated Transfer Functions) are not in the same reference frame and so are out of phase. Therefore, the Transfer Function from each scan line has to first be translated with respect to the "master Transfer Function" separately for the FGS x and y axes. This will minimize the destructive interference due to adding out of phase Transfer Functions (computed from separate scan lines). The Astrometry Pipeline determines the shifts of $N - 1$ of the Transfer Functions from $N - 1$ of the scan lines with respect to the N'th. The optimum translation parameters are not restricted to the least significant bits in encoder space. More explicitly, they are not tied to the STEP-SIZE variable the General Observer will chose (see below). This could not be done because the relationship between a linear step size on the sky and the number of bits necessary to change the Star Selector encoders depends on where the instantaneous field-of-view is with respect to the entire field-of-view. (This is now getting into more of the details of the FGS coordinate systems than a typical GO probably wants to know.) Hence, even though the Transfer Functions from two successive scan lines are being overlaid as best as possible, the photomultiplier tube counts — the raw data associated with any FGS measurement — do not exist at the same places on the celestial sphere. Thus, combining two (optimally translated) Transfer Functions from different scan lines results in a filling in of the ideal Transfer Function rather than in adding up pieces of the ideal Transfer Function.

In TRANS Mode, there is no "step-size" in the sense that the instantaneous field-of-view is picked up and moved xx.xx milli-arc seconds between photon integration times. Rather, the parameter STEP-SIZE, for TRANS Mode observing, is a derived concept. This is a consequence of TRANS Mode observing being under the control of the HST's Pointing Control System rather than the FGE. In TRANS Mode, the Star Selectors, the devices within the FGSs which actually control the placement of the instantaneous field-of-view, are kept in continuous motion. One might have imagined that in TRANS Mode the instantaneous field-of-view would have been positioned at the start of a photon integration period, photons gathered for the desired duration, the Star Selectors engaged to move the instantaneous field-of-view to the new position, and so forth. This is what occurs in WALKDOWN Mode observing (which is under FGE control). For TRANS Mode observing, the Star Selectors, and hence the instantaneous field-of-view, are being continually driven along the scan line at a constant angular speed. Therefore, despite the fact that one can actually specify a STEP-SIZE for TRANS Mode, it is not an independent quantity but intimately related to the total desired exposure time (T_{exp}), the total number of scan lines (N_{scan} = SCANS), and the photon integration time per sample (t_{samp} which is defined by the choice made for DATA-RATE). The formula is given in §13.2 of Appendix B of this Handbook. As a practical matter, choosing the smallest value (STEP-SIZE = 0.3) is the recommended course. This will provide the finest sampling of the Transfer Function. The total length of the scan is much less important as long as the instantaneous field-of-view has been correctly positioned with respect to the scientific target. This requires a detailed knowledge of the Coarse Track to Fine Lock offsets as a function of filter and position in the field-of-view of an FGS; the latter complication is apparently caused by optical anomalies within the particular FGS compounded by the azimuthal variations from the OTA mentioned earlier. These details have been determined to sufficient accuracy during the Space Telescope Astrometry Team Science Verification activities and Instrument Scientist Calibration Observations.

The last major consideration of TRANS Mode observing is the direction of the scan line on the celestial sphere. Suppose one were observing a known binary star. Then, for a maximum signal-to-noise ratio on both axes of the FGS interferometer, the scan line should be oriented at 45° (or 135°) with respect to the separation vector of the components. On the other hand, if one wanted to ensure the maximum signal-to-noise ratio for detection purposes, an orientation of 0° (or 180°) might be chosen. Similarly, when performing scans of an elliptical nebulosity the scan lines might be chosen to be along the principal axes of the light (radio, x-ray, ...) distributions. An ORIENT Special Requirement is necessary to arrange for such orientations.

There are several other Optional Parameters in the Phase II Proposal Instructions which need to be discussed. Two of the acquisition modes, ACQ-MODE = RAPID and ACQ-MODE = AMBUSH have been relegated to engineering-only observations. The motivation for the AMBUSH mode of target acquisition is to lie in wait for a moving object whose orbital element set contains systematic errors thereby biasing (principally) its time of arrival at a specific point on the sky. Implementing AMBUSH mode requires sufficient interest on the part of General Observers in the form of Telescope Allocation Committee approved HST proposals. The RAPID acquisition is designed for those cases where the position of the scientific target with respect to the Guide Stars is known with sufficient precision to bypass the bulk of the $\sim$ 500 milli-arc second "walkdown" (*i.e.*, the transition stage between Coarse Track and Fine Lock).

Similarly, choosing a non-default value of TRACK is now only possible in the context of an engineering observation. (It is always the case that a compelling scientific reason can override this segregation and allow a General Observer to use an engineering mode option.)

2.2 TRANS Mode Calibrations

The FGS optical train includes a 50%–50% polarizing beam splitter with the resulting two parts of the beam linearly polarized in orthogonal directions. Therefore, the practice has been to refer to x and y axes in FGS space. Thus, there is a Transfer Function for each axis, say $S_x(\theta_x)$ and $S_y(\theta_y)$, which depend on θ_x and θ_y respectively [see Eq. (1) in §2.0]. Because Perkin-Elmer Corp. assumed that everything inside the OTA and the FGSs was and would stay symmetric, the Transfer Functions on the two axes should be identical. They are not. Now one must not only deal with an empirically determined S_x, which has no simple nor even analytical form, but a different, and also empirically determined, S_y. One must also contend with the fact that important aspects of these two transfer functions change with position within the FGS field-of-view. It is the (primarily) azimuthal variation in the shapes of the x and y Transfer Functions that has materially complicated the calibration of the TRANS Mode of observing.

The procedure adopted by the Institute's Fine Guidance Sensor Instrument Team has been to build on the Space Telescope Astrometry Team's Science Verification program and to obtain Transfer Functions throughout the field of view of the astrometer FGS (FGS #3). In particular, Transfer Functions have been obtained at 19 different places in this FGS so far. Cycle 4 Instrument Scientist "15 Points of Light" calibration (which actually involves 20 positions because of the complications induced by the movement of the secondary mirror of the OTA following the introduction of the COSTAR device) will include 6 new positions. Seven of these 19 overlap with a "Nine Points of Light" test performed during the OTA collimation exercises. The time difference between the two sets of measurements already performed is about 1.5 years. Hence, the temporal stability of the astrometer FGS, in this regard, can also be ascertained as a by-product of the Instrument Scientist calibration measurements. Moreover, both the azimuthal and radial spacing of the points have been chosen to enable a full investigation of the variations in the Transfer Function, especially where it is changing the most rapidly. The star used during these observations is the same star used for the "Nine Points of Light" test (and all its related collimation exercises). This star is known as Upgren 69 (Upgren, Mesrobian and Kerridge, 1972) and is a $V = 9.58$ mag, $B - V = 0.50$ mag star. From the accumulated observations of this star in all three FGSs, there is no evidence of finite angular size or duplicity. In addition, because this star is relatively bright, a sufficient signal-to-noise ratio can be obtained without requiring the addition of successive scans to overcome the effects of spacecraft jitter.

When a General Observer needs some aspect of the reference Transfer Function, whether to analyze double star data, angular diameter data, or positional data, the "best" reference Transfer Function is found by the Institute's Astrometry Pipeline. By "best" it is meant that Transfer Function taken with the same filter and closest in both time and position in the astrometer FGS field-of-view to the General Observer's data. The analytical details of the

ST ScI's Transfer Function analysis software can be found in Lattanzi, Bucciarelli, Holfeltz, and Taff (1992).

2.3 TRANS Mode Data Processing

The purpose of this Section is to describe the strategy and the basic algorithms that have been implemented in the ST ScI Fine Guidance Sensor Transfer Function Mode Data Reduction Package (TFMRP). The TFMRP software is used for the analysis of Science Verification data, Instrument Scientist Calibration data, and General Observer scientific data. At present, the TFMRP is the principal tool to be used for all double star data analysis (for alternative methods, see §2.3.4). In the following, it is assumed that the reader has some knowledge of the FGS as an astrometric instrument and in particular with the TRANSfer Function astrometric Mode. It is also assumed that the FGS TRANS Mode data are retrieved from the DMF/DADS system through STARVIEW and decoded using the ST ScI AEDP unpacking software (Bucciarelli and Lattanzi 1991).

The present version of the ST ScI TFMRP is designed to do two main things: (1) To calibrate FGS Single Star Transfer Functions by using calibration data taken on selected single stars. Appropriate Calibration Data Base System (CDBS) tables will be populated (or modified) as a result of these calibration observations and the associated data reduction (see §2.2). (2) To analyze FGS Transfer Function observations on double stars (see §2.3.3). The analysis of triple stars and extended objects (i.e., angular diameter measurements or measurements of nebular objects) will be discussed in a future version of the Handbook. (See Lattanzi *et al.* , 1994.)

When running in calibration mode, the TFMRP will produce data for the CDBS or the PDB (Project Data Base) databases. The present version of the TFMRP includes data rectification, data smoothing, and double star measurement. The latter is primarily based on a correlation technique. In the next three subsections each step will be illustrated and a brief discussion of the relevant algorithms given.

2.3.1 Data Rectification

Data rectification is comprised of four main corrections, the encoder readings corrections, the photomultiplier tube (PMT) mismatch corrections, the differential velocity aberration correction, and the minimization of the spacecraft jitter.

The encoder readings correction refers to the application of a look-up table which contains a set of values representing the systematic shifts of the encoder readings as a function of encoder position. These systematic corrections were determined by measurement during on-ground testing. They are to be delivered by Perkin-Elmer Corp. (now Hughes Danbury Optical Systems). Both the signs and the amplitudes of these effects are important, for being systematic errors, applying them with the incorrect parity will double them. The correct table is still not in the CDBS.

The FGS Transfer Function is usually written as $S = (A - B)/(A + B)$ where A and B are the photomultiplier counts from the two photomultiplier tubes per axis. As the subscript x or y is added to S in order to specify which axis is meant, an x or y subscript is attached to A or B when additional clarity is needed. The PMT counts vary in a regular fashion with the angular distance between the current location of the center of the FGS instantaneous field-of-view and the interferometer null (which is roughly aligned with the optical axis of the HST). The zero noise, ideal equation for the transfer function, as illustrated in Fig. 2, predicts that S will vanish when the instantaneous field-of-view is far away from the optical axis (x or y > 0.1 arc sec). In practice, this condition is rarely realized because A and B are never equal (due to differences in responsivities or sensitivities of the two photomultiplier tubes) far from the null or even exactly at it. Thus, a PMT mismatch correction is necessary. It consists of the computation of the mean value of $A - B$ (say Δ_{ab}) far from the null. The revised version of S takes the form

$$S = (A - B - \Delta_{ab})/(A + B).$$

The differential velocity aberration correction involves the reduction of the observed line of sight to the solar system barycenter in a reference frame of fixed orientation (e.g., J2000.0). It includes the motion of the HST spacecraft about the center of mass of the Earth, the motion of the center of mass of the Earth about the Earth-Moon barycenter, and finally the motion of the Earth-Moon barycenter about the solar system barycenter. (The intermediary of going to the heliocenter is unnecessary.) Differential velocity aberration plays a much bigger role in the reduction of POSitional Mode data than it does in the reduction of TRANSfer Mode data.

The minimization, and hopefully complete removal, of the solar-array induced jitter will be a major task during data rectification. Since all FGS data should be taken in the 32 Kbit telemetry mode, there will be the maximum amount of information, from the Guide Stars, with which to accomplish this. However, until recently, despite considerable effort by several groups, no satisfactory general procedure for jitter subtraction had been found. Considerable success has recently been reported by the Space Telescope Astrometry Team in this area; considerations of including a similar technique in the Institute's TFMRP are underway. One viable, albeit less than optimal, approach is that of executing multiple scans while taking science data in TRANS Mode. In this way, jitter corrupted scans can be easily identified (by comparison to the others) and removed from the set which will then be processed through this pipeline. Actual observational data provides an estimate of an average of 1 or 2 jitter corrupted (i.e., unusable) scans out of 10. This did not change with the replacement of the solar panels.

2.3.2 Data Smoothing

In this subsection the data smoothing technique which is applied to the Transfer Function data after rectification is discussed. The idea here is to fit the data in such a way that all the essential features in the Transfer Function are preserved in a noiseless (or at least a higher signal-to-noise) version. A cubic-spline fit might be deemed appropriate for this; instead, a piece-wise polynomial fit was chosen for two reasons. First, as this technique is close to the spline approach, analogous performance was expected. Second, a polynomial representation of the smoothed Transfer Function makes it possible to compute the correlation integral (used during double star measurement) analytically (see §2.3.3).

Having obtained the experimental curve, which is a function of the instrumentally and scientifically corrected star selector encoder angle readings, it is fit piece-wise to low-order polynomials. The fits are executed via a constrained, non-equally weighted, least squares algorithm. Since the data are photon counts, i.e., a Poisson process, the standard deviations of each value of S are known. Hence, the weights can be reliably determined. The polynomials (linear, quadratic, or cubic) are forced to obey continuity conditions at their joining points. In addition, depending on the degree of the polynomial, one may also demand differentiability and even a higher-order of smoothness (all enforced by Lagrange multipliers at the joining points). One can envision possible refinements to this procedure which may be included in the next version of the code, such as enforcing an upper limit for a particular interval's width based on the local curvature of the Transfer Function.

If multiple scans of the same target were made, the observer may wish to co-add or merge the scans. Co-adding Transfer Scans refers to merging together multiple scans taken on the same scientific target. This would be done to improve the signal-to-noise ratio both for fainter targets and as a primitive jitter smoothing technique. Since the coordinate system in which the transfer scans are acquired is not rigidly fixed, the translation or offset that has occurred between successive scans must be determined (see §2.1). This can be done with the TFMRP either approximately, by using the smoothed Transfer Functions, or analytically, by using the polynomial fits of the smoothed Transfer Functions (see §2.3.3). Co-adding has been proven effective to better than 5 milli-seconds of arc.

2.3.3 Double Star Measurement

Double star measurement refers, in the present context, to the determination of the parameters of double stars. It includes, at the moment, two different (although related) functions, namely (1) the determination of the relative offsets of individual scans on the same scientific target for the purpose of co-adding the scans and (2) the determination of the two separations (Δx and Δy), the magnitude difference between the primary and the secondary components (Δm), and, ultimately, the computation of the position angle (PA) of the binary.

Assume that the form of the "Single Star" Transfer Function, that is the reference Transfer Function for this filter for this place in this FGS is known. The hypothesis is that the incoming light from two different sources, close by on the celestial sphere, is incoherent and the application of the superposition principle yields the expected Double Star Transfer Function $D(x)$ in the form of a linear combination of two reference single star Transfer Functions $R(x + x_0)$, viz.

$$D(x) = A(\Delta m)[R(x + x_0) + B(\Delta m)R(x + x_0 + \Delta x)]$$

(and its analog for the y-axis), where the second single star Transfer Function $R(x+x_0+\Delta x)$ is identical to the first but displaced along the x-axis by an additional amount Δx, the projected double star separation. The shared shift of x_0 in the single star reference Transfer Functions is to correct for an arbitrary translation or offset between the reference star Transfer Function and those of the double star under study. $A(\Delta m)$ is an overall normalization factor. $B(\Delta m)$ represents the intensity ratio between the primary and the secondary stars comprising the double. Both of these factors depend on the apparent magnitude difference between the two stars, Δm.

The model just described is fitted to the observed Transfer Function curve and the parameters Δx and Δm derived. It is worth noting here that two independent estimates of

Δm are potentially available, one from each FGS axis. Each model is cross-correlated with the observed Transfer Function by computing the correlation integral

$$C = \int D(t - x)S(t)dt.$$

The modelled function D is being cross-correlated with the observed Transfer Function S. The sought-for value of x, which maximizes the correlation integral C, represents the shift along this axis between the two functions. The optimum value will be denoted by x_0.

The best-fit model is chosen as the one with parameters which minimize the sum of the squares of the differences between the theoretical model in D and observed values in S, viz.

$$\int [D(t - x_0) - S(t)]^2 dt = \text{ minimum.}$$

This approach was preferred to the direct application of a least squares-like scheme for its robustness — in relation to the range of narrow separations (from 100 mas down to about 10 mas) where the astrometer FGS will make its most interesting detections — and the independent difficulty of giving sufficiently accurate initial guesses for Δx and Δm. However, if felt necessary, the accuracy of the fit can be improved, now using the answers from the correlation technique as initial guesses for a final least squares adjustment. Alternately, the user may wish to use only the correlation technique or only the least-squares method; all possible options of correlation/least squares fitting are supported.

As discussed in §2.3.2, before the cross-correlation process, the photon noise in the observed Transfer Function is smoothed via a piece-wise low-order polynomial fit. Continuity is imposed at the boundaries up to a specified level (i.e., continuity, first derivatives continuous, or second derivatives continuous). This polynomial smoothing increases the resolution of the subsequent cross-correlation and makes it possible to compute the correlation integral C, as well as the sum of squares to be minimized, analytically.

The actual formula used to generate a Double Star (D) model is

$$D(x) = \frac{[R(x + x_0) + 10^{-0.4\Delta m} R(x + x_0 + \Delta x)]}{[1 + 10^{-0.4\Delta m}]} \tag{2}$$

where $R(x+x_0)$ is a single star Transfer Function taken through the same filter and as close as possible, within the FGS field-of-view, to the FGS location of the scientific observation $S(x)$. Naturally, an analogous formula applies for the y axis. Once Δx is fixed $R(x + x_0)$ is shifted to the new location $x + x_0 + \Delta x$. This will serve to represent the Transfer Function of the "secondary" star of the model double along the x axis (of course the assignment of primary vs. secondary is just a matter of convention). The heart of the correlation process takes the observed scan and the current model (i.e., given Δm and Δx) and finds the x_0 value that best correlates the two Transfer Functions. This integral can be evaluated analytically because of the simple, analytical representation developed for the smoothed Transfer Function. Similar comments apply to the minimization integral.

The observer can use this double star measurement software to determine the offsets (parameter x_0 in the above equations) of one scan relative to other scans of the same target in order to co-add the scans. The goal is to find the best fit of one of the many scans acquired on a scientific target not to a single star reference Transfer Function, but to that scan of this target labeled the "reference" or "master" scan. The procedure to do so is identical to that for fitting a binary star, only this is a one-parameter problem not a three-parameter problem (i.e., no need for Δx nor Δm). The same software that was just described can, therefore, be used for this simpler purpose by constraining the values of these parameters.

The computation of the position angle (PA) is done in a completely differential way. As discussed above, the double star measurement yields Δx and Δy, the separations between the two stars along the interferometer x and y axes. These quantities are expressed in FGS space in seconds of arc on the sky. Both Δx and Δy are (likely) very much less than one arc second. It is assumed that differential optical distortions can be disregarded over such a small scale length. Thus, to transform Δx and Δy (considered as a plane vector with origin at the primary component of the double) into the $V2$–$V3$ plane of Vehicle space, only the relative orientation of the two frames of reference need to be accounted for by using the most recent (on-flight calibrated) alignment matrices. The distortion correction tables are not applied.

The present version of the code uses the pre-launch transformations matrices. The definition of the $V2$–$V3$ plane as given in Bradley *et al.* (1991, see their Fig. 1) has been adopted. The use of real alignment matrices will result in a small coupling of the reference axes and requires the component Δz defined as $\sqrt{[1 - (\Delta x^2 + \Delta y^2)]}$.

Once in the $V2$–$V3$ plane, knowledge of the spacecraft orientation (attitude) with respect to a reference equatorial North (i.e., at a specified epoch and equinox) gives the position angle of the double. The formula is, with all quantities in degrees,

$$PA = 360 - ANGV3 + \arctan(V2/V3)$$

where $ANGV3$ specifies the orientation of the $V3$ axis as defined by the angle from the North counted positive through West. This quantity is given with quite good accuracy (of the order of 0.5°) in the FGS AEDP header files. $ANGV3 = 360 - PAV3$ where PAV3 is the position angle (in the astronomical sense, i.e. the angle is counted positive from North towards the East) of the spacecraft $V3$ axis. The reference equatorial North is that at equinox J2000.0 and epoch of the date. Notice that the position angle would only be exact if the location of the double observed in the astrometer FGS field of view coincides with the $V1$ axis. Of course, this will never be the case as the field of view is some $10'$ away from the V1 axis. However, this result is appropriate for most applications.

2.3.4 Alternate Algorithms

While not described in detail herein, there is a completely separate least squares version of this process (Franz *et al.* , 1992); a Fourier technique has also proven applicable (Hershey, 1992). Reductions of the identical data by several methods point to a 1-2 mas internal consistency.

3.0 POSITION MODE OBSERVING, CALIBRATION, AND DATA PROCESSING

Let us imagine that the purpose of a GO proposal is to determine the proper motion of the program star (= scientific target). Then, at the minimum, the position of the program star with respect to some nearby, and presumably much further away, reference objects must be measured at at least two different times. A standard observing sequence for this process might consist of: (1) measure the position of the program star, (2) measure the position of N reference stars, and (3) repeat the measurement of the program star. Then repeat this entire sequence every 5 months for 30 months.

What, exactly, does "measure the position mean"? It means that the star, program or reference, is acquired in the astrometer FGS and observed in Fine Lock for some specified time interval. Establishing Fine Lock, from the perspective of the General Observer, means that the parameter LOCK = FINE was chosen as per the Phase II Proposal Instructions (see §3.1). The paragraphs below shall elaborate on the meaning of establishing Fine Lock in an operational sense.

Since Fine Lock is the preferred guidance mode for all astrometric observations with the HST, this section should be of interest to all General Observers. It should be noted that the availability of suitably bright Guide Stars will determine if Fine Lock guidance can be successfully done. Observations without special orientation and time critical requirements have a better chance of finding brighter Guide Stars because the natural roll of the spacecraft eventually sweeps out an annulus $14'$ in radius about the scientific target.

So, what exactly, does "establishing Fine Lock" mean? Fine Lock literally refers to the fact that the Fine Lock Data Valid flag has been set in the Fine Guidance Electronics; there are several steps which must occur before this can happen. These are briefly reviewed immediately below. First, the Fine Guidance Electronics — the microprocessor inside the FGS which controls its operation — directs the FGS Star Selector encoders to move the instantaneous field-of-view in a spiral search pattern seeking the desired star. While nominally $5'' \times 5''$, the net instantaneous field-of-view is somewhat diminished and no longer square owing to photomultiplier tube field stop misalignments. The spacecraft knows that it has acquired the correct star because (a) it was already pointing in essentially the right direction (because of the successful lock on the nearby Guide Stars) and (b) both lower and upper limits on the expected photon counts from this star are known from its apparent magnitude (and color index?). [When it is a Guide Star which is being acquired point (a) is still true but the assurance now comes from the gross control mechanisms within the Pointing Control System — such as the Coarse Sun Sensor, the Fixed Head Star Trackers, the rate reaction wheel gyroscopes, and so on. Point (b) is still applicable and after the second Guide Star is acquired a double check on their angular distance apart, predicted from their coordinates in the Guide Star Catalog, is performed.]

After the presence of the star is established, the Fine Guidance Electronics (FGE) then directs the FGS Star Selector encoders to drive the instantaneous field of view in a circle about the detected photocenter in an attempt to more precisely locate the target. The successful maintenance of this state comprises the Coarse Track guidance mode. (Had LOCK been specified to be COARSE, then the positional measures would have been made in Coarse Track. Note that *this* Coarse Track refers to the program star and its reference stars in the astrometer FGS, not to the guidance mode being used, in the other two FGSs, on the Guide Stars. As the Phase II Proposal Instructions indicate (see §3.1), it is possible to obtain a mixture of Coarse Track and Fine Lock data. For a General Observer to effectively use this, the Coarse Track to Fine Lock offset would have to be known. Unfortunately it, like everything else, is now a function of position within the FGS field-of-view. Using a combination of the Astrometry Team Science Verification measurements and the Instrument Scientist calibration observations, it is fairly well characterized in FGS #3. Nevertheless, unless the scientific argument for such a combination of Fine Lock and Coarse Track is compelling, this should not be attempted.)

After the nominal number (12) of circuits about the photocenter, the FGE then moves the instantaneous field-of-view of the astrometer FGS to approach the photocenter along a line which is at an angle of 45° with respect to the interferometer x-y axes. This process is referred to as "walking down" to the star (and, in effect, is half of what constitutes one scan line in the TRANSfer Mode of operation). Sooner or later, on each axis, the minimum of the Transfer Function will be encountered and the FGE control software will detect this. (If it doesn't detect the minimum, because of photon noise for instance, then it will detect the maximum.) Once this occurs for *both* the x and y axes, the Fine Lock Data Valid Flag is set and the astrometer FGS has entered the Fine Lock state. The steady state maintenance of this configuration on Guide Stars is what Fine Lock guidance means.

At this point a further complication of trying to mix Coarse Track with Fine Lock guidance should be mentioned. The nominal number of Coarse Track nutation circles was set to be 12 because Perkin-Elmer Corp. had concluded that this was sufficient to stabilize the Coarse Track guidance mode. There is now enough evidence to believe that in reality many more circuits are necessary to reach a stable Coarse Track state. Hence, a blend of Coarse Track and Fine Lock guidance should not be attempted unless the Coarse Track section is relatively long, at least 30 seconds (it takes one second to complete a circuit). The Instrument Scientist calibration program has observations built into it to more fully investigate this effect. It has no affect on guidance when the guidance mode is Coarse Track. Its impact on Guide Star acquisition might only be felt when acquiring the dominant Guide Star since this is the one acquired first (at the termination of a spacecraft slew when control is still vested in the Pointing Control System gyroscopes). By the time the secondary Guide Star is being secured, the gross movement of the spacecraft should have been arrested so that any asymptotic motion in the Coarse Track phase of the acquisition of the secondary Guide Star will not cause the walkdown process to miss the star on either axis of the Koesters prism interferometer.

Finally, for astrometric observations, the Fine Lock state is not open-ended but rather the FGE is instructed to terminate it after the GO-specified observing time has been completed. Then the instantaneous field-of-view is commanded by the FGE to move to the next star in the GO-specified observing sequence and the whole spiral search, Coarse Track, Walkdown, Fine Lock sequence is repeated, and so on. Now that the meaning of Fine Lock is clear, what information is obtained and how would one use it to determine the position of the program star or a reference star?

What is obtained during a POS Mode observation is a time series of photon counts in four different photomultiplier tubes, two per FGS interferometer axis. All the counts at the beginning, during the spiral search, the Coarse Track, and the Walkdown, while useful for certain calibrations that the Astrometry Pipeline performs, do not yet relate meaningful information on the high precision direction to the star. This comes from the photon counts gathered when in the Fine Lock state for then the star is at (or near) the nulls of the two interferometer axes and the intersection point of the nulls on the celestial sphere defines the apparent optical axis of the combined OTA/FGS system. [Note that "apparent" is not being used in its technical astrometric meaning as regards general precession, nutation, annual aberration, astronomical refraction (!), and so on but rather in its more general sense.] Both instrumental and scientific corrections have to be applied to bring the unit vector of direction cosines into a meaningful reference frame. These tasks are performed by the Astrometry Pipeline and the final reference frame is centered at the solar system barycenter and its orientation is that of J2000.0.

From the known shape of the reference Transfer Function nearest to the place in the FGS field-of-view where these observations are being performed, and the actual values of the photon counts (suitably adjusted for instrumental effects), one can compute, for each photon integration period (= FES_TIME, see §3.1) specified by the General Observer, how far the star was from the interferometer null. Thus, one has the corrected observed direction to the star in the FGS internal coordinate system per FES-TIME. Each one of these values is then adjusted for the remaining instrumental and scientific effects and brought into the ultimate reference frame. Once this information is at hand it can be averaged to produce the position of this star from this observation, and so on for all the stars in this observation set, and so forth for all observation sets. Within a set of observations (= program star plus reference stars) the differential offset of the program star can be obtained. By analyzing the differences in observed directions between the program star and its reference stars over the course of time the desired proper motions (in this example) are eventually computed.

Note that in order to obtain, for instance, equatorial coordinates one has to use the coordinates of the Guide Stars. Until Version 1.2 of the Guide Star Catalog is available this is not a recommended procedure (Taff *et al.* 1990).

3.1 Phase II Proposal Instructions for POS Mode Observing

For POS Mode observations, the user must specify the instrument and operating mode with the keywords CONFIG: FGS and MODE: POS. As with TRANS Mode, both the APERTURE (FOV) and SP_ELEMENT (spectral element or filter) must be chosen by the General Observer. Also as with TRANS Mode, the recommended APERTURE is the one in radial bay #3 (APERTURE: PRIME or APERTURE: 3) and the recommended position of the filter wheel is PUPIL (SP_ELEMENT: PUPIL).

The parameter DATA-RATE defines the rate at which the telemetry will operate. The recommended DATA-RATE for all POSitional Mode observing is the default value (DATA-RATE = 32; this default value of 32 kbit is not the original one and it has been changed to adjust to the real circumstances of spacecraft jitter). Since the Guide Star telemetry data is transmitted along with the scientific target observing data at this same high data rate, this offers the maximum potential for minimizing spacecraft jitter. Experiments with jitter removal show that the two guiding FGSs maintain a high level of coherence. Hence, it is reasonable to assume that the same jitter spectrum is present in the astrometer FGS and that it can be satisfactorily dealt with at the highest available frequencies (namely 40 Hz).

The only GO-usable acquisition mode is SEARCH (ACQ-MODE = SEARCH). [Neither ACQ-MODE = RAPID nor ACQ-MODE = AMBUSH, at the time of this writing (4/94), are available to GOs as they are both still engineering-only options]. During ACQ-MODE

= SEARCH the Star Selector encoders are directed in an outward spiral search seeking the scientific target much as was discussed in §3.0 for Guide Star acquisitions. The radius of this spiral search is controlled by the keyword ACQ-DIST in the Phase II Proposal Instructions. The default value is 15″.

The Phase II Proposal optional parameter COUNT is the average number of photon counts per second expected from the target. Its computation is discussed in §5.0 of this Handbook. The BACKGROUND parameter refers to the expected sky background in the vicinity of the scientific target and is available to the General Observer in case of measurements of stars embedded in nebulosities, and so forth (see §5.0 for details).

TARGET-SIZE, an engineering-only parameter, would normally be set equal to zero. Exceptions include minor planets and a very small number of stars with large angular diameters.

TRACK is another engineering-only option for use with moving targets.

The default setting for the optional parameter LOCK (= FINE) is recommended. Should a GO want to do astrometry with Coarse Track guidance instead of Fine Lock, then an explanation of why the *loss* of precision was desirable — for instance to gain limiting magnitude — would need to be advanced. A mixture of Coarse Track and Fine Lock may be specified by setting the LOCK parameter equal to a number between 0.0 and 1.0, inclusive. If 0.0 is entered, Fine Lock will be tested but no Fine Lock measurements will be taken. If 1.0 is entered, the situation is identical to LOCK = FINE. If LOCK = COARSE, then the values of other parameters will be overwritten; see §13.1 of Appendix B. This course of action is not recommended.

Special Requirements, such as an ORIENTation Special Requirement are generally inappropriate to POSitional Mode observing (although there are some observing scenarios which could benefit from it; consult the Instrument Scientist).

TIME_PER_EXPosure is the total photon collecting time for this exposure of this target. Multiple exposures of the same object, each with the same, or different TIME_PER_EXP values can be made should the scientific need dictate, for example, to improve the signal-to-noise ratio (see §5.0).

The FES-TIME refers to the duration within a TIME_PER_EXPosure during which photon counts are integrated. The FES-TIME will usually be much shorter than the TIME_PER_EXPosure. Starting with 0.025 seconds, this value increases by powers of 2 to a maximum of 3.2 seconds. Normally, at the end of each of the Fine Error Signal averaging intervals (= FES-TIME) the FGE will move the Star Selector encoders to better place the star at the null of the interferometer axes (see discussion of the parameter NULL immediately below). Therefore one will get Σ (TIME_PER_EXPosure)/FES-TIME independent measures of the direction to the star where the summation indicates that multiple exposures may have been specified. More details on how to calculate the TIME_PER_EXPosure value from the apparent magnitude and color index of the targets are given in §5.0 of this Handbook.

The NULL parameter should be set to its default value (= "YES"). This causes a re-positioning of the Star Selector encoders prior to each FES-TIME to try and ensure that the scientific target is on the nulls of the interferometer axes. Failure to do so does not necessarily imply a loss of precision, as the shape of the reference Transfer Function nearest to this point in the astrometer FGS field-of-view can be used to reconstruct the position, but the real reason to keep the scientific target as near to the nulls as possible is to reduce the possibility of drift and diminish the role of the guiding FGSs in influencing the end result. See §5.0 for more details.

3.2 POS Mode Calibrations

There are two major calibrations necessary to perform POSitional Mode observing with the Fine Guidance Sensors (see, for instance, Taff 1990). One of them is known as the Optical Field Angle Distortion calibration and the other is referred to as the Plate Scale calibration. As their names suggest, these two calibrations are designed to deal with different aspects of the combined OTA/FGS optical systems.

The Optical Field Angle Distortion (OFAD) calibration was created to analyze and measure (what was expected to be purely field angle dependent) distortions (primarily) in the FGS optical system. The Astrometry Team represents the OFAD distortions by two low-order polynomials (each consisting of 13 terms chosen as important by Perkin-Elmer Corp. from a truncated infinite series). They have determined the best fit coefficients of these polynomials by performing a least squares fit to data taken for this purpose through the CLEAR filter on 10 January 1993 (proposal #4765). The reported results are quite impressive with an expected error of less than two milli-arc seconds over most of the field of view (Hubble Space Telescope Astrometry Science Team, 1993). Data taken with filters other than the CLEAR would require a cross-filter calibration. A post-COSTAR set of observations has been completed.

The Plate Scale calibration is necessary to determine the absolute scale (or magnification) of the combined OTA/FGS optical system. This needs to be known to a milli-arc second — as do all the terms in the OFAD function. To reach this level of precision, Instrument Scientist Calibration observations and data analysis are underway which use an asterism observed expressly for this purpose, upon our request, by the European Space Agency's astrometry satellite HIPPARCOS. Other calibration options included observing an artificial satellite, whose orbit is precisely known (but which moves too quickly to be tracked by the FGSs) or an asteroid which moves slowly enough to be tracked by the instrument but whose orbit, based solely on optical observations, may not be known with sufficient precision to reach the milli-arc second calibration level required. The advantages of using measurements performed by HIPPARCOS are multiple. First, as the satellite appears to be functioning perfectly, the calibrating data will have a milli-arc second level of precision. Second, such measurements can be made over arc minutes thereby spanning the FGS field-of-view. Third, because of the level of precision of the HIPPARCOS results and because they are absolute (not relative) the OFAD and Plate Scale calibrations can be combined into one observing sequence with one data reduction technique.

The results of these calibrations will reside in the CDBS and will be called upon by the ST ScI Astrometry Pipeline as appropriate.

3.3 POS Mode Data Reduction

The fundamental unit of time for POSition Mode analysis is the photon integration unit or FES-TIME. In the ST ScI's POS Mode data reduction software, each 25 msec (or whatever the value of FES-TIME is) set of photon counts is separately corrected for all instrumental and scientific effects and brought into the solar system barycentric J2000.0 inertial reference frame. Performing the reductions in this fashion, rather than per "observation", minimized certain time-dependent systematic effects which would otherwise creep in. This is the opposite of, for instance, the HIPPARCOS data reduction strategy.

The unpacked AEDP data file (see Bucciarelli and Lattanzi, 1991) and its corresponding header file are required input for the ST ScI POSitional Mode data reduction software. Also required is an ephemeris for the spacecraft itself (to perform the velocity aberration correction as outlined in §2.3.1 for TRANSfer Mode) and attitude parameters. Solar system ephemerides are taken from the Institute's MOSS software package (specifically PERCY; see Acton, Taber and Underwood, 1990). Finally, calibration data are retrieved automatically by the software from the Project Data Base in the form of Calibration Data Base System files.

Jitter, photon noise, imperfect feedback mechanisms, setting the optional parameter NULL = NO, and so on all contribute to the optical axis of the combined OTA/FGS system not being continuously perfectly pointed at the star. The software corrects the star selector encoder measurements to the null position of the Koesters prism interferometers by means of the measured photon counts (i.e., A_x, B_x, A_y, and B_y) and the S_x and S_y Transfer Function values computed from them once per FES_TIME (the shortest timescale on which the correction can be performed).

The FGS directions are then transformed to vehicle space resulting in a unit vector in the spacecraft's $V1$-$V2$-$V3$ system. The next step in the POS Mode data reduction software is to compute the location and velocity of the spacecraft at the center of this FES-TIME, obtain the spacecraft pointing and velocity and the $V3$ roll angle, and the Earth and Earth-Moon barycentric locations and motions at that instant. A subroutine is then called which corrects, through all second order terms (including the General Relativistic ones) to the solar system barycenter at J2000.0. Parallactic effects, light bending by the Sun and major planets, and so on are taken care of as well. Finally, an equatorial coordinate unit vector is computed. Note that the latter is only as good as the Guide Star Catalog coordinates, which can be poor (see Taff *et al.* 1990).

4.0 WALKDOWN, SCAN, LOS, AND MAP MODES

WALKDOWN, LOS, and MAP operating modes are engineering only options. For more information on LOS or MAP Mode, see the Instrument Scientist.

4.1 WALKDOWN Mode

The principal differences between WALKDOWN and TRANS Mode observing were discussed in §2.1: in WALKDOWN Mode the Star Selector encoders come to a complete halt as the photons from the science target are being gathered while in TRANS Mode they move continuously. The choices for APERTURE or FOV, for filter (SP_ELEMENT), ACQ-MODE, ACQ-DIST, and Special ORIENTation Requirements are the same for the two modes.

The only real Phase II Proposal specification difference is that for WALKDOWN Mode the length of the photon integration, FES-TIME, can be specified just as it can be in POSitional Mode observing. Since the parameter lists, and their meanings, are the same for POS and WALKDOWN, the reader is referred to §3.1 and §5.0 for discussions of the meanings and settings of FES-TIME, COUNT, BACKGROUND, and DATA-RATE.

The major disadvantage of the current version of WALKDOWN Mode is that the step size for the Star Selector encoders is fixed at 9.5 milli-arc seconds. As General Observers show interest in this alternative to TRANS Mode, efforts will be made to make the step-size a GO selectable variable.

The calibration and data analysis for WALKDOWN Mode are essentially identical to those for TRANS Mode (see §2).

4.2 SCAN Mode

There are no parameters for SCAN Mode observing which are not included in either TRANS (§2.1), WALKDOWN (§4.1), or POS (§3.1) Mode. In addition, this mode is not expected to be frequently used by General Observers. Hence, please consult the other sections of this Handbook for information regarding the Phase II Proposal forms.

5.0 CALCULATION OF SELECTED PHASE II OPTIONAL PARAMETERS

A photometric calibration of FGS #3, for the CLEAR (F583W) filter, was carried out using data on M35 from the FGS OFAD calibration (proposal #4765), photoelectric and photographic photometry from Hoag et al. (1961), and photographic photometry from Vidal (1973) (see Bucciarelli *et al.* , 1993). Assuming a relationship between the mean value of the measured counts per 25 msec $< C_m >$, the color index $B - V$, and the FGS magnitude m_{fgs} of the form

$$m_{fgs} = -2.5 log < C_m >, \quad and \quad V = -2.5\gamma log < C_m > +\alpha + \beta(B - V),$$

a best fit to the data was obtained [using GaussFit software (Jefferys *et al.* , 1988)] with $\gamma = 1.0000 \pm 0.0001$, $\alpha = 20.060 \pm 0.003$, and $\beta = -0.164 \pm 0.010$. Figure 7 shows plots of V magnitude of the Hoag and Vidal data vs. the computed FGS V magnitude. There also appears to be a small color index dependent term in the differences between the two PMTs per axis (Δ_{ab}, see §2.3.1) and the y-axis PMTs are slightly but clearly unbalanced. This PMT mismatch is taken into account in the STScI's TRANSfer Mode and POSitional Mode data reduction software.

There is a small but non-negligible correction from measured counts (C_m) to "true" counts (C_t) due to dead time in the FGSs. The formula for this correction is (see Hubble Space Telescope Astrometry Operations Handbook 1986, pp. 3-73 or Lattanzi and Taff 1993)

$$C_t = C_m/[1 - C_m(dT/\tau)]$$

where dT is the dead time constant (= 285 nanoseconds based on pre-launch measurements) and τ is the integration time. The amount of correction (in magnitudes) because of the PMT deadtime can be calculated from the measured counts by taking the common logarithm of C_t/C_m.

The Phase II optional parameter COUNT is the number of photon counts expected per second. The default setting (COUNT = DEF) is recommended. To calculate COUNT from the apparent magnitude and color index of the target, write

$$2.5 log < C_m >= -V + \alpha + \beta(B - V), or < C_m >= 10^{[-V+\alpha+\beta(B-V)]/2.5}.$$

Finally, COUNT= $40\times < C_m >$ (since C_m is counts per 0.025 second).

Similarly, BACKGROUND is the number of photon counts expected due to the sky in one second. The default background rate is 59 counts/second per PMT.

The default value for the FES-TIME (= DEF) is recommended. To calculate the FES-TIME, recall that since this is a Poisson process, the standard deviation of the counts is $\sigma_c = \sqrt{< C_m >}$. It is recommended that FES-TIME is chosen to produce a signal-to-noise ratio of at least 10. Enforcing this constraint, $n < C_m > /\sigma_c > 10$, one finds $n > 10\sigma_c/ < C_m >$ and FES-TIME = $n0.025$ seconds.

The minimum recommended exposure time, TIME_PER_EXP, is $100\times$ FES-TIME. Thus, if the shortest available time (0.025) is chosen for FES-TIME, the shortest recommended exposure time would be 100×0.025 sec = 2.5 seconds.

The default NULL = YES is recommended. In this case, the next photon integration time is delayed until the target is on the nulls of the interferometer axes. If NULL = NO, the next photon integration time begins immediately after the end of the preceding integration time regardless of whether or not the target is centered.

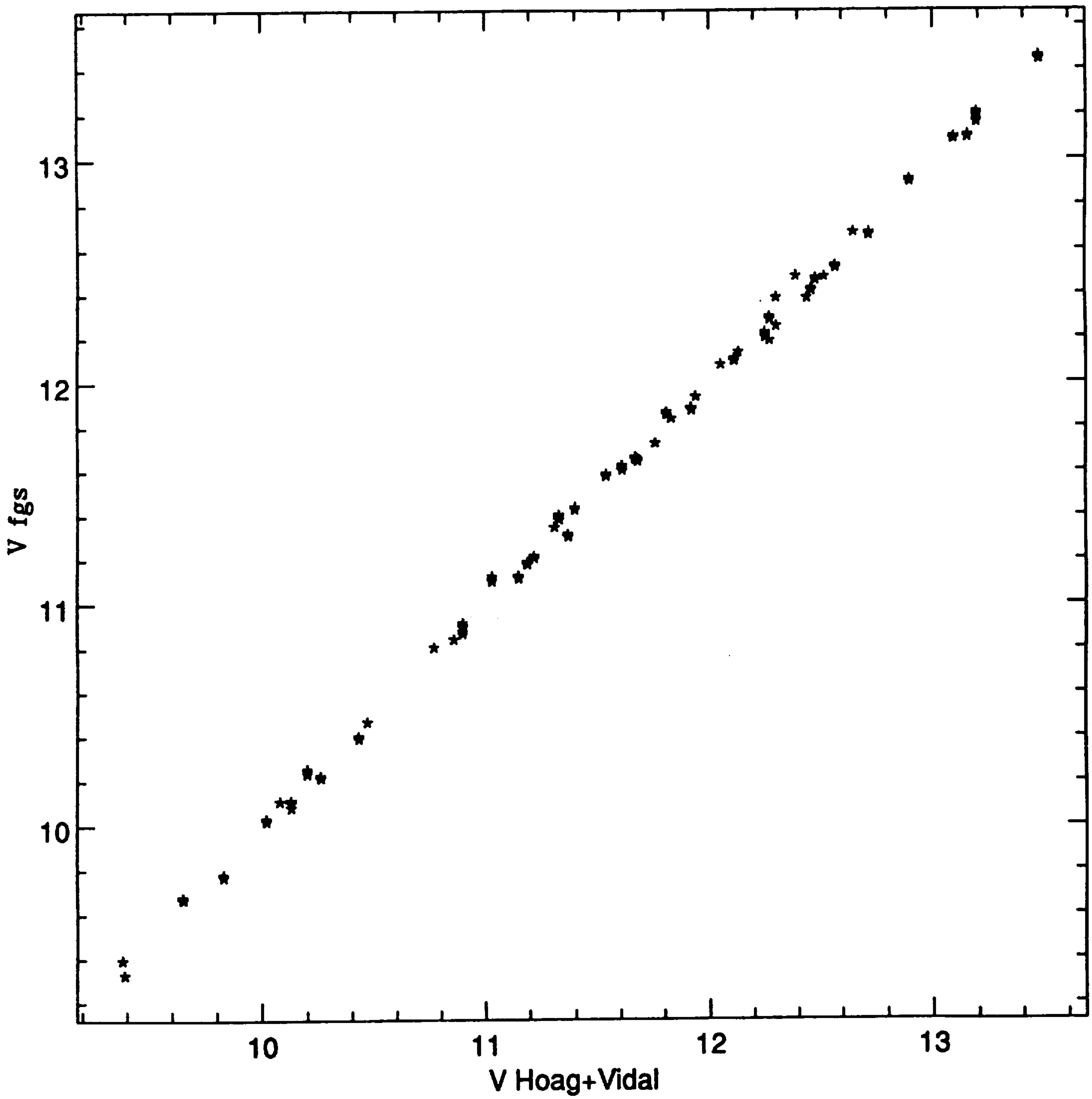

Figure 7. Reference (Hoag and Vidal) V magnitude vs. computed FGS magnitude for each of the four PMTs in FGS #3.

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APPENDIX A. EXAMPLE PHASE II PROPOSAL FORM

The bulk of this Appendix shows examples of typical FGS observing projects already filled in on the Phase II proposal forms. This Appendix was kindly supplied by L. Nagel of the User Support Branch.

Note: the format of the Phase II Proposal forms as well as the procedures for creating the forms are currently being revised; an up-to-date version of the Phase II Proposal template should be available on STEIS. It is strongly recommended that the user checks the available Phase II documentation carefully.

```
COVERPAGE:

  TITLE_1: TEST FGS PROGRAM
  PROPOSAL_FOR: TEST
  PI_TITLE: Ms.
  PI_FNAME: Lauretta
  PI_MI: M.
  PI_LNAME: Nagel
  PI_INST: Space Telescope Science Institute
  PI_COUNTRY: USA
  PI_PHONE: (410) 338-4432
  HOURS_PRI: 27.89
  NUM_PRI: 11
  FGS: X
! end of coverpage

ABSTRACT:

LINE_1: This is a test of the various methods of observing with the
LINE_2: FGSs. This file is NOT intended to replace the Phase II
LINE_3: Proposal Instructions; indeed the observer will need them
LINE_4: in order to determine legal values for a number of parameters
LINE_5: including exposure time.

!
! end of abstract

GENERAL_FORM_PROPOSERS:

  LNAME: Nagel
  FNAME: Lauretta
  INST: Space Telescope Science Institute
  COUNTRY: USA

!
! end of general_form_proposers block
```

```
GENERAL_FORM_TEXT:

QUESTION: 3!Description of proposed observations
SECTION: 1

LINE_1: Lines 1.0 - 7.004 are Proper Motion/Parallax Observations on a star. A
LINE_2: TRANS mode exposure is required first to be certain the program star is
LINE_3: NOT multiple...if it turns out to be multiple, the POS mode exposures
LINE_4: will fail (See the FGS Instrument Handbook for an explanation.) This
LINE_5: should be implemented at least 2 months prior to the POS observations
LINE_6: to enable the observer to analyse the data for duplicity and allow the
LINE_7: scheduling process to get the POS mode observations onto a calendar.
LINE_8:
LINE_9: Then, conditional on whether the TRANS exposures prove the star to be
LINE_10:double or not, POS mode observations will begin. A 4 orbit sequence is
LINE_11:requested, with each orbit being designed as a SEQuence
LINE_12:NON-INTerruptable set of lines. Each SEQ NON-INT is designed to have
LINE_13:the program star observed once at the beginning and once at the end,
LINE_14:with at least 4 of the astrometric reference (-REF) stars sandwiched in
LINE_15:between to get the observations of the program star as close as
LINE_16:possible to those of the -REF stars. Here, we needed 4 just to get a
LINE_17:statistically decent sample of the possible combinations of -REF stars.
LINE_18:The 4 NON-INT sequences should be done as close together as possible.
LINE_20:
LINE_21:It is recommended that the set of sequences should be done 4 times a
LINE_22:year, with 2 of those epochs coinciding with the dates that maximise
LINE_23:the parallax factor.

QUESTION: 3!Description of proposed observations
SECTION: 2

LINE_1: Lines 10.0 - 12.0 are Binary Observations for a target without
LINE_2: well-known orbital parameters. TRANSfer scan mode is the basic
LINE_3: technique used on binary stars and at least 5 scan lines through the
LINE_4: target are recommended in order to increase signal and avoid
LINE_5: contamination due to jitter. The resolution may be set by using the
LINE_6: STEP-SIZE optional parameter. The first observation can be at any
LINE_7: time...the later observations at 2 different roll angles (ORIENTs) are
LINE_8: required later to avoid any bias in determining the parameters. Note
LINE_9: that any use of the ORIENT requirement necessitates a scheduling
LINE_10:constraint on the program; in this example, lines 11 and 12 may be
LINE_11:done much later (and on different Guide Stars) than line 10 in order to
LINE_12:allow the spacecraft to fulfill the ORIENT science requirement *and*
LINE_13:the engineering requirements necessary to run the solar arrays. If the
LINE_14:observations need to be done all at once (because of Guide Stars or
LINE_15:lack of time), the ORIENTs can be changed to -30d and +30d, which is
LINE_16:the maximum the spacecraft can roll off of ''nominal."
LINE_17:
```

```
LINE_18:For binary targets whose parameters are already known approximately,
LINE_19:one TRANS observation near periastron may be all that is necessary.

QUESTION: 3 !Description of proposed observations
SECTION: 3

LINE_1: Line 200.0 and the Scan Data Form are for Interferometric Mapping of an
LINE_2: Extended Object. TRANS mode may also be used, but SCAN permits
LINE_3: two-dimensional scans with orientations either in the celestial
LINE_4: reference frame or the detector reference frame. The ORIENT is required
LINE_5: to place the brightest feature along the scan axis. The STEP-SIZE, and
LINE_6: therefore the resolution, is not specified in SCAN mode but the desired
LINE_7: resolution may be implied by setting the correct exposure time (see the
LINE_8: entry under TRANS mode in the Phase II Instructions) based on the scan
LINE_9: length and number of scan lines specified in the Scan Data section.
LINE_10:Talking to your USB Technical Assistant is HIGHLY recommended when
LINE_11:attempting to fill out the Scan Data Form because of its general
LINE_12:obtuseness.

QUESTION: 5 !Special Scheduling Requests
SECTION: 1

LINE_1: In lines 1-7.004, the TRANS mode exposure must occur at least 2 months
LINE_2: before the POS mode exposures because it is a test of whether of not
LINE_3: POS mode will succeed on the target. The 4 NON-INT POS mode sequences
LINE_4: should be done as close together as possible to achieve the statistics
LINE_5: necessary for relative astrometric measurements. This set of 4
LINE_6: sequences, called PARALLAX, should be done at 4 different, evenly
LINE_7: spaced, epochs, with 2 of the 4 epochs on dates that maximise the
LINE_8: parallax factor.

QUESTION: 5 !Special Scheduling Requests
SECTION: 2

LINE_1: In lines 10-12, The first observation can be at any
LINE_2: time...the later observations at 2 different roll angles (ORIENTs) are
LINE_3: required later to avoid any bias in determining the parameters. Note
LINE_4: that any use of the ORIENT requirement necessitates a scheduling
LINE_5: constraint on the program; in this example, lines 11 and 12 may be
LINE_6: done much later (and on different Guide Stars) than line 10 in order to
LINE_7: allow the spacecraft to fulfill the ORIENT science requirement *and*
LINE_8: the engineering requirements necessary to run the solar arrays. If the
LINE_9: observations need to be done all at once (because of Guide Stars or
LINE_10:lack of time), the ORIENTs can be changed to -30d and +30d, which is
LINE_11:the maximum the spacecraft can roll off of ``nominal."
```

```
QUESTION: 5 !Special Scheduling Requests
SECTION: 3

LINE_1: In line 200.0, The ORIENT is required to place the brightest feature
LINE_2: along the scan axis.

!
!end of general form text

GENERAL_FORM_ADDRESS:

  LNAME: NAGEL
  FNAME: LAURETTA
  CATEGORY: PI
  INST: SPACE TELESCOPE SCIENCE INSTITUTE
  ADDR_1: 3700 SAN MARTIN DRIVE
  CITY: BALTIMORE
  STATe: MD
  ZIP: 21218
  COUNTRY: USA
  PHONE: (410) 338-4432

!
! end of general_form_address records

FIXED_TARGETS:

  TARGNUM: 1
  NAME_1: BD+12D3456
  NAME_2: G123-45
  DESCR_1: A;101
  POS_1: RA = 00H 00M 00.0S +/- 0.1S,
  POS_2: DEC = +00D 00' 0" +/- 1",
  POS_3: PLATE-ID = YYYY
  EQUINOX: 2000
  PM_OR_PAR: Y
  POS_EPOCH_BJ: B
  POS_EPOCH_YR: 1980.0
  RA_PM_VAL: -0.0001
  RA_PM_UNCT: 0.0001
  DEC_PM_VAL: -0.0001
  DEC_PM_UNCT: 0.0001
  AN_PRLX_VAL: 0.0001
  AN_PRLX_UNCT: 0.0001
  RV_OR_Z: V = +100
  COMMENT_1: PARALLAX PROGRAM STAR
```

```
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=G0VI
FLUXNUM_2: 2
FLUXVAL_2: B = 12.34

TARGNUM: 2
NAME_1: BD+12D34561-REF
DESCR_1: A;133
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=F1

TARGNUM: 3
NAME_1: BD+12D34562-REF
DESCR_1: A;139
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=KIV

TARGNUM: 4
NAME_1: BD+12D34563-REF
DESCR_1: A;142
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=MII
```

```
TARGNUM: 5
NAME_1: BD+12D34564-REF
DESCR_1: A;123
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=A2V

TARGNUM: 6
NAME_1: BD+12D34565-REF
DESCR_1: A;110
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=B1IV

TARGNUM: 7
NAME_1: BD+12D34566-REF
DESCR_1: A;104
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=0

TARGNUM: 8
NAME_1: BD+12D34567-REF
DESCR_1: A;138
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
```

```
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=GIII

TARGNUM: 9
NAME_1: BD+12D34568-REF
DESCR_1: A;134
POS_1: RA = 00H 00M 00.0S +/- 0.1S,
POS_2: DEC = +00D 00' 0" +/- 1",
POS_3: PLATE-ID = YYYY
EQUINOX: 2000
POS_EPOCH_BJ: B
POS_EPOCH_YR: 1980.00
COMMENT_1: PARALLAX REFERENCE STAR
FLUXNUM_1: 1
FLUXVAL_1: V=12.34,TYPE=F9


TARGNUM: 10
NAME_1: HD123456
DESCR_1: A;137
POS_1: RA=00H 00M 00.0S +/- 0.1S,
POS_2: DEC=+00D 00' 00" +/- 1",
POS_3: PLATE-ID=XXXX
EQUINOX: 1950
PM_OR_PAR: Y
POS_EPOCH_BJ: J
POS_EPOCH_YR: 2000.00
RA_PM_VAL: -0.0001
RA_PM_UNCT: 0.0001
DEC_PM_VAL: -0.0001
DEC_PM_UNCT: 0.0001
AN_PRLX_VAL: 0.0001
AN_PRLX_UNCT: 0.0001
PLATE_REQ: N
PLATE_AVAIL: N
FLUXNUM_1: 1
FLUXVAL_1: V=2,TYPE=G5III
FLUXNUM_2: 2
FLUXVAL_2: B-V=+3.45
```

```
  TARGNUM: 20
  NAME_1: PK123+12D3
  DESCR_1: G;502
  POS_1: RA = 00H 00M 00.0S +/- 0.1S,
  POS_2: DEC = +00D 00' 0" +/- 1",
  POS_3: PLATE-ID=WWWW
  EQUINOX: 2000
  POS_EPOCH_BJ: J
  POS_EPOCH_YR: 1980.00
  FLUXNUM_1: 1
  FLUXVAL_1: SURF(V)=12.3 +/- 1.2 !UNITS ARE MAG/ SQ. AS
  FLUXNUM_2: 2
  FLUXVAL_2: E(B-V)=+1.23 +/- 1.23
EXPOSURE_LOGSHEET:

! 1.0 - 7.004 Proper Motion/Parallax Observations on a star.
! The TRANS mode exposure is required first to be certain the program star is
! NOT multiple...if it turns out to be multiple, the POS mode exposures will
! fail (See the FGS Instrument Handbook for an explanation.)
! The 4 NON-INT sequences should be done as close together as possible.

  LINENUM: 1.000
  TARGNAME: BD+12D3456
  CONFIG: FGS
  OPMODE: TRANS
  APERTURE: 3
  SP_ELEMENT: PUPIL !Recommended for ALL observations
  NUM_EXP: 1
  TIME_PER_EXP: 12.37S
  PRIORITY: 1
  PARAM_1: SCANS = 5
  REQ_1: CYCLE 5

! This is how one DEFines and USEs an observing sequence.
! NOTE that observing dates (or anything that ties an observation to a
! particular time of year) always go on the USE lines.

  LINENUM: 2.000
  SEQUENCE_1: DEF
  SEQUENCE_2: PARALLAX
  TARGNAME: BD+12D3456
  CONFIG: FGS
  OPMODE: POS
  APERTURE: 3
  SP_ELEMENT: PUPIL !Recommended for ALL observations
  NUM_EXP: 1
```

```
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: SEQ 2-2.002 NON-INT

LINENUM: 2.001
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D34561-REF
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: DO FOR TARG 2-5

LINENUM: 2.002
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32

LINENUM: 2.003
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: SEQ 2.003-2.005 NON-INT
```

```
LINENUM: 2.004
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D34561-REF
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: DO FOR TARG 6-9

LINENUM: 2.005
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32

LINENUM: 2.006
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: SEQ 2.006-2.008 NON-INT

LINENUM: 2.007
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D34561-REF
CONFIG: FGS
```

```
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: DO FOR TARG 2,4,6,8

LINENUM: 2.008
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32


LINENUM: 2.009
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: SEQ 2.009-2.011 NON-INT

LINENUM: 2.010
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D34561-REF
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
```

```
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32
REQ_1: DO FOR TARG 3,5,7,9

LINENUM: 2.011
SEQUENCE_1: DEF
SEQUENCE_2: PARALLAX
TARGNAME: BD+12D3456
CONFIG: FGS
OPMODE: POS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 50S
PRIORITY: 1
PARAM_1: DATA-RATE = 32

! 2 of the 4 epochs should match dates that maximise the parallax factor.
LINENUM: 5.001
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-SEP-95
REQ_2: +/- 10D; CYCLE 5

LINENUM: 5.002
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-DEC-95
REQ_2: +/- 10D; CYCLE 5

LINENUM: 5.003
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-MAR-96
REQ_2: +/- 10D; CYCLE 5

LINENUM: 5.004
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-JUN-96
REQ_2: +/- 10D; CYCLE 5
```

```
LINENUM: 6.001
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-SEP-96
REQ_2: +/- 10D; CYCLE 6

LINENUM: 6.002
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-DEC-96
REQ_2: +/- 10D; CYCLE 6

LINENUM: 6.003
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-MAR-97
REQ_2: +/- 10D; CYCLE 6

LINENUM: 6.004
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-JUN-97
REQ_2: +/- 10D; CYCLE 6


LINENUM: 7.001
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-SEP-97
REQ_2: +/- 10D; CYCLE 7

LINENUM: 7.002
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-DEC-97
REQ_2: +/- 10D; CYCLE 7

LINENUM: 7.003
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-MAR-98
REQ_2: +/- 10D; CYCLE 7
```

```
LINENUM: 7.004
SEQUENCE_1: USE
SEQUENCE_2: PARALLAX
REQ_1: AT 23-JUN-98
REQ_2: +/- 10D; CYCLE 7


! 10.0 - 12.0 Binary Observations: For a target without well-known orbital
! parameters. The first observation can be at any time...the different roll
! angles (ORIENTs) are required later to avoid any bias in determining the
! parameters. Note that any use of the ORIENT requirement necessitates a
! scheduling constraint on the program; in this example, lines 11 and 12 may
! be done much later (and on different Guide Stars) than line 10 in order to
! allow the spacecraft to fulfill the ORIENT science requirement *and* the
! engineering requirements necessary to run the solar arrays. If the
! observations need to be done all at once (because of Guide Stars or lack of
! time), the ORIENTs can be changed to -30d and +30d, which is the maximum the
! spacecraft can roll off of ''nominal."

LINENUM: 10.000
TARGNAME: HD123456
CONFIG: FGS
OPMODE: TRANS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 247S
PRIORITY: 1
PARAM_1: DATA-RATE=32, !This means FES-TIME=0.025
PARAM_2: SCANS=10, !Scans should be at least 5
PARAM_3: STEP-SIZE=1.0, !Set this to achieve needed resolution
REQ_1: CYCLE 5;
COMMENT_1: EACH SCAN-LINE THRU THE
COMMENT_2: TARGET IS 1.55" LONG.
COMMENT_3: N(SAMP) PER LINE = 1096

LINENUM: 11.000
TARGNAME: HD123456
CONFIG: FGS
OPMODE: TRANS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 247S
PRIORITY: 1
PARAM_1: DATA-RATE=32, !This means FES-TIME=0.025
```

```
PARAM_2: SCANS=10, !Scans should be at least 5
PARAM_3: STEP-SIZE=1.0 !Set this to achieve needed resolution
REQ_1: CYCLE 5;
REQ_2: ORIENT 120D +/- 5D FROM 10
COMMENT_1: EACH SCAN-LINE THRU THE
COMMENT_2: TARGET IS 1.55" LONG.
COMMENT_3: N(SAMP) PER LINE = 1096


LINENUM: 12.000
TARGNAME: HD123456
CONFIG: FGS
OPMODE: TRANS
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
NUM_EXP: 1
TIME_PER_EXP: 247S
PRIORITY: 1
PARAM_1: DATA-RATE=32, !This means FES-TIME=0.025
PARAM_2: SCANS=10, !Scans should be at least 5
PARAM_3: STEP-SIZE=1.0 !Set this to achieve needed resolution
REQ_1: CYCLE 5;
REQ_2: ORIENT 240D +/- 5D FROM 10
COMMENT_1: EACH SCAN-LINE THRU THE
COMMENT_2: TARGET IS 1.55" LONG.
COMMENT_3: N(SAMP) PER LINE = 1096


! 200.0 Extended Object - Interferometric Map.
! The ORIENT is required to place the brightest feature along the scan
! axis. The STEP-SIZE, and therefore the resolution, is not specified
! in SCAN mode but the desired resolution may be implied by setting the
! correct exposure time (see the entry under TRANS mode in the Phase II
! Instructions) based on the scan length and number of scan lines specified
! in the Scan Data section.

LINENUM: 200.000
TARGNAME: PK123+12D3
CONFIG: FGS
OPMODE: SCAN
APERTURE: 3
SP_ELEMENT: PUPIL !Recommended for ALL observations
PARAM_1: DATA-RATE=32,
PARAM_2: FES-TIME=0.025
NUM_EXP: 1
```

```
  TIME_PER_EXP: 1414.21S
  FLUXNUM_1: 1
  PRIORITY: 1
  REQ_1: ORIENT 90D +/- 5D;
  REQ_2: SPATIAL SCAN;
  REQ_3: CYCLE 5
  COMMENT_1: INTERFEROMETRY OF NEBULA WITH 28,284
  COMMENT_2: SAMPLES PER SCAN-LINE AT 0.0005" PER
  COMMENT_3: STEP RESOLUTION

SCAN_DATA:

  LINE_LIST: 200
  FGS_SCAN:
  CONT_DWELL: C
  DWELL_PNTS: 0
  DWELL_SECS: 0.000
  SCAN_WIDTH: 2.0000
  SCAN_LENGTH: 10.0000
  SIDES_ANGLE: 90.0000
  NUMBER_LINES: 4
  SCAN_RATE: 0.1000
  FIRST_LINE_PA: 326.00
  SCAN_FRAME: CEL
  LEN_OFFSET: 10.0000
  WID_OFFSET: 1.0000
```

APPENDIX B. PHASE II GENERAL OBSERVER PROPOSAL INSTRUCTIONS

Reprinted in this Appendix are the Phase II General Observer Proposal Instructions from the 15 April, 1993 edition. They have been reprinted in the Instrument Handbook to increase the utility of the explanatory material provided in the Handbook by making cross-referencing easier for the General Observer.

13 Fine Guidance Sensors (FGS)

The Instrument Configurations and Operating Modes described in the following section are used to specify exposures on the RPSS template "EXPOSURE_LOGSHEET" or on the proposal Exposure Logsheets. A summary of the legal Exposure Logsheet entries is provided; more complete descriptions of Instrument Configurations, Modes, Apertures, Spectral Elements, *etc.* are available in the *Instrument Handbooks*.

Note that many of the Optional Parameters have default values; in such cases, *an entry in the Optional Parameter column of the Exposure Logsheet is necessary only if it is desired to override the default value*. In the STScI proposal system the physical units of Optional Parameter quantities are always implicit and should never be entered by the observer.

Table 13.1 lists the permitted Instrument Configuration, Operating Modes, Fields of View, Spectral Elements, and Optional Parameters for the FGS.

Table 13.1: Instrument Parameters for the FGS

Config.	Mode	Field of View	Spectral Elements	Optional Parameters
FGS	POS §13.1	PRIME, 1, 2, 3	F605W, F583W, F5ND, F650W, F550W, PUPIL	DATA-RATE, FES-TIME, ACQ-MODE, ACQ-DIST, COUNT, BACKGROUND, NULL, LOCK
	TRANS §13.2			DATA-RATE, SCANS, STEP-SIZE, ACQ-MODE, ACQ-DIST
	SCAN §13.3			DATA-RATE, FES-TIME, ACQ-MODE, ACQ-DIST

The sections on the following pages provide further details of the entries to be made on the Exposure Logsheet when a particular FGS Mode/Configuration is chosen.

13.1 Mode (§6.5) = POS
Configuration (§6.4) = FGS

This is the basic single-star positional Operating Mode of the FGS. It may be used to measure the relative positions of fixed or slowly moving ($\leq 0''.050\ \mathrm{sec}^{-1}$) targets with a precision of about 0''.003. To achieve better precision, exposures of several astrometric reference stars should also be made. In this Operating Mode the program star or asteroid is first acquired and then held in fine lock for the specified exposure time.

The default values of the Optional Parameters are set in this Mode to provide acceptable data for single, zero angular diameter stars. The default acquisition consists of a spiral search for a target within a radius of 15'', followed by fine-lock tracking of the target. In this default mode star selectors are moved to null the Fine Error Signal and their positions are recorded every 0.025 sec.

Column	Entry	Description
Aperture or FOV §6.6	PRIME, 1, 2, 3	The FGS 3 is designated the "prime" FGS. Requests use of a specific FGS (see Figure 13.1).
Spectral Element §6.7	See Table 13.2	The available spectral elements are listed in Table 13.2. Only one filter can be used at a time. Targets brighter than 9th mag require use of the F5ND filter. The PUPIL is the recommended element.
Optional Param. §6.9	DATA-RATE	= 4, 32 (default) Using the 32-kbps telemetry link, the star-selector positions are recorded every 0.025 sec. The 4-kbps link supplies data readouts every 1.0 sec, even though the actual FES averaging time defaults to 1.6 sec. See the section of FES-TIME below for exceptions to this default. The 32-kbps link is recommended for all astrometric observations.

—continued—

13.1 Mode (§6.5) = **POS** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
Optional Param. (cont'd) §6.9	FES-TIME	=DEF (default); 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2 This optional parameter sets the averaging time (in seconds) for the Fine Error Signal, and consequently, the interval at which the star selectors are adjusted to null the Fine Error Signal. The default value DEF will be calculated from the COUNT, BACKGROUND and DATA-RATE optional parameters values and the selected FGS and FILTER. (See COUNT, BACKGROUND and DATA-RATE optional parameters for default values.). See the *Instrument Handbook* §5.0 for details. It is strongly recommended that the proposer include target V magnitude and B-V color index on the Fixed Target List for all targets.
	ACQ-MODE	=SEARCH (default); This parameter determines the strategy for locating the target. For ACQ-MODE=SEARCH a spiral search followed by a photocenter determination will be executed to establish fine lock.

—continued—

13.1 Mode (§6.5) = **POS** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
Optional Param. (cont'd) §6.9	ACQ-DIST	=DEF (default); 0.0 - 90.0 This Optional Parameter determines the size (in seconds of arc) of the acquisition search region. For ACQ-MODE=SEARCH, the value of ACQ-DIST is the maximum radius of the search spiral. The default value is 15″.
	COUNT BACKGROUND	=DEF (default); 1 - 2621400 =DEF (default); 1 - 2621400 The observer should compute the expected target and sky count rates (in counts per second) for the FGS and enter the values with these Optional Parameters (see the FGS *Instrument Handbook* §5.0.) The default count rate will be determined from the target V magnitude, $B-V$ color index, and the filter and FGS, using simple scaling rules. The default background rate is 59 counts/second for all four (4) PMTs and has been determined from on-orbit measurements. These Optional Parameters are used to verify the value of FES-TIME.
	NULL	=YES (default), NO For NULL=YES the star selectors will be repositioned by the Fine Guidance Electronics after each FES-TIME to null the Fine Error Signal. NULL=NO is called "null-bypass mode." See the FGS *Instrument Handbook* §5.0 for more details.

—continued—

13.1 Mode (§6.5) = **POS** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
	LOCK	=FINE (default); COARSE; 0.0 – 1.0 Tracking of the target in fine lock (FINE) or coarse track (COARSE) may be selected with this Optional Parameter. The fraction of the exposure time in fine lock may be specified by entering a value between 0.0 and 1.0. If 0.0 is entered, fine lock will be tested but no measurements will be made. LOCK=FINE and LOCK=1.0 produce identical results. If LOCK=COARSE, the values of several other Optional Parameters are overridden: FES-TIME , and NULL will be ignored.
Special Req. §6.15		Enter the ORIENTation Special Requirement (§7.2) if the arrangement of the astrometric reference stars requires a particular orientation of the FGS field of view. For targets moving more rapidly than 0.″004 per FES-TIME, enter the SPATIAL SCAN Special Requirement (§7.3) and submit a Scan Parameters Form (Appendix B; which will require the observer to know the speed and direction of the target). Specify on the Scan Parameters Form that the scan is "FGS Only,". Use the GROUP-FGS Special Requirement (§7.5) when several targets fall within the full FGS aperture over a given period of time.
Time per Exp. §6.11		The value to be entered is the photon-collecting time for measuring the position of the target. See the FGS *Instrument Handbook* §3.0 for exposure time calculations.

13.2 Mode (§6.5) = TRANS Configuration (§6.4) = FGS

This Operating Mode is useful for the measurement of the relative positions of binary stars or the sizes of extended targets. In this Mode the transfer function is measured by smoothly moving the FGS instantaneous FOV across the target at 45° with respect to the interferometer axes and recording the Fine Error Signal (FES). The scan is performed by moving the FGS under control of the Pointing Control System (PCS) and the FES is sampled at a rate determined by the telemetry link selected. DATA-RATE=32 is recommended and will produce an FES averaging time of 0.025 sec. For DATA-RATE=4 the FES averaging time is 1.6 sec. These rates ensure that all of the samples are included in the telemetry stream. The Scan Parameters Form **must not** be used in this Mode.

In this Mode a default exposure is optimized for unresolved, fixed targets. Acquisition is accomplished with a 15″-radius spiral search. The transfer function is measured with a single, continuous sweep with the star selectors under control of the PCS. In the default TRANS mode the length of the track is $0''\!.0566 \times T_{exp}$, the transfer function is sampled every 0.025 sec, and the number of samples obtained is $40\,T_{exp}$, where the observer specified exposure time is T_{exp} (in seconds).

Column	Entry	Description
Aperture or FOV §6.6	PRIME, 1, 2, 3	The FGS 3 is designated the "prime" FGS. Requests use of a specific FGS (see Figure 13.1).
Spectral Element §6.7	See Table 13.2	The available spectral elements are listed in Table 13.2. Only one filter can be used at a time. Targets brighter than 9th mag require use of the F5ND filter. The PUPIL is the recommended element.
Optional Param. §6.9	DATA-RATE	=4, 32 (default) Using the 32-kbps telemetry link, the star-selector positions are recorded every 0.025 sec. The 4-kbps link supplies data readouts every 1.0 sec, even though the actual FES averaging time defaults to 1.6 sec. See the section of FES-TIME below for exceptions to this default. The 32-kbps link is recommended for all astrometric observations.
	SCANS	=1 (default) - 200 The value entered is the number of separate scan lines to make through the target, with alternate scan lines taken in the same direction.

—continued—

13.2 Mode (§6.5) = **TRANS** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
Optional Param. (cont'd) §6.9	STEP-SIZE	=1.0 (default); 0.3 - 10.0 The angular separation (along the interferometer axes) of samples of the transfer function (in milliarcseconds) is specified by this Optional Parameter. The instantaneous field of view moves $\sqrt{2}$ × STEP-SIZE between samples (since the motion is always at 45° with respect to the interferometer axes). In general, the number of samples per separate scan line, N_{samp}, is determined by dividing the Exposure Time T_{exp} (§6.11) by the number of scan lines N_{scan} = SCANS and the time per sample t_{samp} (0.025 sec for DATA-RATE=32 or 1.6 sec for DATA-RATE=4). The exposure time would therefore be: $$T_{exp} = \frac{N_{scan} * t_{samp} * scan - length(\text{in milli} - \text{arcsec})}{SQRT(2) * \text{STEP} - \text{SIZE}}$$ Where the length of each scan line is $\sqrt{2} \times N_{samp} \times$ STEP-SIZE. The total length of the scanned track is the length of the scan line $\times N_{scan}$. The minimum scan rate is 0.″035/sec.
	ACQ-MODE	=SEARCH (default); For ACQ-MODE=SEARCH, the acquisition process consists of a spiral search followed by a photocenter operation for the target. Unlike for POS Mode acquisitions, fine lock is not established.

—*continued*—

13.2 Mode (§6.5) = **TRANS** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
Optional Param. (cont'd) §6.9	`ACQ-DIST`	`=0.0 - 90.0` This Optional Parameter determines the size (in seconds of arc) of the acquisition search region and is valid only for `ACQ-MODE=SEARCH` . For `ACQ-MODE=SEARCH`, the value of `ACQ-DIST` is the maximum radius of the search spiral. The default value is 15″.
Time per Exp. §6.11		The exposure time (T_{exp}) is the total photon-collecting time for all N_{scan} scans. The time per individual scan line is T_{exp}/N_{scan}.
Special Req. §6.15		If the position angle of the scan on the sky is important, enter the `ORIENT` Special Requirement (§7.2) with the appropriate position information.

13.3 Mode (§6.5) = SCAN Configuration (§6.4) = FGS

SCAN Operating Mode is similar to TRANS and WALKDOWN Operating Modes, but different scan patterns may be specified. This Operating Mode is recommended for targets that are moving too fast (but less than 0.″04 sec^{-1}) or are too faint ($V = 17$) for the other Modes. The FGS instantaneous field of view is moved under the control of the Pointing Control System. The pattern and its control are specified on the Scan Parameters Form. See the FGS *Instrument Handbook* §4.0 for further information.

A default exposure cannot be obtained in this Mode since the Scan Parameters Form must be entered. However, the default values of the Optional Parameters provide a 15″-radius spiral search acquisition followed by fixed-target tracking.

Column	Entry	Description
Aperture or FOV §6.6	PRIME, 1, 2, 3	The FGS 3 is designated the "prime" FGS. Requests use of a specific FGS (see Figure 13.1).
Spectral Element §6.7	See Table 13.2	The available spectral elements are listed in Table 13.2. Only one filter can be used at a time. Targets brighter than 9th mag require use of the F5ND filter. The PUPIL is the recommended element.
Optional Param. §6.9	DATA-RATE	=4, 32 (default) Using the 32-kbps telemetry link, the star-selector positions are recorded every 0.025 sec. The 4-kbps link supplies data readouts every 1.0 sec, even though the actual FES averaging time defaults to 1.6 sec. See the section of FES-TIME below for exceptions to this default. The 32-kbps link is recommended for all astrometric observations.

—continued—

13.3 Mode (§6.5) = **SCAN** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
Optional Param. (cont'd) §6.9	FES-TIME	=DEF (default); 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2 This optional parameter sets the averaging time (in seconds) for the Fine Error Signal, and consequently, the interval at which the positions of the star selectors are adjusted. The default value DEF will be calculated from the COUNT, BACKGROUND and DATA-RATE optional parameters values and the selected FGS and FILTER. (See COUNT, BACKGROUND and DATA-RATE optional parameters for default values.). See the *Instrument Handbook* §5.0 for details. It is strongly recommended that the proposer include target V magnitude and B-V color index on the Fixed Target List for all targets.
	ACQ-MODE	=SEARCH (default); For ACQ-MODE=SEARCH the acquisition process consists of a spiral search followed by a photocenter operation for the target. Unlike POS Mode, fine lock is not established.

—continued—

13.3 Mode (§6.5) = **SCAN** (continued)
Configuration (§6.4) = **FGS**

Column	Entry	Description
Optional Param. (cont'd) §6.9	ACQ-DIST	=DEF (default); 0.0 - 90.0 This Optional Parameter determines the size (in seconds of arc) of the acquisition search region and is valid only for ACQ-MODE=SEARCH . For ACQ-MODE=SEARCH, the value of ACQ-DIST is the maximum radius of the search spiral. The default value is 15″.
Number of Exp. §6.10		The number of exposures is the number of separate scan lines to make across the target. This value must also be entered as the Number of Lines in the Scan Parameters Form (Appendix B).
Time per Exp. §6.11		The exposure time is the time per scan line for continuous scans.
Special Req. §6.15		Enter the SPATIAL SCAN Special Requirement (§7.3) and specify the scan to be executed on the Scan Parameters Form (Appendix B).

Table 13.2: Spectral Elements for the FGS

Name	Comments	Effective Wavelength (Å)	Full Width at Half Maximum (Å)
F583W	"Clear" filter	5830	2340
F5ND	Neutral Density (5 mag)	.....	.....
F605W[1]	"Astrometry Clear" filter	6050	1900
F650W[2]	"Red" filter	6500	750
F550W	"Yellow" filter	5500	750
PUPIL	Pupil stop	.....	.....

Note to Table 13.2:
[1] F605W is to be specified with FGS3 only.
[2] F650W is to be specified with FGS1 and FGS2 only.

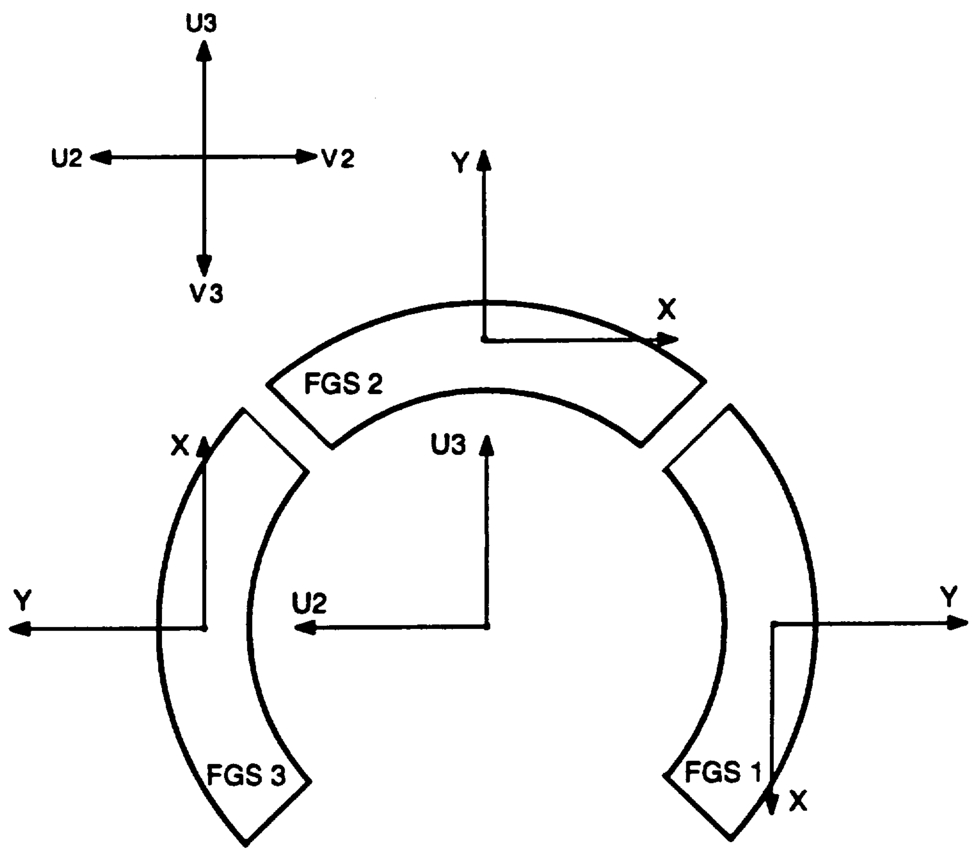

Figure 13.1: The FGS $X - Y$ Coordinate System used in the POSition TARGet and the ORIENTation Special Requirements are defined in this figure.

Table 13.3: Internal Calibration Targets for the FGS

The following internal calibration targets are available for the FGS. These should not be included in your proposal if the routine calibrations (see the *Calibration Notes*) are sufficient for your program. See the FGS *Instrument Handbook* for further details.

Target Name	Description	Spectral Element	Time per Exposure
DARK	The star selectors slew the FGS Field of View off the Pickle Aperture and the dark counts are recorded for a time interval given by the exposure time. This occurs for target= "DARK" for all observing MODEs.	Any	Enter a specific time