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Fine Guidance Sensor Data Handbook

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- **URL:**http://www.stsci.edu/hst/fgs

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Preface

How to Use this Handbook

This handbook is designed to help you manipulate, process and analyze data from the three Faint Guiding Sensors (FGSs) on-board the Hubble Space Telescope (HST). The book is presented as an independent and self-contained document, providing all the required information for understanding the FGS observations and obtaining high precision astrometric data on milli-arcsec scales. This can also be used as a cookbook, guiding users through various steps of FGS data reduction.

The HST Data Handbook has now been subdivided into separate volumes for each instrument. Users are referred to a companion volume, *Introduction to the HST Data Handbooks*, for more general information about the details of acquiring data from the *HST* archive, *HST* file formats, and general purpose software for displaying and processing *HST* data.

The current edition of the FGS Data Handbook is being written early in 2002, as we approach Servicing Mission 3b (SM3b). The behavior of this instrument is not likely to change after the servicing mission. Therefore, the material presented in this handbook is expected to remain up-to-date during the next cycles.

The present revision incorporates significant changes into the data handbook. These include details on data calibration and description of CALFGSA and CALFGSB IRAF/STSDAS tasks, required to process FGS Position and Transfer Mode observations for data analysis. Also, The Data Analysis chapter has been extensively revised to include details on how to run a set of stand-alone tasks to analyze both Position Mode and Transfer Mode data.

While the present version of the Data Handbook contains the latest information for accurate reduction and analysis of the FGS data, readers are advised to consult the Space Telescope Science Institute Web site (http://hst.stsci.edu/HST_overview/instruments) for the most recent up-dates regarding the FGS operation.

Handbook Structure

The FGS Data Handbook is organized in five chapters, which discuss the following topics:

- Chapter 1:Instrument Overview presents a brief overview of the scientific capabilities of the Fine Guidance Sensors, their readout modes, and data products. The material presented here is excerpted from the information presented in the FGS Instrument Handbook, and we refer the reader to that document for more complete information about the properties of the FGS as a science instrument.
- Chapter 2:FGS Data Products describes how to identify and interpret the contents of FGS data files. An FGS data set received from the Archive contains information from all three FGSs, plus supporting data on the spacecraft itself. These files arrive in FITS format and need to be converted to GEIS format before processing.
- Chapter 3:Calibration describes the routine reduction and calibration of raw FGS data. Unlike data from other HST instruments, data from the FGS are not calibrated by an automated *pipeline* process. This task is left to the user. To facilitate FGS data calibration, STScI provides two IRAF/STSDAS tasks - ***calfgsa*** and ***calfgsb*** - which enable observers to calibrate their data using the current best set of reference files and algorithms. This chapter describes these tasks in detail, and should serve as a guide for when to use **calfgsa** or **calfgsb** on FGS data.
- Chapter 4:Data Analysis provides insight and instructions for the analysis of FGS astrometry data. This includes the reduction of multi-epoch Position Mode observations (used, for example, in the determination of an object's parallax), multi-epoch Transfer Mode observations (used to derive a binary system's orbital parameters), as well as the detailed inspection of the data from a single exposure or observation.
- Chapter 5:Astrometric Error Sources discusses those uncertainties, both statistical and systematic, which remain after the pipeline calibrations of raw Position Mode and Transfer Mode observations. Each step in the calibration procedure leaves its own residuals which contribute to the overall error budget.

There are some important pieces of general information about *HST* data, the *HST* Archive, and the **IRAF** and **STSDAS** analysis software that are not specific to the FGS, and which are therefore not discussed here in the *FGS Data Handbook*. We refer the reader to the most recent version of the companion *Introduction to the HST Data Handbooks* for this information. Additional help with *HST* data is always available via email to the STScI Help Desk at `help@stsci.edu`.

Typographic Conventions

To help you understand the material in this Data Handbook, we will use a few consistent typographic conventions.

Visual Cues

The following typographic cues are used:

- **bold** words identify an **STSDAS**, **IRAF**, or **PyRAF** task or package name.
- `typewriter-like` words identify a file name, system command, or response that is typed or displayed.
- *italic* type indicates a new term, an important point, a mathematical variable, or a task parameter.
- `SMALL CAPS` identifies a header keyword.
- ALL CAPS identifies a table column.

Comments

Occasional side comments point out three types of information, each identified by an icon in the left margin.

Warning: You could corrupt data, produce incorrect results, or create some other kind of severe problem.

Heads Up: Here is something that is often done incorrectly or that is not obvious.

Tip: No problems...just another way to do something or a suggestion that might make your life easier.

Online

Information especially likely to be updated on the FGS Web site is indicated by this symbol.

Ed Nelan and Russ Makidon (Editors, FGS Data Handbook)
Bahram Mobasher (Chief Editor, HST Data Handbook)

CHAPTER 1:

Instrument Overview

In this chapter. . .

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This chapter presents a brief overview of the scientific capabilities of the Fine Guidance Sensors, their readout modes, and data products. The material presented here is excerpted from the information presented in the FGS Instrument Handbook, and we refer the reader to that document for more complete information about the properties of the FGS as a science instrument.

1.1 Instrument Capabilities

The Fine Guidance Sensors (FGS), originally designed and built by the Perkin-Elmer Corporation in Danbury, CT (now Goodrich Corporation's Optical and Space Systems), comprise a set of three radial-bay instruments on board the Hubble Space Telescope (HST). The main purpose of the FGS is to maintain the pointing stability of the telescope at the milliarcsecond level, often over exposure times as long as tens of minutes. The HST pointing requirements necessitated a design with a large observable field of view (FOV) with a high dynamic range in order to take advantage of the variety of observing scenarios HST was expected to encounter.

The resultant instruments, the FGS, are dual-axis white light shearing interferometers, each with a ~69 square arcminute FOV. Under nominal operating conditions, the FGS are routinely able point the spacecraft with a precision of ~2 mas or less. Unfortunately, the original design of the FGS did not compensate for the spherical aberration of the mis-formed HST primary mirror, and as a result the original FGSs suffered from degraded performance. In response to this, Goodrich re-engineered the spare FGS to include a commandable mechanism to mitigate the deleterious effects of the spherical aberration. This revised instrument replaced FGS1 during the second Hubble Servicing Mission in 1997. This device, now designated FGS 1R, was joined by FGS2R during the HST Servicing Mission 3a. Goodrich is currently upgrading the old FGS2 with this commandable mechanism for an expected return to the telescope (and replacement of FGS3) during the fourth HST servicing mission.

The high precision pointing capabilities of the FGS coupled with a fourteen magnitude dynamic range enable the FGS to perform as a high-precision astrometer and a high angular resolution science instrument. The 40 Hz readout time and detector stability allow for milli-magnitude relative photometry over orbital timescales and 1-2% relative photometry over long baselines (i.e., months). As a science instrument, the FGS have been used to determine the parallaxes of cataclysmic variable and dwarf novae stars (McArthur et al. 2001, Harrison et al. 2000), to provide dynamical mass constraints for Pre-Main Sequence evolutionary tracks (see Steffen et al. 2001), and to calibrate the optical mass-luminosity relationship at the end of the Main Sequence (Henry et al. 1999). The FGS have been used to search for the astrometric signatures of planets orbiting nearby stars (Benedict et al. 1999), to constrain the angular diameters of Mira variables (Lattanzi et al. 1997) and to place limits on the spatial extent of active galactic nuclei. Within the solar system, FGS observations have yielded information on the structure of the atmosphere of Triton (Elliot et al. 2000)

This chapter briefly describes how the Fine Guidance Sensors operate, summarizing its capabilities, its design, and its modes of operation. A more complete discussion of the design and of the scientific capabilities of the FGS can be found in the *FGS Instrument Handbook*. In addition, the FGS WWW pages at STScI,

http://www.stsci.edu/instruments/fgs/

are also valuable sources of information for the FGS user, particularly concerning technical details of the instrument, as well as a history of its performance throughout its lifetime.

1.1.1 The FGS as a Science Instrument

The FGS has two modes of operation: Position Mode and Transfer Mode. In Position Mode the FGS locks onto and tracks a star's interferometric fringes to precisely determine its location in the FGS FOV. By sequentially observing other stars in a similar fashion, the relative angular positions of luminous objects are measured with a *per-observation* precision of about 1 mas over a magnitude range of 3.0 < V < 16.8. This mode is used for relative astrometry, i.e., for measuring parallax, proper motion, and reflex motion. Multi-epoch programs achieve accuracies approaching 0.2 mas.

In Transfer Mode an object is scanned to obtain its interferogram with sub-mas sampling. Using the fringes of a point source as a reference, the composite fringe pattern of a non-point source is deconvolved to determine the angular separation, position angle, and relative brightness of the components of multiple-star systems or the angular diameters of resolved targets (Mira variables, asteroids, etc.).

As a science instrument, the FGS is a sub-milliarcsecond astrometer and a high angular resolution interferometer. Some of the investigations well suited for the FGS are listed here and discussed in detail in Chapter 3:

- ***Relative astrometry*** (position, parallax, proper motion, reflex motion) with *single-measurement* accuracies of about 1 milliarcsecond (mas). Multi-epoch observing programs can determine parallaxes with accuracies approaching 0.2 mas.
- ***High-angular resolution observing***:
  - detect duplicity or structure down to 8 mas
  - derive visual orbits for binaries as close as 12 mas.
- ***Absolute masses and luminosities***:
  - The absolute masses and luminosities of the components of a multiple-star system can be determined by measuring the system's parallax while deriving visual orbits and the brightnesses of the stars.
- ***Measurement of the angular diameters*** of non-point source objects down to about 8 mas.
- ***40Hz 1–2% long-term relative photometry***:
  - Long-term studies or detection of variable stars.
- ***40Hz milli-magnitude relative photometry over orbital timescales.***
  - Light curves for stellar occultations, flare stars, etc.

1.2 Technical Overview

1.2.1 The Instrument

The FGS is a white-light shearing interferometer. It differs from the long-baseline Michelson Stellar Interferometer in that the angle of the incoming beam with respect to the HST's optical axis is measured from the tilt of the collimated wavefront presented to the "Koesters prism" rather than from the difference in the path length of *two* individual beams gathered by separate apertures. Thus, t*he FGS is a single aperture (single telescope) interferometer, well suited for operations aboard HST. T*he FGS is a two dimensional interferometer; it scans or tracks an object's fringes in two orthogonal directions simultaneously. As a science instrument, the FGS can observe targets as bright as V = 3 and as faint as V = 16.8 (dark counts dominate for targets of V > 17).

Spectral Response

The FGS employs photomultiplier tubes (PMTs) for detectors. The PMTs—four per FGS—are an end-illuminated 13-stage venetian blind dynode design with an S-20 photocathode. The PMT sensitivity is effectively monotonic over a bandpass from 4000 to 7000A, with an ~18% efficiency at the blue end which diminishes to ~2% at the red end.

Each FGS contains a filter wheel fitted with 5 slots. FGS1r contains three wide-band filters, F550W, F583W (sometimes called CLEAR), F605W, a 5-magnitude Neutral Density attenuator (F5ND), and a 2/3 pupil stop, referred to as the PUPIL. Not all filters are supported by standard calibrations. Transmission curves of the filters and recommendations for observing modes are given in Chapters 2 and 4 respectively.

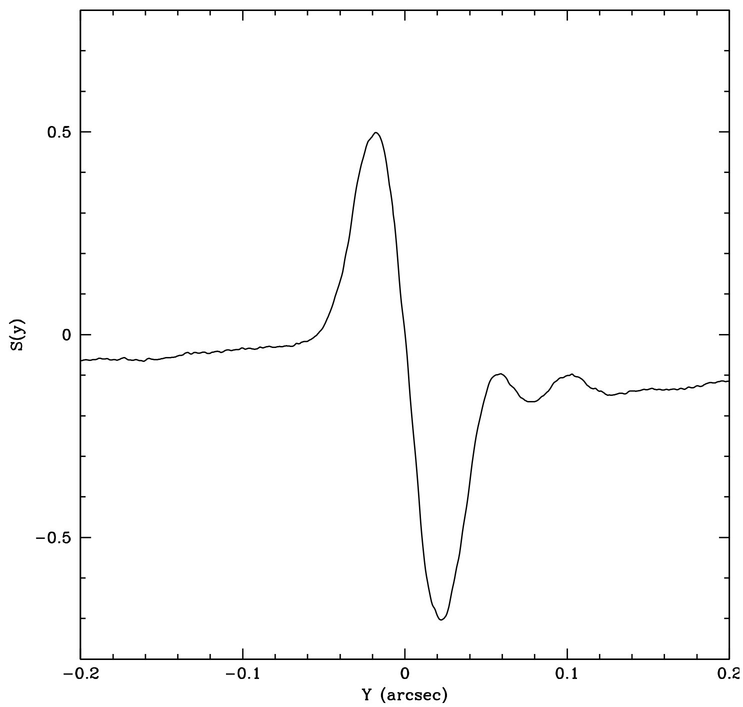
The S-Curve: The FGS's Interferogram

The FGS interferometer consists of a polarizing orthogonal beam splitter and two Koesters prisms. The Koesters prism, discussed in Chapter 2 of the *FGS Instrument Handbook*, is sensitive to the *tilt* of the incoming wavefront. Two beams emerge from each prism with relative intensities correlated to the tilt of the input wavefront. The relation between the input beam tilt and the normalized difference of the intensities of the emergent beams, measured by pairs of photomultiplier tubes, defines the fringe visibility function, referred to as the "S-Curve". Figure 1.1 shows the fringe from a point source. To sense the tilt in two dimensions, each FGS contains two Koesters prisms oriented orthogonally with respect to one another. See the *FGS Instrument Handbook* for more details.

FGS1r and the AMA

During the Second Servicing Mission in March 1997 the original FGS1 was replaced by FGS1r. This new instrument was improved over the original design by the re-mounting of a flat mirror onto a mechanism capable of tip/tilt articulation. This mechanism, referred to as the *Articulated Mirror Assembly*, or AMA, allows for precise in-flight alignment of the interferometer with respect to HST's Optical Telescope Assembly (OTA). This assured optimal performance from FGS1R since the degrading effects of HST's spherically aberrated primary mirror would be minimized (COSTAR did not correct the aberration for the FGSs).

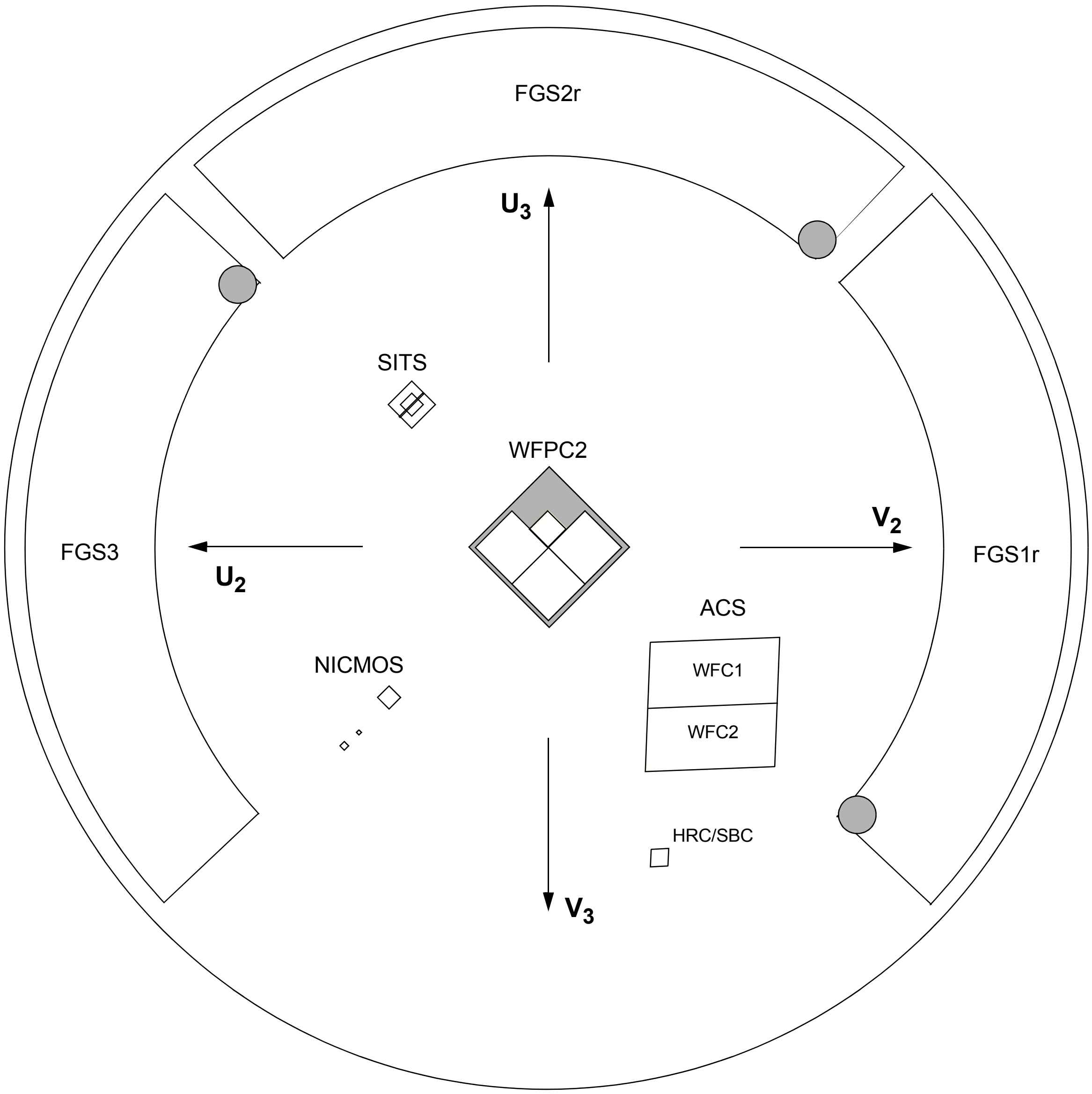
Figure 1.1: FGS Interferometric Response (the "S-Curve")



Field of View

The total *field of view* (FOV) of an FGS is a quarter annulus at the outer perimeter of the HST focal plane with inner and outer radii of 10 and 14 arcmin respectively. The total area (on the sky) subtended by the FOV is ~ 69 square arcmintues. The entire FOV is accessible to the interferometer, but only a 5 x 5 arcsec aperture, called the *Instantaneous Field of View* (IFOV), samples the sky at any one time. A dual component Star Selector Servo system (called SSA and SSB) in each FGS moves the IFOV to a desired position in the FOV. The action of the Star Selectors is described in detail in Chapter 2, along with a more detailed technical description of the instrument. Figure 1.2 shows a schematic representation of the FGSs relative to the HST focal plane.

Figure 1.2: FGSs in the HST Focal Plane (Projected onto the Sky)



1.2.2 Modes of Operation

The FGS has two modes of operation: Position Mode and Transfer Mode.

Position Mode

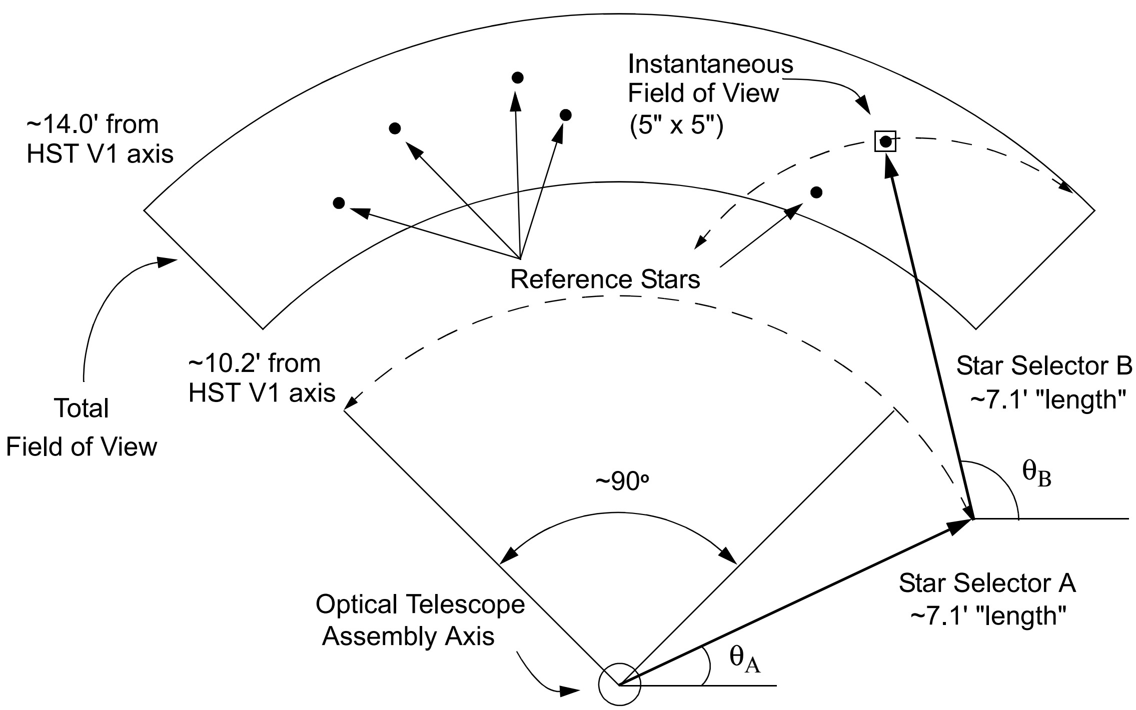
The FGS Position Mode is used for relative astrometry, i.e. parallax, proper motion, reflex motion and position studies. In Position Mode, the

HST pointing is held fixed while selected FGS targets are sequentially observed for a period of time (2 < t < 120 sec) to measure their relative positions in the FOV. Two-dimensional positional and photometric data are continuously recorded every 25 msec (40 Hz). The raw data are composed of a Star Selector encoder angles (which are converted to FGS X and Y detector coordinates during ground processing) and photomultiplier (PMT) counts, is a schematic of the FGS FOV and IFOV. The figure shows how Star Selectors A and B uniquely position the IFOV anywhere in the FGS FOV.

Transfer Mode

In Transfer Mode, the FGS obtains an object's interferograms in two orthogonal directions by scanning the Instantaneous Field of View (IFOV) across the target (typically in 1" scan lengths). Transfer Mode observing is conceptually equivalent to imaging an object with sub-milliarcsecond pixels. This allows the FGS to detect and resolve structure on scales smaller than HST's diffraction limit, making it ideal for detecting binary systems with separations as small as 8 mas with ~ 1 mas precision.

Figure 1.3: FGS Star Selector Geometry



1.2.3 FGS Capabilities

Each Fine Guidance Sensor on HST is an optical-mechanical white-light interferometer that can sense 1–2 milliarcsecond (mas) angular displacements of a point source in two dimensions over the range of apparent visual magnitudes from $3 < V < 15$. It can observe fainter objects down to $V < 17$, but its accuracy degrades to more than 2 mas. The instrument's spectral response is fairly flat from 4000 Å to 7200 Å, with sharp drop-offs outside this range.

The optical path through an FGS is complex because the beam passes through multiple optical elements. The relative alignment of all these components and the wavelength dependencies introduced by their reflective surfaces and refractive optics impose the resolution and magnitude limits of the FGS. Most of the FGS calibration procedure consists of empirical and semi-empirical subtraction of the instrument's signature, necessitating observations of standard stars in various spectral ranges and all modes of observation.

The three FGSs on board HST occupy three of the four radial bays. Normally two FGSs are used for pitch, yaw, and roll control of the telescope, leaving one available for astrometry. The telemetry from the guiding FGSs is captured and processed by the ground system and stored in the Hubble Data Archive. Processed FGS telemetry can be retrieved for any HST observation with any Science Instrument (SI) in the form of observation log files, which provide information on spacecraft jitter.

Position Mode observing is used both to guide the telescope and for positional astrometry. Transfer Mode is used primarily to support astrometry science programs investigating multiple star systems or extended objects, but is on occasion used in engineering tests to evaluate the FGS and the OTA optical systems.

FGS 1R is the only FGS currently designated and calibrated as an astrometer. This FGS can measure point-source angular positions of 1–2 mas over the brightness range of 3 to 17 magnitudes and can resolve the components of binary systems with separations as small as 10 mas. For many scientific studies, this FGS continues to exceed ground based efforts in sensitivity, dynamic range, and resolution.

1.2.4 FGS Control

Two different kinds of computers can control the three FGSs. One is HST's housekeeping computer, the 486. The other is the Fine Guidance Electronics (FGE) microprocessor associated with each FGS. Both the FGEs and the 486 control the FGSs while they are guiding HST. However, when one of the FGSs is being used as an astrometer in Position Mode, it is under the control of its associated FGE. When scanning in Transfer Mode, the FGS is under control of the 486.

The fundamental time interval for an FGS is 25 milliseconds, the shortest time over which the FGSs can compute a fine error signal or respond to commands. Independent of instrument mode or activity, the 486 gathers all FGS data at 25 millisecond intervals, assigns them specific locations in the engineering telemetry stream, and downlinks them to the ground. The engineering telemetry format at the time of transmission determines what FGS data are included in the downlink and the rates at which they are reported.

1.3 Target Acquisition and Tracking

An FGS astrometry dataset contains all the steps in the target acquisition and tracking sequence. This information is necessary because the calibration pipeline uses it in the data reduction process. In this section we describe the acquisition and tracking sequence and define the flags and status bits that record the activities during the acquisition.

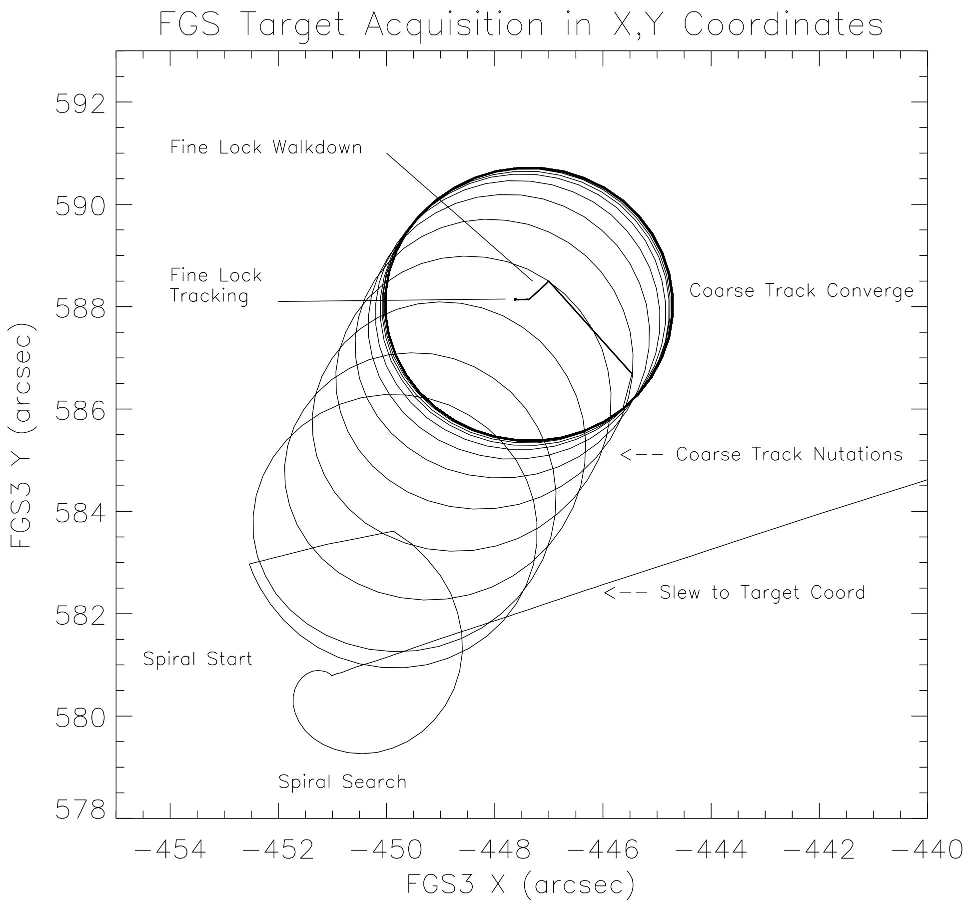
The first step in using an FGS either as a guider or an astrometer is to acquire the target in its instantaneous field of view. To accomplish this task, the 486 slews the FGS's IFOV to the expected position of the target within its pickle. (Uplinked commands specify the SSA and SSB rotation angles that should put the IFOV on the star.) Once the IFOV arrives at the expected position of the star, the 486 delegates control of the FGS to its FGE, which attempts to locate and to track the star by implementing its Search, CoarseTrack, and FineLock algorithms.

Figure 1.4 illustrates the movement of the IFOV during a target acquisition, showing:

1. The end of the slew to the target's expected location.
2. A short spiral search.
3. Coarse track nutations to locate the photocenter.
4. WalkDown to locate interferometric null.
5. Tracking of the star in FineLock.

This particular case was chosen for its clear demonstration of the phases of the acquisition. It is, however, atypical because the 7" difference between the expected location and the true location of the target is unusually large.

Figure 1.4: Location of IFOV as FGS Acquires a Target



1.3.1 Search

The IFOV, under FGE control, steps every 25 msec along an outward spiral while the PMTs count the photons received from the 5” x 5” patch of sky in the IFOV over the same 25 msec. When the counts fall within a specified range, the FGE declares the spiral search a success, and the instrument proceeds to the next phase of the acquisition, CoarseTrack. Otherwise, the FGE continues the spiral search until it either finds the star or completes it maximum search radius, typically 15” for astrometry and 90” for guiding. If no star is detected, the attempt is classified a failure, and the FGE halts further activity.

1.3.2 CoarseTrack

Having successfully completed its SEARCH, the FGE then attempts to acquire and track the star in CoarseTrack. In this mode the FGS determines the photocenter of light by comparing the photon counts from the 4 PMTs as the IFOV nutates in a 5” diameter circular path around the target. Data from each nutation are used to verify that the star is still in view and to adjust the path of the next nutation to improve the centering of the star. If the FGS is being operated as an astrometer in Position Mode, the FGE will initiate the FineLock acquisition after a specified number of nutations: 13 for bright, mv<14 objects, 21 for fainter objects. If the FGS is being operated as a guider or as an astrometer in Transfer Mode, it remains in CoarseTrack until instructed by the 486 to initiate an attempt at FineLock.

If the PMT data ever indicate that the star is no longer present, the FGS reverts back to SEARCH mode, beginning where it left off on the search spiral to resume its outward search for the star.

1.3.3 FineLock

Upon completion of the CoarseTrack, either autonomously or by order of the 486, the FGE assumes control of the FGS and attempts to acquire the target in FineLock. This activity involves two distinct phases, acquisition and tracking. Both make use of the interferometric signal (the S-curve) to achieve success. The fundamental interval of time during FineLock is the *fine error averaging time* denoted as FESTIME. During an FESTIME the FGS integrates the PMT data while holding the IFOV fixed.

This acquisition phase is called “WalkDown to FineLock,” or simply *the WalkDown*. The FGE commands the FGS’s IFOV to a position offset or “backed-off” from the photocenter (determined by CoarseTrack). The back-off distance, equal in (+dx,+dy), is specified by the uplinked command parameter *KB*:

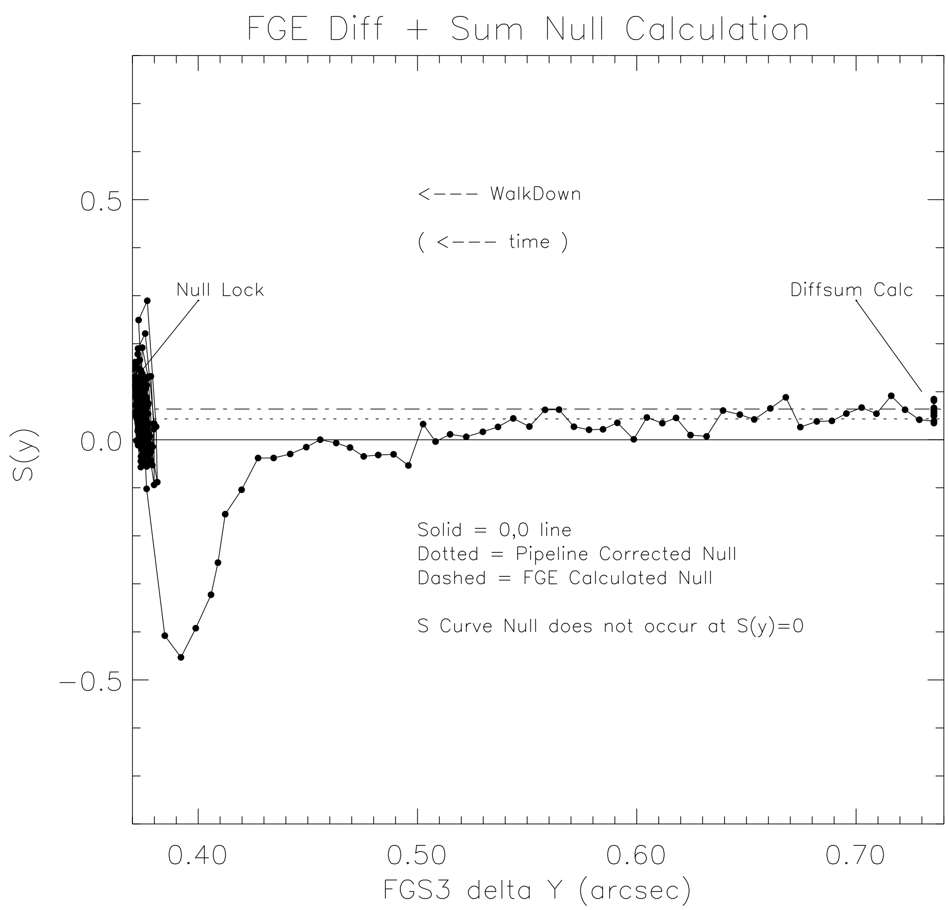
$$KB = \sqrt{dx^2 + dy^2}$$

Once the IFOV arrives at the starting point, its position is held fixed for 0.4 SECONDS or an FESTIME, whichever is longer. The FGE collects data from the 2 PMTs on each of the x and y channels to compute an average sum (SUM) and difference (DIFF) on each channel. The DIFF and SUM values compensate for any difference in the response of the two PMTs on a given axis. Thus, the *x*-axis fine error signal (FES) for the remainder of a Position Mode observation will be:

$$Qx = (Ax - Bx - DIFFx) / SUMx$$

where *Ax* and *Bx* are the average photon counts/25msec (from PMTXA and PMTXB) integrated over the FESTIME, and $DIFF_x$ and SUM_x are the average difference and sum of the PMTXA, PMTXB counts/25msec (determined while the IFOV was held fixed at the starting point of the WALKDOWN). The y-axis FES is computed in a similar fashion. Figure 1.5 shows the instantaneous value of the normalized difference of the PMT counts along the *y*-axis during a WalkDown to FineLock. The fact that the null lies to the positive side of $S_y = 0.0$ clearly demonstrates the need for the DIFF-SUM adjustment to locate the true interferometric null (where $Q_y = 0$).

Figure 1.5: Offset of True Null from $S_y = 0$



During the WalkDown the IFOV creeps towards the photocenter in a series of equal steps, approximately 0.006” in *x* and *y*, and is held fixed for an FESTIME while the PMT data are integrated to compute the fine error signal on each axis. If the absolute value of the fine error signal for a given axis exceeds a command specified threshold for three consecutive steps, satisfying the *3-hit algorithm*, the FGE concludes that it has encountered the S-curve on that axis. From this point on, a continuous feedback loop between the star selector servos and the value of the fine error signal governs the repositioning of the IFOV along that axis from this point on. The FGS continuously adjusts the star selector positions by small rotations after every FESTIME interval to set the fine error signal to zero, repositioning the IFOV so that the wavefront presented to the face of the Koesters prism has zero tilt.

The FGS tracks the star in FineLock by keeping the IFOV loitering about the star's interferometric null (the zero-point crossing of the fine error signal). Once the S-curve has been encountered on, say, the *x*-axis, the correction to the current position of the IFOV along the *x*-axis for the next FESTIME is computed by

$$dx = K1x * Qx + K0x$$

where *K1x* and *K0x* are uplinked command parameters called K-factors.

When the S-curves on both axes have been encountered and have satisfied the 3-hit algorithm, the FGS is said to be tracking the object in FineLock and the FGE sets the DataValid status flag. Until recently, misalignments within the FGS caused the y-xis S-curve to be detected before the x-axis S-curve, yielding a 0.3 arcsec difference between apparent positions of the x- and y-axis interferometric nulls. Commanding changes uploaded to HST in 2001 have since remedied this problem.

1.3.4 Transfer Scans

The acquisition of an object for an FGS operating in Transfer Mode is carried out in the same sequence described above, with the exception that the FGS remains in CoarseTrack until a specified spacecraft time. Thereafter it proceeds to FineLock by slewing the IFOV to the starting point of the first scan. As described earlier for the Position Mode WalkDown, the FGS averages and differences the PMT data for 0.4 seconds, computes the fine error signal, and compares it to a commanded threshold. However, this threshold equals zero for Transfer Mode observations, immediately prompting the FGE to declare that FineLock has been achieved and to set the DataValid flag. Setting this flag signals the 486 that the FGS is ready to begin the Transfer Mode observation.

In a Transfer Mode observation the 486 computer steps the FGS's IFOV across the photocenter (determined by CoarseTrack) along a diagonal path in detector space for a distance specified in the original proposal. Each sweep across the target is referred to as a scan. After the completion of a given scan, the IFOV reverses direction and scans the object again until the total number of scans specified in the proposal have been completed. Every 25 msec the PMT data and star selector rotation angles are reported in the telemetry. The FGS samples the entire S-curve, which can be reconstructed by post observation data processing.

1.4 FGS Guiding

When an FGS is used for guiding HST, it acquires a *guide star* in FineLock. The HST pointing control system then corrects telescope's pointing to bring this guide star (by slewing the telescope) to a pre-determined (*x,y*) position within the pickle of the guiding FGS. Once HST is properly pointed, the FGS continues to track its target in FineLock under control of both the FGE and the 486 while the pointing control system monitors the (*x,y*) position of the guide star and averages that data to determine the current pointing of the telescope. The pointing control system uses these data to eliminate translational and rotational drift of the observatory and to repoint the telescope properly. It also compensates for differential velocity aberration, which is the field-dependent change in the apparent positions of stars owing to the telescope's motion transverse to the direction it is pointed. Because pointing requires two dimensional control, two FGSs are usually used simultaneously to track guide stars. The FGS that controls translational attitude is the *dominant guider*, and the FGS that controls roll is the *roll* or *subdominant guider*.

Sometimes only one FGS actively guides the telescope, maintaining only translational control. Then HST is "free" to roll about the dominant guide star, restrained only by gyroscopic feedback. This situation arises more frequently during astrometry observations than for the other observations because guide star candidates, which can be difficult to find in the first place, are limited to those which appear in two FGSs instead of three.

The FGS astrometry pipeline uses data from the guiding FGSs to provide a high-resolution spatial and temporal HST pointing history over the course of an astrometry observation. These guide star data are useful in both Position Mode and Transfer Mode data reductions.

CHAPTER 2:

FGS Data Products

In this chapter. . .

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2.2 Relationship to Phase II Proposal / 21
2.3 Jitter Files / 21
2.4 SMS Support Data / 22

2.1 Engineering Telemetry Data

The three FGSs are a vital part of HST's pointing control system (PCS). Whether operating or not, either as a science instrument or guiding HST, data from all three FGSs are continuously downlinked on the engineering stream (rather than the science stream). The contents and rates of the FGS data are determined solely by the engineering telemetry format.

For each FGS, the fundamental data of interest for both astrometry and guiding are the photon counts from the four photomultiplier (PMT) tubes, the instantaneous values of the two Star Selector servo angles, and the 13 status and flags bits. The first two items are sampled every 25 msec (40 Hz), while the status flag bits are reported every 150 msec (6.67 Hz) for both telemetry format FN (default for astrometry observations) and for telemetry format HN (default for all other times). Additional FGS mnemonics present in the telemetry either can be reconstructed from those listed above or are of interest only to the system engineering staff.

When an FGS is operated as an astrometer, post observation processing performed at STScI builds the astrometry data products by extracting the PMT data, Star Selector position angles, and FGS status and flags bits for all 3 FGSs from the engineering telemetry. This processor accesses the Mission Support Schedule (MSS) for additional information needed to populate keywords in header files that facilitate the proper identification and interpretation of the associated data files. These products are similar to the GEIS format files produced for WFPC2 and the legacy science instruments (see Chapter 2 for more on GEIS file format).

Before November 1997, generation of the astrometry data products was the responsibility of Astrometry and Engineering Data Processing system (AEDP) based at the Goddard Space Flight Center. However, in early 1998, the STScI Astrometry Pipeline, part of STScI's Observatory Management System (OMS) became operational, and the use of AEDP was discontinued for FGS astrometry data. As of the writing of this document, OMS has been incorporated into part of the OPUS telemetry processing system at STScI.

Although containing the same information, the AEDP science products and OMS science products differ in format and number. The AEDP generated files with 17 groups of data for each FGS, with separate GEIS format header and data products for each FGS for each astrometry observation. OMS products consist of a single FITS format product per FGS per astrometry observation with only 7 groups of data (the remaining 10 groups were not useful for astrometric observations). Each OMS FITS product contains both the header and data information previously contained in the GEIS format products. Specifically, each astrometry FITS file contains a primary header, a primary binary data array containing telemetry data specific to a particular FGS, an ASCII table extension header, and an ASCII table containing summary information about the primary telemetry data array.

Each FGS astrometry observation generates header and data files (`.a*h/.a*d`) for all three FGSs whenever any one FGS is used as an astrometer. The contents of the data files for the guiding FGSs record the photometry and positions of the two guide stars over the same interval of time as that covered in the products for the astrometry FGS. The contents of the header files contain both information common to all FGSs and information specific to the FGS associated with that file, such as the values assigned to uplinked control parameters.

2.1.1 File Description

When an FGS is operated as a science instrument, the four PMT, two Star Selector Servo position angles, and thirteen status flags are extracted from the engineering telemetry. The data are recorded in GEIS files and are grouped by type; groups 1 through 4 contain PMT data, groups 5 and 6 contain the position angle of Star Selectors A and B respectively, and group 7 contains the thirteen status flags. There will be three GEIS data files, one per FGS, each containing 7 groups of data.

Each individual FGS astrometry observation produces one GEIS header and data file pair for each of the three FGSs. A typical FGS Position Mode observing sequence or *visit* consists of an HST orbit filled with observations of several stars, usually the science target and a few reference stars. Therefore, each visit will yield a number of GEIS file sets for three FGSs, each set corresponding to an observation of an individual star. These file sets contain all the FGS tracking and photometry data from the time interval when the specific observation was made.

The rootnames of FGS data sets adhere to the IPPPSSOOT convention described in Chapter 2 in the *"Introduction to HST Data Analysis"*. The first letter is always an F, identifying the file as FGS data, and the last letter is an M, indicating that the data were merged from real time and tape recorded telemetry (using which ever source was of superior quality). Here, 'PPP' and 'SS' correspond to the HST program ID and visit ID respectively, while 'OO' corresponds to the exposure number (as specified in the HST Phase 2 proposal for the program). For example, a set of FGS observations during a hypothetical visit would have the rootnames `f42n0201m`, `f42n0202m`, `f42n0203m`, `f42n0204m`, and `f42n0205m`.

For each observation, there should be seven total files: one header-data pair for each FGS, and one *.dmh file containing scheduling and support data relevant to the observation. Note there is no data file associated with a *.dmh file. The complete list of files associated with an observation are given in Table 2.1.

Table 2.1: GEIS Files in an FGS Dataset

File Name	Contents
fpppss01m.a1h	Header file, FGS1, exposure 1
fpppss01m.a1d	Data file, FGS1
fpppss01m.a2h	Header file, FGS 2, exposure 1
fpppss01m.a2d	Data file, FGS 2, exposure 1
fpppss01m.a3h	Header file, FGS 3, exposure 1
fpppss01m.a3d	Data file, FGS 3, exposure 1
fpppss01m_cvt.dmh	Support schedule for observation 01

In the example given above, if FGS1r is the astrometer and measures the position of a star in a Position Mode exposure of id `f42n0201m`. The files `f42n0201m.a1h` and `f42n0201m.a1d` contain the astrometry data. The guide star data gathered during this astrometry observation are recorded into files `f42n0201m.a2h`, `f42n0201m.a2d` and `f42n0201m.a3h`, `f42n0201m.a3d` for FGS2 and FGS3 respectively.

2.1.2 Group Structure and Group Contents

Each data file contains the same number of data groups (7) and each group is of the same size, having the same number of samples. The duration of the observation and the rate of the most frequently read out mnemonic determine the sizes of the groups for a particular observation. For example, if an observation spans 100 seconds, then each data group will have:

$$100 \text{ sec} * 40 \text{ Hz} = 4000 \text{ samples},$$

governed by the 40 Hz sampling of the photo-multiplier tubes (PMTs) and the Star Selector A and B positions. Unlike the other six groups, the flags/status bits group is sampled every 150 msec (6.67 Hz). In this situation, valid data are packed into the beginning 1/6 of the group, with the remaining 5/6 of the group padded with fill data. Table 2.2 lists the details of the seven FGS groups available.:

Table 2.2: Groups in FGS GEIS Files

Group	Group Mnemonic	Contents	Sample Period	Sample Frequency
1	PMTXA	Photon counts, channel A, *x*-axis	25 msec	40 Hz
2	PMTXB	Photon counts, channel B, *x*-axis	25 msec	40 Hz
3	PMTYA	Photon counts, channel A, *y*-axis	25 msec	40 Hz
4	PMTYB	Photon counts, channel B, *y*-axis	25 msec	40 Hz
5	SSENCA	Star selector A encoder position	25 msec	40 Hz
6	SSENCB	Star selector B encoder position	25 msec	40 Hz
7	FLAGS/STATUS BITS	Indicates specific FGS activity	150 msec	6.67 Hz

The first four groups contain the photometry data for the 5" x 5" patch of sky observed by the FGS. If the FGS is guiding and tracking its guide star, then it registers the photon counts from the guide star. If the FGS is operating as an astrometer, there will be an astrometric target in its instantaneous field of view (IFOV) only after the IFOV has slewed to the target's position and the FGS has successfully acquired the star. While the slew is underway, the FGS records the sky background and serendipitous field stars. These background data are used in the data reduction pipeline.

Table 2.3: Status/Flag Bits

SSM	SR	CT	FL	DV	SP	Action
ON						Slewing the IFOV to star’s location
	ON					Begin spiral search for star
	ON				ON	Spiral search located star
		ON			ON	Star detected, begin Coarse Tracking
		ON		ON	ON	Coarse Track Acquisition successful
			ON		ON	Attempt FineLock acquisition
			ON	ON	ON	Tracking star in FineLock

The PCS status flag was added to the astrometry products in November 2000. It shows a value of 1 (ON) when HST is being guided under control of at least one FGS (plus gyros). A value of 0 (OFF) indicates that HST’s pointing is not maintained by guide stars.

The fifth and sixth groups record the position (to 0.6 mas) of the IFOV in the FGS's full Field of View (FOV), and therefore in the HST focal plane. If the FGS is guiding, the measured position of the guide star is accessed by the Pointing Control System so that the spacecraft's pointing can be maintained or corrected. These guide star data are used in the pipeline processing discussed in Chapter 3.

The flags/status bits group records the value of the thirteen flags and indicators, each of which is a single bit which is either set to 1(ON) or set to 0 (OFF). If the FGS is guiding and is tracking its guide star in FineLock, then the FineLock, DataValid, Star Presence, and PCS flags will be set to 1 (ON) and all others set to 0 (OFF). The astrometer FGS will display a sequence of flags/status bits settings which reflects the current activity of the FGS (but its PCS flag will also be set). If the FGS is operating in Position Mode, then the sequence of flag/status bits shown in Table 2.3 occurs for a successful acquisition.

The flags and status bits have the following meanings when set to 1:

- ***SSM***: FGS under control of the SSM (486) computer.
- ***SR***: FGS in autonomous (FGE) control, performing a spiral search.
- ***CT***: FGS in CoarseTrack mode.
- ***FL***: FGS in FineLock mode, if DV=0, then in WalkDown phase, if DV=1, then tracking in FineLock.
- ***DV***: CoarseTrack or FineLock was successful.
- ***SP***: Star presence, photon counts summed from all four PMTs fell within the commanded range (LOCOUNT < PMTSUM < HICOUNT).
- ***PCS:*** The pointing control system uses data from the guiding FGSs to control the spacecraft's pointing. This can be set to 0 when HST is being guided on gyros only, such as during a re-centering event or after loss of lock on guide stars.

When determining the position of an astrometric object observed in FineLock, the data of interest to the astrometry pipeline are:

- The slew to the star's expected location (provides background data).
- The WalkDown to FineLock (provides critical PMT data to better locate interferometric null) and to support FGS photometry.
- The FineLock tracking of the object (provides the FGS's measured location of star in focal plane).

More details on interpreting and making use of the FGS data are provided in Chapter 3 and Chapter 4.

2.1.3 FITS Header Keywords

The GEIS header files for FGS data contain keywords that will help to interpret the data files. The most important keywords contained in the header files are:

NAXIS	dimensions in the data file (always=1
NAXIS1	# of samples (or pixels) in each data group
GCOUNT	# of groups in the data file (7 after 11/9)
BITPIX	bits/pixel (=32 for FGS)
DATATYPE	datatype (= 32 bit integer for FGS)
FGSID	identifies astrometer FGS
FGSNO	identifies FGS associated with this header file
PASTMODE	observing mode, POSITION or TRANSFER
AUTOS	actual start time of observation (UT)
PUTOS	predicted start time of the observation (UT)
PRAV1	predicted right ascension of HST's V1 axis
PDECV1	predicted declination of HST's V1 axis
PROLLV3	predicted roll orientation of HST
PRATGT	predicted right ascension of target
PDECTGT	predicted declination of target
TARGNAME	proposer’s target name
TARGETID	target identification
PX_POS	HST state vector (position and velocity) at
PY_POS	beginning of observation (at PUTOS)
PZ_POS	
PX_VEL	
PY_VEL	
PZ_VEL	
FGSREFV2	FGS aperture reference V2 position (asec)
FGSREFV3	FGS aperture reference V3 position (asec)
FGS_PAV3	FGS aperture position angle of V3-axis (deg)
FGSOFFV2	V2 offset from the FGS aper ref position (asec)
FGSOFFV3	V3 offset from the FGS aper ref position (asec)
CAST_FLT	filter used for the observation.

The values assigned to these keywords are used in the calibration pipeline processing discussed in Chapter 3. To print an entire header to the screen, you can use the IRAF **imheader** task as in the following example:

```
cl> imheader f42n0201m.a1h long+ | page
```

2.2 Relationship to Phase II Proposal

Associated with each astrometry observation is the Support Schedule file, with file names `*.dmh`. This product is generated at STScI by the Science Planning and Support System (SPSS). It is a GEIS header file with no associated data file. Contained within are keywords and values which repeat some of the information in the FGS header files, such as the HST state vector. More importantly, the contents of this file can be used to map a specific FGS observation to the proposal's Phase II exposure log sheet. The proposal ID, PI identifier, target name, proposal type, proposal title, and exposure logsheet line are among the entries. The only keyword used by the astrometry pipeline is the value of DGESTAR to determine which guiding FGS was tracking the dominant guide star. Observers should review the contents of both the `*.a1h` and `*.dmh` files, which can be done using **imheader** as above.

2.3 Jitter Files

Since 20 October 1994, STScI's Observatory Monitoring System (OMS) has been populating the STScI data archives with the Observation Logs. These logs are of secondary use for the processing of FGS astrometry data because the guide star data are directly available to the astrometry pipeline. The item of interest in the `*_jif.fits` header is the OMS computed HST roll angle. Recall that the `.a*h` header files contain the predicted roll angle. The details of how the telescope is pointed on the sky reveal that the roll angle is not set by the pointing control system using FGS data, rather it is set using less accurate fixed head star tracker data. Whatever roll angle results is then maintained by the roll guide star. OMS uses the FGS data, guide star RA, Dec, and HST/FGS alignment matrices to compute the actual roll of the telescope, which can differ from the predicted roll by as much as 0.4 degrees. The more accurate OMS roll angle is best used for the final computation of astrometric parallaxes and binary star position angles.

More information on the accuracies of the roll calculation, and on general HST pointing issues, are discussed in the Observatory Support pages at:

http://www.stsci.edu/instruments/observatory/

2.4 SMS Support Data

The FGS Field of View is large (~ 60 square arcsec) and therefore sensitive to the effects of differential velocity aberration (DVA), the field-dependent shifts of star positions owing to the telescope's component of motion in the direction it is pointing. It is possible to maintain the pointing of HST so that the effects of DVA can be compensated for, but only at one place in the focal plane—the *alignment point*. Because typical FGS astrometry programs measure the relative positions of stars spread widely throughout the pickle, there can be at most only one star that will not suffer from DVA. Although this effect is potentially large, up to 20 mas, it is simple to correct for this aberration. The correction algorithm requires HST's V1 pointing, V3 roll, and state vector, all obtained from the `*.a*h` header files, plus the specification (in V2,V3) of the alignment point. For observations made before September 2001, the alignment point data for all FGS observations are retrieved from the reference library maintained by the STScI FGS staff. These data originate from the Science Mission Schedule (SMS) and are automatically extracted and entered into this library. The astrometry pipeline accesses this library when the differential velocity aberration connection is made. For observation executing after September 2001, the alignment point is specified by the FGSOFFV2 and FGSOFFV3 keywords in the *.a1h files. The FGS calibration pipeline extracts the values of these keywords for the computation of the differential velocity aberration correction.

CHAPTER 3:

Calibration

In this chapter. . .

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3.1 Preparing FGS Data for Processing

FGS data from the HST Data Archive are stored and distributed in archival "waiver" FITS format, and must be converted back to the machine dependent GEIS format before calibration processing (please see Chapter 2 of the *Introduction to the HST Data Handbooks* for more details on FITS and GEIS file formats). It is important to use the ***strfits*** task in ***stsdas.fitsio*** (or in ***tables.fitsio***) to convert FGS data from FTIS to GEIS formats, as the pipeline which extracts FGS science data from the telemetry stream employs a special convention for mapping GEIS files to FITS format. More detail on using **strfits** is presented in Section 2.3.1 of the *Introduction to the HST Data Handbooks*.

The **strfits** parameter file (`fiostrfis.par`) specific to FGS GEIS data is displayed below. Note that the scale parameter must be set to "no".

```
Image Reduction and Analysis Facility
PACKAGE = fitsio
   TASK = strfits
fits_fil=                *.fits  FITS data source
file_lis=                 1-999  File list
iraf_fil=                        IRAF filename
(templat=                 none)  template filename
(long_he=                   no)  Print FITS header cards?
(short_h=                  yes)  Print short header?
(datatyp=              default)  IRAF data type
(blank  =                   0.)  Blank value
(scale  =                   no)  Scale the data?
(xdimtog=                  yes)  Transform xdim FITS to multigroup?
(oldiraf=              yes) Use old IRAF name in place of iraf_file?
(force  =                  yes)  Force conversion from fits?
(offset =                    0)  Tape file offset
(Version=          23-Mar-1998)  Strfits version
(mode   =                   ql)
```

Two separate IRAF/STSDAS tasks are involved in the reduction and calibration of FGS science data. The first, ***calfgsa*** (also known as the "pipeline") takes as input the GEIS files generated by ***strfits***. The second, ***calfgsb***, processes the output products of **calfgsa**. Note that ***calfgsa*** is used both for Transfer Mode and Position Mode data, while ***calfgsb is only useful on Position Mode data.***

Before executing ***calfgsa***, all FGS data from an HST visit should reside in the same directory. This includes the six GEIS files for the three FGSs `(the *.aih and *.aid files, where i = 1, 2, or 3)` and the support schedule file (the `*.dmh file`). The location of the reference files (available from the FGS Web site) can either be entered in response to prompts from ***calfgsa*** or specified in the *calfgs.par* parameter file.

As an example, if an FGS visit to be analyzed comprises five individual astrometry observations, then the local directory where **calfgsa** is executed should contain the files shown in Table 3.1, where PPP and SS are place holders for the actual program_ID and visit ID, respectively. For this example, there should be a total of 35 files (5 observations, each with 7 files).

Table 3.1: GEIS Files in an FGS Dataset

File Name	Contents
fpppss01m.a1h	Header file, FGS1, exposure 1
fpppss01m.a1d	Data file, FGS1
fpppss01m.a2h	Header file, FGS 2, exposure 1
fpppss01m.a2d	Data file, FGS 2, exposure 1
fpppss01m.a3h	Header file, FGS 3, exposure 1
pppss01m.a3d	Data file, FGS 3, exposure 1
fpppss01m_cvt.dmh	Support schedule for observation 01
...	...
fpppss05m.a1h	Header file for FGS 1, exposure 5
fpppss05m.a1d	Data file for FGS 1, exposure 5
fpppss05m.a2h	Header file for FGS 2, exposure 5
fpppss05m.a2d	Data file for FGS 2, exposure 5
fpppss05m.a3h	Header file for FGS 3, exposure 5
fpppss05m.a3d	Data file for FGS 3, exposure 5
fpppss05m_cvt.dmh	Support schedule for observation 05

When this simple set up is complete, calfgsa can be executed.

3.2 Initial Data Processing - *calfgsa*

The STSDAS task ***calfgsa*** (in **hst_calib.calfgs**) accomplishes several general tasks, regardless of whether the observations were gathered in Position Mode or Transfer Mode. The pipeline:

1. Reads the seven GEIS files belonging to each individual observation.
2. Identifies the FGS used for the observations and its observing mode.
3. Identifies any potentially missing files.
4. Determines the status of the guiding FGSs, checking whether zero, one, or two FGSs were actively maintaining the pointing of the telescope and whether they were guiding in CoarseTrack or FineLock.
5. Inspects the flags/status bits to determine whether the astrometry observation succeeded or failed, and in the case of a failure, to identify the reason for the failure.
6. Prepares output files with keywords whose values are either extracted from the input header files or computed from contents of the data files.

7. Assesses the data quality of successful observations, masking outliers, garbled telemetry, and telemetry dropouts. (Outliers are data that do not appear to be garbled but make no sense when viewed in the context of neighboring data points.)

3.2.1 calfgsa and Transfer Mode Data

The data acquired during a Transfer Mode observation include the initial target acquisition sequence in addition to the individual target scans. (see the *FGS Instrument Handbook* for details on target acquisition). Processing Transfer Mode data with ***calfgsa*** is limited to locating each scan in the astrometer's data file, editing out bad data (due to telemetry drop-outs, etc.), and determining the median position and standard deviations of guide star positions in the guiding FGSs during each Transfer Mode scan.

The pipeline generates three ASCII files for every scan, one for each FGS. Each file contains the 40 Hz raw star selector A and B encoder angles, used to derive the x- and y-position of the FGS's Instantaneous Field of View (IFOV) at all times along the scan, and the photon counts per 25msec in each of the four photomultiplier tubes (PMTs). The guide star data, which spans the entire Transfer Mode observation, are provided for (optional) de-jittering of the astrometer's IFOV during post-pipeline processing. Each of these files begins with a small header containing keywords whose values pertain globally to the observation or specifically to the scan, such as the observed filter or the universal time (UT) at the start of the scan. The HST state vector is also included in the header.

The **calfgsa** task does not carry out further processing of Transfer Mode data. This is most appropriately left to the programs and tasks discussed in Chapter 4.

An example of a session using ***calfgsa*** to process Transfer Mode data from the FGS calibration program 8834 (data set `f6b00201m`) is shown below. User input is highlighted as bold.

```
te> calfgsa
Input observation (or list) (@obs.list): f6b00201m
Reference directory
(/data/phoenix4/testcalfgs/refdir/fgsa_ref/):<ret>
Earth ephemeris (/data/phoenix4/testcalfgs/de200.fits): <ret>
Log file (log): <ret>
 processing obs: .......... -> F6B00201M
 observing mode ........... -> TRANSFER
 number of samples ........ ->  35360
 filter ................... -> F583W
 target magnitude ......... ->  9.70
 target_id ................ -> 8834_1
 obs date ................. -> 2000 356 08:10:17
 telemetry format ......... -> FN


 target_name:latcol-a


 writing data files for scan# :   1
 writing data files for scan# :   2
 writing data files for scan# :   3
 writing data files for scan# :   4
 writing data files for scan# :   5
 writing data files for scan# :   6
 writing data files for scan# :   7
 writing data files for scan# :   8
 writing data files for scan# :   9
 writing data files for scan# :  10
 writing data files for scan# :  11
 writing data files for scan# :  12
 writing data files for scan# :  13
 writing data files for scan# :  14
 writing data files for scan# :  15
```

In this example, ***calfgsa*** outputs 45 files (3 FGSs x 15 scans), each containing the 40 Hz star selector angles and PMT photon counts from each FGS for a specific scan. These files will follow the naming convention *rootname.isn, where* "rootname" is the unique exposure ID (in this example, f6b00201m), *i* = 1,2,3 identifies the FGS, and *n* identifies the number of the Transfer Mode scan. Thus the file f6b00201m.1s13 contains data from FGS1 for scan #13.

An excerpt from a **calfgsa** output file for Transfer Mode data is shown below.

```
OBS ID .................... -> F6B00201M
-------------------------------------------------------
        HST STATE VECTOR at "OBS date"
  OBS date .................................... -> 2000 356:08:14:05.574
  X_POS (km) .................................. ->  4195.629
  Y_POS (km) .................................. ->  4741.467
  Z_POS (km) .................................. -> -2901.636
  X_VEL (km/sec) .............................. ->  -4.945
  Y_VEL (km/sec) .............................. ->   5.457
  Z_VEL (km/sec) .............................. ->   1.746
-------------------------------------------------------
  observing mode .............................. -> TRANSFER
  FGS ID of this data file .................... -> 1
  astrometer FGS .............................. -> 1
  target_id ................................... -> 8834_1
  magnitude ................................... ->   9.70
  filter ...................................... -> F583W
  scan ID ..................................... ->   3
  start_pixel ................................. ->   8000
  end_pixel ................................... ->  10286
  total samples ............................... ->   2287
  scan_length ................................. ->  2.538 (arc seconds)
  median x position ........................... ->   -3.3134
  median y position ........................... ->  726.1536
  median x position, diff velab corrected ..... ->   -3.3136
  median y position, diff velab corrected ..... ->  726.1535
  standard deviation of x ..................... ->   0.6118
  standard deviation of y ..................... ->   0.6126
  total number of scans ....................... ->  15

column 1   -> RAW star selector theta_A
column 2   -> RAW star selector theta_B
column 3   -> PMTXA counts / 25 msec
column 4   -> PMTXB counts / 25 msec
column 5   -> PMTYA counts / 25 msec
column 6   -> PMTYB counts / 25 msec
column 7   -> FGS flags/status

   SSA       SSB      PMTXA   PMTXB   PMTYA   PMTYB     FLAGS
  335827    707821    1308    1194    1151    1255    DV,FL,SP
  335826    707820    1312    1153    1144    1352    DV,FL,SP
  335827    707821    1296    1211    1108    1316    DV,FL,SP
  335826    707821    1324    1153    1141    1258    DV,FL,SP
  335827    707820    1307    1211    1181    1306    DV,FL,SP
  335826    707817    1313    1141    1083    1319    DV,FL,SP
  335829    707816    1383    1140    1163    1297    DV,FL,SP
  335828    707817    1295    1205    1131    1338    DV,FL,SP
```

calfgsa also produces an ASCII file named "*rootname.tab*" (e.g., f6b00201m.tab) which contains information pertinent to the entire exposure, not just individual scans. An example of a (Position Mode) *.tab file is shown in Section 3.4.

3.2.2 calfgsa and Position Mode

Position Mode observations with the FGS are primarily used for wide angle (>10") astrometric studies, such as parallax determinations and/or the measurement of a star's reflex motion in response to the gravitational influence from a bound companion. These programs employ an observing technique where the target star and several nearby reference stars (also in the FGS Field of View) are observed in a sequential fashion as many times as possible during the visibility period of HST's orbit (see the *FGS Instrument Handbook* for more details about Position Mode observing). Typically, on the order of twenty individual exposures are obtained in a Position Mode visit.

Two pipeline processors, first *calfgsa* and then ***calfgsb***, are used to process the Position Mode data. For each observation, ***calfgsa*** sequentially ingests the raw GEIS file and inspects the flags and status bits to determine if the observation was successful. If the observation succeeded, **calfgsa** extracts the 40 Hz star selector encoder angles and PMT counts, masks out bad data, and computes the median (x, y) centroid of each star in FGS detector-space during the FineLock/DataValid (FL/DV) interval (when the FGS was tracking the star's interferometric fringes). The average PMT counts during the FL/DV interval are determined. The same quantities for the guiding FGSs are computed over the identical time interval.

The most convenient way to process a visits's worth of data with ***calfgsa*** is to input a file which contains the rootnames of the exposures contained within the visit.

An example using **calfgsa** to process the Position Mode data from the FGS calibration program 8897 (monitoring the scale and distortions of the FGS1r Field of View) is given below. In this example, the exposures have rootnames f6iy0301m, f6iy0302m, f6iy0303m, ..., f6iy030zm, a total of 45 exposures. These rootnames are listed, one entry per line, in the user-generated file `obs.list`. User input is noted in bold.

```
cl> calfgs
      calfgsa  calfgsb
te> calfgsa
Input file (or list) (f6b00201m): @obs.list
Reference directory (refdir/fgsa_ref/):
Earth ephemeris (refdir/de200.fits):
Log file (log):

 processing obs: .......... -> F6IY0301M
 observing mode ........... -> POSITION
 number of samples ........ ->   3960
 filter ................... -> F583W
 target magnitude ......... ->  9.47
 target_id ................ -> 8897_83
 obs date ................. -> 2001 354 11:03:34
 telemetry format ......... -> FN

 target_name: M401

 processing obs: .......... -> F6IY0302M
 observing mode ........... -> POSITION
 number of samples ........ ->   2996
 filter ................... -> F583W
 target magnitude ......... -> 10.95
 target_id ................ -> 8897_56
 obs date ................. -> 2001 354 11:05:14
 telemetry format ......... -> FN

 target_name: M297

 processing obs: .......... -> F6IY0303M
 observing mode ........... -> POSITION
 number of samples ........ ->   2838
 filter ................... -> F583W
 target magnitude ......... -> 13.25
 target_id ................ -> 8897_141
 obs date ................. -> 2001 354 11:06:30
 telemetry format ......... -> FN

 target_name: M252
```

While processing the data sets associated with each exposure, ***calfgsa*** produces the output *.tab files, such as `f6iy0302m.tab`. These contain the median (x, y) FGS detector-space centroid of the star's position in that exposure, along with other data needed for further processing by ***calfgsb***. The content of f6iy0302m.tab is available as an example from the FGS Web site.

These contain the median (x, y) FGS detector-space centroid of the star's position in that exposure, along with other data needed for further processing by **calfgsb**. As an example, the content of `f6iy0302m.tab` is shown in "calfgsa Output: The *.tab File" on page 38.

3.3 calfgsa Processing Overview

The flowcharts given by Figure 3.1 and by Figure 3.2 provide a graphical overview of the processing steps involved in running the **calfgsa** task.

Figure 3.1: CALFGSA Common Processing Tasks

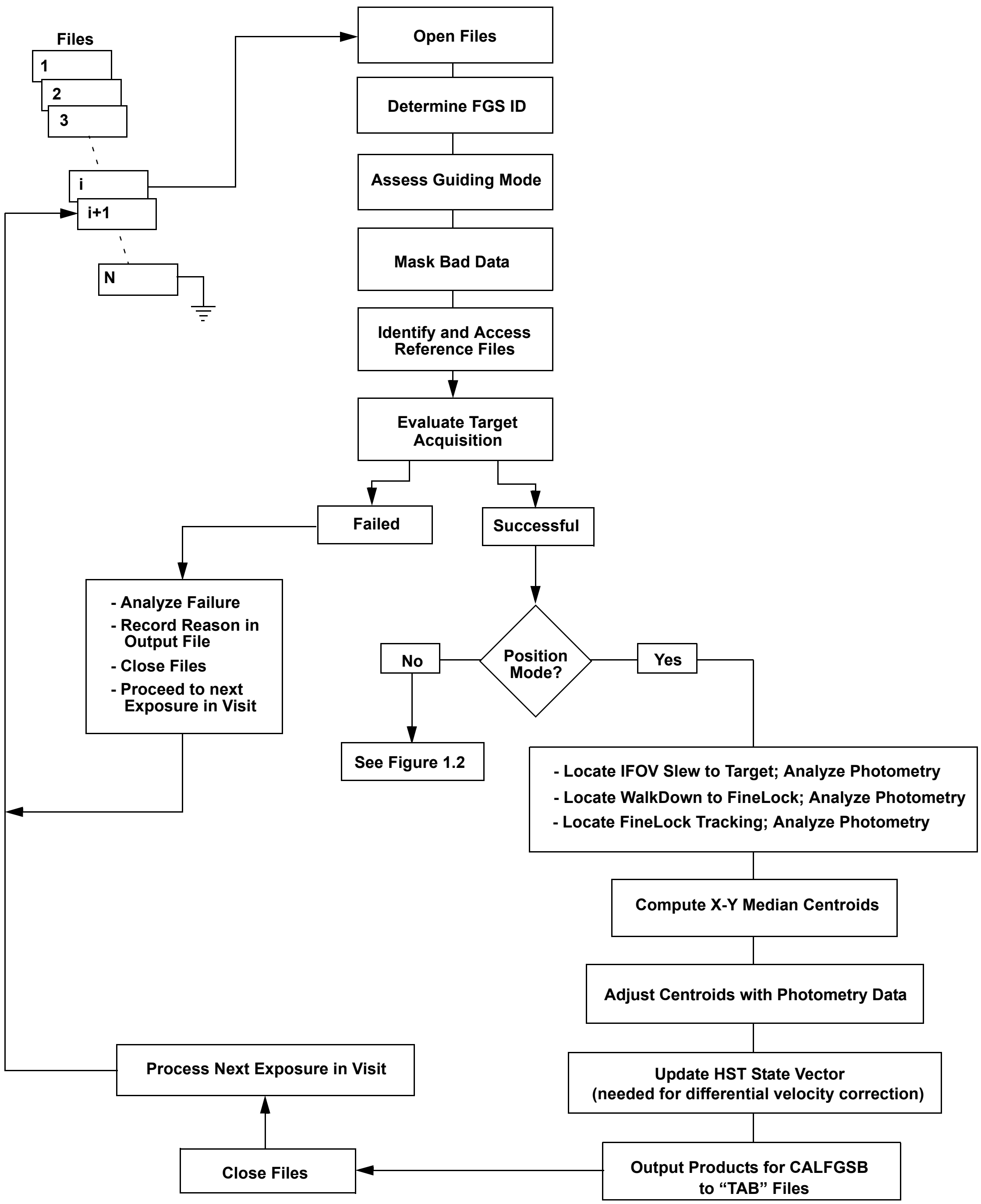
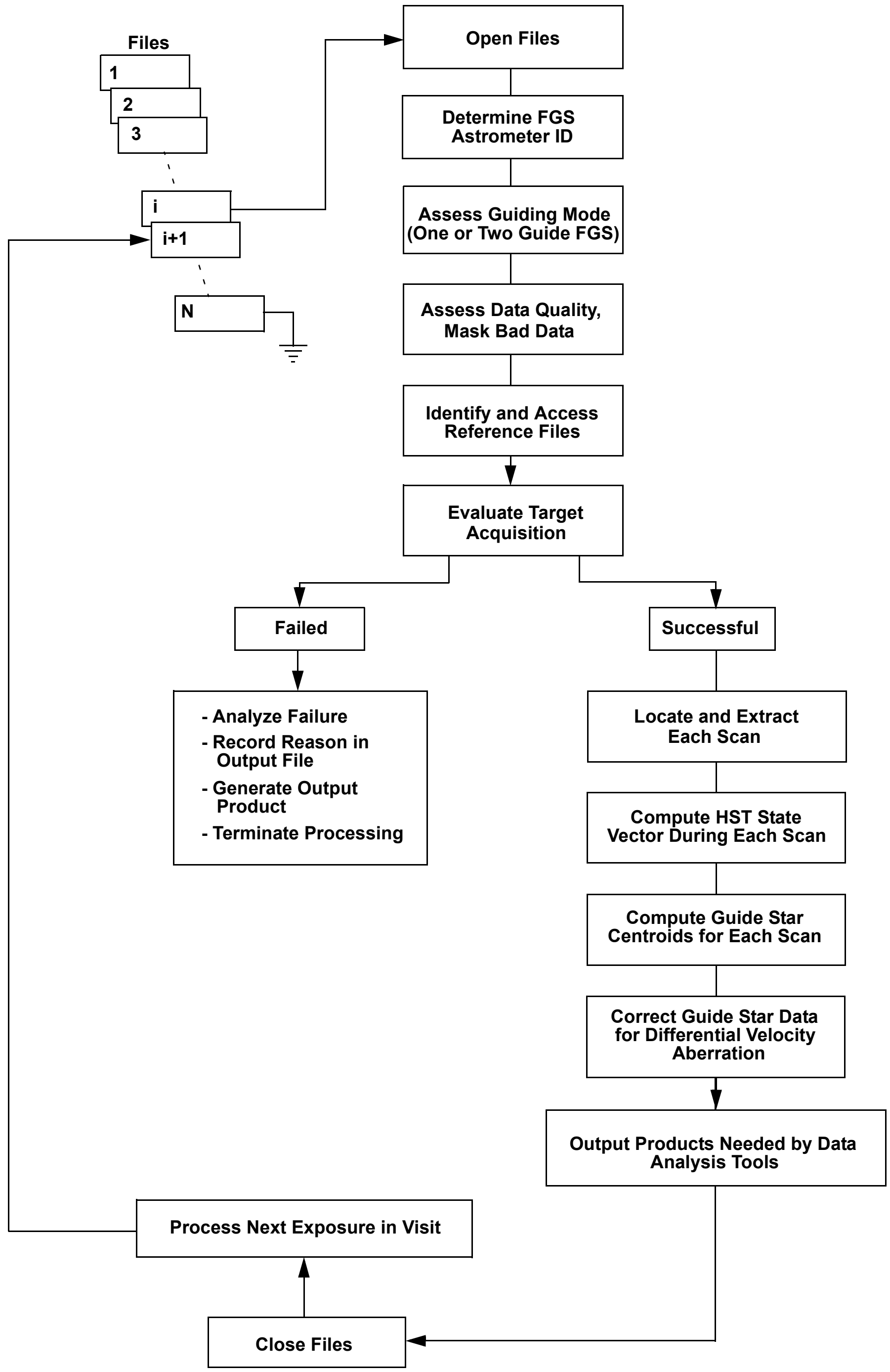


Figure 3.2: CALFGSA Transfer Mode Processing Tasks



3.4 *calfgsb* and Position Mode

While ***calfgsa*** processes each single observation in a stand-alone fashion, ignoring other observations belonging to the same HST visit. ***calfgsb*** processes an entire visit's worth of data as a coherent set, allowing an astrometric "plate" to be produced by tools such as **gaussfit**.

In a typical Position Mode observing program the astrometer FGS sequentially observes *several* stars distributed about the FOV. Any temporal variability in telescope pointing will contaminate the measured relative positions of these targets. FGS astrometry is sensitive to HST body *jitter* and FGS *drift*. The jitter can be eliminated using the guide star data, whereas the drift is removed by applying a drift model derived from *check star* data. A *check star* is a star that is observed multiple times during the visit. Typically the observing strategy should involve at *least two* check stars observed a *minimum* of three times each (see the *FGS Instrument Handbook* for more details on observing strategies).

The calibrations carried out by **calfgsb** to correct a star's observed (x, y) position are, in order, for

- geometric distortions (the optical field angle distortion, or OFAD, correction)
- differential velocity aberration
- space craft jitter
- drift of FGS field of view.

The data needed to carry out these calibrations are contained in the observation's *.tab file (provided by ***calfgsa***) and/or in the ***calfgsb*** reference library. The ***calfgsb*** reference library can be down loaded from the STScI FGS Web site.

3.4.1 preparing to use *calfgsb*

calfgsb has explicit, well defined expectations of directory structures and their contents that are to be in place before **calfgsb** is activated. Residing in the directory from which the **calfgsb** command is executed is the "day.list" file, which contains a list (one entry per row) of the subdirectories containing (**calfgsa**) astrometry data from various epochs. For example, if the "day.list" file contains

```
v01
v02
v03
```

then the sub-directories v01, v02, v03 must also be present. Note that the "/" is not included in the sub-directory specification in day.list, i.e., "v01" is specified, not "v01/". A directory called "pmtdata/", containing the *.tab files generated by **calfgsa, is required** within each of these sub-directories**.**

Note that only *.tab files from Position mode observations should be present. **calfgsb** does not and cannot process Transfer mode data. If Transfer mode *.tab files are present an error results which aborts **calfgsb**.

calfgsb processes each visit's data (each entry in the "day.list" file) independently of the other visits. There is a single exception to this claim. Ultimately, the data from various epochs must be combined in order to achieve one's science goals (for example, to determine an object's parallax). The analysis tool **gaussfit**, discussed in detail in Chapter 5, ingests the output products of **calfgsb** to derive the desired asrtrometry. Each visit is tracked by its "set" number. For convenience, **calfgsb** increments the value of the set number it assigns to each visit in the "day.list" file. Note that calfgsb prompts the user for the starting value of the set number. It is not *necessary* to process more than one visit's worth of data at a time - it's just more convenient to do so when opportunity arises.

3.4.2 executing *calfgsb*

To best way to understand how to execute **calfgsb** is by working through an example. Suppose there are six visits of HST astrometry data to be processed by **calfgsb** with the objective of determining the parallax of an astrophysically interesting star. The visits were obtained at times of maximum parallax factors (0, 6, and 12 month intervals), with two HST visits expended at each epoch. The data (*.tab files) reside in the "pmtdata/" directories of the

```
v01 v02 v03 v04 v05 v06
```

subdirectories, where `v01`, `v02`, etc. correspond to the visit number of the observed data.

The user-created "day.list" file lists the v01 through v06 directories, and should reside in the directory above these sub-directories. From this directory, simply type "**calfgsb**" from IRAF/STSDAS to execute **calfgsb**. The following is a screen snap shot initiating such a session. User input is in **bold**. Entering **<ret>** causes the default value for the given prompt, shown within the parentheses, to be used in the processing.

```
te> calfgsb
    Name of file containing Day subdirectories (day.list): <ret>
    Constants to be used: 93 94 or 95 (95): <ret>
    Constants set 95 will be used

    The pipe executable's env file is
    95envinterp

    Object name (no embedded whitespace) (): ugem
    Starting plate number: unity is typical (1): <ret>
    Root directory for calfgsb ref files (refdir/fgsb_ref/): <ret>
    Astrometer number: 1, 2, or 3 (1): <ret>
```

After entering responses to these prompts **calfgsb** automatically processes all the data specified in the "day.list" file. A series of output is sent to the screen but is also captured in a *.log file. A new directory, "pipedir/" is created parallel to the "pmtdata/" directory. All **calfgsb** products from the processing of a particular visit are placed within the "pipedir/" subdirectory. The rootnames of the output files will, in the example shown above, have "ugem" embedded within. The most important output file will be "ugem_v01_ast" (in "v01/pipedir"). It is this file that is to be edited (as described in Chapter 4 of this document) in preparation for input by gaussfit when, in this example, this visit's data is to be combined with data from the other five visits for a parallax determination of the target star (U Geminorum).

3.5 Position Mode Processing Overview

This section contains a discussion of the detailed corrections that are applied to Position mode FGS astrometry data by **calfgsa** and **calfgsb**. A flowchart is provided in Figure 3.3 to help illuminate data processing with **calfgsb** (please see the flowchart given by Figure 3.1 for an overview of **calfgsa** related processing of Position Mode data).

3.5.1 Processing Individual Observations

Position Mode pipeline processing for each individual observation in the visit executes the following steps:

1. Inspection of the flags/status bits to locate the data fields recording:
    - The slew of the IFOV to the target's location.
    - The WalkDown to FineLock.
    - The FineLock tracking (FineLock/DataValid) of the target.
2. Computing the centroid of the IFOV, taken to be the median of the instantaneous *(x, y)* positions during the FineLock/DataValid interval, in the astrometer as well as the guide star positions in the guiding FGSs. Standard deviations about these centroids are also computed.
3. Updating the HST state vector, specified in the header files for the beginning of the observation, so that it is accurate for the temporal midpoint of the FineLock/DataValid interval.
4. Gathering photon statistics on:
    - PMT background during the slew to the target.
    - PMT data taken during the Walkdown to FineLock (FL) while the IFOV was still far (>0.1") from interferometric null. (These data can be used to calculate SUM and DIFF values more accurately

than those computed at the start of the WalkDown, as they are based on up to 80 times more samples.)

- PMT data taken while FGS was in FL/DV. (These data are averaged to compute the points on the S-curves of both axes which the FGS's microprocessor determined to be the true interferometric null. These values should be approximately the same as the DIFF and SUM computed by the FGS's microprocessor at the start of the WalkDown).

5. Applying the DIFF and SUM corrections to both axes of only the astrometry data in order to locate the true interferometric null. This algorithm determines the slope of the fine error signal near interferometric null as a function of position in the pickle, using a library of reference S-curves, the target magnitude, making use of the background data computed above, and the difference in the photomultiplier averages computed during the WalkDown and the Fine-Lock/DataValid intervals. This correction tends to be small for bright stars ($V < 13.5$) but can be as large as 5 mas for faint ($V > 15$) stars.

6. Converting the raw telemetry encoder positions to instantaneous *(x, y)* detector coordinates using several parameters, such as the star selector lever arm lengths, and offset angles. The lever arm and offset angle are known to vary in time. They are monitored by an ongoing program called the Long Term Stability Monitor (LTSTAB) which executes multiple times a year. The values applied in the pipeline are determined by interpolation of the LTSTAB results.

7. Correcting the *(x, y)* centroids in the astrometer for Optical Field Angle Distortions (OFAD).

8. Correcting distortions in the astrometer arising from the pickoff mirror and aspheric mirror.

9. Removing differential velocity aberration from the *(x, y)* centroids using the updated HST state vector, a JPL Earth ephemeris, HST's V1 RA and DEC, the V3 roll, and the V2,V3 position of the alignment point. This correction is applied to both the astrometer FGS and the guide star FGSs.

The pipeline produces output files that log these corrections, the associated standard deviations about the centroids, and the photometry averages from the four PMTs. **calfgsa** performs the majority of these corrections. However, corrections 6 through 8 are re-done by **calfgsb** which uses the most up to date value of coefficients for the OFAD correction and the star selector angles to *(x, y)* conversion (contained in reference files not accessed by **calfgsa**).

At this point no further processing on the individual observations are possible. The next step is to combine the measurements of the individual targets to correct for Position Mode-mode jitter and FGS drift.

3.5.2 Visit level processing

The goal of this segment of the pipeline (within **calfgsb**) is to map all of the positional measurements of the individual targets onto a fixed but arbitrary coordinate system. It involves Position Mode *de-jittering* and application of the drift correction.

Position Mode De-jittering

The pipeline accounts for spacecraft jitter during the visit by establishing a fixed but arbitrary reference frame determined by the *(x, y)* centroids of the guide stars (within the guiding FGSs) from the first exposure in the observing sequence. The HST pointing control system uses the position of the dominant guide star to fix HST's translational position and that of the roll guide star to fix HST's orientation. The output products of the pipeline processing of the individual observations include the *(x, y)* centroids of the guide star positions evaluated over the same time interval as the astrometer centroids. During the course of the visit any change in the *(x, y)* centroids of the dominant guide star within its FGS is interpreted to be HST translational jitter and is removed from both the astrometer and the guide star maintaining HST roll. Next, any motion of the roll guide star with respect to the dominant guide star perpendicular to the line between them is interpreted as uncompensated roll of HST about the dominant guide star. The pipeline then removes this roll from the astrometry data. Typically the size of the de-jittering correction is less than a millisecond of arc when averaged over the visit but can be as large as 3–5 mas for any given observation (eg., when HST transits from orbital night to orbital day).

De-jittering is not performed at a 40 Hz rate because that would introduce noise into the dataset. Instead the time-averaged centroids of the guide stars are computed for the same time interval that the astrometer was in FineLock/DataValid. The positions of the guide stars in the first exposure, corrected for differential velocity aberration, define the reference frame for the remainder of the visit. So, for example, if the dominant guide star *(x, y)* centroids measured during the *N*th astrometry observation differed from those in the first observation by (*dx, dy*) = (1 mas,1 mas), then the appropriate conversion to *d*V2,*d*V3 is applied to the roll star and the astrometer's local *(x, y)* centroids. This procedure creates a fixed but arbitrary coordinate system for the entire visit.

Position Mode Drift Correction

After the FGS data have been de-jittered, there will remain an apparent motion of those astrometry targets which were observed more than once within the observing sequence. These check stars provide the data required for the drift correction, which assumes that the astrometer is a rigid body which both translates and rotates in the HST focal plane during the course of the visit and corrects the measured positions of the stars in the visit for contamination by this motion.

The time-tagged positions of the check stars are used to generate a model for this drift, and the time-tagged positions of all the stars in the visit are adjusted by application of the model. Three separate models can be applied:

- ***Linear***: Translation only, no rotation.
- ***Quadratic***: Translation only, no rotation.

- ***Linear and roll***: Translation and rotation.

The choice of model depends upon the number of check stars available and the number of times each is observed. Clearly if there is only one check star in the visit the rotation model cannot be applied. Also, if check stars are not observed frequently enough (three times or more), the quadratic models might not be reliable. The pipeline applies all three models, providing three sets of corrected centroids to the data. It is the responsibility of the user to decide which set is the best. The output of the fitting program includes fit residuals and χ^2. Inspecting these values is the best way to determine which model yielded the best result.

The size of the drift correction is typically 2 to 6 mas under two-FGS guidance. The amount of drift appears to be related to the intensity of the bright Earth projected down the V1 boresight during target occultations. This intensity, and hence check star drift (generally), is highest for targets in HST's orbital plane and lowest for those at high inclination.

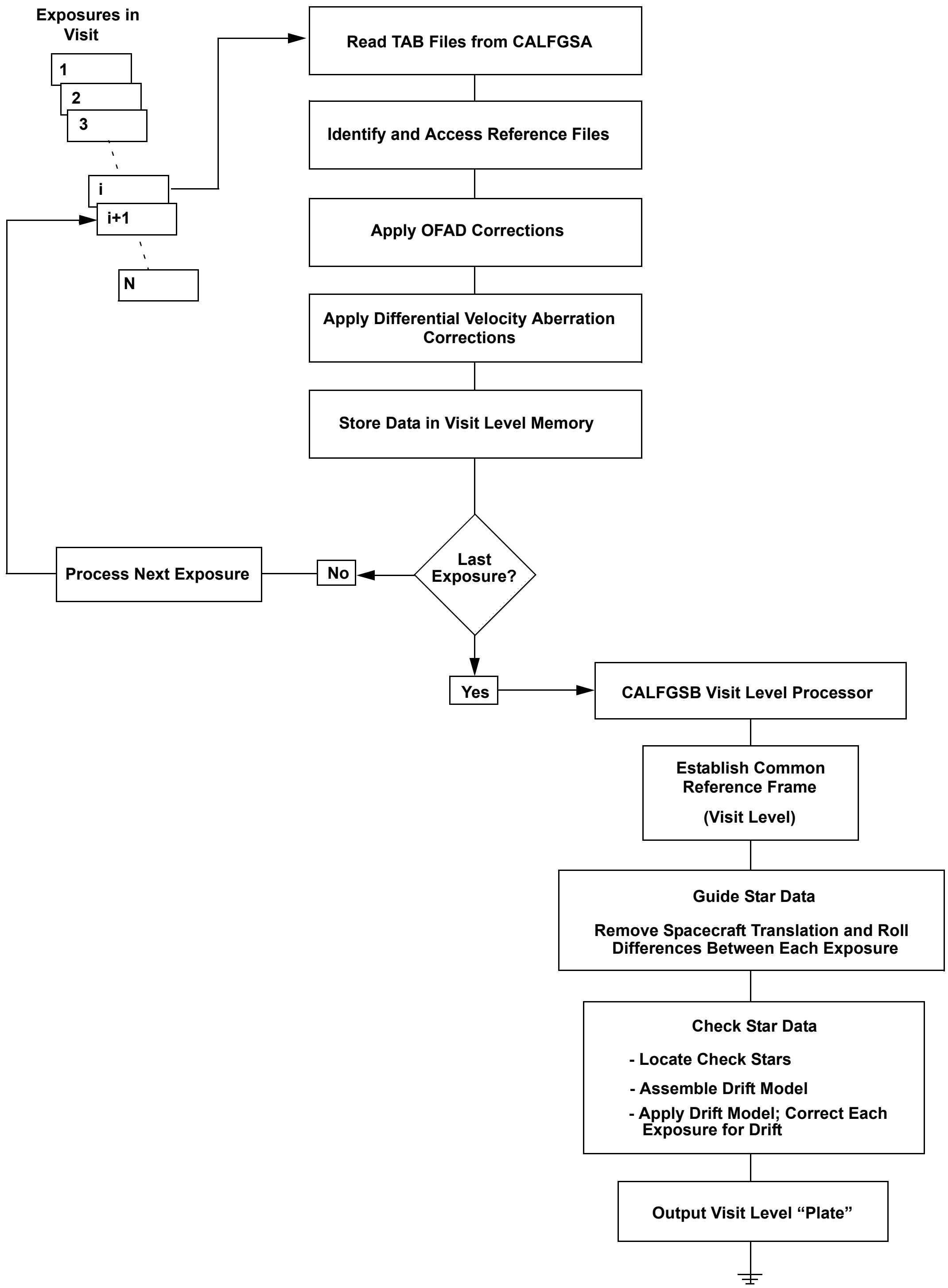
When only one FGS is used for guiding, the telescope is not roll-constrained. Under such circumstances the check stars can reveal very large motions, up to 60 or 70 mas over the course of the orbit (5 to 10 mas is more typical). Nevertheless, this drift can be successfully removed from the astrometry data, provided the proposal contained an adequate check star scenario. For example, the overlay of the plates from two separate Position Mode visits, each measuring ~ 20 stars in an astrometric star field distributed throughout the pickle yielded an rms residual of about 1 mas, even though one of the visits had one-FGS guiding and check-star drifts on the order of 30 mas.

3.6 calfgsa Output: The *.tab File

The content of the output *.tab file `f6iy0302m.tab`, a product of the example shown in Section 3.2.2, is available from the FGS Web Pages (http://www.stsci.edu/instruments/fgs/). Files of this type are required as input to the **calfgsb** task.

A detailed discussion of the contents of the *.tab files can be found on the FGS Web Pages (http://www.stsci.edu/hst/fgs/).

Figure 3.3: CALFGSB Position Mode Processing



Chapter 4: Data Analysis

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This chapter provides insight and instructions for the analysis of FGS astrometry data. This includes the reduction of multi-epoch Position Mode observations (used, for example, in the determination of an object's parallax), multi-epoch Transfer Mode observations (used to derive a binary system's orbital parameters), as well as the detailed inspection of the data from a single exposure or observation. The software (i.e. source code) for analyzing both Position Mode and Transfer Mode observations and pipeline products can be downloaded from the FGS Web site. These tools are written in standard Fortran and/or C and operate in the UNIX environment. A significant amount of this software was provided to STScI by the Space Telescope Astrometry Science Team (STAT) at the University of Texas and Lowell Observatory. However, please note that many of the tools produce graphical displays by calls to the SM[1] library, for which you may require a site license. STScI is working to replace the SM with a publicly licensed package. Until this is accomplished, if you need to use a non-SM graphics package, modest alterations to the source code will be necessary. Check the STScI FGS Web site for updates.

1. SM is an interactive plotting program written by R. Lupton and P. Monger, and is copyright (C) 1987-2000 by R. Lupton and P. Monger.

4.1 Analysis Tools

Not all of the tools described in the following sections will be required to analyze all FGS observations. Some of the tools (like ***binary-fit***) are specific to the analysis of Transfer Mode observations, while tools like ***fgsplot*** are usable to analyze both Position Mode and Transfer Mode observations.

The following list should serve as a general guide to understanding the processes involved in FGS data analysis which tool to use in a given situation. As always, check the STScI FGS Web site for updates.

- fgsplot
    - Used to display a variety of FGS quantities (the location of the FGS Instantaneous Field of View in time as a function of x or y, the fine error signal, the photon counts v. time, etc.). Requires the raw GEIS files a input. Essential for analyzing failed observations and for retrieving useful information from marginal observations.
    - FORTRAN and C modules. Runs in a UNIX and UNIX-based environments.
    - Useful for Position Mode and Transfer Mode observations.
- read-fgs
    - Reads the FGS GEIS header and data files and displays the contents of any of the seven groups of data contained in each data file.
    - FORTRAN and C modules. Runs in a UNIX and UNIX-based environments.
    - Useful for Position Mode and Transfer Mode observations.
- export-fgs
    - Used to generate ASCII output of the six FGS GEIS header and data file combinations produced for each observation. Useful for non-standard processing and analysis.
    - FORTRAN and C modules. Runs in a UNIX and UNIX-based environments.
    - Useful for Position Mode and Transfer Mode observations.
- gaussfit
    - Used primarily in the analysis and reduction of multi-epoch astrometry data, though is applicable to a wide variety of analysis topics - anything requiring robust, least-squares, or other types of estimation.
    - Primarily C modules. Currently only runs under SUN Solaris and SunOS environments.
    - Primarily used for Position Mode plate overlays, but is also applicable to Transfer Mode and Mixed Mode observations.

- plot-rss
  - Tool to display the residuals of an astrometric catalog generated using *gaussfit* on CALFGSB output files.
  - FORTRAN and C modules. Runs in a UNIX and UNIX-based environments.
  - Useful for Position Mode observations only.
- ptrans
  - Tool for processing CALFGSA output of Transfer Mode scans.
  - FORTRAN and C modules. Runs in a UNIX and UNIX-based environments.
  - Useful for Transfer Mode observations only.
- binary-fit
  - Used to model and compare Transfer Mode scans of an unresolved point source with scans of an observed (possibly binary) science target. binary-fit attempts to find a least squares solution to fit the observed S-curve morphology with a superposition of calibration S-curves.
  - FORTRAN and C modules. Runs in a UNIX and UNIX-based environments.
  - Useful for Transfer Mode observations only.

4.2 Analyzing Individual Observations

An FGS observer may find that a single observation requires a detailed investigation. As an example, a particular star in a Position mode observation that appears on one or more plate overlays with large, unexplained residuals, or if the acquisition of the star failed. STScI has developed several tools for analyzing individual observations using the raw GEIS files as input rather than the pipeline products (refer to Chapters 1 and 2 of this Handbook for instructions on retrieving data from the HST archive and for information on the GEIS file format). These tools include the interactive graphics package ***fgsplot*** which allows for a variety of FGS quantities to be plotted, the interactive ASCII display tool ***read-fgs***, which displays the values of selected samples of raw data, and the tool ***export-fgs*****,** which outputs the 40hz x and y position of the FGS's instantaneous field of view (IFOV), the photomultiplier tube (PMT) counts, and the values of the FGS flags and status bits. Each of these will be discussed in the following sections.

Please note that a detailed discussion for the preparation and analysis of Transfer Mode observations, which are treated as individual observations, is provided in Section 1.3. This section addresses more generic tools that are applicable to any FGS observation.

4.2.1 FGSPLOT

The interactive graphics tool ***fgsplot*** can be used to display a variety of FGS quantities from the raw GEIS files. For example, the location of the IFOV in the FGS detector space coordinates can be displayed as a function of *x* vs. *y*, or the fine error signal (partial S-curve) as a function of *x* during the WalkDown to FineLock. The source code for ***fgsplot*** is available via download from the FGS Web site (follow the link under tools). It is a mixture of Fortran and C using SM for the graphic displays.

The ***fgsplot*** tool is both versatile and essential for analyzing failed observations and retrieving useful data from marginal observations. The tool can also be a valuable educational aid for an observer who is unfamiliar with FGS data. An example terminal session using ***fgsplot*** is displayed on the following pages. The reader is encouraged to consult this example while reading about ***fgsplot***.

The ***fgsplot*** tool is a package of Fortran and C modules that can be downloaded from the FGS Web site. A Makefile and instructions are also available to facilitate the building of an executable image on a UNIX or LINUX based host.

Once an executable image is constructed, the tool is activated by simply typing fgsplot.e (or its alias). At the prompt, enter the name of the data set's header file (i.e., f2p30104m.a1h). ***fgsplot*** will open and read the header and data files and prompt for instructions as to what to plot. A menu is presented to facilitate the selection. The options come in two basic varieties. First is a set of options with either numerical digits or double characters. This class contains the most commonly invoked options, such as plotting x vs. y (option 1), or PMTSUM vs. time (option 12), or displaying the acquisition of (or failure to acquire) the fringes of a star in FineLock (options 2 and 3).

The second class of options, denoted by single character alphabetical choices, allows one to plot a variety of items against one another. To invoke this capability one must enter two letters (with no spaces in between) to specify the quantities to be plotted. For example, entering "ab" will plot x vs. y, which, incidentally, is equivalent to specifying a "1".

After entering a choice of quantities to be plotted, ***fgsplot*** will prompt for the range, in sample numbers, of the data to be plotted. To help make the choice meaningful, ***fgsplot*** displays the sample number of when a particular flag or status bit became set or when an event occurred. (If plotting a Transfer Mode observation, please refer to the section "fgsplot for Transfer Mode" on page 29.) For example, if one wishes to plot the location of the IFOV (x vs. y) from the moment when the search for the target began until the completion of the FineLock acquisition, the numerical value (sample number) displayed for the initiation of "Search" should be specified as the first sample, and the sample number of "FineLock DataValid" should be entered as the last sample number to be plotted. Note that simply hitting <*ret*> at the prompt for "first sample" defaults to sample = 1 (plotting from the beginning of the observation), while hitting <*ret*> at the prompt for "last sample" defaults to "Maximum number of Samples", i.e., plotting to the end of the observation.

With the range of the data specified, ***fgsplot*** prompts for a title to be used to annotate the graph, and requests instructions as to whether or not to plot the data with a solid line or symbols at the data points, or both. Simply hitting <*ret*> invokes a solid line plot.

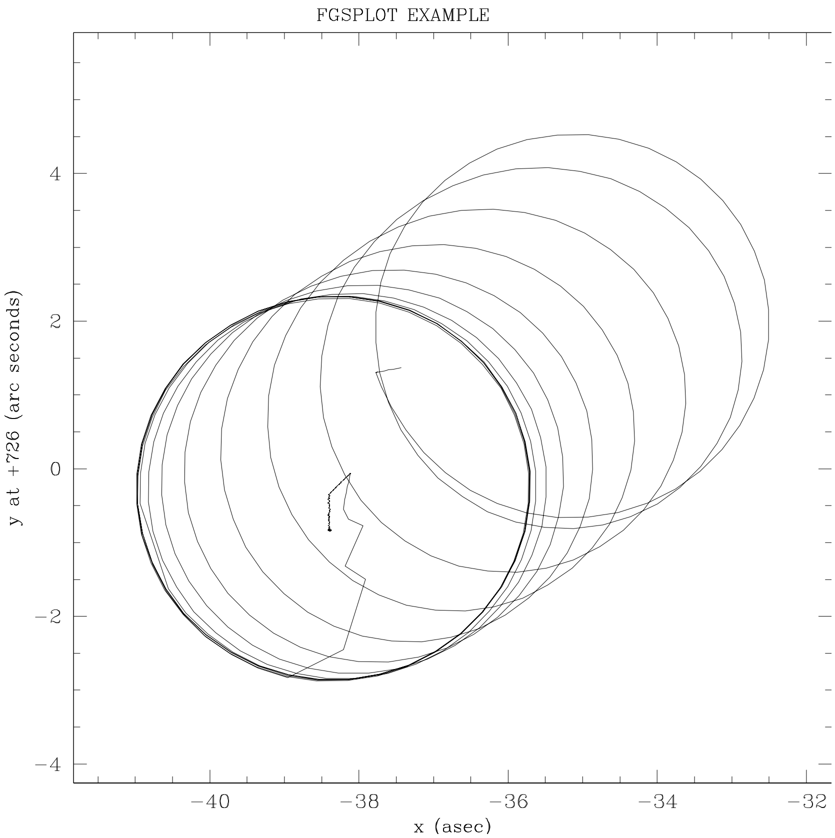
Prior to plotting, ***fgsplot*** will compute the minimum and maximum values (along the abscissa and ordinate) of the items to be plotted, display these values, and offer the user the option to continue or not. Any response other than "N" or "n" will cause the plotting to occur, at which time a SM X11 window appears with the graph, and the user is offered the opportunity to have the plot saved to a postscript file named rootname.i, where rootname is the data set name (f2r30201m, e.g.), and "i" is the value of a counter that increments each time ***fgsplot*** outputs a postscript file in the current session (***fgsplot*** retains no memory of usage in previous sessions).

Next, the user is offered the option to repeat the entire process or to "zoom" in on the currently displayed plot. If the zoom option is invoked (by entering "z" or "Z"), ***fgsplot*** requests the minimum and maximum values of the quantity along the abscissa to be plotted. Over this range of abscissa data the corresponding minimum and maximum values of the quantity along the ordinate are computed and displayed. The user has the option of resetting the full range (in effect scale) of the ordinate axis before plotting the data. The graph is displayed and the option to output to a postscript file is offered.

If the "zoom" option is not invoked, but rather a new plot is specified, the entire process is repeated (with the exception of specifying the header file name). If different quantities (e.g. the y-axis fine error signal instead the x-axis fine error signal), but the same range of samples are to be plotted, one can then enter "-1" (the Turbo option) when prompted to enter the first sample to be plotted.

The data plotted in Figure 4.1 shows an example of the output from fgsplot. This plot shows the path of the FGS's IFOV from the beginning of the search spiral, to Coarse Track, through the "walkdown" (acquisition) of FineLock, and finally the FineLock tracking of the star's interferometric fringes. A terminal snapshot of a ***fgsplot*** session that produced this plot is shown on the following page. User inputs are denoted in **bold**.

Figure 4.1: Sample FGSPLOT result: (x,y) position of IFOV v. time



```
phoenix> fgsplot

 enter header file name: f6cs0101m.a1h

 naxis1:   5082
 ast_id: 1
 mode:   POSITION
 obs_date: 2001 226 15:00:40
 Data loaded, #bytes: 142296
 Flags located
 data quality assessed
                           Table of graphics options:
                        Select the desired graphics option
    (1)  X vs. Y
    (2)  Sx-curve vs. x-axis           (a)  X             (h)  PMTYA
    (3)  Sy-curve vs. y-axis           (b)  Y             (i)  PMTYB
    (4)  Rx vs. X                      (c)  Sx-curve      (j)  [PMTXA + PMTX
    (5)  Ry vs. Y                      (d)  Sy-curve      (k)  [PMTYA + PMTY
    (6)  x-position vs. time           (e)  Time          (l)  PMTsum
    (7)  y-position vs. time           (f)  PMTXA         (m)  Theta A
    (8)  Sx vs. time                   (g)  PMTXB         (n)  Theta B
    (9)  Sy vs. time
    (10) [PMTXA + PMTXB] vs. time
    (11) [PMTYA + PMTYB] vs. time                  (Z)  I/O Parameters
    (12) PMTsum vs. time
    (zx) co-added X s-curves                       (ux)  FESAVG_X
    (zy) co_added Y s-curves                       (uy)  FESAVG_Y
    (xa) co_added XA pmt counts                    (xb)  co_added XB pmt cou
    (ya) co_added YA pmt counts                    (yb)  co_added YB pmt cou
    (xs) co_added XA,B pmt counts                  (ys)  co_added YA,B pmt c
                        Your choice (? for help) ->  1

                              OBS mode -> POSITION
                                   Flags are:
                      Search........................  1038
                      Coarse Track..................  1056
                      Coarse Track Data Valid........  1536
                      Fine Lock.....................  1572
                      Fine Lock Data Valid..........  2040
                      LOS...........................    -1
                      Stop..........................    -1
                      SSM...........................  5034
                      Star Presence False...........    -1
                      Maximum Number of samples .....  5082

                First sample (default = 1, -1 for TURBO) ->  1038
                     Last sample (default =  5082) ->  5000
              graph title ->  FGSPLOT EXAMPLE
              enter line type ([so]lid or [sy]mbols or [bo]th) ->

                 x_min ->   -40.981          y_min ->   723.126
                 x_max ->   -32.507          y_max ->   730.524
 continue? -> y
 output the plot to a file? ................. -> y
 plot another? ([y], [n], or [z]oom) ........ -> n

phoenix>
```

fgsplot for Transfer Mode

Transfer Mode observations typically include many scans of the IFOV across the target, each generating an interferogram or S-curve. ***fgsplot*** offers the capability to co-add all or a selected subset of these scans and to plot data from the entire scan path or over a specified segment. Note, cross correlations and curve smoothing are not currently supported by ***fgsplot***. This capability will be added by the fall of 2002. Check the FGS Web site for updates.

fgsplot reads the header file to determine the data set's observing mode (from the value of the keyword PASTMODE). If the data set is a Transfer Mode observation, ***fgsplot*** determines the number of scans that were executed, the length of the scans, and the start and end sample number of each scan. These results are displayed along with the sample number of the status flags and events listing (as discussed in the previous section) after the user specifies what quantities are to be plotted.

For choices that involve co-adding individual scans, such as "zx" or "zy", ***fgsplot*** queries for the scans to be included in the co-addition. This can be specified either by explicitly entering the scan numbers (i.e. 1, 2, 3, 5, 10), or by specifying a range (i.e., 1-20, 25-50, which excludes scans 21 through 24). Simply hitting <*ret*> at the prompt causes all scans to be included in the co-addition.

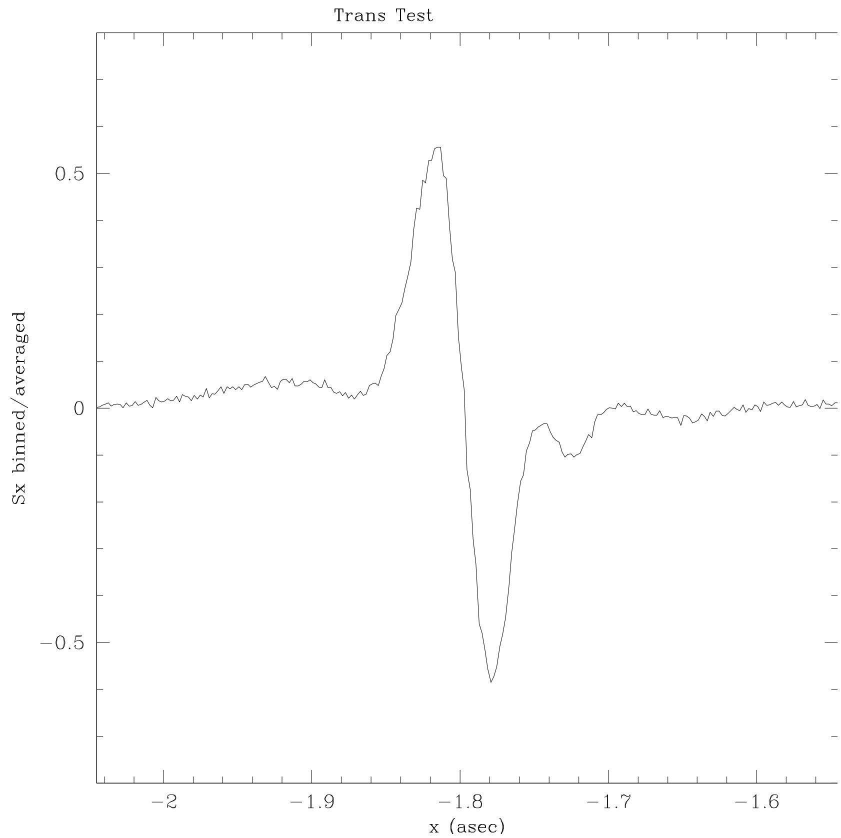
For choices not involving co-addition, such as "1" (x vs. y), ***fgsplot*** prompts for the scan number whose start/end sample numbers identify the segment of the observation from which data are to be extracted for the plot. If the user enters <*ret*>, ***fgsplot*** reverts back to displaying the sample numbers for the various flags and events described earlier. The user then explicitly specifies the start/end sample number to define the interval from which data is extracted for plotting.

Finally, when scan IDs or co-added quantities are used to specify the start/end intervals from which data are extracted for plotting, ***fgsplot*** offers the option of plotting only a central segment of the scan, with a length specified by the user. Hitting <*ret*> at this prompt causes data along the entire scan length to be plotted.

An example terminal session using ***fgsplot*** on a Transfer Mode observation is shown below (user input in **bold**). This observation contained thirty scans on a V=12 white dwarf (single) star. For illustration purposes, scans 1 through 10 and 21 through 30 were included in the co-addition of data along the X-axis, and only the central 0.5" of the full (0.85") scan path is plotted. The scans were binned with 2 mas intervals, and an output file of the resulting plot is requested, which is displayed in Figure 4.2. A reminder: this is a plot of raw data; cross correlation and smoothing are not supported by ***fgsplot***. We plan to upgrade the package to support these tasks. Users are advised to check the FGS Web site for updates.

```
phoenix> fgsplot
 enter header file name: f6jy1102m.a1h
 naxis1:  52970
 ast_id: 1
 mode:   TRANSFER
 obs_date: 2001 314 08:48:30
 Data loaded, #bytes: 1483160
 Flags located
 data quality assessed
                            Table of graphics options:
                         Select the desired graphics option
    (1)  X vs. Y
    (2)  Sx-curve vs. x-axis          (a)  X            (h)  PMTYA
    (3)  Sy-curve vs. y-axis          (b)  Y            (i)  PMTYB
    (4)  Rx vs. X                     (c)  Sx-curve     (j)  [PMTXA + PMTXB]
    (5)  Ry vs. Y                     (d)  Sy-curve     (k)  [PMTYA + PMTYB]
    (6)  x-position vs. time          (e)  Time         (l)  PMTsum
    (7)  y-position vs. time          (f)  PMTXA        (m)  Theta A
    (8)  Sx vs. time                  (g)  PMTXB        (n)  Theta B
    (9)  Sy vs. time
    (10) [PMTXA + PMTXB] vs. time
    (11) [PMTYA + PMTYB] vs. time                (Z)  I/O Parameters
    (12) PMTsum vs. time
    (zx) co-added X s-curves                     (ux)  FESAVG_X
    (zy) co_added Y s-curves                     (uy)  FESAVG_Y
    (xa) co_added XA pmt counts                  (xb)  co_added XB pmt counts
    (ya) co_added YA pmt counts                  (yb)  co_added YB pmt counts
    (xs) co_added XA,B pmt counts                (ys)  co_added YA,B pmt counts
                         Your choice (? for help) ->  zx
                               OBS mode -> TRANSFER
                                    Flags are:
                       Search.........................  1164
                       Coarse Track...................  1182
                       Coarse Track Data Valid........  1662
                       Fine Lock......................  2214
                       Fine Lock Data Valid...........  2238
                       SSM............................  2274
                       ************************************
           Scan 1:   Start sample .....  2794   End sample .......  4568
           Scan 2:   Start sample .....  4221   End sample .......  6176
           Scan 3:   Start sample .....  5823   End sample .......  7771
           Scan 4:   Start sample .....  7420   End sample .......  9382
           Scan 5:   Start sample .....  9019   End sample ....... 10969
           Scan 6:   Start sample ..... 10623   End sample ....... 12576
           Scan 7:   Start sample ..... 12222   End sample ....... 14171
           Scan 8:   Start sample ..... 13831   End sample ....... 15779
           Scan 9:   Start sample ..... 15427   End sample ....... 17373
           Scan 10:  Start sample ..... 17028   End sample ....... 19972
           Scan 11:  Start sample ..... 18627   End sample ....... 21569
           Scan 12:  Start sample ..... 21222   End sample ....... 23174
           Scan 13:  Start sample ..... 22819   End sample ....... 24773
           Scan 14:  Start sample ..... 24424   End sample ....... 26375
           Scan 15:  Start sample ..... 26032   End sample ....... 27980
           Scan 16:  Start sample ..... 27630   End sample ....... 29590
           Scan 17:  Start sample ..... 29236   End sample ....... 31184
           Scan 18:  Start sample ..... 30843   End sample ....... 32789
           Scan 19:  Start sample ..... 32439   End sample ....... 34389
           Scan 20:  Start sample ..... 34043   End sample ....... 36980
           Scan 21:  Start sample ..... 35639   End sample ....... 38578
           Scan 22:  Start sample ..... 38230   End sample ....... 40184
           Scan 23:  Start sample ..... 39834   End sample ....... 41782
           Scan 24:  Start sample ..... 41435   End sample ....... 43382
           Scan 25:  Start sample ..... 43044   End sample ....... 44986
           Scan 26:  Start sample ..... 44630   End sample ....... 46584
           Scan 27:  Start sample ..... 46240   End sample ....... 48189
           Scan 28:  Start sample ..... 47832   End sample ....... 49788
           Scan 29:  Start sample ..... 49448   End sample ....... 51392
           Scan 30:  Start sample ..... 51034   End sample ....... 52970
                       ************************************
                       Maximum Number of Samples ..... 52970
 enter scan numbers to be included in averaging (RET=all) -> 1-10,20-30
 enter binning interval (in milli arc seconds) .... -> 2.0
    ...................... measured scan length -> 0.85
    ..................... enter sub scan length -> 0.5
             graph title ->  Trans Test
             enter line type ([so]lid or [sy]mbols or [bo]th) ->  (<cr)>)
                x_min ->    -2.045          y_min ->    -0.585
                x_max ->    -1.545          y_max ->     0.556
 continue? ->
 enter the "verticle scale (0.8=default) ->
 output the plot to a file? ................. -> y
 plot another? ([y], [n], or [z]oom) ........ -> n
phoenix>
```

Figure 4.2: FGSPLOT output: Co-addition of thirty Transfer Mode scans



Obtaining ASCII Output from *fgsplot*

fgsplot offers the option of creating an ASCII output file containing a two column listing of the data that is plotted. The number of rows will be equal to the number of data points in the plot. This can serve as a convenient method to quickly extract semi-processed data for additional quick look analysis or for input into more sophisticated graphics script (***fgsplot*** offers very little support for annotation which might be desired for display and presentation purposes).

To obtain such an ASCII file one simply appends the choice designating the items to be plotted with an "*". For example, entering "1*" (x vs. y) in response to the selection menu prompt produces a two-column ASCII file containing time-ordered X and Y values, with the number of entries exactly equal to the number of points plotted. Another example would be "zx*", which generates an ASCII file with the x and the co-added x-axis interferogram.

The name ***fgsplot*** assigns to an ASCII file is determined from the header file's rootname (i.e., f2d40203m) and a code that is used to specify what data are output. This code can be discerned from the selection menu of (single) items that can be plotted against one another. For example, if one specifies a plot of x vs. y by entering "ab*" at the selection prompt, then a file with the name "f2d40203m.fab" will be created. (Note that entering "1*" at the selection prompt, which is equivalent to specifying "ab*", also generates a file named rootname.fab). If an output file is requested for options involving the co-addition of data, it will be named rootname.fxx, where xx = selected choice. For example, if an output file containing a listing of x vs. the co-added x-axis interferogram is desired, “zx*” is entered at the prompt, and the file “rootname.fzx” is created. Note that if the target output file already exists, ***fgsplot*** overwrites its contents, even within the same ***fgsplot*** session.

4.2.2 Read-FGS

The tool ***read-fgs*** reads FGS GEIS header and data files and displays selected contents of any of the 7 groups of data contained in the data file. The tool is a package of Fortran and C modules that can be downloaded from the FGS Web site. A Makefile and instructions are also available to facilitate the building of an executable image on a UNIX or LINUX based host.

Once an executable image is constructed, the tool is activated by simply typing read-fgs.e (or its alias). ***read-fgs*** prompts the user for the name of the GEIS header file that is associated with the GEIS data file that is to be read. The appropriate header and data files are opened and read, and the user is prompted to specify the name of the group from which data is to be extracted and displayed. The option to type “h” for help is available to display the names of the groups, whose names and contents are displayed in Table 4.1.

Table 4.1: FGS Groups and Associated Data

group name	data rate	description
PMTXA	40hz	photon counts from PMTXA
PMTXB	40hz	photon counts from PMTXB
PMTYA	40hz	photon counts from PMTYA
PMTYB	40hz	photon counts from PMTYB
SSENCA	40hz	star selector A position
SSENCB	40hz	star selector B position
FLAGS	6.67hz	flags and status bits

To display data from the group PMTXA, simply type “pmtxa” at the prompt. The values of the first 32 samples from this group will be displayed in four columns. The option to display the next 32 samples, or to choose the starting sample number of the next 32 samples to be displayed is offered. Simply hitting <*ret*> defaults to displaying the next 32 samples. And, for example, typing 1000 will cause samples 1000 through 1031 to be displayed. If a number larger than NAXIS (the size of the group) is entered, the last 32 samples from the group are displayed.

To view the contents of a different group, enter either the group’s name or “q” at the prompt. If the group’s name is entered, the values of the first 32 samples are displayed. If “q” is entered, one is prompted to enter the name of the next group to be displayed.

In either case, data from any location within the group can next be displayed as described in the paragraph above.

For illustration purposes, an example of a session with ***read-fgs*** is displayed below. User supplied input is in **bold**.

```
phoenix> read-fgs
 enter name of the header file .... -> f6cs0101m.a1h
 data for which group are to be displayed (h for help) ---------> h
 VALID group specifiers are:
    pmtxa    pmtxb   pmtya   pmtyb   ssenca   ssencb  flags
 data for which group are to be displayed (h for help) ---------> ssen
 group_id  = ssencb       group_num =  6
  sample           i*4 values    group# 6     gtype -> ssencb
      1          827116        827117        827116        827117
      5          827116        827117        827116        827117
      9          827116        827117        827116        827117
     13          827116        827117        827116        827117
     17          827116        827117        827116        827117
     21          827116        827117        827116        827117
     25          827116        827117        827116        827117
     29          827116        827117        827116        827117
 enter starting sample for next 32 sample display or new group name
 (q to exit, <cr> for proceding) -------------------------------> flag
 flags to be displayed in hex (h) or ASCII (a)? ---------------->

  sample           i*4 values    group# 7     gtype -> flags
      1       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
      5       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
      9       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
     13       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
     17       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
     21       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
     25       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
     29       SP,DV,SM       SP,DV,SM       SP,DV,SM       SP,DV,SM
 enter starting sample for next 32 sample display or new group name
 (q to exit, [ret] for proceding) ------------------------------> 500
  sample           i*4 values    group# 7     gtype -> flags
    500       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    504       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    508       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    512       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    516       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    520       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    524       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
    528       SP,DV,FL       SP,DV,FL       SP,DV,FL       SP,DV,FL
 enter starting sample for next 32 sample display or new group name
 (q to exit, <cr> for proceding) -------------------------------> q
phoenix>
```

The flags group warrants special discussion. If this group is selected the user is prompted to choose whether the display is to be in ASCII or hex. The hex values are base16 displays of the 32 bit integers that comprise the flags group. The ASCII option invokes a translation of the values contained in these integers to display which flags or status bits are set (= 1). Flags that are not set (= 0) are not displayed. Table 2 lists the two character code used to represent a given flag or status bit. At any given time more than one flag is usually set. For example, when an FGS is tracking a star in FineLock (as in a Position mode observation), the flag display will be "SP,FL,DV". Here "SP", or Star Presence, indicates that the measured photometry from the star exceeds the minimum detection threshold, while "FL,DV" indicates that the star's fringes have been successfully acquired and are being tracked in FineLock. Table 3 lists the sequence of values in the flags group for a typical FGS observation

Table 4.2: Two-character codes representing FGS flag or status bits

code	flag or status bit	description
ST	stop	FGS acquisition terminated
RE	SRLE	search radius limit exceeded
SP	Star Presence	photometry counts indicate a star in IFOV
DV	Data Valid	FGS successfully completed a process
TH	Transfer Hold	FGS awaiting transition from Coarse Track to Fine Lock acquisition
SE	Scan Step Limit Exceeded	Fringes not acquired on 1 or 2 axis in Walkdown to Fine Lock
SH	Search	FGS in Search phase of acquisition
CR	Coarse Track	FGS in Coarse Track mode of acquisition
FL	Fine Lock	acquiring or tracking fringes
SM	SSM	FGS under control of HST 486 CPU
DF	Default	FGS IFOV retracted from FOV, FGS not observing
LS	LOS	"line of sight" engineering mode

Table 4.3: Sequence of values in FGS flags

flag sequence	description
SP,DV,SM	FGS preparing to slew IFOV to next target
DV,SM	FGS slewing IFOV to next target
SH	IFOV in spiral search for new star
SP,SH	photons from star detected
SP,CR	Coarse Track search for photocenter
SP,DV,TH,CR	Star successfully acquired in Coarse Track
SP,FL	FGS search for stellar fringes
SP,DV,FL	Fringes acquired and being tracked
SP,DV,SM	Observation completed (Pos mode) or scanning in progress (Trans mode)

Two additional items will be encountered when one uses ***read-fgs***. These are the values used for bad data and fill data, denoted by 999999 and 999998, respectively. The processor that extracts the FGS mnemonics from the engineering telemetry to build the GEIS files uses the bad data value when corrupt telemetry frames are encountered. The fill data value is used when the processor encounters missing frames, or, as in the case of the flags group, to pad the last 5/6 of the group. (The flags are sent only 1/6 as often as the other datums, but the flags group must be the same size as the others, so padding is required. This also implies, e.g., that flag group sample number 100 corresponds, in a temporal sense, to sample number 600 in the other groups). If bad data or fill data are encountered while the contents of the flags group is being viewed in ASCII mode, "bad data" or "fill data" is displayed.

The insertion of bad data or fill data indicators into the GEIS files preserves the temporal relation between samples. For example, sample number 100 records data that is (100-1)*25 msec. later than that recorded in sample number 1. This also preserves the mapping of data across groups. For example, the value of sample number 120 in group PMTXA was gathered at the same time as sample number 120 in all of the other groups (except flags, whose corresponding sample number would be 120/6 = 20).

4.2.3 Export-FGS

The tool ***export-fgs*** can be used to generate an ASCII version of the 6 header/data FGS GEIS files for a given observation. This might be useful if non-standard processing and analysis of an observation is desired. The tool can be downloaded from the FGS Web site. Its source code is composed of Fortran and C modules. A Makefile and instructions on how to generate an executable image are also available.

To execute ***export-fgs*** simply type export-fgs.e or its alias from the directory containing the FGS GEIS files that are to be processed. At the prompt, enter the rootname of the data set to be processed. ***export-fgs*** will open and read the available GEIS files for each of the 3 FGS, and will create an ASCII file for each FGS. These files will each have 7 columns of data: x, y, pmtxa, pmtxb, pmtya, pmtyb, and the flags. The x, y values are computed from the star selector servo angles (*ssenca* and *ssencb*), and have units of arc seconds. These values record the position of the FGS IFOV in FGS detector space as a function of time during the observation. Note that each row signifies a 25 msec increment in time. Columns 3,4,5, and 6 record the number of photons counted by the respective PMT during the 25msec interval of time represented by a given row. Column 7, the flags column, displays the FGS flags and status bits for the 25 msec interval time for that row. The codes used to convey the flags status is the same as that used for the tool ***read-fgs*** discussed in the previous section. Values of 999998 and 999999 in the first 6 columns denote bad data or fill data, concepts also discussed in the previous section.

The names of the newly created files will be rootname.fgs1, rootname.fgs2, and rootname.fgs3, where rootname identifies the data set (e.g., f2d40202m). If data for fgs2 is not present, the ***export-fgs*** will not generate the associated *.fgs2 file. An example terminal session using ***export-fgs*** is shown below. User supplied input is in **bold**.

```
phoenix> export-fgs
 enter observation rootname: f6bm0708m
 Header file:  f6bm0708m.a1h
 NAXIS1:                     3878
 Header file:  f6bm0708m.a2h
 NAXIS1:                     3878
 Header file:  f6bm0708m.a3h
 NAXIS1:                     3878
phoenix>
```

An excerpt of the first few lines of the file “f6cs0101m.fgs” created by ***export-fgs*** is shown below.

```
phoenix> more f6bm0708m.fgs1
 Header file:  f6bm0708m.a1h
 NAXIS1:                     3878
     x         y           pmtxa     pmtxb   pmtya   pmtyb      flags
   60.7417  633.4212          18         9      11      16      sp,dv,sm
   60.7384  633.4172          14         6       4      12      sp,dv,sm
   60.7417  633.4212           9         9      13      12      sp,dv,sm
   60.7384  633.4172          11         6       8      14      sp,dv,sm
   60.7417  633.4212          19         5      12      13      sp,dv,sm
   60.7384  633.4172          11         4      11      11      sp,dv,sm
   60.7417  633.4212           7        10       7      14      sp,dv,sm
```

4.3 Analyzing Multi-Epoch Astrometry Data: gaussfit

Multi-epoch astrometric observations are necessary to measure the parallax, proper motion, and reflex motion of a given object with respect to reference field stars. Combining these observations is facilitated by "overlaying" calibrated astrometric data from several visits, possibly spanning years. The data are collected and mapped onto a common reference frame, or catalog, by an astrometric plate solution. This solution can be used to determine whether the object of interest moves in a systematic, time-dependent way with respect to the reference field, as it would if a parallax, proper motion, and/or reflex motion is present.

The Space Telescope Astrometry Science Team (STAT) from the University of Texas at Austin developed the versatile tool “***gaussfit***” for constructing plate overlays, and has made this tool available to STScI for distribution as part of the FGS data analysis package. ***gaussfit*** is a robust least squares estimator. It reads a model file that specifies the observed quantities, the parametric relation between them, and the constraints these quantities are subject to. It also reads the “environment” file which identifies the various input and output files that are involved in the process. ***gaussfit*** will solve for values of the parameters specified in the model that best satisfy the constraints, i.e., a minima on the Chi-Square manifold. ***gaussfit*** source code is composed of C modules and currently runs only under the SUN Solaris and SunOS operating systems. It is available from the FGS Web site for download. An example of using ***gaussfit*** on HST/FGS astrometry data to determine a star's parallax and proper motion is presented here and discussed in depth.

4.3.1 4 and 6 Parameter Plate Solutions

"Plate" solutions allow for astrometric data gathered over several epochs and possibly at a variety of HST roll angles and pointings to be combined on to a common fiducal reference frame. The plate solutions can be generated from either a four parameter or six parameter model. The four parameter model adjusts for translation, rotation, and relative scale, while the six parameter model accommodates the additional adjustment of the relative scales along the x and y axis independently. Formally the six parameter model requires at least three common stars in each plate (or epoch), but in order to avoid over-constraining the plate solution, the six parameter model should not be applied if fewer than ~five stars are common to all plates.

If a sufficient number of stars common to all plates (or visits) is available, the six parameter solution is recommended, as this enhances the overall quality of the plate overlays. Indeed, the known tendency of HST's magnification to oscillate or "breathe" by small amounts during an orbit alters an FGS's plate scale by different amounts in the *x* and *y* directions (due to a secondary effect caused by HST's spherical aberration). The same effect occurs on longer time scales, owing to the continual desorption of the optical telescope assembly and consequent refocusing every several months. Therefore, the focus of HST varies with time, resulting in different relative scales along the *x* and *y* axes among a set of astrometric visits.

The four-parameter model is appropriate for obtaining FGS astrometric plate solutions when the reference fields around the science target(s) is too sparse for a six-parameter model. Formally only two reference stars are needed to apply the four-parameter model, but obviously such a solution is highly constrained and vulnerable to motions of the reference stars and errors in their measured positions as well as focus changes in HST's OTA.

The Science Target as Part of the Plate Solution

The object under scientific investigation can (and should) be included in the plate solution. However, for multi-epoch observations care must be taken to include in the model the object's parallax and proper motion as well as any other perturbation of its position relative to the reference field stars, such as reflex motion if it has an orbiting companion. Examples of how to model parallax and proper motion with ***gaussfit*** are presented in this section.

Identifying "Problem Stars"

For a variety of reasons it might be necessary to delete one or more reference stars from some or all of the visits contributing to the plate solution. For example, if a reference star is actually a binary, the FGS might lock onto one component on the *x*-axis and the other on the *y*-axis during one visit, then some other combination on subsequent visits. Or, a star might be significantly fainter than anticipated, preventing the FGS from reliably acquiring it in FineLock, or a particular observation might have been compromised by an incidence of extreme spacecraft jitter. Generally, such outliers are noted by inspection of residuals, but only after an attempt at a plate solution.

Another potential problem encountered with the plate solutions is when one or more of the reference stars displays an unanticipated but detectable proper motion or parallax. This effect manifests itself as relatively large residuals in the "catalog" position of the star compared to residuals of other stars used in the solution, or more generally the "active" star and its nearest neighbors display relatively high residuals. These motions can be modeled in the plate solution, and if accurately determined, the residuals of the overall solution used to derive the catalog should diminish.

4.3.2 Preparing Files for input by *Gaussfit*

In the following sections we describe the generation or modification of files needed for input by ***gaussfit***. This includes the construction of the model which drives ***gaussfit***, modifications to the output products of CALFGSB, and the generation of ancillary files. In subsequent sections we describe tools to manipulate the ***gaussfit*** output that generate graphical displays to help isolate outliers and to facilitate the evaluation of the astrometric accuracy that has been achieved. These tools, with instructions for generating executables for a UNIX environment, can be downloaded from the FGS Web site.

Preparing the Model File

The model file, required by ***gaussfit***, specifies the observed quantities, data items, variables, and parameters. The observed quantities might be the (x,y) positions of the stars in the FGS detector coordinate system as measured in a given HST orbit. "Data" could be the time (e.g., the Modified Julian date) of an observation or roll angle of HST. Variables are quantities calculated from the observations, data, and parameters. Parameters are entities whose values are to be solved for, subject to constraints, to find the minimum on the Chi-Square manifold, i.e., the best global solution that combines the multi-epoch data. For a simple parallax program the "observations" are the (x,y) positions of the science target and reference stars measured in each of the proposal's HST orbits. The "data" are the star IDs, their (approximate) celestial coordinates, and the HST roll angle and time at each epoch. The parameters are the parallax and proper motion of each star relative to the field. The rotation, translation, and scale changes of the FGS detector space coordinate system from an HST visit relative to a chosen fiducial are determined by additional parameters (invoking the 4 or 6 parameter plate solution). The variables are the quantities that relate the data and observations to the parameters. The model defines the relations between the parameters that form the constraints that the solution must satisfy.

The "observations" and "data" are read in from the output *.tab files generated by the pipeline component CALFGSB. The parameters are specified in the model file. Their initial input and final output values are recorded in the "parameter files" associated with the data reduction process (as discussed below).

The syntax and structure of the model emulates a pseudo C program, and is best demonstrated by the following example. The text below displays the contents of a

gaussfit model file that is appropriate for determining the parallax and proper motion of star "1" relative to field stars. In this example the reference field stars (stars != 1), are constrained to have no bulk parallax and proper motion, i.e., the sum of all reference star proper motions is constrained to zero. Some of the reference stars might have a detectable parallax or proper motion relative to the most distant stars in the field. ***gaussfit*** will compute a "positive" parallax for these and a "negative" parallax for the more distant stars (since the sum is constrained to zero). It might be appropriate to iterate the process whereby stars with detectable motions are excluded from the constrained sums, and their parallax and proper motions are solved for as part of the grand solution. The "template" shown here is available for download from the FGS Web site.

```
/*  A Gaussfit model for deriving an overlapping FGS plate with          */
/*  proper motion and parallax effects present.                          */
/*  Basic specifications and assumptions:                                */
/*      (1) a 6 parameter plate solution is employed.                    */
/*      (2) the sum of the reference field (all star>1) parallax         */
/*          and proper motion sums to zero. Individual reference         */
/*          stars can have a parallax and proper motion.                 */
/*      (3) the reference plate is from set=1 (in this example,          */
/*          but a different set can be used as the reference).          */
/*      (4) The astrometry FGS is FGS1r (relates xi,eta to North)        */
parameter xi[star], eta[star], mux[star], muy[star], par[star];
parameter a[set], b[set], c[set], d[set], e[set], f[set];
        /*   xi,eta are the "catalog positions" of the stars that        */
        /*   are to be derived by this model. This reference frame       */
        /*   will have an orientation relative to the celestial          */
        /*   sphere defined by the orientation of the visit (HST         */
        /*   orbit) that is designated as the fiducal, i.e., with        */
        /*   plate constants (a,b,c,d,e,f) constrained to unitary        */
        /*   transformations in translation, rotation, and scale.        */
        /*   (constraints defined below)                                 */
        /*                                                               */
        /*   mux, muy are the star's proper motion in R.A. and Dec.,     */
        /*   respectively, expressed as asec/day. par is the star's      */
        /*   parallax, expressed as asec.                                */
data obstime, P_alpha, P_delta, rollV3, pRA, pDec;
        /*   P_alpha and P_delta are the parallax factors of the         */
        /*   field at the time of the observation (obstime). obstime     */
        /*   is expressed in MDJ, rollV3, pRA, pDec are in degrees.      */
        /*   rollV3 is the angle from HST's V3 axis to North,            */
        /*   counter clockwise. pRA and pDec are the predicted RA        */
        /*   and Dec. of each observed star. These quantities are read   */
        /*   from files produced by CALFGSB.                             */
observation X, Y;
        /*   the observations (X,Y), in asec, are the positions of       */
        /*   the stars in the FGS detector measured in each of the HST   */
        /*   orbits used to gather these data. These are read from       */
        /*   files output by CALFGSB.                                    */
variable u, v, i, pxt, pyt, tc, pix, piy, mx, my, R, OFF, DtoR;
        /*  the variables are used to relate the data, observations,     */
        /*  and parameters.                                              */
/*  Local variables for use within Gauss?it model                        */
data star;
variable obstime1 = 0;
variable lx,     ly,     xx,    yy;
variable sumx,   sumy,   smxx,  smyy,  smxy, smyx;
variable sumpix, sumpiy, smpix, smpiy;
main(){
       /*  Set initial values of summed proper motions, parallaxes      */
       /*  and their moments and correlations to zero                   */
    sumx   = 0;                      /* sum of proper motions along x  */
    sumy   = 0;                      /* sum of proper motions along y  */
    smxx   = 0;                      /* sum of (x pm * x)              */
    smyy   = 0;                      /* sum of (y pm * y)              */
    smxy   = 0;                      /* sum of (x pm * x)              */
    smyx   = 0;                      /* sum of (x pm * y)              */
    sumpix = 0;                      /* sum of (y par * x)             */
    sumpiy = 0;                      /* sum of (x par * y)             */
    smpix  = 0;                      /* sum of x parallax              */
    smpiy  = 0;                      /* sum of x parallax              */
    doconstraints();
    while(import())          /*  Read available data from file...       */
    model();                 /*  form an equation for observed data     */
    domoreconstraints();}
doconstraints() {
            /*   the "export" functions constrains the quantity or      */
            /*   expression contained within the ( ) to have a value    */
            /*   of zero. Thus;                                          */
            /*                                                           */
            /*         exportconstraint(x + y -1):                       */
            /*                                                           */
            /*   constrains (x+y) = 1                                    */
                                     /*  constrain plate constants.     */
       exportconstraint(a[1]-1);     /*  specifies coordinate system    */
       exportconstraint(b[1]);       /*  from data set #1 as fiducal.   */
       exportconstraint(c[1]);       /*  coordinate systems from all    */
       exportconstraint(d[1]);       /*  other visits to be translated, */
       exportconstraint(e[1]-1);     /*  rotated, and scaled to the     */
       exportconstraint(f[1]);       /*  coordinate system defined by   */
                                     /*  this (arbitrary) visit.        */
domoreconstraints() {
       /* lock down reference stars: no bulk parallax or proper motion  */
       /* sum of x and y proper motions = 0    : plate motion           */
       exportconstraint(sumx);
       exportconstraint(sumy);
       /* sum of x proper motions times x = 0  :plate "breathing"       */
       exportconstraint(smxx);
       /* sum of y proper motions times y = 0                           */
       exportconstraint(smyy);
       /* sum of x proper motions times y = 0  :plate rotation          */
       exportconstraint(smxy);
       exportconstraint(smyx);
       /* sum of parallaxes= 0                                          */
       exportconstraint(sumpix);
       exportconstraint(sumpiy);
       /* sum of parallaxes times x and y = 0                           */
       exportconstraint(smpix);
       exportconstraint(smpiy);
model(){
       if (obstime1 == 0)
           obstime1 = obstime;
       DtoR = 3.141592/180;
    /* R = DtoR * (rollV3 - 270.0);         .... astrometer = FGS3       */
       R = DtoR * (rollV3 - 90.0);      /*       astrometer = FGS1r      */
       tc = obstime - obstime1;
    /*  Projected displacements of star's position due to parallax       */
       pxt = P_alpha * cos(DtoR * pdec);
       pyt = P_delta;
       pix = (+pxt*cos(R) + pyt*sin(R)) * par;
       piy = (-pxt*sin(R) + pyt*cos(R)) * par;
    /*  Projected proper motion factors                                  */
       mx = (+mux*cos(R) + muy*sin(R));
       my = (-mux*sin(R) + muy*cos(R));
    /*  include shift of (x,y) due to proper motion and parallax         */
       xx = X - mx*tc - pix;
       yy = Y - my*tc - piy;
    /*  Linear elements of 6 parameter plate solution                    */
       lx = a*xx + b*yy + c;
       ly = d*xx + e*yy + f;
    /*  Combine linear transformation, proper motion, parallax, and      */
    /*  data points and solve.                                           */
       u = lx - xi;
       v = ly - eta;
       do_sums();           /*  Sum pm, par for reference objects       */
       export2 (u,v);       /*  Export equations of condition           */}
do_sums(){
       if (star != 1)  /*  Remove target (science) star from summation  */
       {
              sumx   = sumx + mux;
              sumy   = sumy + muy;
              smxx   = smxx + mux*X;
              smyy   = smyy + muy*Y;
              smxy   = smxy + mux*Y;
              smyx   = smyx + muy*X;
              sumpix = sumpix + pix;
              sumpiy = sumpiy + piy;
              smpix  = smpix + pix*lx;
              smpiy  = smpiy + piy*ly;}}
```

It is worth noting that the parallax and proper motions computed by ***gaussfit*** are, of course, *relative* to the reference stars that were also measured by the FGS. To determine an object's *absolute* parallax, one must apply the relative-to-absolute correction. This is typically done by identifying each star's spectroscopic type and luminosity class, and then from the HR diagram, determining its distance. From this an average distance, and hence parallax, for the reference field is computed. This parallax adds to the science target's relative parallax, yielding the target's absolute parallax. More sophisticated applications of ***gaussfit*** include the spectroscopic distances as "observations" which are constrained by the uncertainties in the spectroscopic analysis. If feasible, this enhances the reliability of relative-to-absolute parallax correction.

Preparing the Output Products of CALFGSB for Gaussfit

CALFGSB applies a variety of corrections to the (x,y) centroids of the observed stars. The final corrections applied by CALFGSB are for drift of the HST focal plane over the course of the orbit during which the stars' relative positions were measured. CALFGSB applies two standard models to remove HST/FGS drift: a 2nd order translation model, and a first-order translation plus rotation model. The Chi-Square fits of the data to each of these models is computed and recorded in the *log file. In a standard CALFGSB execution, the centroids for the 2nd order translation model are grouped into two columns in the *_ast file (named Xvaofadapj2d and Yvaofadapj2d), while the centroids from the first-order translation plus rotation model are grouped into two additional columns (named Xvaofadapjrd and Yvaofadapjrd). However, the ***gaussfit*** model displayed above requires as input the "observation" values (X,Y). The CALFGSB output product (*_ast) should be edited to modify either the pair of column names:

```
Xvaofadapj2d  ---> X
Yvaofadapj2d  ---> Y
```

or

```
Xvaofadapjrd  ---> X
Yvaofadapjrd  ---> Y
```

The choice of which pair to specify as the "observation" (X,Y) should be based upon whichever drift model yielded the smallest Chi-Square residual (from inspection of CALFGSB's *.log file). Incidentally, the name Xvaofadapj2d derives from the fact that the X-position centroid has been corrected for - in sequence - differential velocity aberration (va), optical field angle distortions (OFAD), asphere and pickoff mirror distortions (ap), spacecraft jitter (j), and finally the HST/FGS drift (2d or rd models). The reason why (Xvaofadapj2d, Yvaofadapj2d) are not specified as the "observation" in the ***gaussfit*** model is because it is generally necessary to combine data from many epochs of HST observing to determine the scientific objective. It may be best to extract the centroids corrected with the second-order translation model for some of the epochs and those corrected with the first-order translation plus rotation model in the others. Editing the data files to specify (X,Y) provides the flexibility to enforce this choice.

The parameter files

A ***gaussfit*** parameter file contains data gathered into columns and rows. Each column is labeled with the name of a particular parameter, as it appears in the ***gaussfit*** model file. Each row contains the values of all the parameters for the particular entity defined by the row, such as a star. The example shown below displays the contents of the file "catalog-par" that would be needed to run ***gaussfit*** with the model file presented above. The file provides for an initial estimate of each star's position (xi,eta), proper motion (mux,muy), and parallax (par).

```
/* example "catalog-par" file for input to gaussfit.        */
/* defines fiducal coordinate system and catalog entries    */
/* these comment lines must be removed before executing     */
star     xi           eta        mux      muy      par
double   double       double     double   double   double
1        -159.33790   748.57261  -0.0013  -0.0006   0.079
2        -262.61412   703.79643   0.0      0.0      0.0
3          95.57049   751.19511   0.0      0.0      0.0
4          52.67597   699.95072   0.0      0.0      0.0
5          19.26876   654.89445   0.0      0.0      0.0
6        -274.76243   580.68658   0.0      0.0      0.0
7         233.89334   764.03519   0.0      0.0      0.0
```

Note that for each star in the FGS observations, there **must** be an entry in the "catalog-par" file containing an initial estimate of the star's "catalog position" in (xi,eta) space (see below), the star's proper motion (mux,muy, in arc-seconds/day), and parallax, (par, in arc-seconds). In the example model shown above, these correspond to the model statement;

```
parameter xi[star], eta[star], mux[star], muy[star],
par[star];
```

The "star" number in the catalog-par file is nominally derived from the corresponding value of "Target_Number" in the RPS2 phase2 proposal. For example, star = 5 would be assigned to an observation of a star defined in a proposal's RPS2 target list as:

```
Target_Number: 5
    Target_Name: REF4
Alternate_Names: GSC2822.02075
    Description: STAR,CALIBRATION,ASTROMETRIC
       Position: RA=01H 36M 39.9S +/-1",DEC=41D 23' 48.3"+/- 1"
        Equinox: J2000
Coordinate_Source: GUIDE_STAR_CATALOG
Annual_Parallax: 0.0
           Flux:
                V = 14.72 +/- 0.1
       Comments:
```

Note that astrometry programs typically span several HST observing cycles, and therefore may have several phase2 proposals associated with the investigation. This may result in situations whereby a given object is assigned different values of "Target_Number", and hence "star" across proposal boundaries. In such instances, one must manually edit the CALFGSB output products so that a unique value of "Star" is assigned to each object for all epochs.

In the current example, the gaussfit model also contains the statement:

```
parameter a[set], b[set], c[set], d[set], e[set], f[set];
```

These parameters define the transformation (translation, rotation, and scale) of the coordinate system (the FGS X,Y frame) specific to one epoch on to that constraint epoch, or plate (as can be seen from the model file). This accommodates the fact that the observations across epoch boundaries are generally made at a variety of different spacecraft roll angles and attitudes. In the current example, the initial values of these transformation parameters are contained in the file "**plate-par**", whose content is displayed below. Note that there will be one row for each orbit of HST FGS astrometry data in the observing program. Thus in this example, the astrometry program spans 10 orbits of HST observing. The value assigned to "set" is determined by user input to CALFGSB. It is most convenient (but not required) that the data obtained from the program's first HST orbit are assigned to set=1, and all others are automatically assigned to (set+*i*), where *i* sequentially increments by one for each additional entry in the "day.list" file associated with the execution of CALFGSB. (Note that the ordering of the data sets in the day.list file need not be sequential in a temporal sense, although such ordering is highly recommended to minimize confusion when analyzing the results fully reduced data sets.)

```
/* example "plate-par" file for input by gaussfit   */
/* These comments must be deleted before executing  */
/* gaussfit.                                        */
set     a       b       c       d       e       f
double  double  double  double  double  double  double
1       1       0       0       0       1       0
2       1       0       0       0       1       0
3       1       0       0       0       1       0
4       1       0       0       0       1       0
5       1       0       0       0       1       0
6       1       0       0       0       1       0
7       1       0       0       0       1       0
8       1       0       0       0       1       0
9       1       0       0       0       1       0
10      1       0       0       0       1       0
```

While the first parameter file contains data relating to the astrometry of each star, the parameters in "**plate-par**" contain the values needed to transform the FGS (x,y) coordinate system from each HST orbit (or set) on to the (xi,eta) fiducial coordinate system displayed in the "**catalog-par**" file. Finally, the fiducial coordinate system is determined from the set which is constrained in the model. In the example ***gaussfit*** model file displayed above, this is set = 1, enforced by the statements:

```
exportconstraint(a[1]-1);      /* sets a[1] = 1  */
exportconstraint(b[1]);        /* sets b[1] = 0  */
exportconstraint(c[1]);        /* sets c[1] = 0  */
exportconstraint(d[1]);        /* sets d[1] = 0  */
exportconstraint(e[1]-1);      /* sets e[1] = 1  */
exportconstraint(f[1]);        /* sets f[1] = 0  */
```

In this case (xi,eta) will be the same coordinate system as (x,y) from observation set 1. Note that to align this to the celestial sphere, (x is east, y is north) one must rotate the coordinate system (clockwise) by an angle computed from the HST V3roll angle of set 1. For astrometry with FGS1r, this is angle given by (V3roll - 90).

Preparing the Catalog Parameter File

The initial "**catalog-par**" file can be conveniently constructed by editing the output product from CALFGSB (the *_ast file) of the data set which will also define the fiducial (xi,eta) coordinate system. Once the *_ast file has been edited so that either (Xvaofadapj2d, Yvaofadapj2d) or (Xvaofadapjrd, Yvaofadapjrd) becomes (X,Y), the columns (star, X, Y) should be extracted and written to the "catalog-par" file. This can be done using the utility "***extract***", a tool composed of C modules which can be downloaded from the FGS Web site. The Makefile needed to generate the executable is included in the tar file.

Once the executable has been generated, one types "extract" (or its alias) while in the local directory containing the *_ast file to be input. ***extract*** prompts for the name of the input file to be read and the output file to be created (assumed to be "catalog-par" for this discussion.) ***extract*** displays the name and number of each column in the input file and prompts for the column numbers to be extracted; one should enter the numbers of the columns named (Star, X, Y). This will generate an output file with the following characteristics:

```
star    X           Y
double  double      double
1       -159.3778   748.5757
2       -262.6193   703.8305
7       -274.7650   580.7143
23       -82.5666   712.9790
5         52.6686   699.9966
1       -159.3778   748.5757
2       -262.6190   703.8325
6         19.2643   654.9374
4         95.5635   751.2397
9        233.8837   764.0848
23       -82.5677   712.9762
1       -159.3776   748.5760
2       -262.6196   703.8321
7       -274.7629   580.7165
5         52.6690   699.9954
9        233.8824   764.0831
4         95.5615   751.2389
23       -82.5685   712.9757
1       -159.3778   748.5752
2       -262.6187   703.8322
7       -274.7654   580.7145
23       -82.5656   712.9789
1       -159.3775   748.5764
```

Note that there will generally be multiple entries (rows) for a given star since stars are usually observed several times over the course of an HST orbit. The output file should be edited to remove all multiple entries to leave only one row for each star. Generally, it does not matter which rows are retained and which are deleted; at this time the significance of a row in this file is to denote a catalog entry. The actual coordinates that appear will be over written by ***gaussfit*** when the final catalog is generated.

In keeping with the example ***gaussfit*** model, additional edits to the "**catalog-pa**r" file are needed. The columns named (X,Y) should be renamed (xi,eta). Three additional columns need to be created. These are (mux, muy, par), for proper motion and parallax. The second row, which specifies the data type of the column ("double", for "double precision variable" in this example), needs to be added for each new column. The values entered in each new row can either be zero or an initial estimate of the appropriate entity's value. Note that proper motion has the units arc-seconds/day, and parallax has the units arc-seconds.

Preparing the Transformation Parameter File

In the example ***gaussfit*** model presented on the preceding pages, a parameter file is also required to accommodate those parameters which define the translation of a given set's (X,Y) coordinates on to the fiducial (xi,eta). The current example employs a 6 parameter solution to make this coordinate transformation. The "**plate-pa**r" file will satisfy this need. Note there are 6 columns (a,b,c,d,e,f) and one row for each data set. A template of this file can be downloaded from the FGS Web site. The template should be edited to either add or delete rows as needed to match the number of data sets available for the analysis on hand.

Preparing the Environment File

gaussfit inputs an "environment" file from the command line. The environment file specifies the names of the data sets to be input, which are in fact the *_ast files created by CALFGSB (renamed in this example to par_v01, par_v02, ... , par_v10, where v01, v02, etc. correspond to visits 01, 02, ... , 10 for a parallax program with data from 10 HST visits). The environment file also identifies by name the catalog parameter file and the transformation parameter file ("**catalog-par**" and "**plate-par**" in this example). The entry RES6 specifies the root name of various files that will be created and written to by ***gaussfit*** to record intermediate results from each iteration in the convergence process. These are not particularly useful for non-developers (of ***gaussfit***) and will not be discussed further.

Note that there must be a row in the "**plate-par**" file for each data set identified in the environment file. For example, the environment file shown below identifies 10 data sets (par_v01 through par_v10). Therefore, the "**plate-par**" file must identify 10 data sets as well. Shown below is the contents of environment file (named **envfile**) appropriate for the ***gaussfit*** example under discussion.

```
results = 'RES6par'
data1   = 'par_v01'
data2   = 'par_v02'
data3   = 'par_v03'
data4   = 'par_v04'
data5   = 'par_v05'
data6   = 'par_v06'
data7   = 'par_v07'
data8   = 'par_v08'
data9   = 'par_v09'
data10  = 'par_v10'
param1  = 'plate-par'
param2  = 'catalog-par'
triang  = 1.0
prmat   = 1.0
prvar   = 1.0
tol     = 0.0
iters   = 20.0
sigma   = 0.4
scale   = 0.5
END
```

Running *gaussfit*

With the model, environment (**envfile**), and parameter files ("**catalog-par**" and "**plate-par**") properly prepared, and the appropriate output products from CALFGSB (the *_ast files or renamed versions of them specified in the **envfile**) edited to rename a pair of columns X and Y, one is finally ready to execute the ***gaussfit*** program. This is done from the command line, simply by typing:

```
> gaussfit model envfile
```

where "**model**" is the name of the model file and "**envfile**" is the name of the environment file. ***gaussfit*** reads the environment file to identify the input data files and parameter files, which are then read in. ***gaussfit*** reads the model file for instructions on how to relate the observations to the parameters subject to the constraints stated in the model. A least squares approach is iteratively utilized to find the solution with the global minima on the Chi-Square manifold. The results of this process are written into the parameter files. The initial (input) values of the parameters are overwritten with the values determined from the solution, New columns with the "deltas" and "sigmas" for each parameter are added to the parameter files. The data files (par_V01, e.g.,) have columns _X and _Y appended to them. Their row entries record the "error" of the X,Y measurement of the star's position for each individual observation relative to the derived catalog position (in the coordinate system of the visit).

For the model under discussion in this example, the most interesting quantities to result from this analysis are the new values for the proper motion and parallax (mux, muy, par) and their errors (sigma_mux, sigma_muy, sigma_par). Also of great interest are the residuals of the catalog positions (ξ,η), namely (sigma_xi, sigma_eta). In the example presented here, these residuals are recorded in the file "**catalog-par**" revised by ***gaussfit***.

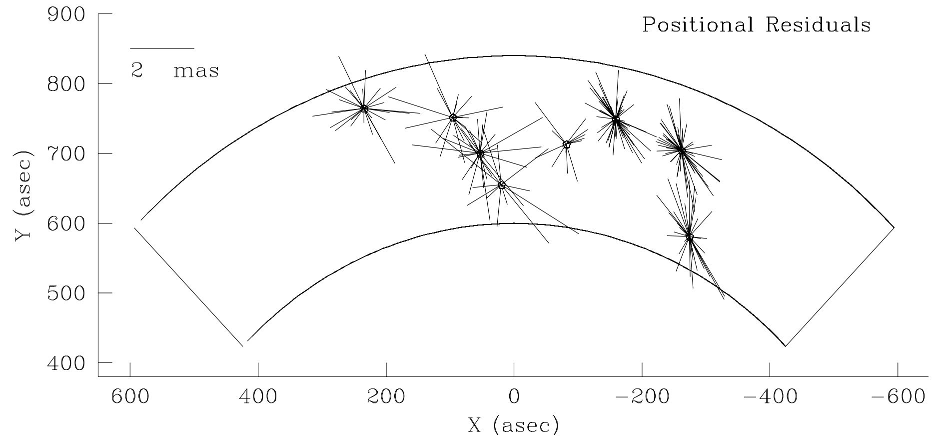
A note of ***extreme caution***. ***gaussfit*** overwrites the input parameter and data files. If it is necessary to rerun ***gaussfit*** on the same data after one or more outlier observations have been removed, it may be desirable to restore the parameter files to their initial condition. For this reason it is best to maintain a "/backup" directory which contains the initial parameter and data files. If single observations are to be removed from the analysis, the data files (par_V01, e.g.) can be edited to delete the troublesome data. If data from the entire visit are to be ignored in the analysis, the environment file "**envfile**" and the "**plate-par**" file will need to be appropriately edited to remove pointers to the undesirable visit. Finally, if a given reference star is to be deleted from the analysis for all visits, it needs to be removed from all of the data files and the "catalog-par". (Actually the model file can be modified to ignore the specific star, e.g. "if (star != 1)".)

Displaying the Residuals; *plot-rss*

STScI has developed a convenient tool that can be used to display the residuals of an astrometric catalog generated using ***gaussfit*** on the output from CALFGSB. This tool, ***plot-rss***, can be downloaded from the FGS Web site. It is composed of C and Fortran modules that call SMSM for plotting. (You may need a site license for SM. STScI is working to replace the SM component with a publicly licensed graphics package.)

On the following page, a terminal session where ***plot-rss*** was invoked to plot the astrometric residuals of the individual measurements of star positions relative to their catalog positions derived (from these individual observations) using ***gaussfit***. User input is in **bold**. Figure 4.3 shows the plot generated by ***plot-rss*** in this example.

Figure 4.3: Sample plot-rss output showing positional residuals in the FGS FOV




```
phoenix> plot_rss
Choose type of overlay plotting:
        A. Singular data file for per-obs plotting
        B. Multiple data files for per-obs plotting
        C. Singular .srms file for day plotting
        D. Multiple .srms files
        E. Plot the star positions only (no res)
        Q. quit
 ................................................ -> b
 enter name of the file with the list of input file:
visit.list
 Enter catalog parameter filename ............... ->
catalog-par
 enter title of plot: Positional Residuals
 What do you want to do next?
     Enter 'p' to output plot to a file with current scale.
     Enter any integer value to change (mas) scale value.
     Or, enter q or Q to quit and go back to main menu.
 ................................................ -> 2
 What do you want to do next?
     Enter 'p' to output plot to a file with current scale.
     Enter any integer value to change (mas) scale value.
     Or, enter q or Q to quit and go back to main menu.
 ................................................ -> p
 What do you want to do next?
     Enter 'p' to output plot to a file with current scale.
     Enter any integer value to change (mas) scale value.
     Or, enter q or Q to quit and go back to main menu.
 ................................................ -> q
 Choose type of overlay plotting:
        A. Singular data file for per-obs plotting
        B. Multiple data files for per-obs plotting
        C. Singular .srms file for day plotting
        D. Multiple .srms files
        E. Plot the star positions only (no res)
        Q. quit
 ................................................ -> q
 phoenix>
```

Note from the dialog in the terminal session that a variety of results can be displayed. In this particular case, the file “**visit.list**”, generated by the simple unix command "ls par_V* > visit.list", contains the names of the data files that have been processed by ***gaussfit*** (par_v01, par_V02, etc., for example). ***plot-rss*** also prompts for the name of the catalog parameter file (**catalog-par**), which defines the location of the stars in (xi,eta) space, and is used to plot their catalog positions in the FGS. ***plot-rss*** reads the data files and extracts (star, _X, _Y), where "star" identifies the catalog entry (and provides a map to its catalog position). _X and _Y are the residuals of the star's measured position for that particular observation (relative to its catalog position). ***plot-rss*** plots the vector (_X, _Y) with its origin located at the catalog position of "star". The scale length of the vector can be adjusted as needed to optimize the usefulness of the display. In the case of Figure 4.3, the scale length of 2 mas, as indicated on the plot, was chosen.

4.4 Transfer Mode Data Analysis

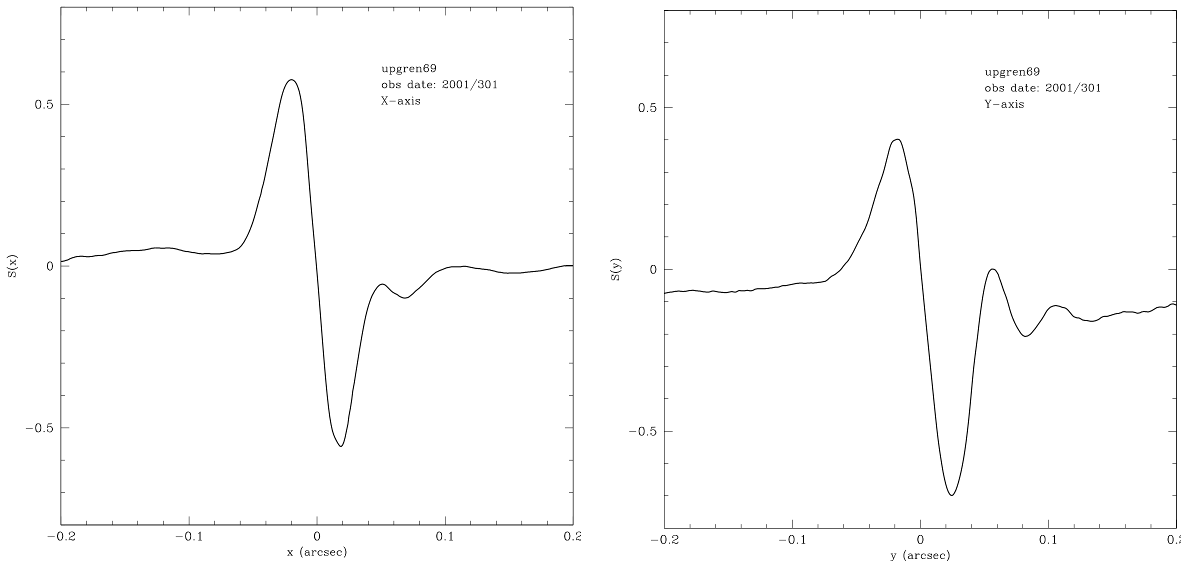
Transfer Mode observations with the FGS can resolve the individual components of multiple star systems and measure the angular diameters of extended objects. These observations scan the FGS's instantaneous field of view (IFOV) across an object to accumulate the necessary data for a post observation reconstruction of the x and y axis interferograms, or S-curves. By comparing the observed S-curves with those from a single (point source) reference star in the calibration database one can deconvolve the contribution of each component in a multi-star system or each chord of an extended object. Such an analysis can reveal the magnitude difference and relative separation and position angle of a binary star system or the apparent angular diameter of an extended object in both the x and y directions.

Routine pipeline processing of Transfer Mode data by CALFGSA, (discussed in Chapter 3), is confined to locating the individual scans within the data files, editing out bad data, and computing guide star centroids and standard deviations during each scan. The CALFGSA output consists of a variety of files to be used by the analysis packages discussed in this section.

Although some observers have used the FGS in Transfer Mode as a photometer or to measure the angular diameters of giant stars, by far the most common use of Transfer Mode has been to resolve close binary or triple star systems to measure the component separation(s), position angle(s), and relative brightness(es). A multi-epoch program that monitors a binary over time can derive its visual orbit. Unlike radial velocity studies, an orbit determined by the FGS reveals the system's inclination. Additional information about the system's parallax (which can be obtained by FGS Position mode observations) or radial velocities (for double lined spectroscopic binaries) can be used to determine the component masses.

To provide some background for the analysis of Transfer Mode observations, we briefly discuss the interferometric response of the FGS to the wavefront from a point source and a binary star (for a detailed discussion, please consult the *FGS Instrument Handbook*).

Figure 4.4: Point-source reference scans for the FGS in Transfer Mode



Single Stars (Point Sources)

The wavefront of a point source at the face of a Koester prism (the interferometric element of the FGS optical train) is collimated, coherent, polarized, and characterized by a propagation vector. As the instantaneous field of view of the FGS scans across the target, the tilt of the wavefront varies and the PMTs register different relative intensities. Plotting the position of the IFOV along the scan path against the normalized difference of the PMTs reveals, for example, the characteristic point source X and Y axis interferograms, or S-curves, of the FGS1r (Figure 4). Note that the response along the X-axis is different than that along the Y-axis. This is due to a slight difference in the alignment of the FGS optical axis along X and Y relative to HST's OTA. These misalignments, coupled with HST's spherical aberration, produce higher order aberrations which effect the X and Y axis interferograms differently. (The X-axis S-curve is nearly ideal.) These small aberrations do not degrade the instrument's performance; performance tends to be limited by the S-curves' temporal stability and spacecraft jitter, factors that become more important as one attempts to resolve structure on smaller scale (nominally below ~15 mas).

Binary Stars

If the source is a double star, then its wavefront will have two components, each coherent with itself but incoherent with respect to the other. Two propagation vectors characterize this wavefront and the angle between them is directly related to the angular separation of the stars on the sky. As the FGS's IFOV scans across the object, each component of the wavefront generates its own (point source) S-curve, whose amplitude is reduced by the non-coherent "background" contributed by the other star.

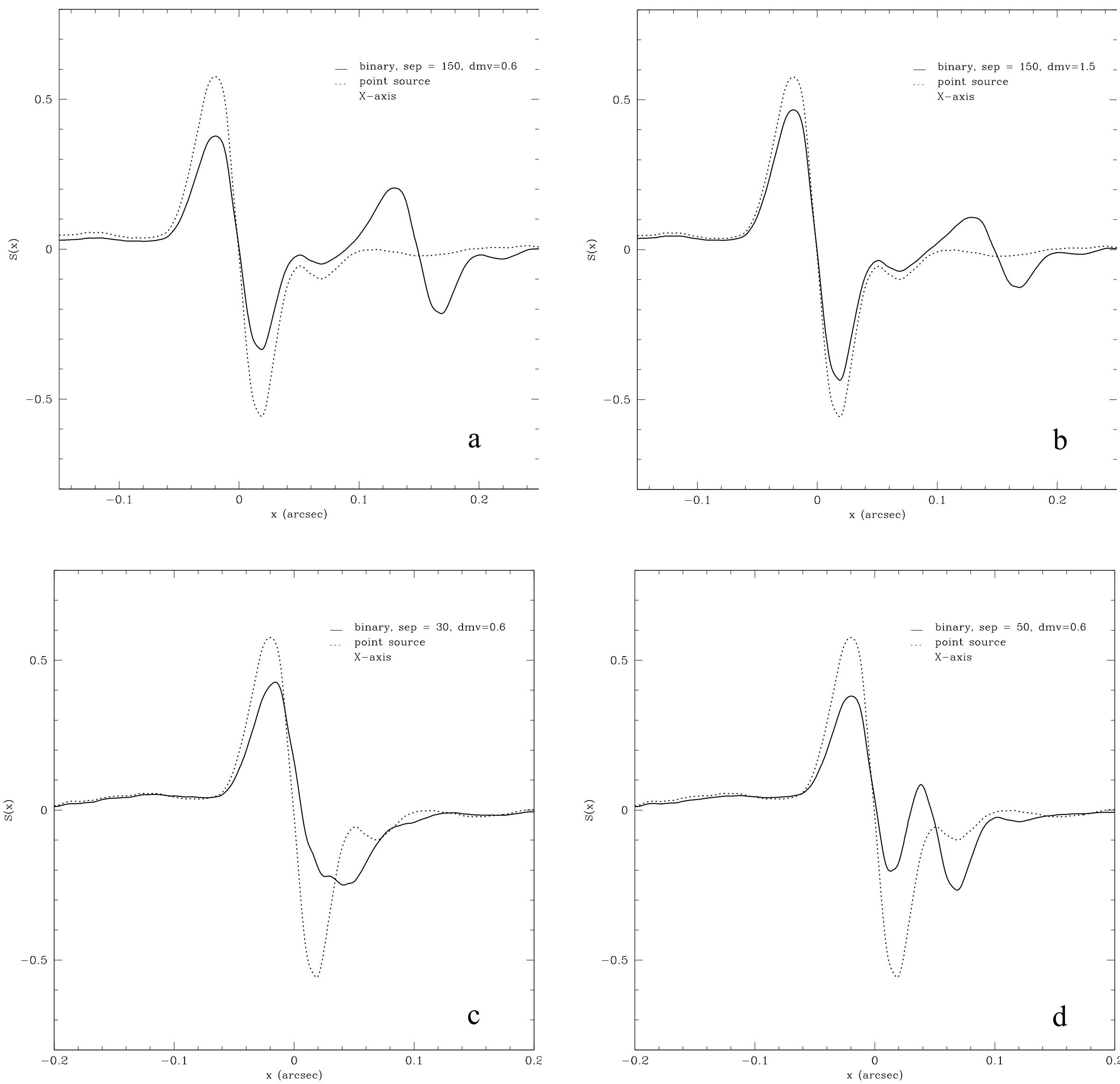
If the angular separation of the stars is greater than the characteristic width of an S-curve (about 60 mas), two distinct S-curves will be apparent, but the modulation of each will be diminished relative to that of a single star by an amount depending on the relative intensity of the stars.

For illustration, Figure 4.5 shows X-axis interferograms to be expected from (a) a binary with a separation of 150 mas and $\delta m_V = 0.6$ and (b) the same separation as (a) but with $\delta m_V=1.5$. For reference the S-curve of a point source (dotted line) is superimposed on that of the brighter component in both (a) and (b).

On the other hand, if the angular separation is sufficiently small, the S-curves will be superimposed, and the morphology of the resulting blend will be complicated. Figure 4.5 shows the X-axis S-curves to be expected from a binary system with a $\delta m_V = 0.6$ and (c) a separation of 50 mas and (d) a separation of 30 mas. As in Figure 4.7a and b, a point source S-curve (dotted line) is superimposed on the brighter component in (c) and (d) for reference.

In either case, the composite S-curve can be deconvolved using reference S-curves from point sources, provided the angular separations are not too small and the magnitude difference is not too large. To be more precise, fitting the observed double star S-curve with two appropriately weighted, linearly superimposed reference S-curves from single stars can determine the projected angular separation and magnitude difference of the binary's components along each FGS axis. By combining the X and Y data the binary's true projected angular separation and position angle can be measured.

Figure 4.5: Transfer Mode scans of binary stars (relative to point source scans)



Transfer Mode and Faint Targets

The modulation, morphology, and temporal stability the point-source S-curves ultimately determine the resolving power of an FGS for objects brighter than V ~15. For fainter objects, the photon noise inherent in the individual scans makes cross correlation of the individual scans more challenging, which in turn makes the removal of spacecraft jitter more difficult. FGS1r has successfully observed stars in Transfer Mode as faint as V=16.6 with good S/N. However the loss of fringe visibility, due to the dark + background light, which is comparable to the source for such faint targets, probably degrades FGS1r's angular resolution to about 12 mas (compared to ~7 mas for brighter stars) for binaries with $\delta m_V < 2$.

4.4.1 Transfer Mode Data Reduction

The astrometry pipeline routine CALFGSA locates and extracts the individual scans of a Transfer Mode observation. As discussed in the previous chapter, files with names such as rootname.1s1, rootname.1s2, ... , rootname.*i*s*j*, are output, where rootname identifies the observations (i.e., f4mb0602m), *i* = fgs_id (1,2,3) and *j* = scan_id. Files for all three FGSs are output by CALFGSA (unless one of the guiding FGSs is inactive, i.e., not tracking a guide star, in which case no files for that FGS are output).

The analysis package "***ptrans***", available for download from the FGS Web site (http://www.stsci.edu/instruments/fgs/), is a convenient tool for the processing CALFGSA output files. ***ptrans*** takes as input the rootname.*i*s*j* files for the astrometric FGS and cross correlates, co-adds, and smooths the co-added S-curves in an interactive, iterative fashion. During the process, individual Transfer Mode scans can be plotted against the current iteration's co-added S-curve. Data from individual scans can be evaluated for quality and corruption (from space craft jitter). Individual scans can be eliminated from the next iteration's co-addition process (if desired). As with the other FGS analysis tools that offer graphical output, the current package utilizes SM. A site license may be needed if you wish to port ***ptrans*** to non-STScI sites.

Aside from the graphical displays and data quality assessments, ***ptrans*** performs the following routine operations on the input scan data:

1. Cross-correlation of each scan in order to detect any drift of the FGS across the sky during the course of the observation. Cross-correlation is an option that can be declined. This might be appropriate when processing observations of objects fainter than V~15 since the data from individual scans are photon noise dominated to such an extent that cross correlation becomes increasingly unreliable (i.e. harmful) with increasing V magnitude.

2. Shifting of each scan by the amount determined necessary in step (1) so that all scans are mapped to a common reference frame. If the option to cross-correlate is declined, no shifts are performed.

3. Co-adding the individual scans to generate a high signal to noise ratio (S/N) S-curve. Each step of the IFOV along each scan is placed into an appropriate bin, and then all entries in a given bin are averaged to produce the high S/N co-added S-curve.

4. Fitting of a piece-wise third-order polynomial fit to the binned and co-added S-curve. **ptrans** provides the user with the ability to interactively fine tune the smoothing process. This helps to avoid imposing false artifacts into the final product on the one hand but also yields the highest (reliable) S/N final product.

If the observation under analysis is of a binary star system and the observer wishes to determine the angular separation, position angle, and magnitude difference of its components, the following additional steps are undertaken.

5. Select the appropriate set of reference S-curves from the calibration library on the basis of the target color (or colors) and the dates of observation of both the binary system and the calibration stars. These dates should be as close as possible to minimize the impact of temporal variations in the particular FGS. (FGS3 was the astrometer before cycle 8, FGS1r has been the astrometer since.) The appropriate calibration data files can be downloaded from the FGS Web site; follow the links to calibration data files.

6. Use the tool "***binary-fit***", also available for download from the FGS Web site, to determine the component angular separation, position angle, and magnitude difference. This fitting is done on both the *x* and *y* axis. ***binary-fit*** inputs the products from ***ptrans***, the rootname.tab file from CALFGSA, and the appropriate files gather from the STScI FGS calibration library in step (4).

The following sections describe the tools ***ptrans*** and ***binary-fi***t. Detailed instructions in their use, supported by examples captured from terminal sessions, are provided.

ptrans

The analysis package **ptrans** is composed of Fortran and C source code. ***ptrans*** inputs the rootname.*isj* products output by CALFGSA for Transfer Mode observations. ***ptrans*** makes extensive use of graphical output (calls to SM graphical routines). ***ptrans*** is available for download from the FGS Web site. The source code and necessary Makefiles and README files are available in the tar ball.

Once an executable image of ***ptrans*** is available, one prepares for using the package by gathering all of the observation's rootname.isj files into one directory. Then, while in that directory, simply type ptrans.e or its alias to activate the tool. Displayed below is the first iteration of ***ptrans*** captured from a terminal session while processing a Transfer Mode observation of a calibration point source. This particular observation of a bright source (V=9) had only 10 scans. User input is in **bold**.

```
phoenix>
phoenix> ptrans
 enter: name of the obs or file with list of scans -> f6jy0603m
 perform cross correlation (y/n) ................ ->
 process which axis (<CR> = both X and Y) ........ ->
 shall the individual scan files be output? ...... ->
 processing raw data files:
 scan number:   1
 xmin, xmax:     -3.2016769795403   -2.4839188936758
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   2
 xmin, xmax:     -3.2016769795403   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   3
 xmin, xmax:     -3.2016780051335   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   4
 xmin, xmax:     -3.2016780051335   -2.4795632243181
 ymin, ymax:      725.77640246615    726.49651093320
 scan number:   5
 xmin, xmax:     -3.2005912829108   -2.4795632243181
 ymin, ymax:      725.77640246615    726.49651093320
 scan number:   6
 xmin, xmax:     -3.2005912829108   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   7
 xmin, xmax:     -3.2005912829108   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   8
 xmin, xmax:     -3.2005912829108   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   9
 xmin, xmax:     -3.2016780051335   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan number:   10
 xmin, xmax:     -3.2016780051335   -2.4828317962067
 ymin, ymax:      725.77640246615    726.49515453408
 scan:   1    -2.837  0.642  -0.634          1.276
             726.113  0.420  -0.710          1.130
 scan:   2    -2.834  0.623  -0.632          1.255
             726.112  0.424  -0.710          1.134
 scan:   3    -2.841  0.621  -0.633          1.255
             726.108  0.422  -0.731          1.153
 scan:   4    -2.830  0.641  -0.621          1.263
             726.106  0.406  -0.718          1.124
 scan:   5    -2.835  0.636  -0.628          1.264
             726.112  0.417  -0.711          1.129
 scan:   6    -2.828  0.641  -0.616          1.257
             726.102  0.422  -0.719          1.142
 scan:   7    -2.846  0.610  -0.640          1.250
             726.112  0.428  -0.711          1.139
 scan:   8    -2.845  0.643  -0.639          1.283
             726.109  0.428  -0.721          1.149
 scan:   9    -2.842  0.640  -0.642          1.282
             726.112  0.417  -0.724          1.141
 scan:  10    -2.842  0.622  -0.624          1.246
             726.110  0.417  -0.708          1.125
 processing X axis, iteration #  1
        ----------- X axis -----------
  scan    shift     rel_diff    sd_fr       sd_wg      ave_sd_fr   sd_wings
     1    -3.38      1.36       0.1383      0.0104      0.1015      0.0014
     2     0.00      0.88       0.0898      0.0103      0.1015      0.0014
     3     0.64      0.94       0.0949      0.0110      0.1015      0.0014
     4     1.47      1.19       0.1209      0.0101      0.1015      0.0014
     5     0.35      0.82       0.0832      0.0105      0.1015      0.0014
     6    -1.31      0.85       0.0862      0.0110      0.1015      0.0014
     7    -0.63      1.00       0.1016      0.0097      0.1015      0.0014
     8    -0.65      0.83       0.0845      0.0102      0.1015      0.0014
     9    -1.41      1.18       0.1197      0.0108      0.1015      0.0014
    10    -0.18      0.95       0.0961      0.0089      0.1015      0.0014
 enter scan numbers to omit,
 or    set maximum allowable threshold (fx.xx)
 or    choose to plot a scan (p#)
 or    compare smoothed/un-smoothed data (cp)
 or    change the smoothing parameter (sm) .... ->
```

In the first iteration of ***ptrans*** the user is prompted for the rootname of the files to be processed, or for the name of a file that contains a list (by name) of the files to be processed. This option allows for scans of the same object gathered by different observations (and hence different rootnames) to be processed by ***ptrans***, as might be the case when a given object is scanned in several different exposures in a given visit or if the visit contains more than one HST orbit.

The user is next offered the choice to have **ptrans** perform cross correlation of the individual scans so they can be shifted (to eliminate space craft jitter and/or drift). Simply entering ***<ret>*** defaults to invoke cross correlation. The option to decline may be appropriate for faint objects (V > 15) whose individual scans are dominated by photon noise rather than spacecraft jitter/drift. In such cases it is recommended that the analysis be tried both with and without cross correlation and the output be compared.

The next option - to process the scan data along only the x or y axis, or both - occurs if one simply enters ***<ret>.*** This option is convenient in situations where there is known to be useful data along only one of the FGS axis (a determination that can be quickly made using ***fgsplot***), or in situations when a smoothed and co-added final S-curve of satisfactory quality is already available for one of the axis (and there is no need or desire to repeat the processing of that data).

Next, ***ptrans*** offers the option to output the individual scan files. If this option is invoked, files with names such as *rootname.x1*, *rootname.x2, ...* , *rootname.xn*, will be output. The contents of each will be a listing of (X,Sx) for the given scan, where X is the location of the FGS IFOV along the scan path, and Sx is the instantaneous value of the S-curve along the x-axis for that 40 Hz sample. The same holds true for the *rootname.yi* files along the y-axis. This capability is usually not invoked. However it can be useful for analysis when confronted with garbled data or instances of high spacecraft jitter.

Once the initial input is provided, ***ptrans*** completes the setup by reading in and processing the data in all of the scan files. As discussed in the previous chapter, these files contain the star selector servo rotation angles (from which the IFOV x,y coordinates are computed), and the counts/25msec from the four PMTs. From these data the S-curves of the individual scans are re-constructed. The first set of screen output shows the (x,y) start and stop end points of each scan. This can be useful for quickly verifying the completeness of each scan. The next set of screen output shows data for each scan grouped into two rows. The first row shows the mid point of the x-axis scan and the +/- peaks of the value of that scan's x-axis S-curve. The second row shows the equivalent data along the y-axis. These data can also be useful for trouble shooting or identifying bad scans. At this point ***ptrans*** has completed the initial setup.

The results from the initial iteration are displayed next. Statistical data for each scan are presented in rows. The first column (*scan*) identifies the scan; the second (*shift*) displays the amount of shift, in milli-arcseconds (mas), deemed necessary by cross correlation; the third column (*rel_diff*) is a ratio of the values in columns 4 and 6; while the fourth column (*sd_fr*) shows the standard deviation of the individual scans'

S-curve relative to this iteration's co-added (but not smoothed) scan. These values are computed via the relation:

$$sdfrj = \sqrt{\sum_{i=m}^{n} (Sc\langle i\rangle - Sj\langle i\rangle)/(n-m)}$$

where *Sc(i)* is this iteration's co-added S-curve at position x(i), *Sj(i)* is the value of scan *j*'s S-curve at position x(i), and the range in i (=*m* to *n*) covers only the central 100 mas of the scan, to assure that only the fringes (and not the wings) are included in the calculation. Thus, the values in column 4 provide a rough estimate of the quality of the individual scans. The value in column 6 (*ave_sd_fr*) is simply the average of all values in column 4. The values in column 3 (*rel_diff*) is a more user friendly method of identifying the true outliers in column 4. Column 5 (*sd_wg*) is similar to column 4 (and is computed in the same way), except that the summation integral is restricted to the wings of the scan. This provides an assessment of the photometric noise in the S-curves, which is dominant in the wings (the wings of the S-curves are not sensitive to spacecraft jitter). Finally, column 7 (*sd_wings*), shows the standard deviation of the co-added S-curve compared to the best fit straight line in the wings of the scan, yielding insight about the photometric noise present in the co-added scan.

At this point the user is prompted to provide input for starting the next iteration. The first choice "***enter scan numbers to omit***", allows for specific, individual scans to be eliminated from consideration in the next iteration. These can be identified by scan number(s). If more than one is to be eliminated, the entries should be delineated with either comas or spaces. Note, entering a negative scan id, e.g., -3, will force scan #3 to be included in the next iteration. This can be useful if scans are inadvertently deleted, or to restore the quality of the final co-added S-curve if it is found to degrade when specific scans are deleted.

The second choice, "***set maximum allowable threshold (fx.xx)***", allows for the user to eliminate all scans whose value in column #2 (*rel_diff*) exceeds a specific (entered) value, e.g., *f1.15* would disqualify scans *1,4,9* in the example sited above (note the "*f*" must be entered to allow ***ptrans*** to apply this option). Invoking this option can be convenient when processing observations with a large number of scans (typically > 50).

The option to "***choose to plot a scan (p#)***" offers the ability to explicitly view a particular scan's S-curve and compare it to the current iteration's co-added (but not smoothed) S-curve. This can be useful when deciding whether or not to delete or retain scans that appear questionable on the basis of values shown in the 7 columns. If a particular scan is to be plotted, ***ptrans*** displays the (min,max) of the scan path (in x or y, depending upon which axis is being processed at the moment). The user is prompted to choose the segment of the scan path to be plotted. Entering "***a***" plots the entire scan, entering "***s***" plots the same segment that was chosen for the last plot (if this is the first iteration, entering "*s*" plots the entire scan). If numerical values for xmin and xmax are entered (instead of ***<ret>***, ***a***, or ***s***), the user is prompted to set the vertical limits of the plot. Entering ***<ret>*** sets the vertical limits to +/- 0.8, which is a convenient standard.

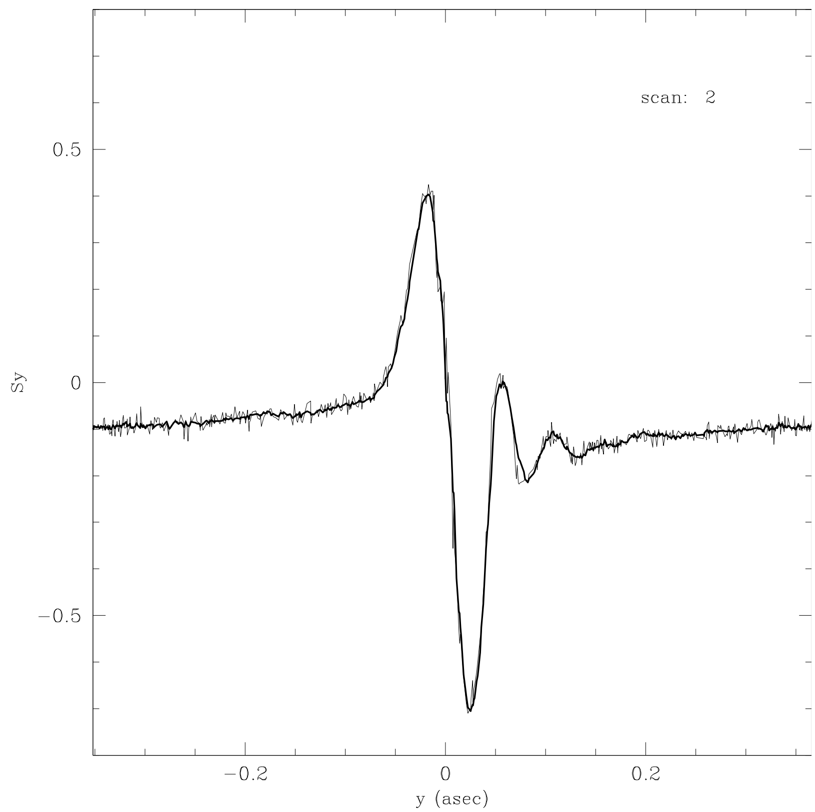
Once a plot is generated, the user is offered the opportunity to direct the plot to a postscript file ("***output the plot to a file?***"). If this option is invoked, a file named *scan_jX.ps* is generated, where *j* is the scan_id (and the X-axis is being processed in this example). Subsequent plots of scan *j*'s X-axis S-curve will over write this file.

The user is next presented with the opportunity to re-plot the data with different limits along the abscissa and ordinate. Entering ***<ret>*** defaults to "**no**". The user can mark the scan for deletion in the next iteration, and finally can plot a different scan (specified by scan #). The extracted terminal session segment shown below illustrates this interaction.

```
enter scan numbers to omit,
 or    set maximum allowable threshold (fx.xx)
 or    choose to plot a scan (p#)
 or    compare smoothed/un-smoothed data (cp)
 or    change the smoothing parameter (sm) .... -> p2
 "x" data ranges from (min,max) = (-0.352, 0.366)
 enter range to be plotted ("a" plots all, "s" plots same as before)
                                 --------------> xmin: a
 output the plot to a file? ................. -> y
 re-plot data with different limits? ........ ->
 mark scan for deletion? .................... ->
 enter next scan to plot .................... ->
```

The plot generated by this segment is shown in Figure 4.6. Note that responding to the ***ptrans*** prompts with <*ret*> generally causes the most commonly desired action to be taken (in the session excerpt displayed above, blanks after prompts correspond to <*ret*> responses.

Figure 4.6: ptrans plot showing co-added and smoothed Transfer Mode scans



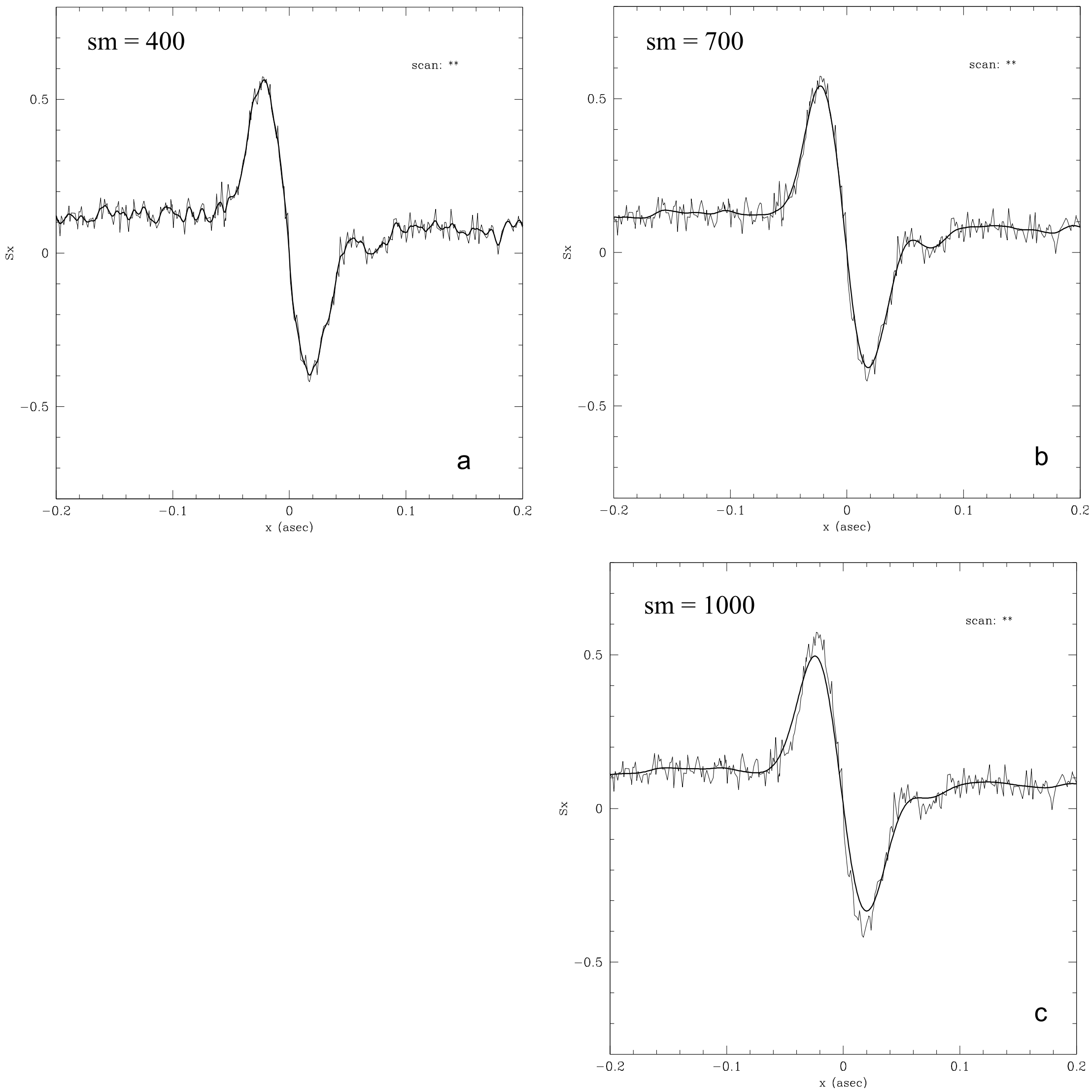
The last two options,

```
compare smoothed/un-smoothed data (cp)
change the smoothing parameter (sm) .... ->
```

allow for a fine tuning of the parameter "***sm***" which determines the degree to which the co-added S-curve is smoothed. The smoothing algorithm applies a third-order polynomial approximation to segments of the scan data. The length of the segments determines the degree to which the S-curve is smoothed. The value of ***sm***, in part, determines the length of these segments, and hence the degree to which the scan is smoothed. Too little smoothing (small ***sm***) needlessly retains noise in the final S-curve. To much smoothing (***sm*** too large) suppresses signal, which compromises the scientific conclusions one might make about the observation.

Figure 7 shows a comparison of smoothed vs. unsmoothed S-curves for three different values of ***sm***: 400, 700, 1000 (in panels a, b, and c respectively). These data are from an observation of a V=15.6 white dwarf star. The photometric noise in the wings of the fringe is apparent in the unsmoothed data. A value of ***sm***=400, does a poor job of suppressing the noise, as is evident in the how closely the smoothed curve tracks the noise in the wings. On the other hand, a value of ***sm***=1000 over suppresses the noise and results in the poor fit of the smoothed data within the S-curve peaks. The optimal value, ***sm***=700, smooths out the wings while retaining a good fit to the S-curve.

Figure 4.7: Smoothed vs. unsmoothed S-curves for three different values of *sm*



The initial value of ***sm*** is set to 500, but this might not be optimal. The best value can be found by invoking the ***ptrans*** option "***cp***". For example:

```
enter scan numbers to omit,
or    set maximum allowable threshold (fx.xx)
or    choose to plot a scan (p#)
or    compare smoothed/un-smoothed data (cp)
or    change the smoothing parameter (sm) .... -> cp
smoothing parameter currently set as sm =  500
enter new value (<CR> retains current value) --- > 800
"x" data ranges from (min,max) = (-0.466, 0.417)
enter range to be plotted ("a" plots all, "s" plots same as before)
                                   -------------> xmin: s
output the plot to a file? ................ -> y
re-plot data with different limits? ........ -> n
```

The script displayed above was extracted from the terminal session that produced figure 7a.

The last option, "**change the smoothing parameter (sm)**", displays the smoothed, co-added S-curve without the unsmoothed, co-added S-curve superimposed. As with the other options, the display can be output to a PostScript file if desired.

ptrans output

In addition to plots of Transfer Mode observations, ***ptrans*** generates three ASCII files listing x and S(x) of the co-added S-curve. These files follow the nomenclature

```
rootname.cx    -----------> co-added S-curve, x-axis

rootname.cx0 ------------> co-added, shifted S-curve,
x-axis,

rootname.cx0s -----------> co-added, shifted, smoothed
S-curve, x-axis
```

where rootname identifies the observations (e.g., f2bm0203m);

Similar files are generated for the y-axis data (*.cy, *.cy0, *.cy0s). The "shift" refers to a redefining of the x-axis coordinate system such that x=0 corresponds to the so-called zero point crossing of the S-curve, which is between the positive and negative peaks of the fringe. The plots displayed in figure 7 were all generated from the *.cxo and *.cx0s files. This zero point is also referred to as interferometric null, or the null point crossing. The same applies to the y-axis S-curves.

Two other files of interest - "xy.shifts" and "*rootname*.zero_point" - are ***ptrans products***. "xy.shifts", which records the shift of each scan as a result of the cross correlation procedure. If the option to cross correlate was declined, the shifts will be 0. The final file, "*rootname*.zero_point", lists the actual (x,y) location of the S-curve zero point crossing in FGS detector space coordinates (the same coordinate system used in the *.cx and *.cy files). It also lists the amplitude of the +/- peaks of the S-curves for both the x and y-axis.

Files "rootname.cx0s" and "rootname.cy0s" are the main products of ***ptrans***. Each contains the data-quality edited, cross correlated, co-added, and smoothed interferometric fringes of the observed target. This is the fully optimized S/N product of the observation. If the object is a binary system, for example, it is these files that serve as input to the binary star analysis package to be discussed in the next section. On the other hand, if the observation is of a point source calibration star, these files will become part of the FGS calibration library, and will serve as the point source "templates" needed for the analysis of Transfer Mode observations of binary or multiple star systems.

4.4.2 Analyzing Observations of Binary Stars

The most common use of the FGS as a science instrument in Transfer Mode is to resolve binary or multiple star systems. Because it is possible to sample the FGS's interferometric fringes in steps of ~1 mas, binary systems with separations well below HST's diffraction limit (down to ~10 mas) can be "resolved" by applying a model which compares the observed fringes of the target system to those from a (unresolved) point source. The point source calibration fringes are available from the FGS calibration library, and files containing these data can be downloaded from the FGS Web site.

Members of the Space Telescope Astrometry Team (STAT) from Lowell Observatory developed an analysis package which can be used to deconvolve the composite fringes of a binary star system to yield the separation, position angle, and relative brightness of the binary's components. The package employs a four-dimensional least squares algorithm to find the best fit (minimum Chi-square) of superimposed point source fringes to the observed binary star fringes. The four "dimensions" here refer to star separation projected along an FGS axis, the relative brightness of the components, the location within the scan of the brighter component, and a bias term which accounts for changes in the sensitivity of the photomultiplier tubes over the time between when the science data and calibration data were obtained.

This package has been made available to STScI, and has been modified by the STScI FGS group to account for the effect of (dark + background) photon counts in order to accommodate the analysis of faint (V > 14) binary systems. To facilitate an evaluation of the quality of the model fit to the observed data, STScI has further enhanced the package to graphically display an overlay of the observed binary star interferogram with that of a "synthetic binary" generated from the point source calibration data (using the derived values for star separation and relative brightness).

This Unix/Linux based analysis package, referred to as ***binary-fit***, is composed of Fortran and C modules. The source code and associated Makefiles can be ported by download from the FGS Web site.

binary-fit

Once an executable image of ***binary-fit*** is built on the host machine (using the source code and Makefiles provided by STScI), and an alias pointing to the executable is specified, the tool can be run by simply typing ***binary-fit*** (or some other user defined alias) while residing in the directory containing the files needed for input.

binary-fit takes as input the *.cx0s and *.cy0s files generated by ***ptrans***. These files, containing the co-added and smoothed interferograms, are needed for both the science target and the point source calibration star (which can be obtained from the

FGS Web site). Also needed are the *.tab files (generated by ***calfgsa)*** associated with both the science and calibration observations. Initially, ***binary-fit*** determines the projected component separation and magnitude difference (δm_V) along the FGS x and y axis independently. However, the δm_V of the stars should be the same along both FGS axis. ***binary-fit*** enforces this constraint (to within a small tolerance). If there is significant disagreement between the results along x and y, the user is prompted to identify which axis is to be refit (for component separation), with the constraint that the stars' δm_V is held fixed at the value determined along the other FGS axis. The choice of which axis to refit is usually based upon the quality of the fits along each axis (the Chi-Square values), i.e., refit the axis with the highest Chi-Square, or by adopting the δm_V determined from the axis with the wider projected separation of the stars. Examples of this are presented below.

An estimate of the relative brightness and separation (along an FGS axis) of the binary's components is useful for defining the region of parameter space that is probed for a minimum Chi-Square solution. These estimates need not be very accurate (especially for relative brightness); they serve only to avoid having ***binary-fit*** converge on a local minimum rather than the true global minimum on the Chi-Square manifold. Examples of this are also presented below.

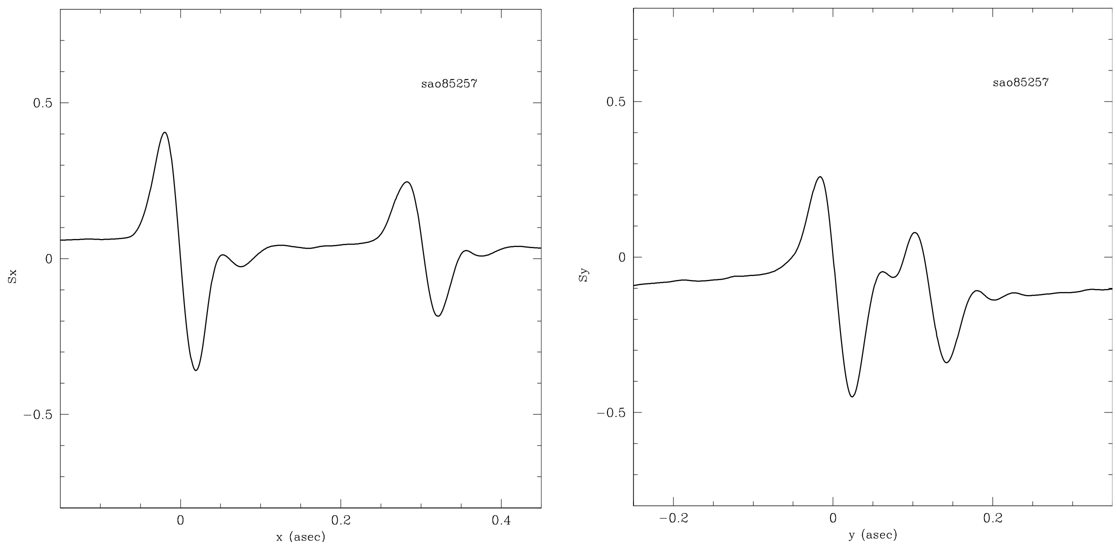
In the following two sections, examples are given for the analysis of "wide" and "narrow" binary star systems. Generally, wide systems refer to cases where the projected separation of the stars is larger than ~70 mas, resulting in two distinct S-curves, as displayed in Figure 4.5a and Figure 4.5b. Narrow systems have smaller separations, resulting in blended S-curves, as seen in Figure 4.5c and Figure 4.5d. Note however that the orientation of HST can be such that the binary's position angle is nearly aligned with one of the FGS axes. This will result in small projected separation of the binary's components along the orthogonal FGS axis, so even a wide binary might need to be treated as a "close" binary when analyzing the data along that axis.

binary-fit and wide binary systems

The example shown below displays a terminal session using ***binary-fit*** to determine the separation and position angle from observations of the wide binary system SAO85257 (V = 9.5, B-V = 1.2) from HST proposal 8835. The point source calibration star used in this analysis is the V = 9.7 FGS standard HD233877, chosen on the basis of its B-V = 1.1 color which is sufficiently close to that of the binary system (see "Uncertainties in Transfer Mode Data" on page 72 for a discussion about the effect of spectral color on FGS S-curve amplitude and morphology).

After processing the observation's raw GEIS files through the pipeline processor ***calfgsa***, the resulting products are processed through ***ptrans***. The graphical output from ***ptrans***, shown in Figure 4.8, clearly shows this to be a wide (sep > 100 mas) binary system a projected along both FGS1r axes. In cases such as this it is easy to estimate the separation of the stars along each FGS axis as well as their magnitude difference, δm_V (the relative amplitudes of the S-curves corresponds to the relative brightness of the two stars). These values can be used as initial estimates for ***binary-fit***.

Figure 4.8: ptrans output showing a binary projected along both FGS axes



In this example, the files needed for input by ***binary-fit*** for are

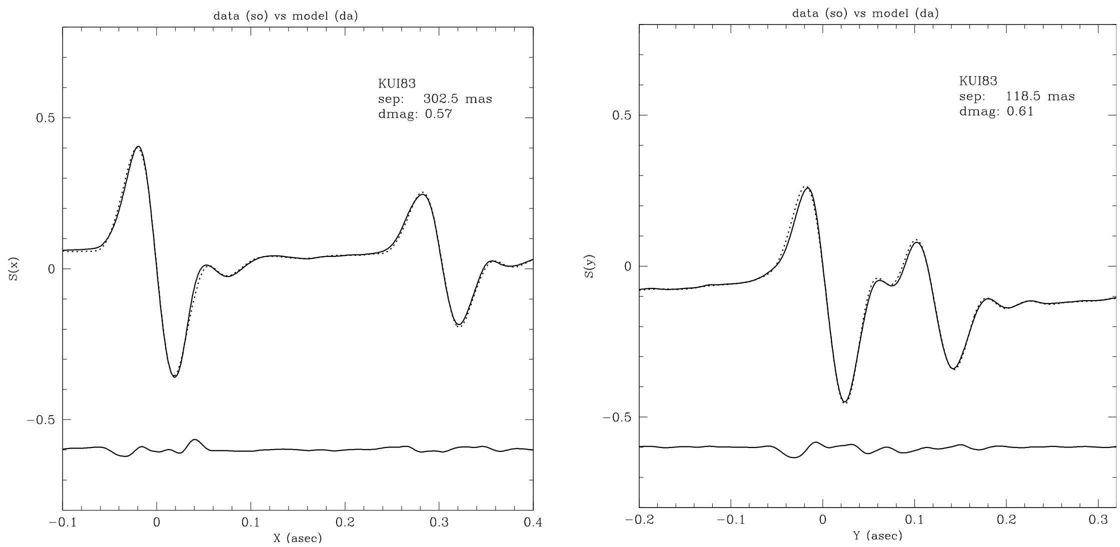
```
sao85257.cx0s
sao85257.cy0s
sao85257.tab

hd233877.cx0s
hd233877.cy0s
hd233877.tab.
```

With these files present in the default (current) directory, a session with ***binary-fit*** would appear as shown below. The entries in **bold** are input by the user in response to prompts (“>”) from ***binary-fit***. <*ret*> is entered for prompts with no explicit response.

```
phoenix> binary-fit
 enter name of the output file to be created .......... -> sa085257.v02.fit
 enter X-axis data file name ......................... -> sao85257.cx0s
 enter X-axis bright calibration star file name ....... -> hd233877.cx0s
 enter X-axis faint calibration star file name ........ ->
 BACKGROUND VALUES READ FROM TAB FILE ARE INVALID
 Enter PMTXA BACKGROUND (0 for default values)...-> 0
 USING DEFAULT VALUES
 enter N if the separation is narrow    <|0.025|:
 enter W if the separation is wide      <|0.100|:
 enter V if the separation is very wide <|0.300|:
 enter G for specific inital estimate [N/W /V/G]: v
 enter the estimated magnitude difference -> 0.3
 delta mag, b1, b2 --->  0.300      0.569      0.431
 magnitude difference to be held fixed?   -> n
 Initial X-axis solution:
      Star brightnesses: 0.600 0.400
             Separation:  300.0 mas
      Zero-point offset:    0.0 mas
                   Bias:  0.000
 X-axis Solution:
 Star brightnesses: 0.628   0.372 +/- 0.001
        Separation:  302.5 +/- 0.1 mas
 Zero-point offset:   -0.3 +/- 0.0 mas
              Bias:  0.000 +/-  0.000
    Sum of squares:  0.0479
 enter Y-axis data file name ......................... -> sao85257.cy0s
 enter Y-axis bright calibration star file name ....... -> hd233877.cy0s
 enter Y-axis faint calibration star file name ........ ->
 enter N if the separation is narrow    <|0.025|:
 enter W if the separation is wide      <|0.100|:
 enter V if the separation is very wide <|0.300|:
 enter G for specific inital estimate [N/W /V/G]: w
 enter the estimated magnitude difference -> 0.3
 delta mag, b1, b2 --->  0.300      0.569      0.431
 magnitude difference to be held fixed?   -> n
 Initial Y-axis solution:
      Star brightnesses: 0.600 0.400
             Separation:  120.0 mas
      Zero-point offset:    0.0 mas
                   Bias:  0.000
 Y-axis Solution:
 Star brightnesses: 0.636   0.364 +/- 0.001
        Separation:  118.5 +/- 0.1 mas
 Zero-point offset:    1.2 +/- 0.0 mas
              Bias: -0.001 +/-  0.000
    Sum of squares:  0.0357
 Solution good in X and Y
          X sep:   302.5 mas    dmag(x):  0.57
          Y sep:   118.5 mas    dmag(y):  0.61
  Total separation: ....................... -> 324.9 mas
  Magnitude diff for larger separation: ... ->  0.57
  Binary position angle ................... ->  98.5469
 ------- Preparing Graphic Overlays of Model and Data -----
  star name: KUI83
  xdmag:        0.56926279807765
  ydmag:        0.60589577453119
  xsep:          302.50721028580
  ysep:          118.54765305366
 -------------------- X-axis overlays ---------------------
 separation (mas) ... ->  302.5
 delta_magnitude .... ->    0.6
 s_curve max ........ ->  0.400
 s_curve min ........ -> -0.355
 s_curve pk-pk ...... ->  0.755
 shift (mas) ........ ->  0.244
 in fringe: number of points      :  200
            normalized difference :  0.036661
            total fringe area     :  0.026817
            total fringe diff     :  0.001614
 in wings:  number of points      :  400
            normalized difference :  0.055576
            total wings area      :  0.011349
            total wings diff      :  0.000631
 (xmin, xmax) = (-1.1, 0.7)
 enter desired range to plot: (<cr> plots -0.2,0.2)
                              ("a" plots all)
                                                     xmin: -0.125
                                                     xmax: 0.4
                                                     ymin: -0.8
                                                     ymax: 0.8
 Does diff curve need to be adjusted? ....... -> n
 Output the plot to a file? ................ -> y
 re-plot data with different (x,y) limits ... -> n
 -------------------- Y-axis overlays ---------------------
 separation (mas) ... ->  118.5
 delta_magnitude .... ->    0.6
 s_curve max ........ ->  0.266
 s_curve min ........ -> -0.456
 s_curve pk-pk ...... ->  0.722
 shift (mas) ........ -> -0.675
 in fringe: number of points      :  200
            normalized difference :  0.059618
            total fringe area     :  0.026580
            total fringe diff     :  0.001917
 in wings:  number of points      :  400
            normalized difference :  0.016001
            total wings area      :  0.020777
            total wings diff      :  0.000332
 (xmin, xmax) = (-0.7, 1.1)
 enter desired range to plot: (<cr> plots -0.2,0.2)
                              ("a" plots all)
                                                     xmin: -0.2
                                                     xmax: 0.325
                                                     ymin: -0.8
                                                     ymax: 0.8
 Does diff curve need to be adjusted? ....... -> n
 Output the plot to a file? ................ -> y
 re-plot data with different (x,y) limits ... -> n
 phoenix>
```

The graphics output by the package, showing the fit of the model to the data, are shown in figures 9a and 9b.

Figure 4.9: Output from binary-fit, comparing the model with observed data



As can be seen from the terminal session display, ***binary-fit*** prompts the user for the names of the files containing the science data and calibration data, the initial estimate of the stars' magnitude difference δm_V and their projected separation along each FGS axis, and a choice to either solve for δm_V or to hold it constant (at the initial estimate) while finding the best fitting separation. The option to hold the magnitude difference fixed is discussed in the section that addresses the analysis of close binary systems. A discussion about responding to the prompt:

```
BACKGROUND VALUES READ FROM TAB FILE ARE INVALID
Enter PMTXA BACKGROUND (0 for default values)...-> 0
USING DEFAULT VALUES
```

is likewise deferred to the section that addresses the analysis of faint (V > 14) binary stars. (For brighter stars, the default background values are recommended, i.e., respond with a "0").

The user has the option of entering then name of a "*faint calibration star file name*". Because the amplitude and morphology of point source S-curves is a mild function of the spectral color of the source (see "Uncertainties in Transfer Mode Data" on page 72), this option is useful in situations where the components of the binary are known to be of different spectral colors (e.g., a B star and a red giant). Note that the star that is expected to be the brighter component (in V) will be represented by the "*bright calibration star*" reference file, while the fainter component is represented by the "*faint calibration star*" (where "*faint*" is used as a relative term in this case). If both components have approximately the same color (δ(B-V) < ~0.2), then only one reference file is needed. By responding to the second prompt with a <*ret*>, the same reference S-curve will be used for both components in the fitting process.

After solving for (sep,δm_V), ***binary-fit*** compares the values of brightness ratios computed along both the x and y axis. If they differ by more than 20% the user will be alerted and prompted to specify which axis is to be re-fit. The brightness ratio on that axis will be held fixed at the value computed from the other axis.

Once a solution is achieved along both FGS axes, ***binary-fit*** reads the *.tab file associated with the science data to access the HST roll angle at the time of the observation. From this, the binary star's position angle is computed (the HST roll angle allows for a determination of the orientation of the FGS coordinate system relative to celestial North, while the measured separations δx,δy give the binary's position angle in the FGS coordinate system).

Next, ***binary-fit*** generates the fringes of a model "binary star" using the point source calibration data (from the files specified as the bright and faint model stars) and the (sep,δm_V) determined from the fitting process. This model fringe is cross correlated and differenced with the science data. A plot showing the overlay of the model with the data, along with their difference, is displayed to screen (see Figure 4.9). These plots can be adjusted for range along the abscissa and ordinate. The difference curve is displaced from 0 (for illustration purposes) by a default of -0.6 units. The user has the option to modify this placement if desired (e.g., if the default displacement causes the difference curve to become superimposed on the data/model curves). Finally, the plot shown on the screen can be captured to a postscript file.

binary-fit output files

Three files are output by binary-fit: the two postscript files containing the data/model overlay, and file TARGET_NAME.fit, where TARGET_NAME is the value specified by that keyword in the science observation's *.tab file. In the example cited above, TARGET_NAME = SAO85257. Therefore, a file named SAO85257.fit will be one of the output files. The postscript output with the model/data plots will be named SAO85257xfit.ps and SAO85257yfit.ps. The contents of the *.fit file records names of the data and calibrations input files and the details of the derived solution. The *.fit file generated by the example discussed above has the following contents:

```
x-axis:
 Data File ............... -> sao85257.cx0s
 Model star file ......... -> hd233877.cx0s
 y-axis:
 Data file ............... -> sao85257.cy0s
 Model star file ......... -> hd233877.cy0s
X-axis Solution:
Star brightnesses: 0.628   0.372 +/- 0.001
       Separation:  302.5 +/- 0.1 mas
Zero-point offset:   -0.3 +/- 0.0 mas
             Bias:  0.000 +/-  0.000
   Sum of squares:  0.0479
Y-axis Solution:
Star brightnesses: 0.636   0.364 +/- 0.001
       Separation:  118.5 +/- 0.1 mas
Zero-point offset:    1.2 +/- 0.0 mas
             Bias: -0.001 +/-  0.000
   Sum of squares:  0.0357
Solution good in X and Y
X sep:   302.5 mas    dmag(x):  0.57
Y sep:   118.5 mas    dmag(y):  0.61
Total separation: ...................... -> 324.9 mas
Magnitude diff for larger separation: ... ->  0.57
binary position angle .................. ->  98.5469
```

binary-fit and close binary systems

The FGS is well suited for resolving binary systems with component separations on the order of and below the HST diffraction limit. In such cases, “resolution” of a binary system results in a composite fringe that is clearly different from that of a point source, i.e., “resolution” does not mean that the observation produces two distinct S-curves. The morphology and amplitude of the composite fringe is a direct function of the projected angular separation of the stars and their relative brightness.

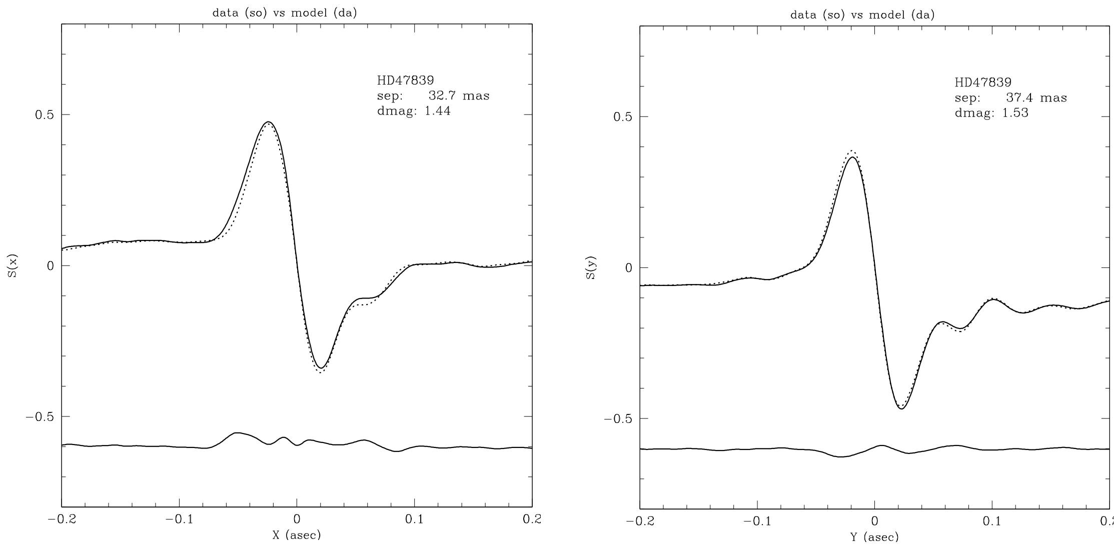
The analysis of a close binary system is carried out in the same way as for wide systems. However, for separations less than ~20 mas, ***binary-fit*** may find several different solutions with nearly the same Chi-Square values. In these situations, one solution tends to have a (comparatively) large δm_V and large separation, while another solution has a smaller δm_V and smaller separation. This underscores the utility of being able to specify and hold fixed the magnitude difference while executing ***binary-fit***, if the δm_V is known from another source, such as spectroscopy, or from another FGS measurement (e.g., the binary is observed at a different epoch with a wider separation, or has a wide separation on the other FGS axis in the same observation).

In the example shown below, ***binary-fit*** is used to determine the magnitude difference, separation, and position angle of the two stars comprising the O-star binary system 15 Monoceros in NGC 2264. These data show that at the epoch of this observation (HST proposal 7484, PI Gies), the stars had an angular separation of ~35 mas along both FGS axis. The user inputs are shown in **bold.**

```
phoenix> binary-fit
 enter name of the output file to be created .......... -> 15mon.fit
 enter X-axis data file name .......................... -> 15mon.cx0s
 enter X-axis bright model star file name ............. -> mucol.cx0s
 enter X-axis faint model star file name .............. ->
 BACKGROUND VALUES READ ARE INVALID
 Enter PMTXA BACKGROUND (0 for default values)...-> 0
 USING DEFAULT VALUES
 enter N if the separation is narrow    <|0.025|:
 enter W if the separation is wide      <|0.100|:
 enter V if the separation is very wide <|0.300|:
 enter G for specific inital estimate [N/W /V/G]: n
 enter the estimated magnitude difference -> 1.0
 delta mag, b1, b2 --->  1.000      0.715      0.285
 magnitude difference to be held fixed?   -> n
 Initial X-axis Solution:
      Star brightnesses: 0.800 0.200
             Separation:   36.0 mas
      Zero-point offset:    0.0 mas
                   Bias:  0.000
 X-axis Solution:
 Star brightnesses: 0.790   0.210 +/- 0.002
        Separation:   32.7 +/- 0.2 mas
 Zero-point offset:   -1.9 +/- 0.1 mas
              Bias: -0.006 +/-  0.000
    Sum of squares:  0.1512
 enter Y-axis data file name .......................... -> 15mon.cy0s
 enter Y-axis bright model star file name ............. -> mucol.cy0s
 enter Y-axis faint model star file name .............. ->
 enter N if the separation is narrow    <|0.025|:
 enter W if the separation is wide      <|0.100|:
 enter V if the separation is very wide <|0.300|:
 enter G for specific inital estimate [N/W /V/G]: g
 enter the estimated magnitude difference -> 1.0
 delta mag, b1, b2 --->  1.000      0.715      0.285
 magnitude difference to be held fixed?   -> n
 Bias held at 0.0
 Enter separation (mas) ..... -> 30.
 Enter zero point ........... -> 0.
 Y-axis Solution:
 Star brightnesses: 0.804   0.196 +/- 0.001
        Separation:   37.4 +/- 0.1 mas
 Zero-point offset:   -0.5 +/- 0.0 mas
              Bias: -0.001 +/-  0.000
    Sum of squares:  0.0307
 Solution good in X and Y
          X sep:    32.7 mas    dmag(x):  1.44
          Y sep:    37.4 mas    dmag(y):  1.53
 Total separation: ....................... ->  49.7 mas
 Magnitude diff for larger separation: ... ->  1.53
 Binary position angle ................... -> 221.5719
 ------- Preparing Graphic Overlays of Model and Data -----
 star name: 15Mon
 xdmag:         1.4403873195281
 ydmag:         1.5314270327478
 xsep:          32.714523260215
 ysep:          37.407251672547
 -------------------- X-axis overlays --------------------
 separation (mas) ... ->   32.7
 delta_magnitude .... ->    1.4
 s_curve max ........ ->  0.468
 s_curve min ........ -> -0.355
 s_curve pk-pk ...... ->  0.823
 shift (mas) ........ ->  1.876
 in fringe: number of points      :  200
            normalized difference :  0.062590
            total fringe area     :  0.036673
            total fringe diff     :  0.003067
 in wings:  number of points      :  400
            normalized difference :  0.126479
            total wings area      :  0.006100
            total wings diff      :  0.000772
 (xmin, xmax) = (-1.3, 0.8)
 enter desired range to plot: (<cr> plots -0.2,0.2)
                              ("a" plots all)
                                                     xmin:
 Does diff curve need to be adjusted? ....... -> n
 Output the plot to a file? ................. -> y
 re-plot data with different (x,y) limits? .. -> n
  -------------------- Y-axis overlays --------------------
 separation (mas) ... ->   37.4
 delta_magnitude .... ->    1.5
 s_curve max ........ ->  0.387
 s_curve min ........ -> -0.459
 s_curve pk-pk ...... ->  0.846
 shift (mas) ........ ->  0.826
 in fringe: number of points      :  200
            normalized difference :  0.035642
            total fringe area     :  0.037526
            total fringe diff     :  0.001621
 in wings:  number of points      :  400
            normalized difference :  0.015880
            total wings area      :  0.017848
            total wings diff      :  0.000283
 (xmin, xmax) = (-0.8, 1.3)
 enter desired range to plot: (<cr> plots -0.2,0.2)
                              ("a" plots all)
                                                     xmin:
 Does diff curve need to be adjusted? ....... -> n
 Output the plot to a file? ................. -> y
 re-plot data with different (x,y) limits? .. -> n
phoenix>
```

The plots output by ***binary-fit*** are shown in Figure 4.10, where the observed data is given by the solid line and the model by the dashed line. Note that the calibration (presumed single) star, μ *Col*, is a run away O-star ejected from Orion.

Figure 4.10: Model fit compared with data for the O-star binary 15 Mon

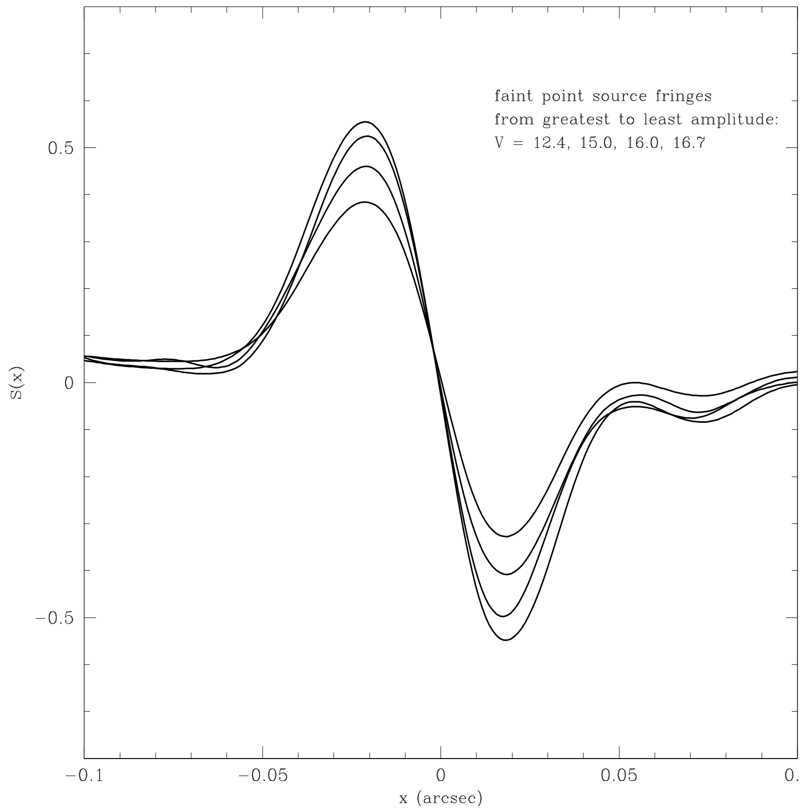


Analyzing Faint Binary Systems

For stars fainter than about V = 14.5, the dark + background counts registered by the FGS photomultiplier tubes (PMTs) becomes non-trivial compared to the counts registered from the source. At about V = 16.5, the source counts are about the same as the dark + background. Since the light from the star is not coherent with the "light" from the dark + background contribution, there is a loss of fringe "visibility", or amplitude, that becomes more and more dramatic as the instrument's faint limiting magnitude (V ~ 17) is approached. Figure 4.11 shows the S-curves obtained from scanning faint white dwarf stars (proposal 9169, PI Nelan). The S-curve with the greatest amplitude is from a V=12.4 star and is shown here to demonstrate the FGS fringes when the dark + background is insignificant. The increasingly lower amplitude S-curves are from white dwarfs with V = 15.0, 16, and 16.7, respectively.

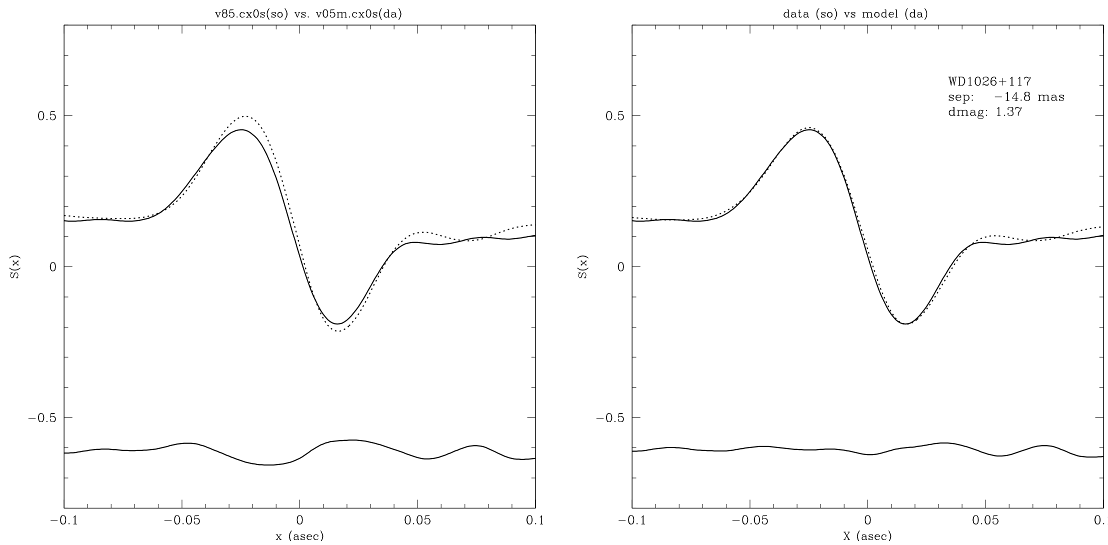
The calibration S-curves that populate the FGS reference library of point source fringes were all obtained from observations of stars typically brighter than about V < 9.5. When using these reference fringes to analyze Transfer Mode observations of faint stars, the reference fringes must be adjusted to account for the effect of the dark + background. In essence, the calibration S-curves must be processed to serve as a suitable proxy for point source fringes at the appropriately faint magnitude. The dark + background counts for both the science and calibration observations are recorded in the *.tab files. Using these values, as well as the photometry data (also included in the *.tab files), ***binary-fit*** adjusts the calibration S-curve for the dark + background effect.

Figure 4.11: Comparison of point source S-curves of decreasing magnitude



Using the S-curve from the V = 12.4 white dwarf shown in Figure 4.11 as a point source "calibration" S-curve, Figure 4.12a shows adjustment made by ***binary-fit*** to allow this S-curve to be used as a reference fringe for a V = 16.5 object that is most likely a very close (~20 mas) binary composed of white dwarf stars. For illustration, the faint science target (solid line) is displayed along with the adjusted calibration fringe (dashed line). Figure 4.12b compares the best fitting model found by ***binary-fit*** to this faint star's fringes. Only the x-axis data are displayed here, but similar effects also hold true along the y-axis which produced a fit consistent with that along the x-axis. Note that the negative separation (-14.8 mas) means that the fainter component is displaced to the left (negative direction) of the brighter primary.

Figure 4.12: Model fit compared with data for a possible white dwarf binary



4.5 Uncertainties in Transfer Mode Data

This section discusses several error sources associated with analysis of Transfer Mode data:

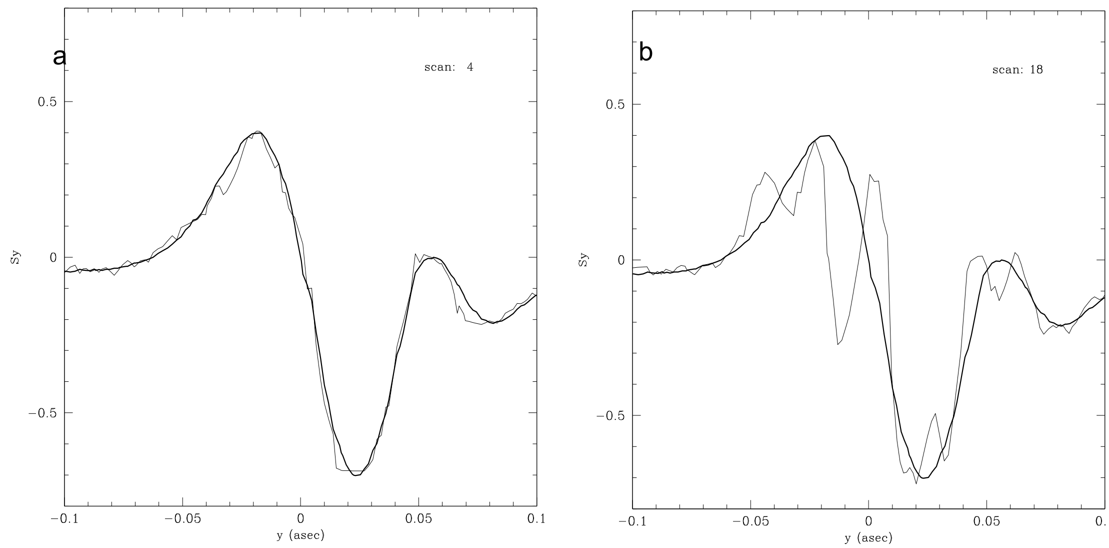
- Spacecraft jitter.
- FGS drift.
- Temporal variability of the S-curves.
- Wavelength dependence of the S-curves.
- Roll dependence of the FGS plate scale.

Spacecraft Jitter

When the FGS is used as an astrometer in Transfer Mode the observer typically specifies between 15 and 35 individual scans of the target in an exposure. Periods of extreme spacecraft jitter or telemetry dropouts can compromise the data from an individual scan. The usually mild jitter of the spacecraft is tolerable in the averaging process. But for incidents of extreme jitter, it is best to disqualify all corrupted scans from further analysis, an option supported by ***ptrans***.

To obtain high signal-to-noise S-curves, the single scans must be cross-correlated and co-added. Any (small) spacecraft motion that occurs during each scan will effectively blur the individual S-curves, ultimately causing the co-added S-curve to suffer some loss of spatial resolution. (Experience has shown that using the 40hz guide star data to "de-jitter" the Transfer Mode scans yields no benefits because the guide star centroids are photon noise dominated over such short integration periods.) Figure 4.13 compares the S-curves from two scans in the same exposure, one obtained during a time of nominal HST jitter (Figure 4.13a), and the other observed during a time of high spacecraft jitter (Figure 4.13b - HST was emerging from orbit “night” into orbit “day”, a terminator transition). The badly jittered scan is best deleted from the co-addition. These plots were produced with ***ptrans***. In each figure, the individual scan is plotted along with the current iteration’s coadded, unsmoothed S-curve.

Figure 4.13: "Quiescent" and "noisy" spacecraft jitter in Transfer Mode scans



Spacecraft and FGS Drift

As discussed in the calibration chapter, astrometry stars observed in Position Mode more than once in a given visit reveal that the FGS’s field of view drifts across the sky over the course of an HST orbit. This drift is also apparent in Transfer Mode observations. The cross-correlation of S-curves prior to co-adding automatically accounts for (removes) drift in Transfer Mode observations. Each single-scan S-curve is shifted so that the particular feature of the S-curve used for the cross correlation (typically the 100 mas region centered on the fringe’s zero point crossing) coincides with that of the fiducial S-curve. The reliability of implicitly removing the drift is only as good as the accuracy of the cross correlation procedure.

Proper cross correlation is relatively straightforward for bright objects ($V < 14$), but for fainter objects it becomes more difficult, just as binning and co-adding becomes all the more important. In such cases it might be advantageous to construct a drift model iteratively by time tagging the shifts determined by the cross-correlation procedure. Fitting of these shifts to a linear or quadratic drift model might align the individual S-curves more reliably than a procedure that depends solely on individual photon noise dominated scans. For bright stars with V < 14, drift in the FGS is estimated to degrade the resolution of Transfer Mode observations by about 1 mas. For fainter stars, the degradation will increase significantly in a way that depends on details of HST’s orbital environment during the visit. It’s noted in the discussion of drift in the *FGS Instrument Handbook* that the origin of this phenomenon is not well understood. It is not repeatable, and its amplitude depends weakly upon the declination of HST’s

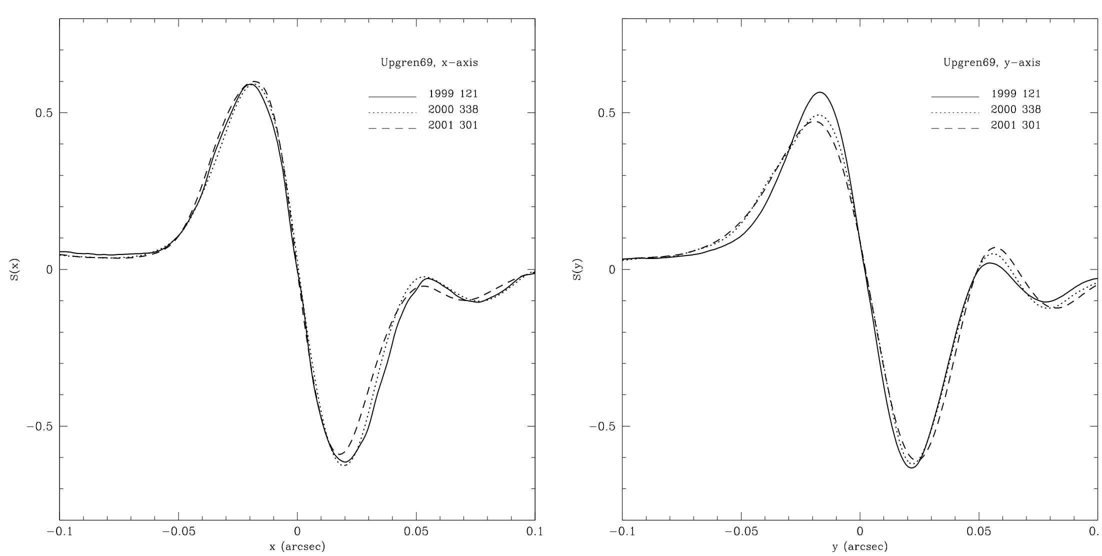
V1 axis. If a particular observation of a faint star (V > 15) was subject to typical drift of ~10 to 12 mas, then the estimated loss of angular resolution would be of order 4 mas.

Temporal Variability of S-Curves

Measurements of the standard star Upgren69 through the period when FGS3 functioned as the astrometric science instrument revealed a persistent but random temporal variability of the S-curve morphology and amplitude along both the x and y-axis. The large variability (~10%) of its x-axis S-curve rendered the instrument unusable for reliably resolving binary systems with separations less than ~20 mas.

Fortunately, FGS1r has not shown this behavior. Instead, changes in the FGS1r S-curves since October 1998 (the last time the AMA was adjusted) have been monotonic, and varies on long, year-like time scales. (FGS3's x-axis S-curves randomly varied on time scales of orbits!) Figure 14 plots the x and y-axis FGS1r S-curves obtained from observations in May 1998, Dec. 2000, and Oct. 2001. The x-axis S-curves have changed little over this time, while those along the y-axis showed considerable monotonic evolution between 1998 and 2000. Since late 2000, however, the changes have slowed dramatically. This evolution is thought to be a result of desorption of H_2O from graphite epoxy within the FGS which changes the alignment of the FGS with the telescope's optical axis. Because of HST's spherically aberrated wavefront, higher order aberrations are induced which results in the S-curve evolution. A comprehensive discussion of this topic is provided in the *FGS Instrument Handbook*.

Figure 4.14: Temporal evolution of FGS1r's S-curves along the X- and Y-axes



There are three ways to minimize the effects of temporal S-curve evolution:

- Obtain an observation of a calibration reference star at nearly the same time of the science observation.

- Select from the library of calibration S-curves the one obtained closest in time to the science observation.
- Determine a correction algorithm which interpolates in time between S-curves taken from the S-curve library.

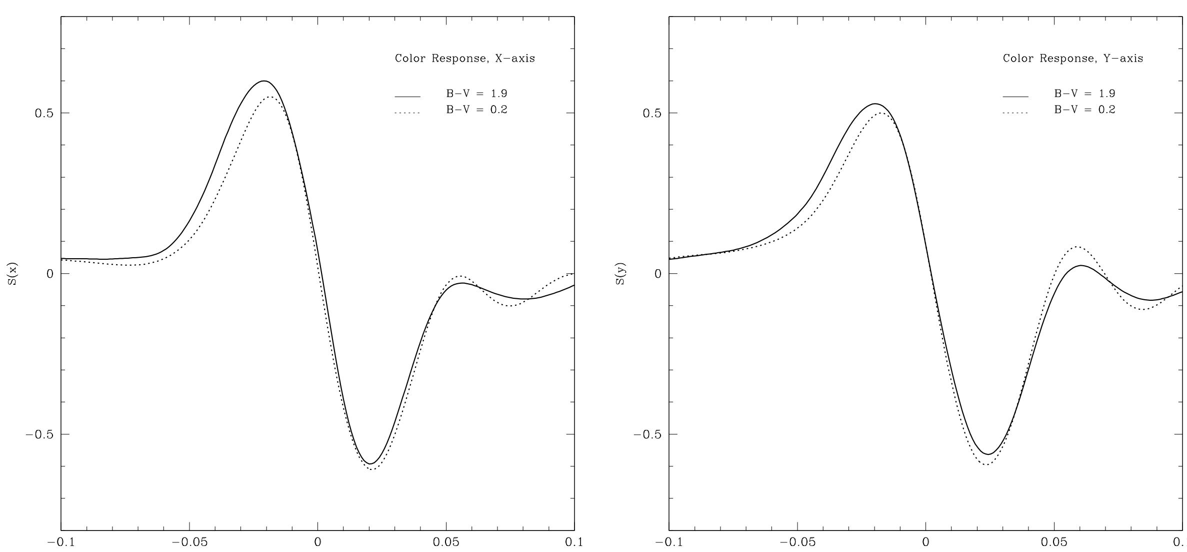
Calibration standards for binary and/or multi-component systems with small (sub-diffraction limited) separations may have to be observed close in time (~weeks) with the science target (as part of the GO proposal, or in coordination with the FGS calibration program). For less constrained programs, such as observations wide binary systems, selection of reference S-curves from the calibration library that are obtained within a year of the science observation should be adequate. (As part of the routine FGS calibration program, the standards in the FGS S-curve library are observed every cycle if needed to support the GO proposals.)

Interferometric Response and the Source's Spectral Color

The FGS interferometric response is sensitive to the spectral color of the observed source. Semi-empirical modeling and observational experience has shown that when the color difference δ(B-V) between a standard reference star and a science target exceeds about 0.3 magnitudes, the residuals of the ***binary-fit*** deconvolution rise and the derived parameters determining the component separation, position angle, and relative brightness becomes less reliable. This effect is most important for binary's with separations less than HST's diffraction limit. Wider systems are much less sensitive, although the fits of derived models to the data degrades.

The FGS calibration program includes observations of standard, unresolved (presumed single) stars whose colors are comparable - within 0.2 to 0.3 magnitudes - to the targets in that cycle's GO programs. Typically these are observed once per Cycle (if needed) and are available from the calibration library, which can be downloaded from the FGS Web site. For a non-subtle illustration of the importance of this effect, Figure 4.15 compares the S-curves from observations (separated by hours to minimize temporal variations) of two standards which differ in δ(B-V) by 1.7 magnitudes (B-V = 0.2 and 1.9 for the dashed and solid lines, respectively).

Figure 4.15: Color response of FGS1r along both the X- and Y-axes



CHAPTER 5:

Astrometric Error Sources

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5.1 Levels of Position Mode Errors

An FGS in Position Mode measures the relative angular separations of several objects. The objects generally will be separated by angles on the order of arc minutes, ranging over several magnitudes in brightness (possibly from V = 3 to 16.7), and will have different B-V colors. Because their parallaxes and proper motions need to be determined, HST will visit a given astrometric field several times, spanning perhaps two to four years or longer, over the course of an observing program. During each visit, the FGS will track each target in FineLock, one at a time, according to the instructions and sequence specified in the proposal.

Sources of error in these Position Mode measurements can be categorized into three distinct levels:

- ***Observation level***: errors associated with each individual FineLock acquisition and tracking sequence.
- ***Visit level***: errors involved in constructing a virtual plate for a given FGS astrometric visit.
- ***Field level***: errors that arise when comparing virtual plates of the same field taken during different visits.

Errors from lower levels will percolate through to the top.

5.2 Observation-Level Position Mode Errors

An individual observation in Position Mode acquires a single target in FineLock and tracks it for a specified period of time. The goal of the observation is to pinpoint the target's location in FGS detector space. Pipeline processing of Position Mode data converts the Star Selector A and B encoder angles into detector space (*x,y*) coordinates for the three FGSs and computes the median of these values over the period of time when the object was being tracked in FineLock by the astrometer. It then adjusts the astrometer's (*x,y*) centroid using data gathered by the four photomultiplier tubes (PMTs) during the slew of the Instantaneous Field of View (IFOV) to the target (to measure the background and dark counts), the WalkDown to FineLock, and the FineLock tracking of the object. This adjusted centroid is subsequently corrected for optical field angle distortion (OFAD), the aberration of the aspheric mirror, the cross filter effect if applicable, and finally, differential velocity aberration. Here we address the errors remaining after these steps.

5.2.1 Rotation Angle Errors

The Fine Guidance Electronics (FGE) reads rotation angles of the Star Selector A and B assemblies as 21-bit integers. The 14 most significant bits are determined by optically reading an absolute binary code pattern, while the 7 least significant bits are derived from an optical resolving device that reads a special encoder disk pattern that generates a quadrature set of sinusoidal signals. A correction to the 7 least significant bits leaves an uncertainty in the (*x,y*) values estimated to be about +/– 0.3 mas owing to noise and non-repeatability of the optical reader. The corrections to the 14 most significant bits are absorbed in the optical field angle distortion and therefore do not contribute here.

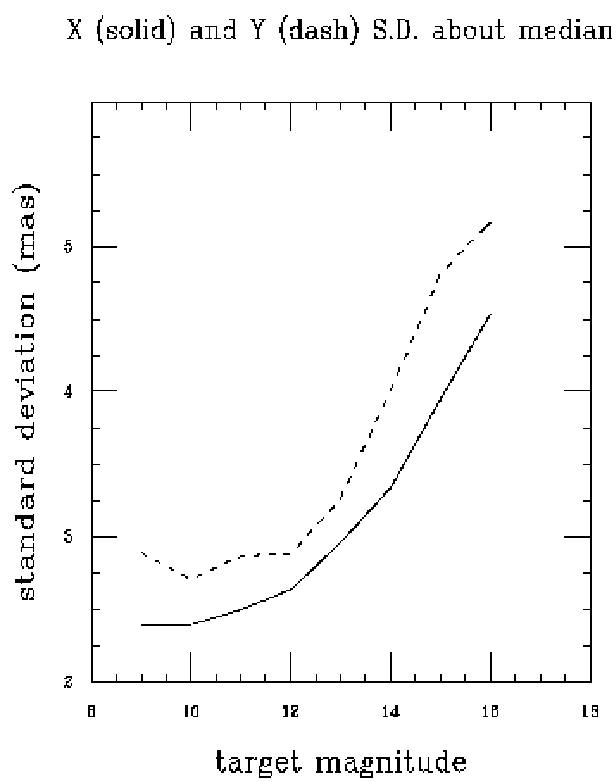
5.2.2 Centroiding Errors

During nominal FineLock tracking of an object, the instantaneous field of view of the FGS will jitter and drift about the (*x,y*) median over time scales not shorter than the fine error signal averaging time (FESTIME) and as long as the low frequency vibrational modes of the spacecraft (up to 40 seconds). The standard deviation of these excursions depends upon the magnitude of the target and HST vehicular jitter.

Target Magnitude

Because the FGS tracks an object by computing and implementing corrections to the current position of the IFOV on the basis of the fine error signal, noise in the PMT counts can introduce errors in the corrections. To compensate for the increase of the photometric noise for fainter targets, the FESTIME is increased to boost the signal/noise of the fine error signal. This adjustment not only yields fewer independent samples of the target's position but also results in more sluggish tracking. For example, a 320s exposure of a 17th magnitude object having an FESTIME = 3.2s generates only about 100 independent measurements of the target's position, while an observation of the same duration of a V = 9 object with FESTIME = 0.025s yields 12800 independent samples. In addition, as the FESTIME increases, the rms excursions of the IFOV about the interferometric null tend to be larger because the FGS responds more slowly to the high frequency HST vibrational modes (faster than 0.1 Hz). Figure 5.1 plots the standard deviation about the *x* and *y* centroids of 5000 stars measured in FineLock as a function of the target's magnitude. Note how steeply the standard deviation rises past V > 12.

Figure 5.1: Standard Deviation of IFOV about Median (x,y) Position as Function of Target Magnitude



The standard deviation of the FineLock tracking is not a direct measure of the observation's accuracy—it is the repeatability of the centroiding that reflects the observation's reliability. The pipeline computes the centroids over segments of the exposure, and it is the dispersion of these values that should be used to assess accuracy. Generally, the repeatability is about 1 mas for V < 14.5, increasing to about 2 mas for V = 16.

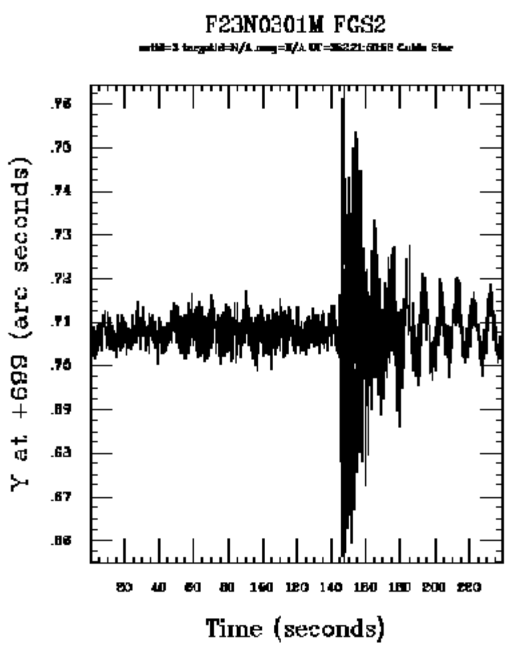
Vehicular Jitter

Analysis of both the guide star and astrometry data can reveal how successfully HST's pointing control system guided the spacecraft and stabilized its attitude during an observation. The guiding FGSs track their guide stars in FineLock, so their centroids and standard deviations can be computed and compared to those from the astrometer for identical intervals of time. The centroids of all three FGSs will show some jitter owing to the magnitude effect discussed above. However, the pointing control system is designed to minimize the impact of the internal jitter in the guiding FGSs on the pointing of the spacecraft, and for the most part, it succeeds. The jitter of bright astrometry targets is not systematically higher than that of the guide stars.

Nevertheless, transient events during the course of an observation can jitter the telescope, introducing additional noise in the tracking of the guide stars and the astrometry target. For example, as HST moves from orbital day to night or night to day, its solar panels undergo large temperature changes that excite HST's vibrational modes. These vibrations increase the standard deviations of FineLock tracking in the three FGSs by up to a factor of eight over the pre-transition values on short timescales (~180 seconds or less). Some events actually cause a small (5 mas) but significant temporary repointing of the telescope.

Figure 5.2 shows how night-to-day transitions can affect HST's pointing. The excited vibrational modes of HST are readily apparent and contrast sharply with the quiescence of normal guiding seen prior to the transition. This extreme case clearly demonstrates how such terminator crossings can induce significant spacecraft jitter.

Figure 5.2: Guide Star Motion in FGS 2 Before and During Night-to-Day Transition



Spacecraft jitter had been a major problem for astrometry observations during the first three years of the mission. The FGSs could not reliably hold the guide stars in FineLock over the span of the visit, and once lost, the guide stars for astrometry observations would not be recovered for the remainder of the orbit. However, improvements to both the pointing control system, in January 1993, and the solar panels, replaced in the first Servicing Mission, have reduced spacecraft jitter to a mild nuisance in the astrometry data reduction process which is well handled by proper application of the guide star data.

5.2.3 Locating Interferometric Null

During the acquisition of an object in FineLock, the Fine Guidance Electronics (FGE) attempts to eliminate differences in the responses of the two PMTs on a given channel by computing their average difference (DIFF) and average sum (SUM) at the starting point of the WalkDown to FineLock. For the remainder of the WalkDown and tracking in FineLock, the fine error signal is computed making use of these values.

The quality of this correction to the fine error signal depends in part on the errors in the determinations of DIFF and SUM, which depend in turn on the target magnitude and the integration time used to compute them. For bright stars (V < 12.5) the FESTIME is 25 msec and the DIFF, SUM values are computed from 16 intervals of 25 msec (0.4 sec total). On the other hand, the FESTIME for a V = 13 star is 50 msec, but the DIFF, SUM integration time remains at 0.4 sec, so only 8 FESTIME intervals are represented. Table 5.1 shows the FESTIME and DIFF, SUM integration times as a function of target magnitude. The important point to note is that as target magnitude increases, fewer FESTIME integrations are included in the evaluation of the DIFF and SUM. The values in this table are representative; actual FESTIME values depend on the filter and mode in use.

Table 5.1: FESTIME and DIFF, SUM Integration Times as a Function of Target Magnitude

Magnitude	FESTIME (seconds)	DIFF/SUM Integration Time (seconds)	# of FESTIMES Represented in DIFF/SUM
9	0.025	0.4	16
10	0.025	0.4	16
11	0.025	0.4	16
12	0.025	0.4	16
13	0.050	0.4	4
14	0.200	0.4	1
15	0.400	0.4	1
16	0.800	0.8	1
17	3.200	3.2	1

As targets become fainter, the FGE applies increasingly unreliable DIFF and SUM values in its calculation of the fine error signal and therefore risks locking onto a region of the S-curve which is not the true interferometric null. In such cases, the FGS's estimate of the fine error signal's value at null is not quite correct. Pipeline processing can determine the true null more accurately by using the WalkDown data to calculate better values of DIFF and SUM. The following values go into the adjustment of the median (x,y) centroid of the astrometer for this effect:

- The average counts / 25 msec of each PMT during the WalkDown, before the S-curves are detected.
- The average counts / 25 msec of each PMT during the FineLock tracking of the star while the FGS tracks what it believes is true interferometric null.
- The background contribution to the PMT counts.
- A reference S-curve providing the slope of the S-curve near null.

The size of the correction computed by the pipeline is small for bright stars but can be large for faint (V > 15) stars, up to 5 mas.

Each of the four components specified above contribute to the formal error associated with this adjustment. Errors from the first two depend on the number of photons counted during the WalkDown and the FineLock tracking. The error associated with the third also depends upon the number of photons registered while the background and dark counts were being evaluated, but note that these counts do not have a Poissonian distribution. The S-curve correction, which accounts for the field dependency of FGS1r's S-curves, interpolates the slopes of S-curves at nearby locations in the pickle, measured in a calibration program, to estimate the S-curve at the target's location.

Clearly the overall uncertainty of this correction will depend strongly upon the magnitude of the star and less sensitively on the exposure time. Figure 1.3 provides estimates of this error as a function of target magnitude for a typical Position Mode observation and background. These estimates assume that 80 *x*-axis WalkDown steps and 40 *y*-axis WalkDown steps were available for PMT averaging and that the target was tracked in FineLock for 60 sec.

Table 5.2: Estimated DIFF/SUM Correction Error as a Function of Target Magnitude

Magnitude	Error (mas)	
	X-axis	Y-axis
10	< 1	< 1
12	< 1	< 1
13	< 1	< 1
14	1	1
15	1.5	2
16	2	2
17	> 2	> 2

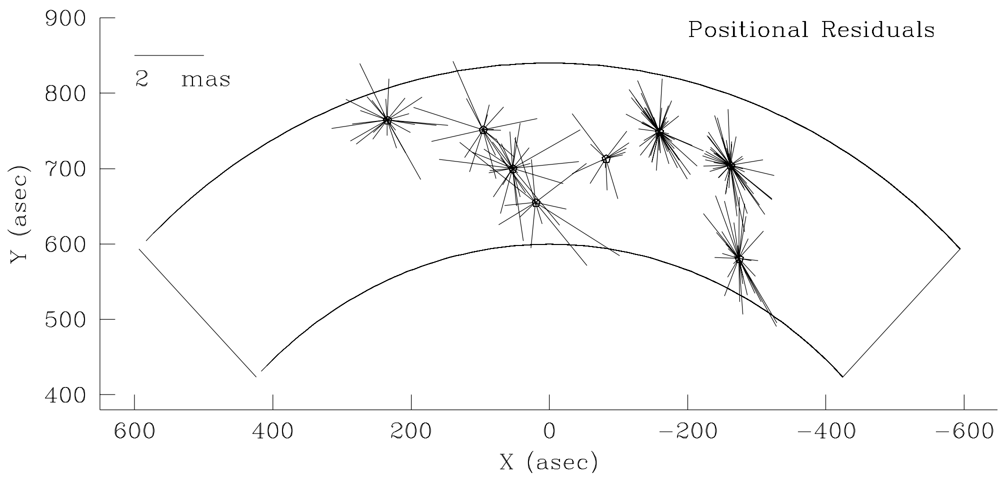
5.2.4 Optical Field Angle Distortion

Optical field angle distortion (OFAD) alters the measured relative angular separations of stars distributed across the FGS's pickle from their true angular separations. This distortion originates from both the FGS/OTA optical train and errors in the 14 most significant bits of the 21-bit Star Selector A and B encoder values. Correcting for this distortion is absolutely necessary for all Position Mode observing programs that visit the target field at a variety of HST orientations (roll angles). The Space Telescope Astrometry Science Team has made extensive efforts to calibrate optical field angle distortion and to maintain this calibration.

This correction is independent of target magnitude, color, or exposure time, and depends only upon the location of the object within an FGS's detector space. Residuals from the calibration itself indicate how well it accounts for this uncertainty in Position Mode observations. In an OFAD calibration, the FGS observes a field of stars at several different HST pointings and roll angles. Measured changes in the angular separations of these stars as a function of the telescope's orientation on the sky must be a signature of the instrument itself.

Because no ground-based astrometric catalog of adequate accuracy exists for calibrating the FGS, the OFAD calibration program must simultaneously and self-consistently generate a 2 mas star catalog while deriving the distortion correction. Comparisons of this star catalog, taken to represent the true positions of the stars, with the individual FGS observations, corrected according to the derived distortion model, reveal the accuracy of the correction itself in terms of the residuals that remain. This procedure is analogous to the simpler case of fitting a line to a distribution of points and computing the standard deviation of the points along the line to determine the quality of the fit. In this case, the star catalog corresponds to the line, while the corrected star positions correspond to the points. Because of boundary effects and the distribution of the stars in the pickle that were observed in the calibration proposal, the smallest residuals occur in the central region of the pickle, with larger residuals near the edges or extreme azimuthal ends. In the area where most astrometry science observations are made, residuals are typically slightly more than 1 mas per axis, suggesting that the uncertainty of a given measurement is about 1.5 mas. Towards the pickle edges and azimuthal extremes, the errors can become as large as 3 to 4 mas. Figure 5.3 shows a plot of the residuals from the OFAD calibration as a function of position in the pickle of FGS1r. The residuals shown can be attributed both to small errors in the catalog and to errors in the OFAD calibration.

Figure 5.3: Comparison of Observed Star Positions (Corrected for OFAD) with Cataloged Star Positions (Derived from OFAD Calibration)



5.2.5 Lateral Color Error

The chromatic response of the five element corrector group, the polarizing beam splitter, the filter, and the Koester prisms, introduces a slight color dependence into the tilt of a wave front measured by the FGS. This chromatic effect results in both a displacement of the target's position in the FGS's field of view and stretching of its S-curve. The effect on the S-curve is important for Transfer Mode observing and is discussed in Chapter 4. The displacements of greater concern are Position Mode observations. If left uncorrected, these will result in an apparent HST roll-dependent motion of the star with respect to the background reference stars of different color.

The lateral color effect will masquerade as roll-dependent motion of an object if it has a color temperature significantly different from that of the reference field. The size and sign of this effect as a function of color difference are not well understood. It is suspected to be important only when the color differences exceed one magnitude, where it is estimated to be about 1 mas.

5.2.6 Cross Filter Effect

The cross filter calibration addresses the apparent change in the measured position of an object observed in Position Mode as function of the filter selected for the observation. As with the lateral color effect, any shift, if unaccounted for, will result in an apparent HST roll-dependent motion of the object relative to those stars measured through a different filter.

The FGS filter wheel can be rotated to bring any one of five different filters into the optical path. Of these filters, generally only the F583W and F5ND are used in Position Mode astrometry. The other, full-aperture filters, F550W and F605W have not been used because their spectral band passes offer no observing advantage over the wide bandpass F583W. The F5ND is actually an attenuator of approximately five magnitudes rather than a filter, and it is used when the target is too bright to be observed with the F583W filter.

Occupying the 5th slot on the wheel is the PUPIL. It is not a filter but rather a 2/3 pupil stop. Use of the pupil significantly reduces the degrading effect of spherical aberration but collaterally alters the field dependence of the distortions. Consequently, the OFAD calibration for the F583W filter cannot be applied to PUPIL observations. Because there are no OFAD calibrations for the PUPIL, it is not supported in Position Mode for science observations.

Because Position Mode astrometry uses only the F583W and F5ND filters, only these two need to be compared for the cross filter calibration. The calibration program itself was a three orbit test which measured the position of a bright (V = 8.08) star at three locations in the pickle. The position of the star was measured in each orbit by alternate observations using the F583W and the F5ND, for a total of 12 pairs (24 observations). The shifts were found to be different at each of the three locations, indicating a field dependent response. The shifts were also larger than expected, up to 7 mas in *x* and *y*, but the formal errors of the test were small, at about 1 mas.

Because of the field dependency of the cross filter calibration and the paucity of locations (three) within the pickle where it has been measured, it is risky to apply these large corrections to data collected at any other position in the pickle. Nearly all science observations that require this correction use the F5ND filter at pickle center, a location supported by the calibrations. In such fortunate cases, the uncertainty of the measurement is about 1 mas.

5.2.7 Differential Velocity Aberration

Differential velocity aberration modifies the apparent angle between the optical axis of the telescope and a point on the celestial sphere by an amount depending on the component of the spacecraft's velocity vector along the line of sight. During the course of an observing session the angle between the HST's velocity vector and its optical axis changes as the spacecraft orbits the Earth, thereby changing the apparent angle between the optical axis and a given point on the celestial sphere. It is possible to repoint the telescope continuously to maintain the angle between its optical axis and a single, chosen position on the celestial sphere, or equivalently, to keep the light from a patch of sky at given RA and Dec focused at a chosen *alignment point* in HST's focal plane. However, it is impossible to do so across the entire field of view of an FGS. Therefore, the measured position of an object within an FGS must be corrected for differential velocity aberration.

The factors that contribute to the overall error of this correction include uncertainties in the relative positions of the three FGSs, and hence the precise (V2,V3) coordinates of the astrometry targets, plus uncertainties in the guide-star coordinates and the location of the alignment point. Other contributing factors include errors in the HST orbital ephemeris and the Earth's heliocentric ephemeris. Inspection of one-minute integrations of the (V2,V3) coordinates of the dominant guide star, corrected for this aberration, over the course of the visit provide a good assessment of the overall residuals to be expected from the differential velocity aberration correction. While these corrections can be as large as 30 mas (under suitable geometric conditions) the corrected dominant guide star positions repeat at scales of sub-millisecond of arc. Therefore, the correction for differential velocity aberration is estimated to be uncertain at about +/– 0.3 mas.

5.2.8 Lever Arm Length and Offset Angle

Early in the HST mission it became clear that FGS 3 was undergoing a scale change over time. Such changes were not unexpected because several of the optical elements in the instrument are mounted on graphite-epoxy composite surfaces known to absorb water vapor at atmospheric pressure and to outgas once in orbit, changing the alignments within the instrument and the effective scale of the detector space. Monitoring of the standard astrometric field M35 has helped to track these changes, leading to time-dependence of Star Selector A's lever arm length and offset angle. These time dependent adjustments are referred to as the *RhoA* and *KA* corrections.

Although there is little physical basis for the success of this approach, the result is the preservation of the internal relative scale and a minimization of temporally evolving gradients to the OFAD calibration. The uncertainties which remain after this correction are estimated from the residuals of plate comparisons of the individual visits in the calibration program. Over the entire field of view of FGS1r, the rms residuals are typically on the order of 2 mas along both the *x*- and y-axes. Much better performance is achieved in the central region of the pickle, 1 mas on each axis.

5.3 Visit-Level Position Mode Errors

A Position Mode observing program uses the FGS to derive the relative angular separations of several objects distributed across an astrometric field. In traditional astrometry, images of objects are recorded simultaneously onto a photographic plate, and the plate is later analyzed to determine the relative separations of the objects. Astrometry with the FGS, by contrast, proceeds in the reverse order; the positions of the individual objects are found first, and then a virtual plate is constructed with the help of data from the guide stars and check stars.

Both approaches must deal with optical field angle distortions, lateral color shifts, and plate scales. However, FGS measurements are far more vulnerable to temporal variations that might occur during the observing sequence. The challenge is to assemble an astrometric plate by defining a common but arbitrary coordinate system onto which the individual observations are mapped. Observers must assume that the telescope's yaw, pitch, and roll might be slightly different for each observation, causing the sky to wobble about in FGS1r's detector space. Such motions can be detected and eliminated using guide star data and check star measurements. Corrections based on guide star data are referred to as *Position Mode dejittering*, and those based on check star data are called *drift corrections*. Here we discuss the errors associated with each procedure.

5.3.1 Position Mode De-jittering Errors

During a nominal FGS visit, two FGSs guide the telescope, tracking their guide stars in FineLock, while the third sequentially measures the positions of the astrometry targets in detector space. The pointing control system uses one of the guide stars, called the dominant guide star, to minimize unintended translation of HST's optical axis across sky. It uses the other, called the roll star, to control the rotation of the focal plane. The section "Preparing the Output Products of CALFGSB for Gaussfit" in Chapter 4, decribes how the Position Mode pipeline accounts for spacecraft jitter during a visit by mapping all observations into the frame defined by the guide star centroids during the first observation.

The adjustments to the astrometry centroids from this Position Mode dejittering correction are typically about 1 mas. However, the corrections occasionally can be as large as 5 mas for one or two observations of a visit. These large corrections arise most frequently when orbital day-to-night or night-to-day transitions excite HST's vibrational modes. During such events the residuals depend upon the amplitudes of these excited modes but are estimated to be typically about 1 mas. During quiet times, the residual of this correction is about +/– 0.3 mas.

5.3.2 Drift Correction Errors

Astrometry targets observed multiple times per visit typically drift across the FGS by about 2 to 7 mas when two FGSs guide the telescope and by up to 70 mas with only one FGS guiding. Because astrometry observations execute sequentially, the resulting errors in the measured angular separations between objects increase as the time between the measurements lengthens. The pipeline must then remove an effect that is typically 4 and not infrequently up to 25 times the overall astrometry error budget (2.7 mas).

To remove this drift, the calibration pipeline applies a model derived from the check star data to all the observations in the visit. The residuals from this correction are difficult to quantify in the usual way because the standard deviation of the data from a fit means little if only three to five points determine the fit. On the other hand, the success of the drift correction is clearly demonstrated by comparing the residuals of two plate overlays, one where the individual visits are drift corrected, the other where they are not. Provided adequate check star data are available to generate a reliable model, plates with the drift correction applied correlate well, typically with 2 mas rms residuals. At minimum, two check stars should be observed three times each. Residuals between those same visits without drift correction range up to 15 mas rms.

Recall that the pipeline can generate three separate drift models: Linear, Quadratic, or Quadratic with rotation.

The first two models are translational only. The third model requires more than one check star and is unreliable if there are not enough visits to any given check star. The pipeline applies all three algorithms, where applicable, and computes chi squares and degrees of freedom for each result. The observer should review these data to determine which result is best suited for further data processing. Experience has shown that often one cannot determine which drift model is best until data from several visits are compared and the plate overlay residuals are evaluated.

5.4 Field-Level Position Mode Errors

Position Mode astrometry involves observations of several objects in a given visit followed by subsequent visits to the same field over the lifetime of the observing program, which can span years. The scientific goal is typically to measure systematic temporal changes in the angular separations between one or more objects and the reference field. Just as the individual observations in each visit must be mapped onto a common fixed coordinate system to define the visit's virtual plate, the visits themselves must also be mapped to a common reference frame to produce a *plate overlay*. The errors associated with several of the pipeline corrections will not manifest themselves until data from individual visits are compared via the plate overlay process.

A plate overlay is performed by translating and rotating the individual plates from each visit and adjusting their relative scales to form a single master plate common to all visits. The locations of the individual reference stars on each plate determine how to map the data from that visit onto the common master plate. Because the reference star positions for each visit are themselves slightly uncertain, the master plate will not be error free but rather an optimal compromise. The quality of the fit for a given visit can be assessed by comparing the positions of the reference stars in that visit with their positions on the master plate. The rms residuals of the fit, referred to as the *plate overlay residuals*, can be as small as 1 mas or as large as 6 mas.

Two commonly used plate solutions are the four-parameter and the six-parameter plate solutions. The four-parameter solution adjusts for translation, rotation, and relative scale, while the six-parameter solution adjusts the relative scale independently along the x and y axes. The six-parameter solution can be used only when enough reference stars are available to provide the necessary degrees of freedom. Typically five or six reference stars will suffice; otherwise, the four parameter technique must be used.

Often an observer realizes that the reference stars, initially assumed to be fixed on the sky, in fact do have measurable parallaxes and proper motions. If these apparent motions are not accounted for, they will contaminate the master plate, resulting in needlessly large residuals that compromise the scientific investigation. For the sake of overall error assessment, let us assume that all the stars in every visit are fixed on the sky, so that any residuals in the master plate can be traced to errors in the individual measurements made during the individual observations.

The most dominant source of error in Position Mode data reduction is the OFAD correction, followed by the uncertainty of the corrections to the star selector RhoA and KA values used in the pipeline for a given epoch. The third most important source of error is the drift correction. The size of this error depends most importantly upon the check star scenario used and to a much lesser extent the amplitude and temporal signature of the drift experienced during the visits.

Target magnitude is not an important contributor to the overall error until $V > 16$, after which it can quickly dominate. Before the DIFF/SUM correction was added to the pipeline, stars with $V > 15$ were found to have large residuals in the plate overlays

(> 4 mas). With the DIFF/SUM correction, such residuals have decreased to about 2.5 mas.

The cross filter effect (F5ND to F583W) contributes only about 1 mas to the residual of targets requiring this correction, provided the observations are made at a place in the FGS where this effect has been calibrated. The lateral color effect, not corrected for in the pipeline, shows up either as noise or is absorbed in a correction for presumed apparent parallax of a reference star.

Table 5.3 summarizes the contributions from a variety of sources to the overall Position Mode error budget. Also indicated are the typical size of the corrections that are made during the calibration process. If these errors were “root sum squared,” the resulting uncertainty would be about 2.7 mas (for bright stars). Note that these estimates are based on a number of assumptions about the observation strategy and star distribution across the pickel: it is assumed that all of the stars are brighter than about V = 14.4, that they are widely distributed across the pickle, and that an adequate check star scenario was used in the observing sequence.

Overall, the plate residuals for a field of numerous bright stars confined to near the pickle's center can be as small as 1 mas per axis. More often the observer finds that the reference field is sparse or faint, the stars are not confined to the central region of the FGS, or that an optimal check star strategy was not used. In less optimal cases with these deficiencies, the residuals might still be as good as 3 mas but can be as large as 7 mas.

Table 5.3: POSITION Mode Corrections and Errors

Correction	Size (mas)	Error (mas)
Median of FL data	–	~1, V < 14.5 ~3, V > 16
Diff/Sum	1–5	~1
LTSTAB	> 100	~1.5
OFAD	> 4000	~2.2
Diff. Vel. Aber.	0–30	< 0.5
HST jitter	0–5	< 0.5
FGS drift	2–70	< 1
Cumulative	> 4000	~2.5 (on average)

5.5 Transfer Mode Errors

Automatic pipeline processing of Transfer Mode data is limited to locating each scan in the astrometer's data file, editing out bad data arising from garbled telemetry, and determining for each scan the median position and standard deviations of the guide stars. These activities do not introduce errors or uncertainties.

Chapter 4 presents a detailed description of Transfer Mode analysis and uncertainties inherent in the data.

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