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THE FLIGHT HARDWARE AND GROUND SYSTEM FOR HUBBLE SPACE TELESCOPE ASTROMETRY

A. BRADLEY

Allied Signal Aerospace Company, Bendix Guidance Systems Division
P.O. Box 91, Annapolis Junction, Maryland 20701

L. ABRAMOWICZ-REED

Hughes Danbury Optical Systems, 100 Wooster Heights Road, Danbury, Connecticut 06810

D. STORY, G. BENEDICT, AND W. JEFFERYS

McDonald Observatory and Department of Astronomy, University of Texas at Austin, Austin, Texas 78712

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ABSTRACT

The Hubble Space Telescope guidance and astrometric instrument, the Fine Guidance Sensor, is reviewed. We will discuss (1) the interferometric design of the instrument and its usefulness to astrometry, (2) the astrometric observing modes and the software commands used to implement them, and (3) the expected state of the spacecraft during an observation with respect to the line-of-sight jitter, drift, and guidance mode.

Key words: instrumentation–Fine Guidance Sensor–Hubble Space Telescope astrometry

1. Introduction

There are six scientific instruments on the Hubble Space Telescope (HST). This paper will only discuss the astrometry payload. The HST is equipped with three Fine Guidance Sensors. A Fine Guidance Sensor (FGS) is an interferometric measuring instrument which will serve dual purposes on the HST. It can be used for astrometric observations or as part of the Pointing Control System (PCS) to correct the spacecraft attitude with respect to known star positions. Two computers control the FGS, either in tandem or synchronously, depending on the operations being performed.

This paper discusses the

- optical design of the FGS,
- operational modes of the FGS,
- astrometric modes of operation,
- computer interface,
- spacecraft configuration for astrometry, and
- FGS calibrations for astrometry.

Hughes Danbury Optical Systems is the prime contractor for the Optical Telescope Assembly, which includes the design and development of the FGSs. Bendix Guidance Systems, a division of Allied Signal Aerospace Company, was contracted by Lockheed Missiles and Space Corporation to design and develop the HST Pointing Control System. The HST Astrometry Science Team consists of the following members: G. Benedict, R. Duncombe, P. Hemenway, W. Jefferys, P. Shelus (University of Texas at Austin), L. Fredrick (University of Virginia at Charlottesville), O. Franz (Lowell Observatory), and W. van Altena (Yale University).

2. Electro-Optical Design of the FGS

The optical train of the FGS is displayed in Figure 1. The main mirror system of the HST is a Ritchey-Chrétien Cassegrain design, with a concave primary mirror and a convex secondary mirror. The main mirror system has an angular magnification of 8.22 and a focal length of 57.6 meters. The combined angular magnification of the primary and secondary mirrors with a FGS is approximately 57.3. The optical train shown in Figure 1 has been rotated to facilitate the component descriptions.

2.1 *Optical Path Description*

The starlight is reflected from the telescope mirrors onto a pickoff mirror and then onto an aspheric collimating mirror. Two optical star-selector servoassemblies rotate to direct the collimated light through a filter and into a polarizing beam splitter. Each plane-polarized beam enters a Koesters prism which performs a wavefront division of the incident light. The beam is then detected by a pair of photomultipliers (PMT).

2.2 *Optical Train Elements*

The following is the optical-path description for one FGS. Each of the three units contains the identical number of elements. The optical train consists of the following elements.

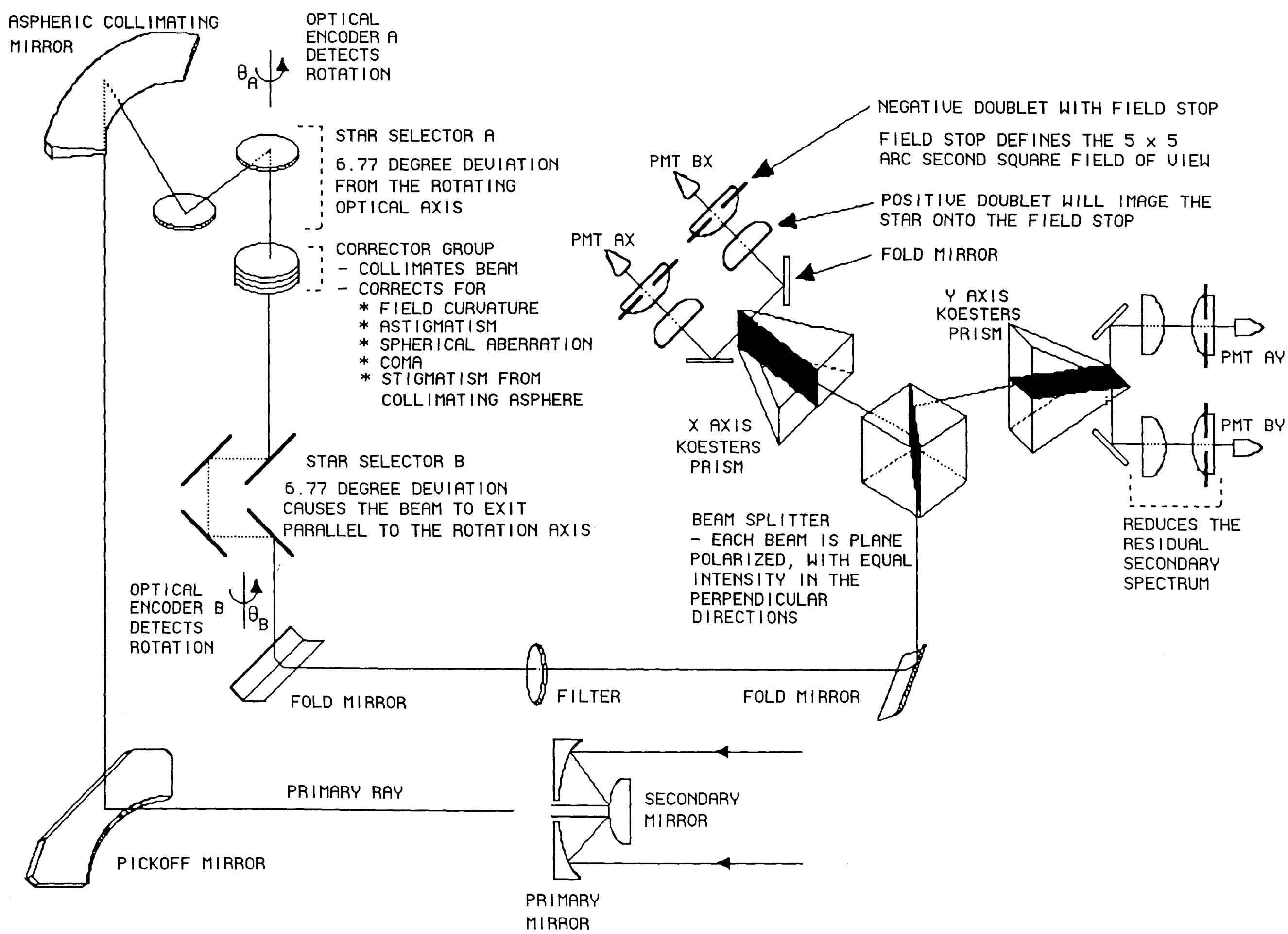


FIG. 1–FGS optical train.

Pickoff Mirror: Placed before the prime focus is a plane pickoff mirror which deflects starlight into the FGS. The FGS fields of view, as defined by the three pickoff mirrors, are shown projected onto the celestial sphere in Figure 2.

Aspheric Collimating Mirror: Diverging light from the pickoff mirror hits an off-axis aspheric mirror which nearly collimates the beam. The collimated beam is required for sensing wavefront tilt at the Koesters prism.

Star Selector A: The beam then travels to Star Selector A. This unit consists of two mirrors which are rigidly fixed with respect to each other. The pair rotates about the shaft encoder axis. The optical encoder rotates with the Star Selector which indicates the angle of rotation, denoted as θ_a. A ray striking Star Selector A, parallel to the rotation axis, will be deviated by (nominally) 6.77 degrees (406.2 arc minutes). This angular deviation is denoted as the deflection angle δ_a and the measured values for each FGS are shown in Table 1. In Figure 3 the projection of the deviation angle is indicated by vector **A**.

Corrector Group: The five-element corrector group is placed just before the first pupil and provides exact collimation. Also, this refractive group corrects for field curvature and astigmatism which are characteristics of the Ritchey-Chrétien design. In addition, it corrects for spherical aberration, coma, and small amounts of astigmatism found in the collimating asphere. The corrector group rotates with Star Selector A as one mechanical assembly.

Star Selector B: The next unit in the optical train is Star Selector B, which is comprised of four rigidly fixed mirrors. One pair of mirrors accomplishes a (nominal) 6.77-degree deviation, while the remaining pair produces a parallel displacement of the ray. The angular deviation is denoted as the deflection angle δ_b and the measured values for each FGS are shown in Table 1. In Figure 3 the projection of the deviation angle is indicated by vector **B**.

Like Star Selector A, the four-mirror system of Star Selector B rotates about the shaft encoder axis. The optical encoder senses the angle of rotation, denoted as θ_b. The Star Selector exit light beam is colinear with the rotation axis; this ensures correct placement of the beam onto the Koesters prism. The result of independently rotating each Star Selector is to locate any star within the field of view of the FGS and to rotate the beam direction of that star so that it is normal to the face of the Koesters prism.

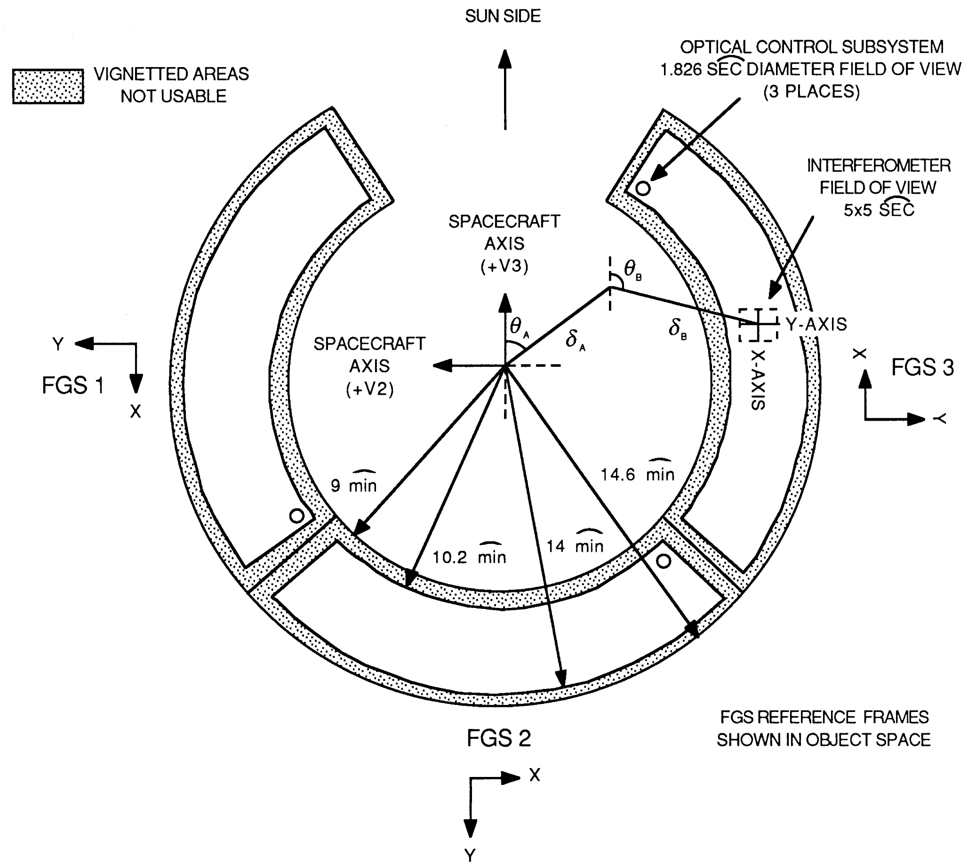


FIG. 2–FGS field of view projected onto the celestial sphere.

TABLE 1

Star Selector Deflection Angles

FGS	δa (arc minutes)	δb (arc minutes)
1	411.7494	411.7494
2	406.3668	406.3668
3	410.5344	411.4464

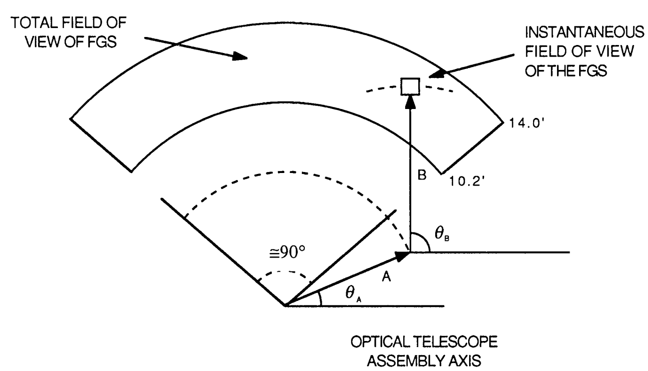


FIG. 3–Deflection angles projections. Positioning of the FGS Instantaneous Field of View by the Star Selectors. A and B are the radii of the cones swept out by the Star Selectors A and B, respectively (parameters are displayed in Image Space).

The next element in the optical path is a fold flat mirror, which serves only to change the direction of the beam. For brevity, the remaining fold flats will be eliminated from discussion. They are, however, illustrated in Figure 1.

Filter Wheel: The filter-wheel assembly contains a 2/3 aperture stop, neutral density, red, clear, and yellow filters. FGS No. 3 contains the astrometry clear in lieu of the red filter. The 2/3 aperture stop is used during the Orbital Verification mission phase. It will minimize any aberrations and permit coarse track and fine lock acquisitions to succeed. The 2/3 aperture stop will reduce the field of view from 25 to 16.6 square arc seconds, which will reduce the PMT counts by 44%. The neutral density filter will reduce the light by 5 magnitudes; this will permit stars as bright as 4 m_v to be viewed by the FGS. The clear filter consists of fused silica, which is the same material as the other filters.

The three remaining filters were added for lateral color suppression (see Section 7.4), of which only two will be used. The astrometry clear is a restricted bandpass clear filter installed in FGS 3 only. At one time FGS 3 was designated as the astrometry FGS, which is why the filter was placed there. However, further hardware testing revealed FGS 3 had the highest lateral color effect, so FGS 2 was designated as the astrometry FGS. The astrometry clear filter in FGS 3 no longer serves any purpose.

The red and yellow filters will be used to reduce the position error caused by lateral color. The yellow filter should be optimal when observing a number of stars from red to blue in one observation set. Figure 4 displays the spectral transmission characteristics for each filter, with the sensitivity curve of the PMT for comparison. The filter wheels are commanded by the DF-224 computer. In order to change a filter, the high-voltage power supply to the PMTs must be turned off. The filter will be inserted within 4 seconds and the high voltage will then be turned on.

Beam Splitter: The polarizing beam splitter divides the light into two equal-intensity perpendicular directions. Each beam is plane polarized. Two beams, hence two Koesters prisms, are required, since the Koesters prism only senses wavefront tilt in one axis.

Koesters Prism: There are two Koesters prisms per FGS, one prism for each axis. The collimated light is incident on the face of the Koesters prism. It is divided by a dielectric beam splitter which performs a wavefront division of the incident ray into two channels, denoted as A and B. The dielectric coating retards the transmitted beam by $\lambda/4$, while the reflected light is not affected (see Fig. 5).

Doublet Lens: Located beyond the Koesters prism is a set of reimaging optics for each channel. The first unit, the doublet, images the star onto the field stop. The combination of a positive long crown element and a negative short flint element reduces the residual secondary spectrum.

Field Stop/Lens: The lens/field stop assembly is located in the back focal plane of the doublet. The lens produces the pupil image on the photocathode. The 5 arc second by 5 arc second (object space) field stop provides sharp boundaries for the region to which the PMTs are exposed.

PMT: There exists one PMT for each channel of each Koesters prism; hence, four PMTs reside in each FGS. Each pair of PMTs must have a matched response in wavelength and efficiency. The PMTs are matched by prism. Referring to Figure 1, PMTs X_A and X_B are a matched pair, and PMTs Y_A and Y_B are a matched pair. The signals from the PMTs are processed through the Fine Guidance Electronics and converted into pointing errors.

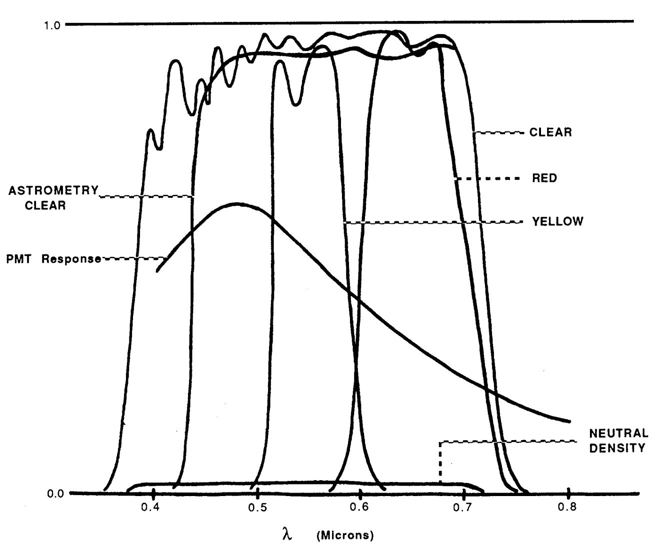


FIG. 4–Filter transmittance curves overlayed with the PMT response.

2.3 *The FGS Transfer Function and Fine Error Signal*

2.3.1 *Transfer Function*

Before discussing the algorithms contained in the Fine Guidance Electronics (FGE), it is important to describe the FGS Transfer Function. It is the linear portion of this signal which maintains the high-accuracy pointing required for astrometric measurements. As stated previously, the Koesters prism senses wavefront tilt interferometrically. Figure 5 illustrates two situations. The top picture shows zero tilt in the wavefront; that is, a combination of repositioning the telescope and the Star Selectors has placed the target on axis. Each PMT in that axis senses the same amount of light. In the lower picture the wavefront has a quarter wave tilt as it hits the face of the prism. The wavefront which is transmitted through the beam splitter is retarded by $\lambda/4$. The reflected wavefront is not affected.

As the beam exits the left side of the Koesters prism, constructive interference occurs. The right side will experience destructive interference. Hence, the counts for the left PMT are greater than those in the right PMT. A graph of the counts versus tilt angle is known as the Transfer Function or S-curve. The FGE combines the curves from both the A and B channels of the Koesters prism to form the S-curve (see Fig. 6). That is,

$$S = \frac{C_A - C_B}{C_A + C_B}$$

in which C_A and C_B are the counts in the A and B channels, respectively. It is obvious to the reader that one PMT per axis will furnish the required signal. In the event of a PMT failure, the FGE processor will recognize the anomaly and adjust the S-curve accordingly. Hence, redundancy is built into each axis. The diffraction limit of the interferometer is 43 milliarc seconds; thus, binary stars must exceed this angular distance for more than one S-curve to be apparent.

2.3.2 *Fine Error Signal*

Once the FGS is locked onto a star (in astrometry mode), the Fine Error Signal is used to update the Star Selector positions to zero out wavefront tilt at the

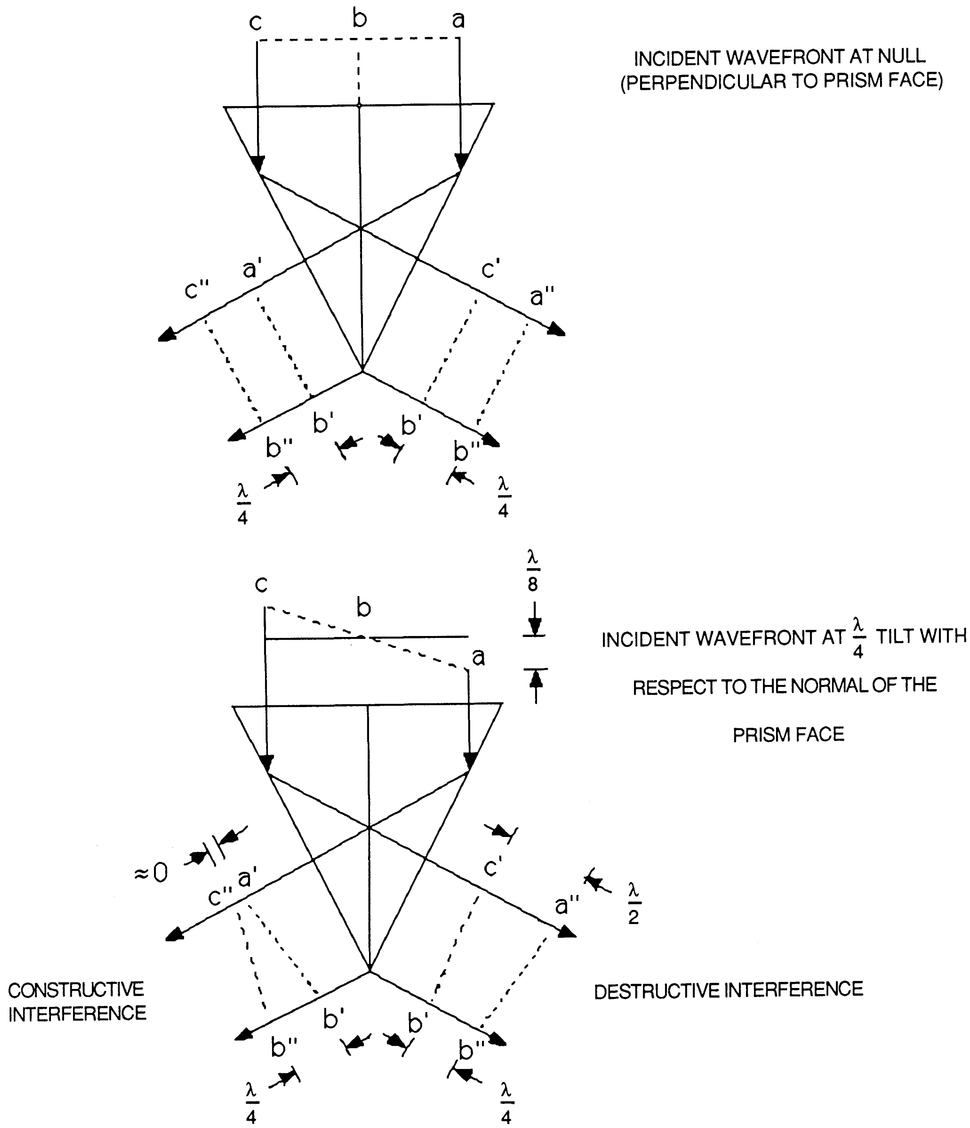


FIG. 5–Koesters prism interferometry.

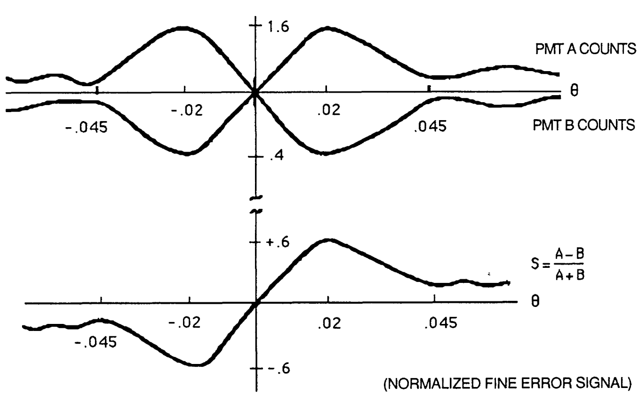


FIG. 6–Transfer function S-curve construction.

Koesters prism. It is the linear portion of the S-curve which is utilized in computing the Fine Error Signal. This segment of the S-curve ranges from approximately -10 to $+10$ milliarc seconds. The linear region of the interferometer transfer function is proportional to the $\lambda/4$ phase shift due to the dielectric in the Koesters Prism. However, the linear region will not vary significantly for various star colors.

The Fine Error Signal is defined by

$$R_x = K_{1x} * S_x$$
$$R_y = K_{1y} * S_y$$

where S_x and S_y are the S-curve for the X and Y axes, respectively. K_{1x} and K_{1y} are the applied signal gains for each axis and are dependent on stellar magnitude and background brightness. These gains can be varied, allowing for some flexibility in observing scenarios.

In ground-system testing, each FGS acquired and locked onto a 17th-magnitude star, with a measured dark-count rate of 12 to 16 PMT counts per 40 hertz sample.

The FGS is required to perform this task on-orbit. In addition to adjusting the gains for individual star and background brightness, the Fine Error Averaging period can also be adjusted. During an averaging period, the Star Selector Servos do not move and PMT counts are accumulated for computation of the Fine Error Signal at the end of the period. The result of this integration period is to decrease the pointing error caused by interferometer noise.

3. Operational Modes of the FGS

The FGS modes of operation are SSM (Support Systems Module) Control, Search, Coarse Track, Fine Lock, LOS (Line of Sight) Scan, and Stop. Each of these modes is described in the following sections.

3.1 *SSM Control Mode*

As previously mentioned, two components exercise control over the FGS: a Rockwell Digital Fixed-Point, 2's complement, 24-bit, programmable computer (DF-224) and a firmware-based Fine Guidance Electronics (FGE) computer. When a FGS is in the SSM Control mode, the DF-224 computer has control. In this mode, the DF-224 software will compute incremental rate commands for the FGS Star Selectors at a sampling rate of 40 hertz, which will cause the FGS Instantaneous Field of View (IFOV) to maneuver from one point in the field of view to another. The function of the FGE during SSM Control mode is to receive, format, and transmit the servorate commands from the DF-224 flight computer, via the Data Interface Unit (DIU), to the servocontrol units of the appropriate FGS assembly at a 40-hertz sampling rate. SSM control mode is entered when the DF-224 computer sends a Search/Track Off command to the FGE.

3.2 *Search Mode*

SSM Control mode is exited and Search mode is entered when the DF-224 computer issues a Search/Track On command to the FGE. The FGE will generate the appropriate Star Selector servocommands, at a 40-hertz sampling rate, to move the IFOV in an outward spiral. A spiral with an extent of 25 arc seconds in radius is shown in Figure 7. The time required to perform the spiral search for Map and Acquisition modes, as a function of radius, is shown in Figure 8.

The purpose of Search mode is to search for a specific target. Success is based on the PMT count rate exceeding a lower-limit threshold, which may be background, dark count, and target magnitude specific. The adjustable search-mode spiral parameters are the final radius (ρ) and the initial offset radius (K_a). The final radius can vary from 0 to 100 arc seconds and the initial offset radius will nominally vary from 0 to 10 arc seconds. Both spiral parameters depend on the astrometry observation mode.

In Search mode there is a 30% IFOV overlap in coverage from one spiral line to the next. The overlap compensates for spacecraft motion due to uncompensated gyro drift and environmental torques (aerodynamic and gravity gradient).

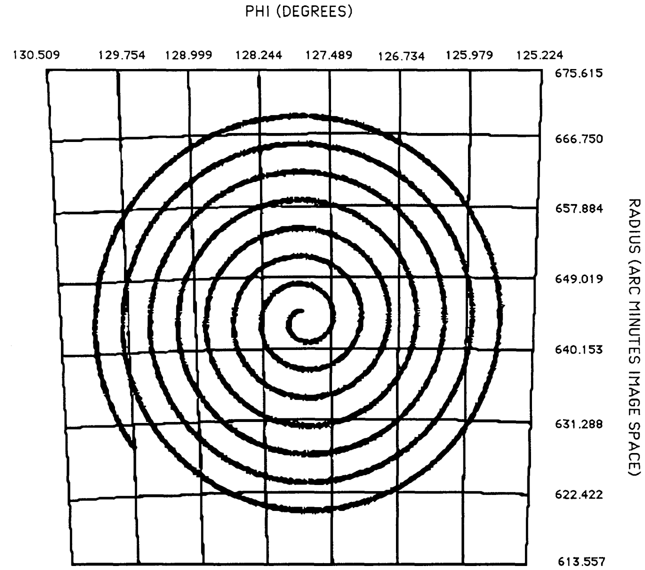


FIG. 7–Search mode. Polar plot of a 25-arc-second spiral search.

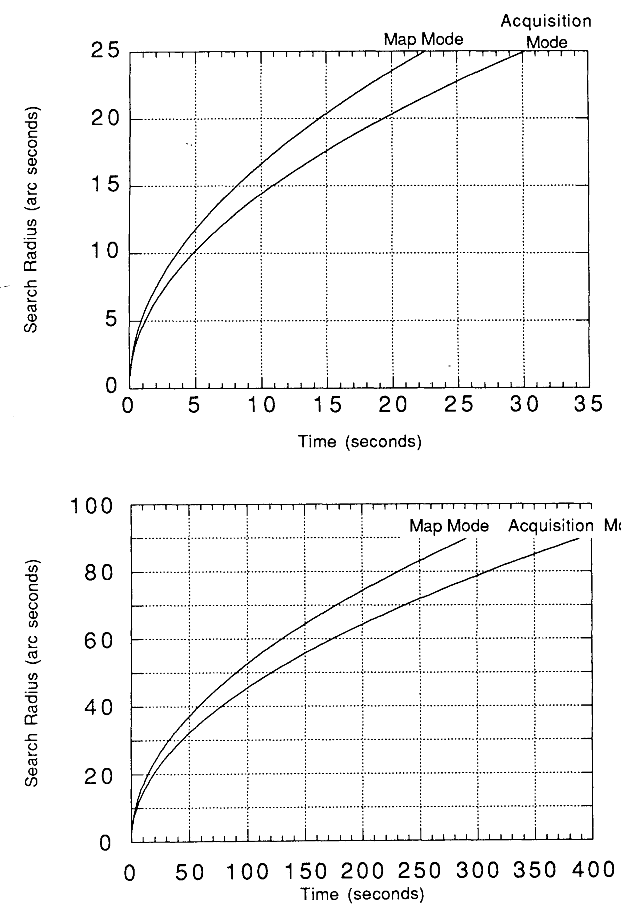


FIG. 8–Spiral search time. Search time for Map and Acquisition mode uplink parameters are compared for search radii of 25 and 90 arc seconds.

The FGE computed Star Selector Servo rate commands for the spiral search will continue to be generated until either the final search radius is exceeded or the PMT count rate exceeds the lower threshold. If the final search radius is exceeded, then the FGS is commanded into Stop mode, indicating the search has failed. Otherwise, when the count-rate threshold is exceeded, the FGS will be commanded into Coarse Track mode by the FGE. Exceeding the lower count rate threshold is denoted as star presence.

During Search mode, the control loop of the FGS is capable of acquiring targets moving up to 0.05 arc second/second.

3.3 *Coarse Track Mode*

Once the target has been detected in Search mode, the FGE will command the Star Selectors such that the IFOV will nutate about the target at a 1-hertz rate. A typical nutation is illustrated in Figure 9. The nutation radius is 2.5 arc seconds and the number of nutations may vary from 0 to 12, as a function of the astrometry observation mode. The FGE algorithm for Coarse Track causes the combined motions of the Star Selectors to nutate at a 1-hertz rate about the center of light, updating the position of that center every 25 milliseconds. Coarse Track produces an error signal based on the combined PMT counts it senses in each of the four quadrants of the nutation cycle (see Fig. 10). This signal is then fed back to the Coarse Track algorithm resulting in a new center of nutation. The objective of Coarse Track is to determine the approximate position of the star to 20 milliarc seconds. For a bright star with low background, approximately six nutations are required to obtain a positional uncertainty of 20 milliarc seconds.

If Coarse Track succeeds, then either

(1) the FGE will command fine lock mode, or
(2) the DF-224 will command fine lock mode, or
(3) the FGS will remain in Coarse Track mode.

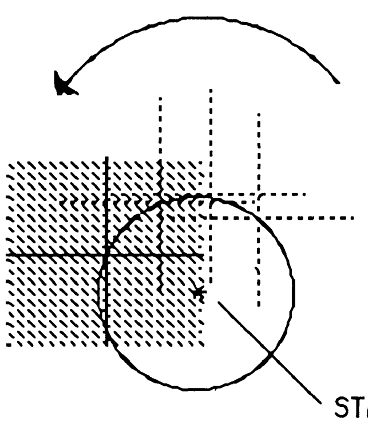


FIG. 9–Coarse Track nutation. The interferometer axes, which are both 5 arc seconds in length, revolve about the center of a circle (the luminosity centroid) which is 2.5 arc seconds in radius. Each revolution is one second in duration and consists of 40 steps.

The above options are dependent on the astrometry observation mode. The Star Selector rate commands, in Coarse Track mode, are derived from both computers. The FGE is computing the servo rate commands to maintain the nutations about the target center of light, while the DF-224 computer is determining the velocity aberration and parallax effects and issuing the appropriate servo rate commands to track the target. In Coarse Track mode, the maximum rate tracking capability of the control loop is 0.3 arc second/second.

3.4 *Fine Lock Mode*

The geometry of Fine Lock mode is shown in Figure 11. The orthogonal intersection of the interferometers is commanded to a position K_b arc seconds away from the target position, which was determined in Coarse Track. It will then be commanded by the FGE to approach the target position in a K_5 number of steps, with each step length being K_d arc seconds. The process of stepping down to the star is denoted as the walkdown. Each walkdown step can be accompanied by a period of magnitude-dependent averaging as defined in Table 2.

Averaging is a function of the apparent target magnitude, and its intent is to increase the signal-to-noise ratio. For astrometry operations, the integration period is set such that the photon noise encountered over the integration period is larger than the least significant bit of the Star Selector Servos. This induces small, discernible Star Selector motions.

The number of walkdown steps may vary from 16 to 200, depending on the astrometry mode, with a walkdown step size of 0.009 arc second. When the target is detected in one of the interferometer axes, the step size is halved to prevent overshoot. Detection is determined when the interferometer signal exceeds a predetermined threshold (K_z). A target is considered to be captured in an interferometer axis when its signal exceeds the threshold K_z for three consecutive averaging samples during the walkdown. The maximum rate-tracking capability of the control loop in this mode has been demonstrated to be 0.5 arc second/second with no averaging during the walkdown.

Once a target is acquired, the FGE control system will

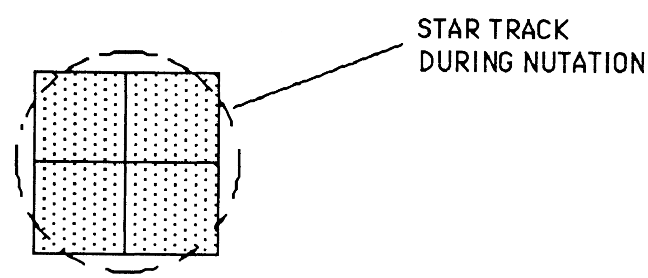


FIG. 10–Coarse Track Nutation. As the IFOV nutates about the star, all four quadrants will detect a count rate which exceeds the threshold setting.

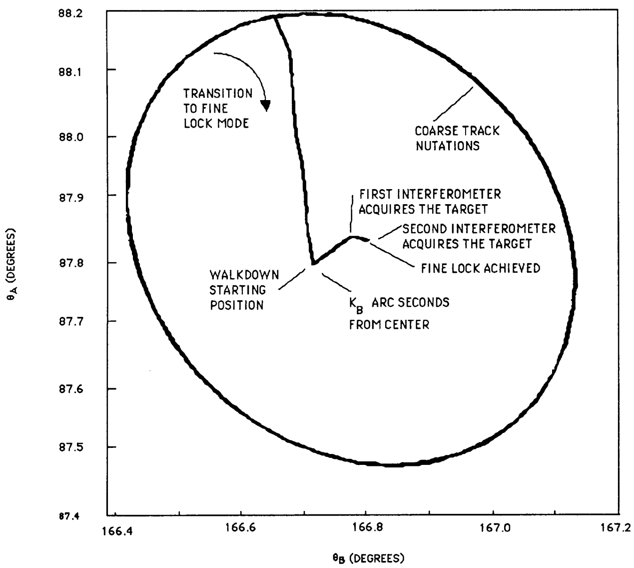


FIG. 11–Fine Lock mode. Plot of Star Selector angles A versus B.

TABLE 2

Magnitude Dependent Averaging

visual magnitude	averaging period (seconds)
≤14	0.025
14.0 - 14.5	0.05
14.5 - 15.0	0.10
15.0 - 15.5	0.20
15.5 - 16.0	0.40
16.0 - 16.5	0.80
16.5 - 17.0	1.60
>17	3.20

position the Star Selectors such that the target will be maintained simultaneously in the linear region (at or near null) of both interferometer axes. In Fine Lock mode both computers are contributing to the Star Selector rate commands. The FGE computer is issuing the appropriate servo rate commands to maintain the interferometer signal at null, while the DF-224 computer is determining orbital velocity aberration and parallax effects and issuing the appropriate servo rate commands to track the target.

Fine Lock mode can fail in one of two ways: either Star Presence will be lost during the walkdown, or the maximum number of steps (K_5) will be exceeded before the target is acquired. If Fine Lock mode fails, the FGS will transition into Stop mode. The entire acquisition process is illustrated in Figure 12. Fine Lock failure due to the effects of Cerenkov radiation and secondary fluorescence was examined in Howell & Kennel 1984, which led to control-system modifications to minimize the effect.

3.5 *LOS Scan*

The Line-of-Sight (LOS) Scan can only be entered from the Coarse Track mode. The LOS Scan geometry is an orthogonally intersecting set of serpentine scans, displayed in Figure 13. Once the target has been acquired in Coarse Track mode, the DF-224 computer can issue a command to transition the FGS into LOS Scan mode. It takes the FGS 47 seconds to execute the scan maneuver, after which it will transition back into Coarse Track. The LOS Scan can be 6, 10, or 12 square arc seconds; the area is a function of target size.

3.6 *Stop Mode*

Stop mode is entered when an FGS operation fails. If star presence is lost, or the search radius limit is reached, or the walkdown step limit has been reached, then the FGS will enter Stop mode. The Star Selectors will not respond to rate commands until SSM mode has been commanded.

4. Astrometry Modes

The astrometry modes which are presently supported are shown graphically in Figure 14. Astrometry modes, which are planned to be available early in the General Observer phase, are identified by the dashed lines. The astrometry observational modes can be classified as Transfer Function, Acquisition, Line-of-Sight scan, and Map mode. This paper will only describe the types of astrometry functions that can be performed. Examples of possible observations can be found in van Altena 1983.

4.1 *Acquisition Modes*

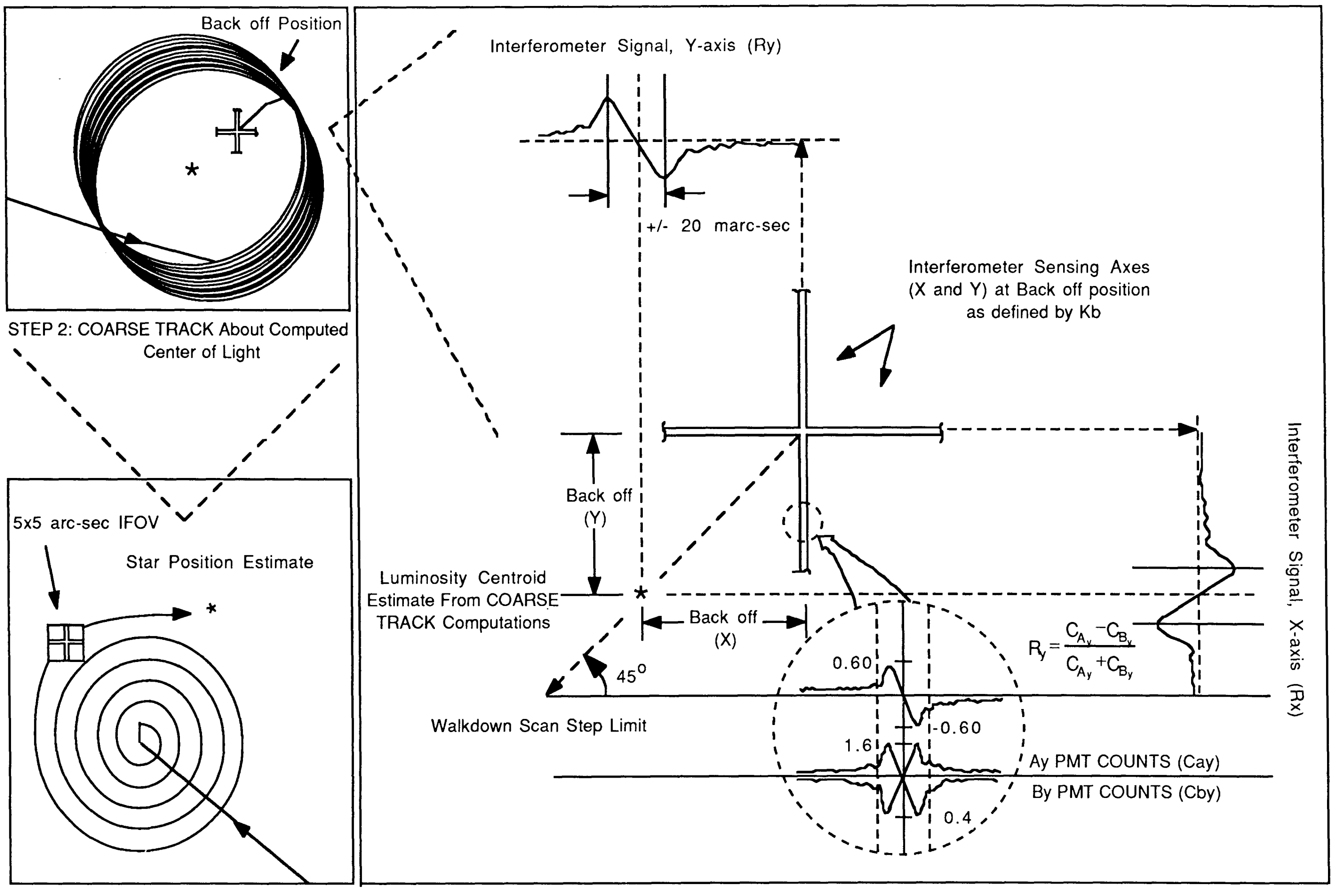
The acquisition modes consist of Coarse Track, fine lock, Rapid fine lock, and Fast Moving Target.

4.1.1 *Coarse Track*

The objective of Coarse Track mode is to acquire a target in coarse track. The maximum search radius will be set to 5 arc seconds. After the target is successfully acquired, the FGS will continue to nutate about the computed center of light until the user-defined data-collection period has expired. Coarse Track mode can acquire diffuse objects and resolvable binary stars, objects which cannot be acquired in fine lock.

4.1.2 *Fine Lock*

The objective of Fine Lock mode is to acquire a target in fine lock. The maximum search radius will be set to 5 arc seconds. Once the target is detected during the spiral search, the FGS will nutate about the target for 12 cycles to sufficiently center it for the fine-lock attempt. When



STEP 1: Slew FGS IFOV to expected target position, offset Ka arc seconds and begin SEARCH

STEP 3: Move the IFOV to Kb arc seconds away from the COARSE TRACK estimated target position and begin walking down toward the target

FIG. 12–Acquisition summary.

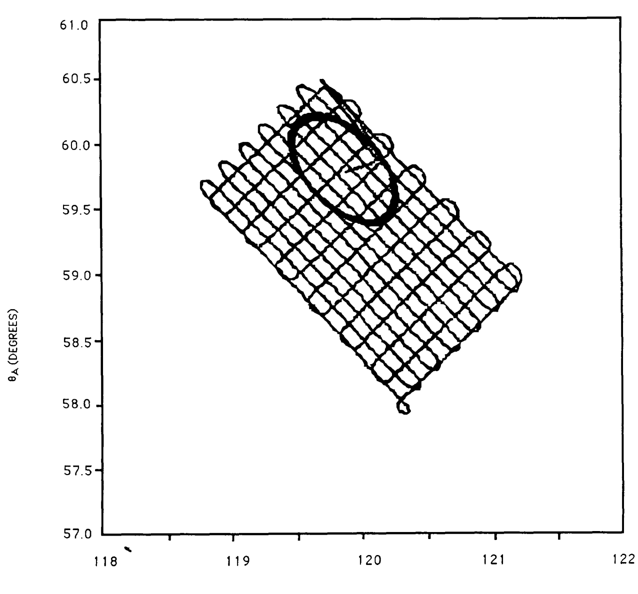


FIG. 13–LOS Scan mode. Plot of Star Selector angles A versus B.

fine lock is initiated, the interferometers will move close to the center of the nutation and begin to step down toward the center. Dim stars will require averaging at each step. Fine Lock mode can only acquire targets whose diameter approaches the diffraction limit of 43 milliarc seconds. The FGS will remain in fine lock until the user-defined data-collection period has expired.

4.1.3 *Rapid Fine Lock*

The objective of Rapid Fine Lock mode is to acquire a target in fine lock, in a minimum amount of time. For this to be successful, the spacecraft must be well calibrated and the target position(s) must be known to within 0.1 arc second. For this mode, the spiral search radius is set to zero arc seconds and no Coarse Track nutations will be performed, since they would only corrupt an accurately known star position.

4.1.4 *Fast-Moving Target*

The objective of this mode is to acquire targets moving faster (> 0.5 arc second/second) than the rate-tracking

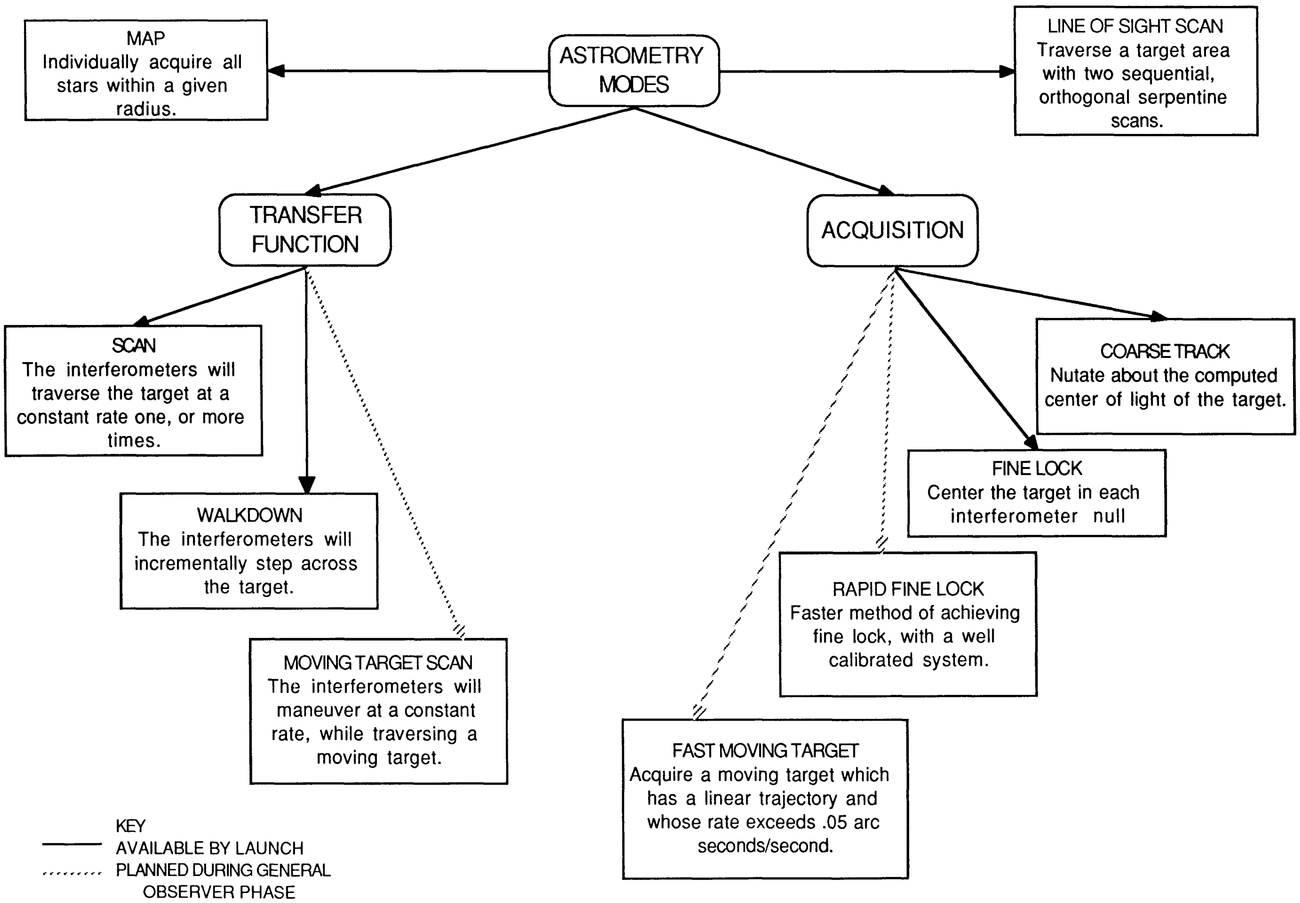


FIG. 14–Astrometry observation modes.

ability of the FGS control loop. The DF-224 computer will assist the FGE by simultaneously issuing Star Selector rate commands, such that the interferometers will be moving at the same rate as the target, while it is maintained in fine lock. The target-acquisition process will be Rapid Fine Lock, immediately followed by servo rate commands from the DF-224 computer to initiate tracking.

4.2 *Transfer Function Modes*

There are three methods for obtaining a transfer function. They are the Walkdown, Scan, and Moving Target Scan modes.

4.2.1 *Walkdown*

The objective of Walkdown mode is to generate a transfer function of the target. Walkdown mode is similar to Fine Lock mode, except the criteria for success (K_z) is set greater than the expected K_3 limited peak of the S-curve. This causes the interferometer to walk across the target and fail to acquire it, which produces the transfer function of the target. The commanded incremental steps during the walkdown are 0.009 arc second in length in the X and Y axes. The steps can be performed at a 40-hertz rate, or can be averaged.

4.2.2 *Scan*

The objective of the Transfer Function Scan mode is to generate multiple transfer functions, which will increase the signal-to-noise ratio. Once the object is acquired in coarse track, the FGE commands the Star Selectors to place the interferometers at a distance K_b away from the computed center of the nutation. The DF-224 computer then commands the FGE to transition into SSM Control mode and issues Star Selector rate commands to move the interferometers back and forth across the target at a constant rate. The rate can be varied from 0.001 to 5.0 arc seconds/second.

4.2.3 *Moving Target Scan*

The objective of the Moving Target Scan mode is to traverse a moving target and generate a transfer function. The method is similar to Dougherty et al. 1983; but a single scan, rather than multiple scans, will be performed. This mode is completely controlled by the DF-224 computer. Star Selector rate commands will be issued to move the interferometers at a constant rate across a moving target. The scan rate can vary from 0.001 to 5.0 arc seconds/second. The trajectory of the scan and that of the moving target should intersect at a 45-degree angle, so the target will intersect both interferometer axes. This mode is suitable for moving targets which cannot be acquired in fine lock.

4.3 *LOS Scan*

The objective of this mode is to generate a three-dimensional plot of PMT counts versus X and Y coordinates in the FGS reference frame. Once the target is acquired in Search mode, the FGE transitions into coarse track. After 12 nutations and while the interferometers are still nutating about the center of light of the target, the DF-224 computer will then command the FGE to initiate a Line-of-Sight (LOS) Scan. The LOS Scan consists of two orthogonal serpentine scans, which complete in 47 seconds. Once the LOS Scan has completed, the FGE will issue the appropriate Star Selector rate commands to resume nutating about the center of light of the target. The available options for coverage are 6, 10, and 12 square arc seconds. The 6-square-arc-second option will center the target in the scan, while the others will place the target in a corner.

4.4 *Map*

The objective of this mode is to acquire all targets within a given radius whose magnitudes exceed a lower count threshold. Each target will be acquired in coarse track and held for a user-defined data-collection period, after which the DF-224 computer will command resume search. This will cause the FGS to break away from the target and resume the spiral search for more targets. The target search will continue until the search radius is exceeded. For Map mode, the IFOV coverage overlap between spiral lines is 16%.

4.5 *Astrometry Mode Summary*

The approximate time durations and accuracies for each astrometry mode are summarized in Table 3. For the Acquisition modes and the Walkdown Transfer Function, the duration is given for a distribution of 10 stars in the 14th–17th magnitude range. The distribution used in calculating the times is 0.85 star at $m_v = 14$, 1.52 stars at $m_v = 15$, 2.88 stars at $m_v = 16$, and 4.75 stars at $m_v = 17$. The Moving Target Acquisition and Scan modes assume the data-collection period will be from 10 to 60 seconds. With command overhead, the total duration will be from 1 to 2 minutes.

The Scan Transfer Function duration, as it relates to binary (double) stars, is proportional to the magnitude and separation of the stars. Map mode requires 319 seconds to search a field 90 arc seconds in radius, plus sufficient time to sample each target acquired in the field. The LOS Scan mode, used for calibrating the telescope, is presently not planned for astrometric science mode operations.

5. Computer Interface

The two computers that share control of the FGS are the DF-224 and the FGE. The high-level interface is shown in Figure 15. The DF-224 computer maintains

TABLE 3

Astrometry Mode Performance

mode	approximate duration	accuracy (arc seconds)	comments
Coarse Track	10 stars in 6.25 minutes	0.02	
Fine Lock	10 stars in 26.0 minutes	0.003	
Rapid Fine Lock	10 stars in 13.0 minutes	0.003	
Fast Moving Target	1.0 to 2.0 minutes	0.003	Target rate >4 milliarc seconds/second.
Walkdown Transfer Function	10 stars in 24.0 minutes	0.001 to 0.003	Measurement accuracy of distance between stars.
Scan Transfer Function	1.0 to 10.0 minutes	0.001	Measurement accuracy of distance between stars. Duration depends upon scan rate and length.
Moving Target Scan	1.0 to 2.0 minutes	0.006	To be determined in post-launch calibrations.
Line of Sight Scan	114.0 seconds maximum	n/a	
Map (Coarse Track)	319.0 seconds to search + 12.0 seconds per star	0.02	90 arc second search radius.
Map (Fine Lock)	319.0 seconds to search + 24.4 seconds per star	0.003	90 arc second search radius.

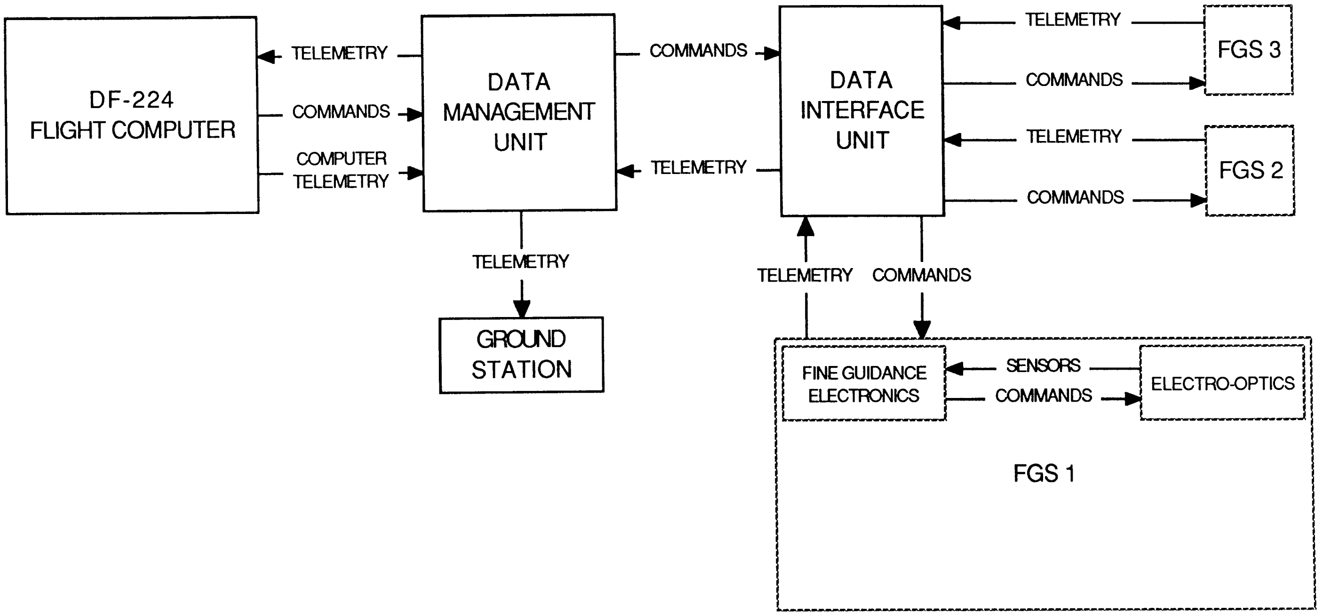


FIG. 15–Computer interface.

control of all three FGSs. It is planned to have two FGSs locked on guide stars, while the third FGS is being tasked to perform astrometric measurements. The DF-224 astrometry commands are processed by the Data Management Unit (DMU), which directs the commands to the proper FGS. The commands proceed via the Data Interface Unit (DIU) and into an FGE. The FGE may respond by issuing one or more commands. The sensor information is routed back to the DF-224 through the reverse path. The return data (telemetry) are processed by the DMU and transmitted to the ground station. The flow of commands, from the DF-224 computer to a FGS, is illustrated in Figure 16.

The DF-224 computer is comprised of several processors (Dougherty, Rodoni & Tompetrini 1981), one of which is the Conditional Processor, designated to share the astrometry commanding. The astrometry commands in the DF-224 computer are metalevel commands. In some instances they may simply result in information being sent to the astrometry FGS, while in others they may activate one or more software processes. The astrometry commands are usually combined with logic, so that other commands may be issued based on whether or not success was achieved on the previous step. A detailed description of the commands and logic has been discussed in Dougherty et al. 1982b and Dougherty et al. 1983.

The seven basic DF-224 computer astrometry commands which can be executed from the Conditional Processor are shown in Figure 16. The FGS Serial Digital Command can either modify a value in the FGE database or request the FGE to affect a mode transition. The Load Star Data command initializes the velocity aberration compensation and command generator software processes, while the FGS Quaternion Slew command will activate these processes and cause Star Selector rate commands to be issued. The Establish Coarse Track command can either command the FGE to initiate a new spiral search or to resume an interrupted spiral search. The Establish Fine Lock command requests the FGE to transition from Coarse Track to Fine Lock mode. The Single Constant Rate Scan command activates the command generator software process, which will compute the appropriate Star Selector commands to move the FGS IFOV at a constant rate. The Multiple Constant Rate Scans command is similar to the single scan, except that it is repeated a number of times. The total number of scans performed is a function of the target magnitude.

The Astrometry Control Loop is illustrated in Figure 17. Several times a day a forward command link will be established with the spacecraft via the Tracking and Data Relay System (TDRS).

The Astrometry commands will be loaded into the Conditional Processor of the DF-224 Flight Computer, where the Command Handler will direct them either to the Command Generator or the FGE. Target slews (Quaternion) and constant rate scans (Eigenvector) are routed to the Command Generator.

The Command Generator will incorporate the velocity aberration and parallax commands (for solar-system targets) into an incremental quaternion command ($q_{r/c}$). Although the quaternion $q_{r/c}$ has a sampling rate of 10 Hz, the velocity aberration and parallax updates occur at a 1-Hz sampling rate. The quaternion will be transformed into the FGS Star Selector frame, resolved into Star Selector angle and rate commands, and sent to the FGS Control Law.

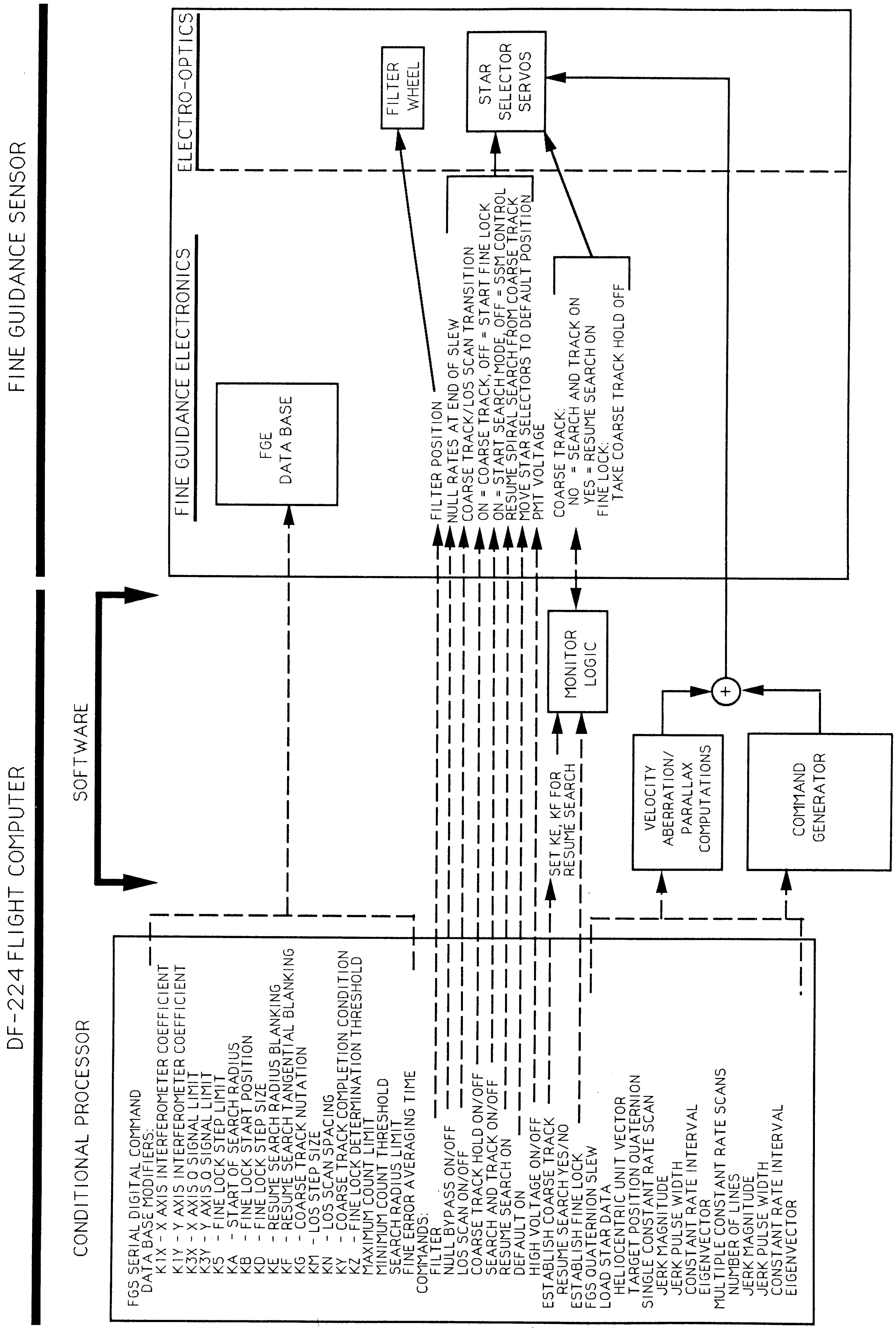


FIG. 16–FGS command flow.

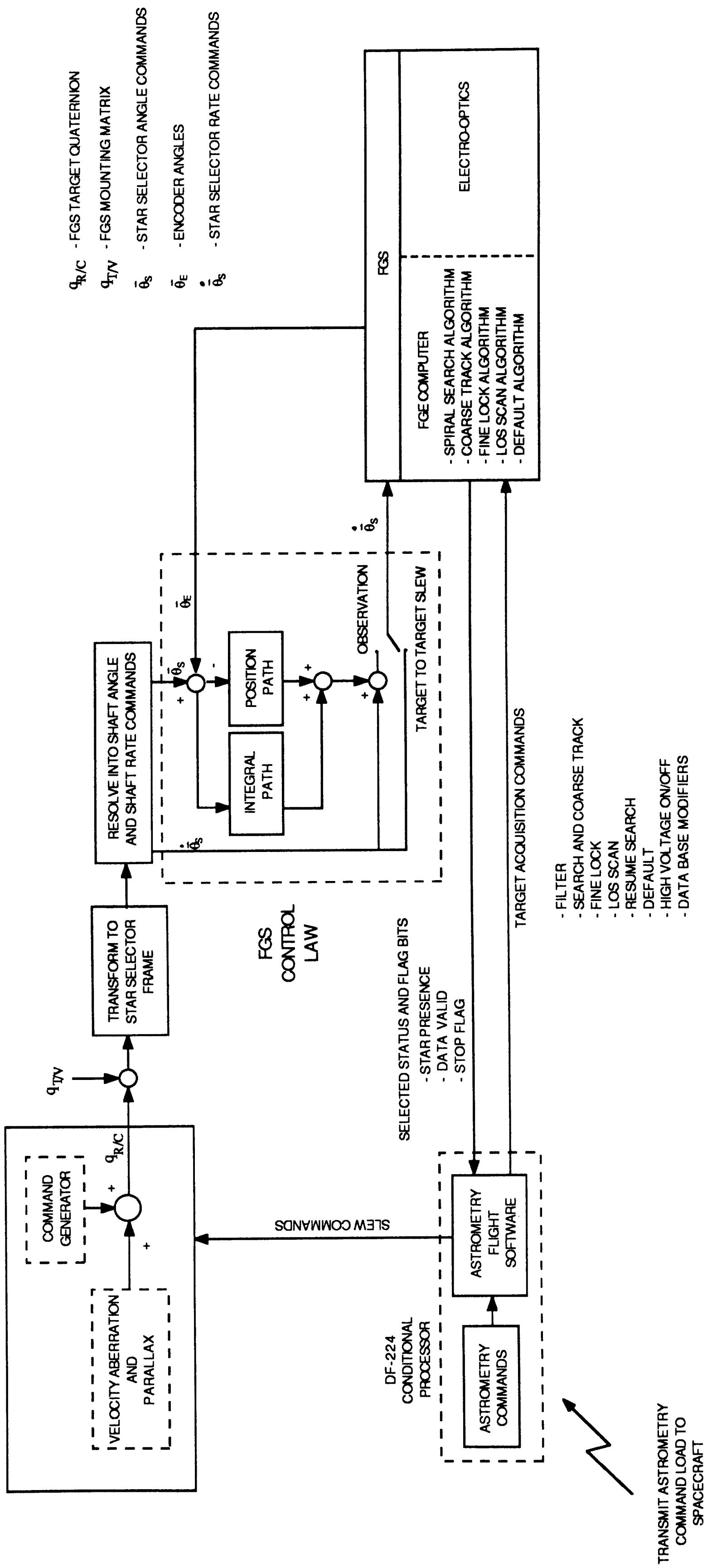


FIG. 17–Astrometry FGS control law.

The FGS Control Law is a Proportional, Integral, and Derivative (PID) Control Law. The Control Law functions as an open loop controller for target slews. The Star Selector A and B rate commands are sent directly to the FGE, whereas for observations, the Star Selector angle command and encoder signals are used to fine tune the rate commands and compensate for any tracking errors.

The astrometry telemetry format will yield data at the sampling rates shown in Table 4.

TABLE 4

Astrometry Data Sampling Rate

Data	Frequency (hertz)
X axis PMT A counts	40.0
X axis PMT B counts	40.0
Y axis PMT A counts	40.0
Y axis PMT B counts	40.0
star selector servo angle A	40.0
star selector servo angle B	40.0
X axis average (A+B) counts	6.67
Y axis average (A+B) counts	6.67
stop mode indicator	6.67
search radius limit exceeded indicator	6.67
star presence indicator	6.67
data valid indicator	6.67
coarse track hold indicator	6.67
scan step limit exceeded indicator	6.67
search mode status	6.67
coarse track mode status	6.67
fine lock mode status	6.67
SSM control mode status	6.67
default mode status	6.67
LOS scan status	6.67
filter position	6.67
X axis average fine error	6.67
Y axis average fine error	6.67
age word	6.67
star selector A average position	6.67
star selector B average position	6.67
star selector A coarse track nutation center position	6.67
star selector B coarse track nutation center position	6.67

6. Pointing Control System

6.1 *Control Law Description*

Astrometry observations will be conducted when the spacecraft control system has been configured for FGS fine lock guidance mode. The control system is three-axis stabilized on sensed gyro signals. Unfortunately, the gyro signals will drift from the true rate for any number of reasons, such as temperature sensitivities of the gyro and its electronics control loop. The gyro drift should be stable to within ± 0.003 arc second/second while under gyro control and will be periodically calibrated in orbit. Noise can emanate from the guidance hardware, solar arrays, high gain antennas, tape recorders, and even other science instruments.

To reduce the noise level (referred to as vehicle jitter) and the vehicle drift, due to the gyro control system, two FGSs will be used to acquire guide stars in fine lock and feedback incremental positional error to the control system. The feedback control signals from the guidance FGSs are referred to as attitude updating. The FGS attitude updates will not replace the gyro control loop but, rather, fine-tune it to the accuracy of the FGSs. The FGS control loop corrects errors with a bandwidth of 0.5 Hz. Figure 18 is a high-level block diagram of the spacecraft control loop. The two guiding FGSs will supply attitude error information to the Observer Filter. The Observer Filter will pass attitude error information into the proportional path of the vehicle control law and estimate the rate, in order to compensate for the gyro drift. With the guidance mode under FGS fine lock control, the vehicle jitter should not exceed 0.007 arc second. For short observations the high-frequency disturbances will be averaged out, and the thermal disturbances have a long time constant, so they will have no impact. For longer observations, from a few minutes to hours, thermal variation will be averaged out. Vehicle drift will be reduced to a negligible amount, since the guiding FGS signals are compensating for the sensed vehicle drift. The estimated vehicle drift based on FGS data is resolvable to 0.00012 arc second/second per axis.

6.2 *Acquisition Logic*

Although the guide-star acquisition procedure has been revised over the years, the original concept as described in Dougherty et al. 1982a has remained intact. The guide-star acquisition commanding shares the Conditional Processor of the DF-224 computer along with the astrometry commands. To maintain stable vehicle control during an observation, two FGSs must be locked on guide stars. The two guide stars (and their FGSs) are denoted as primary and secondary. The primary star will advance through the acquisition process a step ahead of the secondary star. At the beginning of the acquisition process, each IFOV of the guiding FGSs are maneuvered to the expected guide-star position. The primary FGS will enter Search mode and may spiral out to 90 arc seconds to locate the guide star. When a star satisfying the desired count range has been detected, the primary FGS will transition into Coarse Track mode. The difference between the primary-star location and its expected position is an attitude error. The secondary FGS IFOV is maneuvered to account for the error. The secondary FGS then enters Search mode and spirals out to 15 arc seconds to locate the

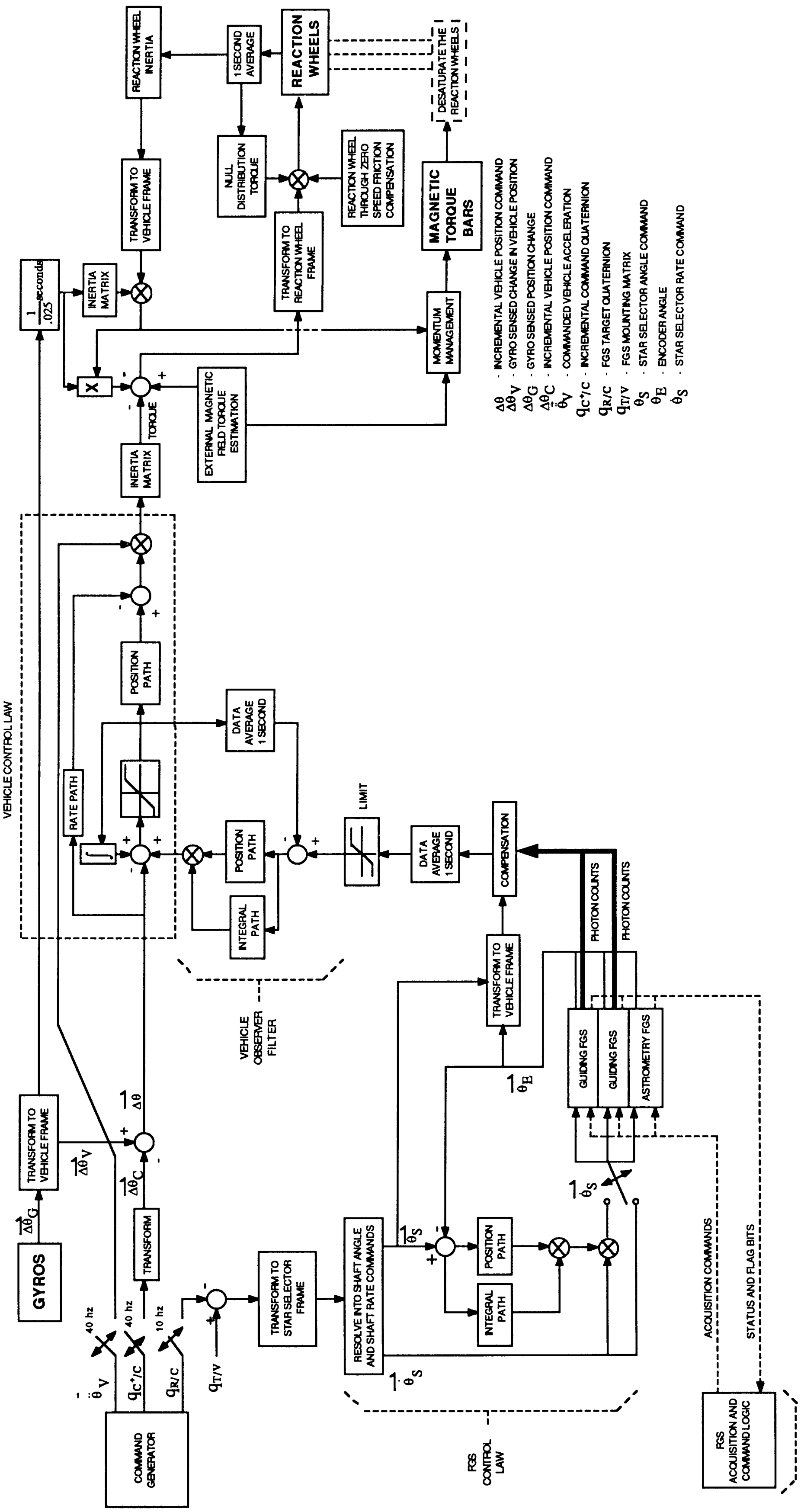


FIG. 18–PCS control loop.

guide star. When the secondary star is found, the FGS will then transition into coarse track. With both stars in coarse track, the angular separation is computed and compared to an expected value. If the angular separation is correct, then the acquisition process continues to fine lock; otherwise, the primary FGS is commanded back into Search mode to continue looking for its guide star.

Assuming the correct guide-star pair has been found, first the primary and then the secondary FGS will transition into Fine Lock mode. Once both guide stars are in fine lock, the attitude error is computed and the vehicle is maneuvered such that the guide stars end up at their expected positions. Following a 100-second wait for the control law to stabilize the vehicle jitter, astrometric observations can begin. It should be noted that some of the instruments on HST can observe while the vehicle is guiding in coarse track mode, rather than fine lock. Accurate astrometric measurements require fine lock guidance.

Fine Lock Guidance mode will maintain the vehicle jitter to 0.007 arc second and nominally requires 20 minutes to acquire a pair of guide stars. The coarse track Guidance mode jitter is 0.020 arc second and nominally requires 15 minutes to acquire a pair of guide stars. The acquisition duration is a function of the number of possible guide-star pairs to attempt and the search radius.

7. FGS Calibrations for Astrometry

Prior to performing FGS calibrations, the wavefront quality of the telescope must be optimized via the Optical Control System (OCS). The OCS adjusts for best focus and removes other classical aberrations such as coma and astigmatism. The adjustments are made by moving the secondary mirror in such a way as to minimize the aberrations. These aberrations degrade the wavefront quality; coma, in particular, affects the FGS Transfer Function. Wavefront calibrations will be performed during the initial stages of Orbital Verification of the telescope, after which the activity will be performed as needed. What follows is a description of the FGS calibrations which will be accomplished after the wavefront quality is deemed acceptable.

In each FGS the major calibration procedures include plate scale (magnification), optical field angle distortion, and lateral color. The three FGSs will be tied together with the FGS-to-FGS alignment activity. The calibrations for magnification, distortion, and FGS-to-FGS alignment will be executed using both iterative and bootstrapping techniques.

7.1 *Plate Scale*

The magnification of the telescope/FGS system may change due to launch stress and desorption from the metering truss and the FGS optical bench. The plate scale, magnification calibration will be performed in stages. An intermediate plate scale compares the relative separations of stars from a ground calibrated cluster (NGC 188 or NGC 5617) to the FGS measured star vectors of the same stars. The accuracy of the solution is limited by the calibrated plates and by errors in the distortions.

The high-accuracy plate scale will be performed after the intermediate calibrations have been accomplished. The algorithm compares the positions of an asteroid as it traverses the FGS field of view to the known ephemeris of the target. Using least-squares techniques, the magnification and any center-of-light variations in the asteroid are computed.

7.2 *Optical Field-Angle-Distortion Calibration*

For an astrometer it is essential that all relative position errors be understood and characterized. Distortion perturbs the relative positions of stars in an FGS. The aberration called distortion is actually field-dependent magnification and does not degrade the wavefront quality. Additional boresight errors such as local tilts in various components of the FGS optical train also displace the star vector. In this text, the term distortion refers to all pointing errors. None of these items degrade the wavefront quality.

The optical field-angle-distortion calibration is performed after the wavefront quality is optimized. The calibration must be accomplished on each FGS, since each instrument will have slightly different distortion signatures. Several factors contribute to distortion in the telescope and FGS, and they are divided into the following categories:

(a) The largest amount of distortion is caused by the optical design of the aligned system, including the primary, secondary, and FGS optical surfaces. The analytical form of design distortion is well-known and, if not corrected, will result in positional errors of 3 arc seconds.

(b) The optical components of the FGS will not be perfectly aligned. Distortions in a system with broken symmetry could add as much as 1-arc-second error to positional measurements.

(c) The optical elements of the telescope will have figure error. Misfigured surfaces that are not near the pupil or pupil conjugates will generate local tilt or slope errors across the beam aperture. The critical optical elements in this category are the FGS pickoff and collimating aspheric mirrors. To a lesser extent the mirrors of Star Selector A will also inject figure errors into the beam.

(d) Other errors are mechanical in nature. These include the Star Selector encoder errors, Star Selector deviation angle, and clocking errors.

Once the errors are recognized, the next step is to determine the form of the polynomial which characterizes the signature of the distortion. Two polynomials have been chosen to correct for distortion, one for the X-axis and one for the Y-axis. The X-Y reference frame for each FGS is depicted in Figure 2. The forms for the polynomials are

$$\Delta X = a_{10}X + a_{11}XY + a_{20}X^2 + a_{02}Y^2 + a_{30}X^3 + a_{03}Y^3 + a_{12}XY^2 + a_{21}X^2Y + a_{50}X^5 + a_{32}X^3Y^2 + a_{14}XY^4 \ ,$$

$$\Delta Y = b_{01}Y + b_{11}XY + b_{20}X^2 + b_{02}Y^2 + b_{30}X^3 + b_{03}Y^3 + b_{12}XY^2 + b_{21}X^2Y + b_{05}Y^5 + b_{23}X^2Y^3 + b_{41}X^4Y \ .$$

Some distortions such as misfigure and encoder error give unacceptable residuals when fit to the polynomial. Since these errors are known, they will be subtracted from each star vector as a routine part of the calibration.

The distortion calibration, known as the Optical Field Angle Distortion calibration, or OFAD, will be accomplished in stages. An intermediate OFAD, which compares ground data for the star vectors of either NGC 188 or NGC 5617 to the measured data from the FGSs, will compute the distortion coefficients using least-squares techniques. The accuracy of the intermediate solution is limited by the accuracy of the plates and by the relative simplicity of the algorithm. That is, the Star Selector deviation angles and clocking errors are omitted from the solution, since they add another level of complexity to the least-squares Loss Function. The Loss Function is defined as the function to be minimized in the least-squares algorithm.

Intermediate OFAD will be initialized with the best current estimates of distortion, magnification, Star Selector deviation angles, and clocking errors. The expected accuracy of the intermediate OFAD/Plate Scale is approximately 15 milliarc seconds rms.

OFAD, the high-accuracy solution, is a constrained least-squares algorithm which solves for the coefficients of the distortion polynomials, the true star positions, a Star Selector deviation angle, the clocking or zero error in one Star Selector, and rotations which move the telescope from one pointing to the next. Details of the least-squares techniques used in this algorithm can be found in Jefferys 1980, 1981. The true star positions are treated as unknowns since no calibrated plates exist to the required level of accuracy. Constraints are required since no calibrated plate is used as the comparison or constraining condition. The deviation angle of one Star Selector is computed since the error in one deviation angle is reflected in the other. They are not linearly dependent. The same statements pertain to the clocking errors of the Star Selectors.

OFAD is initialized with the solutions from the intermediate OFAD and Plate Scale. The expected accuracy of the combined OFAD/Plate Scale calibration is approximately 3.0 milliarc seconds.

7.3 *FGS-to-FGS Alignment*

If the relative positions of stars are only measured in one FGS, the error caused by misalignments of the three FGSs is a small second-order effect which creeps into the velocity aberration corrections in the guiding FGSs. Regardless, some mention of the calibration is needed, since it is a required step in the Scientific Instrument alignments.

Like OFAD and plate scale, the FGS-to-FGS alignment calibration has an intermediate and a high-accuracy solution. For the intermediate solution, stars are observed in the three FGSs simultaneously. FGS 2 is the fiducial and its field of view is extended to encompass the remaining FGSs. The star vectors as seen in the extended FGS 2, the star vectors as actually measured in each FGS, and the angular separations computed from ground measurements are used to calculate relative alignments of FGS 3 with respect to FGS 2, and FGS 1 with respect to FGS 2. The algorithms consist of least-squares techniques for extending the field of view of FGS 2 and the Q Method for determining the rotation matrices. Further information regarding the Q Method can be found in Wertz (1978). The high-accuracy solution utilizes the same algorithm, but the ground-calibrated plate measurements are substituted with measurements obtained by HST.

In the iterative scheme, the intermediate FGS-to-FGS alignment calibration would be performed after the intermediate OFAD and plate scale for each FGS. The new alignment matrices would be fed into the OFAD and plate-scale algorithms, thus refining the distortion and magnification values. A similar scenario exists for the high-accuracy algorithms.

7.4 *Lateral Color and Filter Wedge*

The FGS filters do not possess perfectly parallel surfaces. Instead, there exists some wedge in each filter which results in a shift in star position when observing the target with two or more filters. The wedge error is not field dependent. To obtain the values for the shift in star positions, several stars from a cluster will be observed in the FGS field of view using one of the four filters. After all the star vectors are observed, the next filter is commanded into the optical train and the measurements are repeated. The process continues until all filters have been utilized.

Also present in each FGS is lateral color. Chromatic tilts are attributed to refractive elements which possess slightly different indices of refraction at different wavelengths. In the FGS, the five-element corrector group, which is a set of five lenses, is probably contributing to the color error. The consequence of lateral color can be realized with the following experiment. Two star pairs with the same known angular separations and magnitudes are observed. One pair contains two 4000-degree stars, while the other pair contains a 4000-degree and a 20,000-degree star. When observed in the FGS, the angular separations of the two pairs would no longer be equal. Furthermore, the pair whose stars possess different color temperatures would appear to "breathe" (angular separation oscillation) when placed in various field positions. In summary, lateral color errors are dependent on field position and star temperature.

To remove the effects of chromatic tilt, a star pair with well-known color temperatures will be observed at various field positions in the FGS and with all the FGS filters. The star pair is situated such that a 180-degree vehicle rotation, about the telescope boresight, can be accomplished, after which the same observing scenario is repeated. The rotation is required so that the maximum shift in the star vectors can be observed. The data will be processed through a least-squares algorithm to produce the relationship of color and field position to positional error.

7.5 *PMT Counts Versus Star Magnitude*

A calibration for the sum of the four PMTs versus star magnitude will be accomplished by observing stars of well-known magnitudes in specific temperature bands.

7.6 *Summary of Calibration Errors*

The calibrations which will be performed on the telescope are listed in Table 5. The expected error is our judgment of what will nominally be observed in orbit, and these errors should be calibrated to the values shown.

TABLE 5

Calibration Summary

calibration	expected error (arc second)	accuracy of correction (arc second)
Intermediate Plate Scale	< 5.0	0.0150 - 0.030
Intermediate OFAD	< 5.0	0.0150 - 0.030
Final Plate Scale	0.0150 - 0.030	0.0030
Final OFAD	0.0150 - 0.030	0.0030
Intermediate FGS to FGS	< 3.0	0.0150 - 0.030
Final FGS to FGS	-	0.010
Filter Wedge	< 0.0040	< 0.0010
Lateral Color	< 0.0030	< 0.0010

8. Conclusion

This article has presented various aspects of the Hubble Space Telescope Fine Guidance Sensor. It is unique among the six instruments in that it doubles as an astrometric instrument and a guidance instrument for spacecraft attitude control. As guidance instruments they will maintain the spacecraft to within 0.007 arc second jitter (telescope boresight motion); for astrometric measurements they can achieve 0.003 arc second relative positional accuracy, but only after painstaking calibration. This series of instrument calibrations will be performed during the Orbital Verification and Science Verification phase of the mission. Given the current conditions of the HST (October 1990) calibration could take a year or more. The three interferometers will be calibrated separately and to each other.

The astrometry observation modes have been designed to measure stationary and moving targets. Single stars and slow-moving objects can be acquired by the interferometer, while binary (double) stars and fast-moving objects can be scanned by the interferometer. The scientific return is expected to include accurate parallaxes of astrophysically interesting stars, precise measurements of binary stars, establishing detection thresholds for planetary companions of nearby stars, and a better understanding of the kinematics of star clusters. It is hoped that this paper has given astronomers a better understanding of the capabilities and complexities of astrometry with the Hubble Space Telescope.

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