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# Hubble Space Telescope

# Fine Guidance Sensors Instrument Handbook


(NASA-CR-[illegible]) HUBBLE SPACE TELESCOPE: FINE GUIDANCE SENSORS INSTRUMENT HANDBOOK. VERSION 2.1 (Space Telescope Science Inst.) 48 p CSCL 03A N92-[illegible] Unclas G3/[illegible] [illegible]


**Version 2.1**
**May 1990**

## Note

This edition of the FGS *Instrument Handbook* is a reprinting of Version 2.0, which was issued in 1989. A few minor corrections and errata are noted below.

The HST Fine Guidance Sensors are complicated electro-optical devices with their own micro-computer. The current FGS *Instrument Handbook* explains their operation. Additional sources of information are needed to understand the operation of the FGS in full detail. It is important that potential General Observers understand the basic measurement capabilities of the FGS and ascertain the technical feasibility of their observing projects. Hence, we want to reiterate the scientific capabilities of the FGS. The FGS can be used to (a) measure the relative positions of fixed and moving sources of light to a few ($\sim 3$) milli-arc seconds; (b) measure the separation, position angle, brightness ratio, and total brightness of binary systems with separations larger than 5 mas and brightness differences less than 3 mag; (c) measure the apparent diameters of stars in the 5-50 mas range; (d) roughly measure the color indices of stars ($\pm 0.1$ mag); (e) study both stellar and non-stellar objects. The brightness limit on these observations is 17th mag.

Potential General Observers are encouraged to call L. G. Taff at 301-338-4799 or M. G. Lattanzi at 301-338-4866 with technical or scientific questions regarding their observing projects. (Electronic mail may be sent to SCIVAX::LGTAFF or LGTAFF@STSCI.BITNET, or to LATTANZI). The FGS Instrument Scientists are eager and willing to assist potential General Observers in extending the uses of the FGS and to help promote astrophysically rewarding observing projects.

Minor Corrections to FGS *Instrument Handbook*:

pg. 12: Count rates are confused throughout the *Handbook*. The standard 13th-mag star produces 9600 counts per sec in each of the four photomultiplier tubes in each FGS. Included in this result are all nominal losses, quantum inefficiencies, obscurations, and so on. The nominal dark count plus background count is 360/sec/photomultiplier tube. This nominal count rate, the stated dark count rate, and the stated dynamic range imply saturation occurs at 6.1 mag.

pg. 19: (4.2.3) All references to TRANS/MOVING mode should be to SCAN mode. (Also on pages 22, 23, and 24.)

pg. 20: Last sentence of Target Position paragraph: There is no longer expected to be a limited area of good calibration. The cause of this belief was a computer programming error in the STAT OFAD software.

pg. 36: Labels are incorrect. The $y$ axis label should be "total counts per sec per photomultiplier tube." The "per FGS axis" note on the top should be eliminated.

pg. 42: Top $x$ axis label should be "wide," not "close."

CONTENTS

# 1.0 INTRODUCTION

## 1.1 OVERVIEW

The Fine Guidance Sensors are a system of photomultiplier tubes and white-light amplitude interferometers (Koesters' prism) which are used for the fine guidance of the Hubble Space Telescope. Since only two Fine Guidance Sensors are required for precision guidance of the telescope, the third Fine Guidance Sensor can be used to conduct astrometric observations. A precision of 0.003 arcsec in the relative positions of three stars should be possible for stars with apparent visual magnitudes in the range $m_V = 4$ to 17. The Fine Guidance Sensors are also expected to provide a photometric precision of 1% for stars as faint as 17th magnitude.

The FGS is not an imaging device like a camera, but is instead an assembly of two interferometers which determine the tilt of a wavefront relative to the full Hubble Space Telescope primary mirror (the entrance pupil of the interferometer). This arrangement was chosen because the positional precision which can be achieved by the interferometer is not limited by the resolving power of the Hubble Space Telescope (HST) (the size of the Airy disk at 6328 Å is 0.066 arcsec), but by the variation of the interference fringe visibility.

## 1.2 EXAMPLES OF ASTROMETRIC PROGRAMS SUITABLE FOR THE FGS

1. Parallax and Proper Motions
   Parallaxes and eventually proper motions are expected to be measurable with a precision of 0.0005 arcsec. The improvement over the value of 0.003 arcsec for a single measurement is achieved by making three sets of observations, using ten astrometric reference stars during each set (*i.e.*, $0.0005 \simeq 0.003 / \sqrt{30}$ ). This precision will allow the measurement of the parallax of several stars of fundamental importance to establishing the distance scale. These include RR Lyrae stars and Cepheid variable stars, stars in the Hyades and Pleiades, and the central stars of some planetary nebulae. As systematic errors remain an unexplored field within the HST, it is not recommended that such observing plans follow the ground-based practice of only observing at the extremes of the parallactic ellipse.
   One advantage of the FGS is that stars with a wide range of apparent magnitudes can be measured during the same observational sequence. This will make it possible to determine the parallaxes of very bright stars relative to faint background stars. Similarly, the detection of planetary system gravitational influences on bright nearby solar-type stars may also be possible. Cluster membership determination by proper motion methods will refine the Zero Age Main Sequence. A precision of 0.001 arcsec per year for proper motions will permit observations of tangential velocities of about 8 km/s at 1 kpc, typical for O and B stars.

2. Double Stars, Diameters, and Extra-Solar Planets
   For double star studies, the FGS interferometer is scanned across both components. This yields information about the separation, position angle, and magnitude difference of the two members. Double stars whose components differ in magnitude by less than about 3 mag and have separations in the range 0.005 to 2 arcsec are detectable down to a visual magnitude of 14 (for the brighter star).

8. Astrometry as Parallel Science
The third FGS can be used for astrometric observations in a parallel mode, as long as the jitter induced by the star selectors (see below) will not damage the scientific quality of the primary observation. The feasibility of this option will not be known before the deployment of the spacecraft.

9. Astrometry With the Cameras
The Wide-Field/Planetary Camera and the Faint Object Camera can be used for astrometric observations, especially for objects which are too faint to observe with the FGS (visual magnitude greater than about 18). The cameras might also be more efficient than the FGS if a large number of objects within the cameras' field-of-view can be simultaneously studied. However, it should be noted that the centering algorithms for defining the objects' image locations are only efficient over a range of 5 magnitudes if it is desired to avoid bias resulting from different image sizes. It might therefore be necessary to take many frames with different exposure times. The positional precision expected from one Wide-Field/Planetary Camera frame is about 0.003 arcsec (1/30th of a pixel in the Wide Field mode) for relative separation measurements in the wide-field configuration. The precision of the internal relative positions with respect to the FGS reference frame will be determined after launch, but should be a few milli-arc seconds.

## 1.3 HOW TO USE THIS HANDBOOK

The purpose of this handbook is to provide information to a potential user of the FGS so that he may explore the feasibility of performing various observations. Some instructions for filling out the HST observing forms are also included, although you should refer to the *Phase II Proposal Instructions* and the *Call for Proposals* for details. This handbook does not provide a detailed description of the FGS at a systems level (*e.g.,* the algorithms implemented on microprocessors in the Fine Guidance Electronics). Section 2 provides a brief overview of how the FGS works along with an explaination of the instrument in some detail. The procedure for estimating exposure times is explained in Section 3. Section 4 describes the observing modes, while Section 5 explains some details needed to specify the exposures and observation requirements on the proposal forms. Section 6 outlines the data-reduction procedures. Section 7 contains appendices and all of the figures.

The precision estimate of 0.003 arcsec also assumes that the observations can all be taken within a 20 minute period. This includes both the exposures for the target and the astrometric reference stars (generally between 3 and 10 in number). Thermal stability considerations become important for longer periods of time. Should the sequence of observations be longer than 20 minutes, or should a new HST pointing occur, then a new sequence of observations must be prepared with some targets in common to reach a similar precision. Of course, systematic errors can creep in at this point.

## 2.2 HISTORICAL BACKGROUND

- 1975: The interferometric design is considered as the most precise and the most sensitive way to measure an angle, but works over a narrow angle (±0.018 arcsec in the case of the HST). The Koesters' prism is adopted during the phase B activity and the FGS is designed to be used for the fine guidance of the spacecraft: utilization for precise differential astrometry is included as a supplementary scientific function.
- 1977: The two star selector encoders A and B are adopted with readings over 21 bit encoders and the star selectors are designed to be stationary during an observation (the measured signals are driving the spacecraft).
- 1981: The star selector motors are requested to be continuously active during an observation in order to keep the signal of the interferometer at null and the concept of astrometric averaging with active star selector servos is implemented.
- 1983: A study is proposed to replace the Koesters' interferometer by a quadrant detector, but successful observations of fringes of interference for sources as faint as visual magnitude 15.5 with a 0.025 sec integration time shows that the interferometric design is indeed working.
- 1984: The original instantaneous field-of-view of 3 by 3 arcsec is changed to 5 by 5 arcsec because of alignment constraints under gravity release.
- 1985: A significant color effect is measured in the FGS engineering model; this result is a concern for astrometry as the FGS design was to minimize these color effects. To handle this problem the blue part of the bandpass of the last FGS flight unit is cut off by a new coating of the clear aperture filter. This unit is expected to be used for astrometry. In-flight tests to be performed during the science verification period (6 months after HST launch) will show the best performing FGS unit.
- 1985: A design flaw in the FGS is found which limits astrometric precision to a few milli-arc seconds. Its source is the juxtaposition of a heating element and an (internal) FGS mirror.

## 2.3 SCHEMATIC DIAGRAM

The three Fine Guidance Sensors (FGSs) are positioned as three of the four radial instruments on the HST. The Wide-Field/Planetary Camera is in the fourth radial bay. The FGSs receive light from pickoff mirrors placed in front of the HST focal plane in such a way that, between the three FGSs, an area consisting of three-quarters of the annulus from 10.2 to 14 arcmin of the HST optical axis is accessible (Figure 1). The FGS pick-off mirror

Light converging toward the focal plane of the main optics is sampled by a plane pick-off mirror which has an aperture of roughly a quarter annulus. This light is diverted into a direction perpendicular to HST's V1 axis. This light comes to a real focus before diverging to the off-axis aspheric collimating mirror from which it emerges nearly parallel but essentially reversed in direction. This light then encounters the "A" and "B" star selectors, which, by independent adjustments, transforms the direction of light from any star in the FGS total field-of-view into a direction normal to the Koesters' prism interferometer. A pupil lies between the corrector group and the "B" star selector. The five-element corrector group is rigidly attached to the "A" star selector, its axis is along the image of HST's V1 axis. The function of the corrector group is to compensate for the residual aberrations remaining in the beam after collimation by the off-axis asphere.

The light emerging from the "B" star selector is reflected by a plane mirror through the filter assembly. The light transmitted by the filter is again reflected by a plane mirror to the polarizing beam splitter. The beam splitter performs a 50/50 intensity division of the incident (unpolarized) light and produces linear polarization in each of the exit beams (see Figure 5). This linear polarization is necessary for proper operation of the two Koesters' prism interferometers, one residing in each exit beam of the beam splitter, for the Koesters' prism interferometer is only sensitive to tilts of the incoming wavefront which occur in a plane normal to the prism's roof edge. In order to achieve sensitivity in each of the two orthogonal directions, two Koesters' prisms are used and oriented with their roof edges perpendicular to one another.

Each Koesters' prism has two exit beams. Each beam is focused by a positive doublet on the field stop assembly. This field stop limits the instantaneous field-of-view to a square area 5 arcsec on a side. At this field stop is a field lens which images the system's pupil on the sensitive surface of the photomultiplier tube detector. Since there are four final beams, there are four doublet/field stop/detector assemblies.

### 2.4.2 Measurement of a Direction

The FGS operations may be completely described using only two reference spaces, the detector space (or X,Y, and Z axes, with the Z direction corresponding to the illumination by the off-axis target of the full HST mirror as seen by the interferometer) and the FGS object space (corresponding to the alignment of the FGS optical bench in the HST graphite-epoxy structure), each defined with respect to V1, V2, and V3 vehicle space (V1 is the HST line-of-sight, the plane (X,Y) and the focal plane (V2, V3) are parallel). Opto-mechanical misalignments and optical distortions are perturbations from the nominal rotations between these two references. As the HST magnification is of the order of 57.3, one arcsec on the sky is transformed into one arcmin in the interferometer space (the beam size is demagnified from the 2.4 m HST mirror to about 42 mm and the off-axis beam deviation is magnified from 14 arcmin to about 13.4 deg). The FGS measures two spherical angles ($\theta_A, \theta_B$) with respect to the HST optical axis (V1) and the results of the astrometric measurements are reported in polar coordinates; $\phi$ = azimuth in deg and $\rho$ = angular offset in arcmin from the V1-axis (direction of the HST optical axis on the sky). The sensed coordinates $\rho$ and $\phi$ may be transformed into the standard coordinates ($\xi$ and $\eta$) usually used in traditional photographic astrometry. However, the uncorrelated measurements of a target direction are

### 2.4.4 The Filters

Located in the optical path, between the "B" star selector and the polarizing beam splitter, is the filter wheel assembly. This assembly consists of a wheel bearing five filters and a driving mechanism. These filters are used to minimize the lateral color effects in the FGS astrometer. Intensity reduction will be accomplished by a neutral density filter (ND = 2); five magnitudes of attenuation will be used when viewing bright objects.

Spectral bandwidth limitation can be accomplished by using either the red or the yellow filters. The yellow filter more closely approximates the "V" filter than does the clear filter. The yellow filter was chosen to eliminate the effects of almost all of the strong lines from emission line nebulae.

Instead of the aforementioned red filter, the astrometer FGS possesses a modified version of the clear filter in which the short wavelength cut-off has been increased to 5100 Å. This modification is useful in reducing chromatic effects in the astrometer FGS (see Table 1). The fifth position in the filter wheel is occupied by an annular aperture having a linear obscuration ratio of 2/3.

**TABLE 1**
**Spectral Elements for the FGS**

| Name | Position | Comments | Effective Wavelength (Angstroms) | Full Width at Half Maximum (Angstroms) |
|---|---|---|---|---|
| PUPIL | 1 | Pupil stop | — | — |
| F583W | 2 | "Clear" filter | 5830 | 2340 |
| F5ND | 3 | Neutral density (5 mag) | — | — |
| F650W | 4 | "Red" filter (in 2 FGSs) | 6500 | 750 |
| F550W | 5 | "Yellow" filter | 5500 | 750 |
| in the FGS for Astrometry, the "red" filter is replaced by the filter: | | | | |
| F605W | 4 | "Astrometry Clear" filter | 6050 | 1900 |

### 2.4.5 The Polarizing Beam Splitter

This element splits the incident beam into two equal intensity beams travelling in perpendicular directions. In addition, each of these beams is plane polarized in mutually orthogonal directions. Two beams are required because the Koesters' prism interferometer is sensitive only to tilt in one axis. Therefore, for two dimensional sensitivity two Koesters' prisms are needed (one in each beam and oriented so that their tilt sensitivities are orthogonal to each other).

When normalized to their sum, the difference between the two channel outputs of a given photomultiplier tube subsystem forms the "S" variable illustrated in Figure 6. This variable is an indicator of the tilt of the wavefront incident on the input plane of the Koesters' prism. Under conditions of normal incidence, the outputs of the two channels will be equal. The normalization and differencing are performed in the Fine Guidance Electronics.

Each of the two independent channels incorporates a photomultiplier tube, a high voltage power supply, which provides the approximately 2000 volt dynode potential for the photomultiplier tube, and a pulse amplitude discriminator, which performs local processing of the photomultiplier tube anode signal as well as squelch, pulse shaping and transmission line driving functions. The dynamic range of each channel is approximately $4.5 \times 10^4$. The lower limit is set by the approximately 120 count/second dark count performance of the photomultiplier tube, while the upper limit is set by saturation of the pulse amplitude discriminator. This occurs at approximately $5.4 \times 10^6$ counts/second.

As the normalized difference between the outputs of the two channels is the indicator of tilt of the wavefront at the input plane of the Koesters' prism, any differences in the responsivities of the two channels will introduce pointing errors. In order to bound these errors, responsive matching has been controlled during system intergration and by photomultiplier tube matching.

A "squelch" function has been incorporated into the photomultiplier tube subsystem to prevent the passage of high energy particles through the photomultiplier tube faceplate from appreciably degrading subsystem performance. The signature produced by such an event is an exceptionally large anode pulse caused by Cerenkov radiation in the faceplate as the particle velocity diminishes, followed shortly by a shower of typically from 10 to 30 "daughter" single-photoelectron pulses. This shower of single-photoelectron pulses is a result of faceplate phosphorescence initiated by the Cerenkov pulse.

While the initial Cerenkov pulse does not introduce an appreciable pointing error, as it introduces only one additional noise count, if allowed to appear in the calculation of the "S" variable, the shower of daughter pulses has the potential for seriously disturbing the interferometer null position. To prevent this from occurring, the outputs of both channels are inhibited for a period of nominally 150 microseconds following the detection of the large initial pulse by either channel. This squelch duration has been chosen to roughly match the expected decay rate of the daughter pulse shower. As a result of the squelch operation, the net effect of a high energy particle impact is a reduction by 150 microseconds of the nominal 25 msec integration period.

The photomultiplier tube itself has an end-illuminated design employing a 13 stage venetian blind dynode structure. The photocathode is a transparent, multi-alkali type with an S-20 spectral response. In order to limit dark counts resulting from thermionic emission from the photocathode, the effective photocathode area is limited to a circle of 3.6 mm diameter by electron optics. The dynode potential for each photomultiplier tube is set during system integration to establish an operating point on the single electron plateau.

Each FOS utilizes a pair of matched photomultiplier tubes behind each Koesters' prism. They are selected for similar spectral response. Matched photomultiplier tubes meet the following criteria:

a. For a 6000 deg K star the output count of the photomultiplier tube pair each will be within 10% of the mean output from the two tubes.

# 3.0 INSTRUMENT PERFORMANCE AND EXPOSURE TIME CALCULATIONS

## 3.1 SEQUENTIAL STAR MEASUREMENT

In traditional differential astrometry the observations are performed with the simultaneous detection of all objects of interest (*i.e.*, by a photographic plate). With the FGS only one star may be processed at a time. The individual measurements must be referred to other measurements made at different times with the reference system provided by tracking on the Guide Stars. Uncalibrated drifts are potential problems for FGS astrometry. It is appropriate to bear in mind that the 0.007 arcsec HST pointing stability and the 0.005 arcsec relative astrometry specification. The pointing specifications for the spacecraft as a whole include disturbances with periods between 0.1 second and 24 hours. The goal in designing an astrometric observation is to keep integration times longer than the principal high frequency disturbances (above about 0.5 to 1.0 Hz) and shorter than the long term drifts (50 minutes to 24 hours). This may require breaking up longer observation sets into a number of short sections, with each section terminating by returning to the original reference star, but potentially different Guide Stars (thus introducing a potential source of systematic error).

The acquisition by the FGS of a star before tracking is expected to take at least 20 seconds of time, independent of the star's brightness. This is not considered as part of the exposure time per se.

The Fine Error Signal averaging time can be selected from among the 8 values: 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, or 3.2 sec. A measurement of a stellar position consists of 32 successive integrations. At the end of each of the 32 integration periods, the star selectors reposition themselves within approximately 0.050–0.075 seconds.

If the observing time for a set of stars (generally the program star plus several astrometric reference stars with the same continuous HST pointing) becomes longer than about 20 minutes, thermally induced deviations in the pointing stability will degrade the accuracy of the measurements. Also, the brightness distribution of the stars in the field around the target will limit the number of background stars that can be used. A tradeoff has to be made between the number of targets to observe in one observing sequence and the selection of the exposure time necessary to acquire and observe each individual target. It has also to be kept in mind that 10 seconds are necessary for a complete rotation of the filter wheel (five positions), and that the target and both Guide Stars then need to be reacquired when any command to the filter wheel has been issued. Therefore, a time interruption as long as 2 minutes may be necessary in the observing sequence when the clear filter is not continuously used.

## 3.2 THE SIGNAL PRODUCED BY THE INTERFEROMETER

The intensity of the light at any point in the output beam of the interferometer is given by

$$I' = I \times [1 + OPD \cos(2\pi/\lambda)]$$

where $OPD$ is the optical path difference which is proportional to $\epsilon$ which is the wavefront tilt of the interferometer (60 times the HST mispointing error). $I$ is the number of photons per unit area of the interferometer (3600 times the star illumination at the telescope aperture).

$$\epsilon = \frac{1}{60f} \times \frac{\sqrt{I+F}}{I\sqrt{\tau}} \tag{3}$$

with $\tau = 2^n \times 0.025$ seconds ($n$ selectable from 0 through 7) and $I = 9600 \times 10^{-0.4(V-13)}$. $I$ is expressed in counts/sec and $V$ is the target apparent visual magnitude (see subsection 2.4.8 and Figure 8, in order to change the nominal counting rate per second for a 13th visual magnitude star of 9600 counts/sec by the correct value for a 13th magnitude star of a specific spectral type or for an observation with a non-"clear" filter). $\epsilon$ is the resulting measurement error standard deviation of one integration period ($\tau$) in arcsec in object space per interferometer axis.

**Example**: A 17th visual magnitude star would contribute to $I = 239$ counts/sec. With $\tau = 1.6$ sec, $F = 611$ counts/sec (current estimate), and $f = 0.7$ (a fudge factor for degradation), $\epsilon \simeq 0.003$ arcsec for one integration period on the 17th visual magnitude star observed with the "clear" filter. Over 32 integration periods, the mean value of the encoder readings will be improved by $\sqrt{32}$. The contribution of the interferometer noise to the astrometric measurement (the mean value of 32 readings) is estimated to be about 0.0006 arcsec which is about one least significant bit of the encoder readings. Of course, since the star selectors have been continuously commanded to null the Fine-Error Signal at a 0.025 sec rate, the integration periods are not independent.

Figure 9 indicates the positional precision of the mean value of 32 encoders readings resulting from the eight possible different Fine Error Signal averaging times as a function of the target apparent visual magnitude.

## 3.4 THE JITTER NOISE

In the course of astrometry measurements, the spacecraft will undergo small random motions as a consequence of the lack of perfect pointing stability. The line-of-sight jitter appropriate for the maximum integration time of 3.2 seconds is about 0.003 arcsec. This introduces a pointing error of less than 0.0005 arcsec since the average of 32 readings is used for the position ($0.0005 \simeq 0.003/\sqrt{32}$). If very precise positions are required, it will be generally wise to measure the position of the target at least twice in the observing sequence in order to monitor the stability of the jitter noise.

## 3.5 COLOR-TEMPERATURE EFFECTS

Systematic effects have been identified as a result of the 5 element refractive corrector group. This group can produce an offset of the zero position of the transfer function for a 3000 deg K star relative to a 10000 deg K star of as much as 0.001 arcsec. If the color of the target (for example, a quasar) is different from the mean color of the reference stars, it may be appropriate to determine color indices to correct for this effect which is also dependent on the position of the target in the field-of-view.

## 4.0 OBSERVING MODES

All astrometry operations commence with two FGSs stabilized on Guide Stars. This results in a sensing environment for the astrometry FGS which is free of steady-state drift and has a modified and reduced gyro noise spectrum. In astrometry the sensor may acquire and track stars as faint as V = 17 mag (or even 18 with appropriate dark and background counts calibration).

## 4.1 TARGET ACQUISITION

The following short acquisition sequences are used to identify the target and to keep the interferometer locked on the null position.

1. Search
The acquisition begins with a spiral search scan by the starselectors in the FGS total field-of-view to locate the target around its expected position ($\rho$, $\phi$ or $\theta_A$, $\theta_B$ are determined from the equatorial coordinates of both the target and the V1-axis). The search scan terminates when either a star is found within the designated magnitude range, or the maximum search radius is reached and no star has been found. As the spacecraft drift rate is controlled by the two Guide Stars, the search for an astrometric target will be very fast.

2. Coarse Track
If the search scan is successful (a target of the appropriate apparent visual magnitude is found), then the coarse track scan automatically commences. During coarse track the Fine Guidance Electronics uses an algorithm that utilizes the signals from all four photomultiplier tubes to identify the location of the center of light. The position of the target ($\rho_0$, $\phi_0$) is then known with an accuracy of about 0.1 arcsec.

3. Fine Lock
The fine lock scan automatically commences too. The FGS instantaneous field-of-view is first offset by a small angle (0.04 arcsec) from the target position ($\rho_0$,$\phi_0$) estimated after coarse track, and then is moved along a diagonal path toward the originally estimated position ($\rho_0$,$\phi_0$) until both interferometer axes detect the first interference fringe. This detection is then used to set the position of the star selectors at the central zero crossing of the interferometer pattern, measured by the mean value of 32 readings of ($\theta_A$,$\theta_B$). A feedback loop is continuously established between the Fine Error Signal and the star selector servos which keeps the encoder motors tracking the target near these directions in the $\pm$0.018 arcsec range. This is referred to as Fine Lock. If the interferometric pattern is not identified, or if the positional offset of the zero crossing (Figure 4c) from ($\rho_0$,$\phi_0$) seems too large, then the FGS will fail to achieve Fine Lock for the object. Such a failure can occur for stars embedded in nebulosity or if the background in the instantaneous field-of-view is very high. If the central zero crossing has been successfully identified at the place ($\rho_1$,$\phi_1$), then the star selectors follow the target as long as the tracking offset remains well within the linear characteristics of the transfer function (*i.e.,* $\pm$0.018 arcsec around the null position).

### 4.2.3 Transfer Function on Moving Target Mode

The Transfer Function on Moving Target mode (TRANS/MOVING) can be used for targets which are moving too fast or are too faint for the TRANS or POS modes. This mode allows one to determine the target location ($\rho_0$,$\phi_0$) after Coarse Track (4.1.2) without identification of the interference fringe by the Fine Lock logic (4.1.3). It can also be just a scan of an area, as in the Transfer Function Mode (4.2.2), but from the location ($\rho_0$,$\phi_0$) determined after Coarse Track. The interactive analysis on the ground of the photomultiplier tube counts correlated with the time-tagged star selector encoder readings ($\theta_A$,$\theta_B$) will then identify the target direction ($\rho$,$\phi$) in the HST field-of-view. Generally, the aim of this mode is to measure the position relative to a set of background stars (which are observed in POS mode) of a target which would not provide the interference fringe visibility at all and would not provide a successful fine lock acquisition.

### 4.2.4 Other Modes

POSition and TRANSfer function are the principal modes of the FGS. Other modes have been designed (Line-of-Sight TRACK, MAP TRACK) are being developed (Rate Feed Forward to capture fast-moving objects, AMBUSH to lie in wait for moving targets, RAPID Acquisition for precisely located stars), or one in place (Line-of-Sight Scan, WALKDOWN, and MAP). See the Phase II Proposal Instructions.

about 3 mag) in the 5 by 5 arcsec square instantaneous field-of-view, or targets with bright backgrounds (*i.e.*, nebulae). The corresponding entries for this column are EXT (extended), COMP (companion), and BKG (bright background). These considerations only apply to the POS and TRANS modes.

Flux Data and Reference Number(s) (Col 10)

Since the FGS sensitivity with the clear filter is near the Johnson V band, visual magnitudes should generally be given. If a different filter is used then the corresponding flux or broad band magnitude should be provided. See Figure 10 and Table 1, to extract the counts per FGS axis (2 photomultiplier tubes) for a specific filter bandpass. Examples are given in section 2.4.8 to evaluate the counts per second in one FGS axis which are then used in Eq. (3), to estimate the Fine Error Signal averaging time.

## 5.2 PARAMETERS REQUIRED FOR EXPOSURES

This section refers to the Exposure Logsheet of the ST ScI proposal forms.

Operating Mode (Col 5) Specify POS, TRANS, WALKDOWN, or SCAN.

Aperture or Field of View (Col 6)

An individual radial bay (1, 2, or 3) can be specified, or the choice can be left open (ANY), or the "PRIME" astrometry FGS can be requested. Radial bay number two is always oriented towards the Sun and therefore may work in a warmer environment. The prime astrometry FGS is the FGS flight unit with a clear filter bandpass of 5100 Å to 7000 Å which may reduce the color error (which depends on the field angle position). This FGS will be installed in the +V2 or −V2 direction in order not to observe the parallactic displacement along the radial direction of the focal plane. Otherwise, we would be sensitive to an uncalibrated radial distortion. A different prime astrometry FGS unit may be chosen shortly before launch (based on test data).

Optional Parameters (Col 9)

STEP-SIZE:

This parameter has to be specified for the astrometric scan in TRANS mode and indicates the sampling interval of the transfer function in each axis. The recommended value is 0.001 arcsec. The smallest value is 0.0003 arcsec. The scale factor between commanded STEP-SIZE and object space will be calibrated by observing some known single stars or some close binary systems with known orbital elements.

DATA-RATE:

This parameter provides a means of specifying the time resolution in the data (as for moving targets) is required to accomplish the scientific objectives. Two rates are available, the 32 kbps data rate and the 4 kbps data rate. These provide either a sampling of one data set (essentially the star selector readings $\theta_A$, $\theta_B$ and the Fine Error Signal in both FGS axes) every 0.025 second, or every one second. The highest precision (about 0.003 arcsec) is expected when the 32 kbps data rate is used, and is the only mode recommended. The 32 kbps rate is difficult to schedule because it requires real-time access to NASA communication satellites.

FES-TIME:

mode a given direction of scan is in general scientifically equivalent to the opposite direction, so unless otherwise stated, the scheduler will choose the most convenient of the two.

POSITION TARGET

By default, a target will always be placed within the unvignetted region of FGS field-of-view. For some projects it may be important to specify the position of the target more precisely. This can be done with the POSition TARGet special requirements. The POS TARG is identified by the appropriate settings of $\theta_A$ and $\theta_B$ (Figure 2). For example, the set $\theta_A = 65$ deg $\theta_B = 115$ deg defines the target to be at the center of the field-of-view. Any different optimum FGS area will be identified by the $\theta_A$ and $\theta_B$ (for instance, the zone with the smallest local errors of the aspheric collimator, or the zone with the smallest encoder wobble errors). Gauss' equations in Section 2.4.2 enable one to transform ($\theta_A$, $\theta_B$) into $(\rho, \phi)$ to locate the target image in the (V2,V3) plane. In general, the position target will be the central part of the FGS pick-off mirror.

SEQuential NO GAP

Since the sequence of observations is usually of prime importance in positional astrometry, the SEQuential NO GAP special requirement should generally be used. If this requirement is not stated, **the exposures may be taken in any order and at any time.**

GROUP

Positional astrometry sequences will in general be continuously done within one orbit whenever possible. If very long continuous sequences (for example, longer than 50 minutes) are required and are possible, given the orbit geometry (transition from cold to hot orbit), they should be requested using the GROUP keyword. Similarly, sequences of observations to be done on successive orbits can be requested using GROUP .

SPATIAL SCAN

Whenever the TRANS/MOVING mode is requested, you may also include this special requirement. This will indicate that the HST spacecraft should be used to scan across a target as TRANS/MOVING can operate with or without HST tracking. HST has the capability to track solar system objects at rates up to 0.21 arcsec per second of time.

#### 6.2.2 Preparation for Reduction

1. Raw star selector encoder readings are corrected for utilizing ground calibrations. The mean value of 32 readings is computed by a least sum of errors minimization. Outliers can be removed.
2. For double star studies, the separation and relative brightness of the two components are determined by the observed transfer function.

#### 6.2.3 Astrometric Reduction

The REDUCE module supplied by the Astrometry Team is the core of the ADRS system. It applies a general reduction model for the current field to the data. The module supports the determination of parallaxes, proper motions, and stellar positions. It also provides estimates of the effects of optical distortion, color and magnitude corrections, and position offsets caused by the filters.

### 6.3 ARCHIVING AND STANDARD DATA PRODUCTS

At present, the design of the Science Operation Ground System (SOGS) is such that science data from the other Scientific Instruments will be automatically processed and calibrated by the Post Observation Data Processing Software (PODPS) and processed files will be placed in the HST archive with references in the archive catalog. For astrometry data, the design for these procedures has not yet been completed.

The default data product supplied to a General Observer will be a magnetic tape of FITS-format files containing the data in two different forms:

1. A set of files containing edited but uncalibrated data with raw encoder values and raw photomultiplier tube counts.
2. A set of calibrated files with the data presented as stellar positions processed through the ST Scientific Data Analysis Software (STSDAS) system to correct for known distortions, but not including analysis using the REDUCE module (which the General Observer may use).

### 6.4 FGS CALIBRATIONS

#### 6.4.1 Star Selector Encoders

The star selector 21-bit encoder readings are a combination of two levels of encoder which are separately read. The high-order 14 bits are derived from an optical encoder while the low order 7 bits are derived from an optical resolving device which synthesizes sine and cosine functions whose period is the seven bit interval. Two sets of corrections are required for a given star selector.

1. The high-order correction varies as the star selector angle varies from 0 to 360 deg.
2. The low-order correction varies through the 7 bits of the "interpolator" from 1 to 128.

All these corrections have been measured on the ground and will be applied in the calibration of the FGS data.

strong polarization may also introduce a systematic effect in the position measurements over different HST roll angle orientations.

### 6.4.4 Transfer Function Calibration

The shape of the transfer function (Figures 6 and 7) is defined by the slope of the curve at the origin (57.3 $arcsec^{-1}$), the peak-to-peak width (0.0356 arcsec), and the values of the maximum and minimum amplitudes (+0.72 and −0.72).

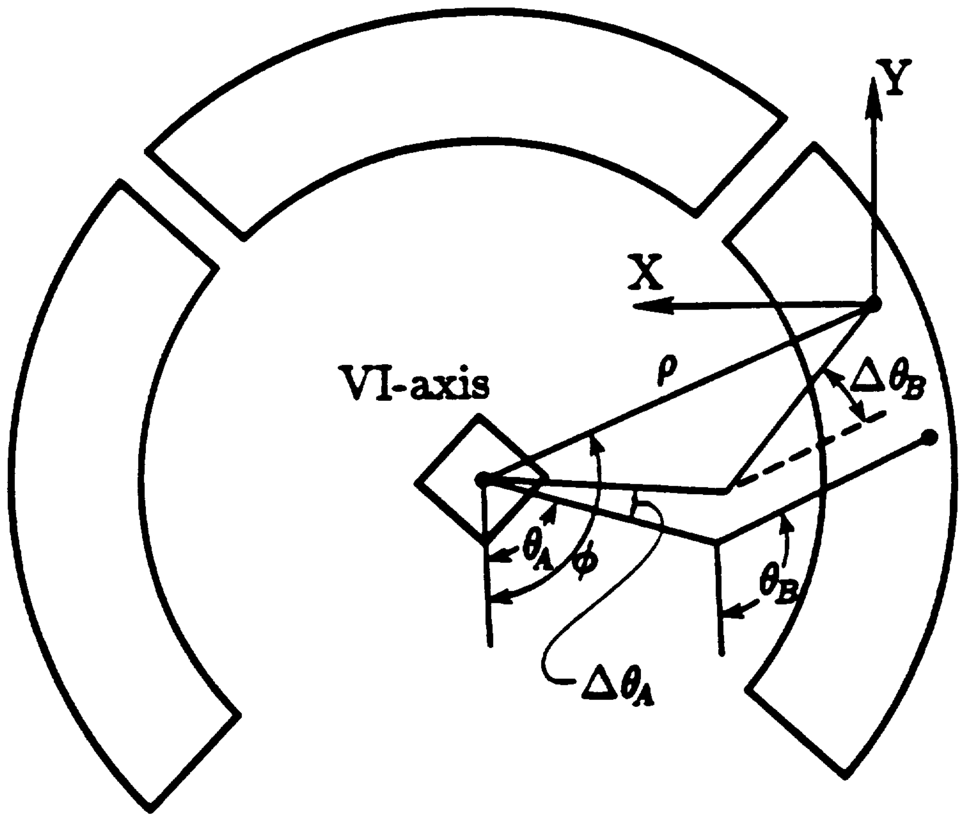
Figure 14 shows the transfer function of a binary system with an angular separation of the components (with the same luminosity) of 0.050 arcsec. A zero crossing is detected between two separated transfer functions. Figure 15 shows the transfer function of a binary system with a close angular separation $\alpha$ of the components (of the same luminosity). The gain of the interferometer (the slope at the zero crossing) is reduced.

Calibration of all six interferometer transfer functions will be done on a set of stars which show no signs of being double, and on a set of well known close binaries in the separation range of 0.1 to 0.2 arcsec.

## 7.3 FIGURES

### 7.3.1 HST Focal Plane Showing Location of the FGS Field-of-View

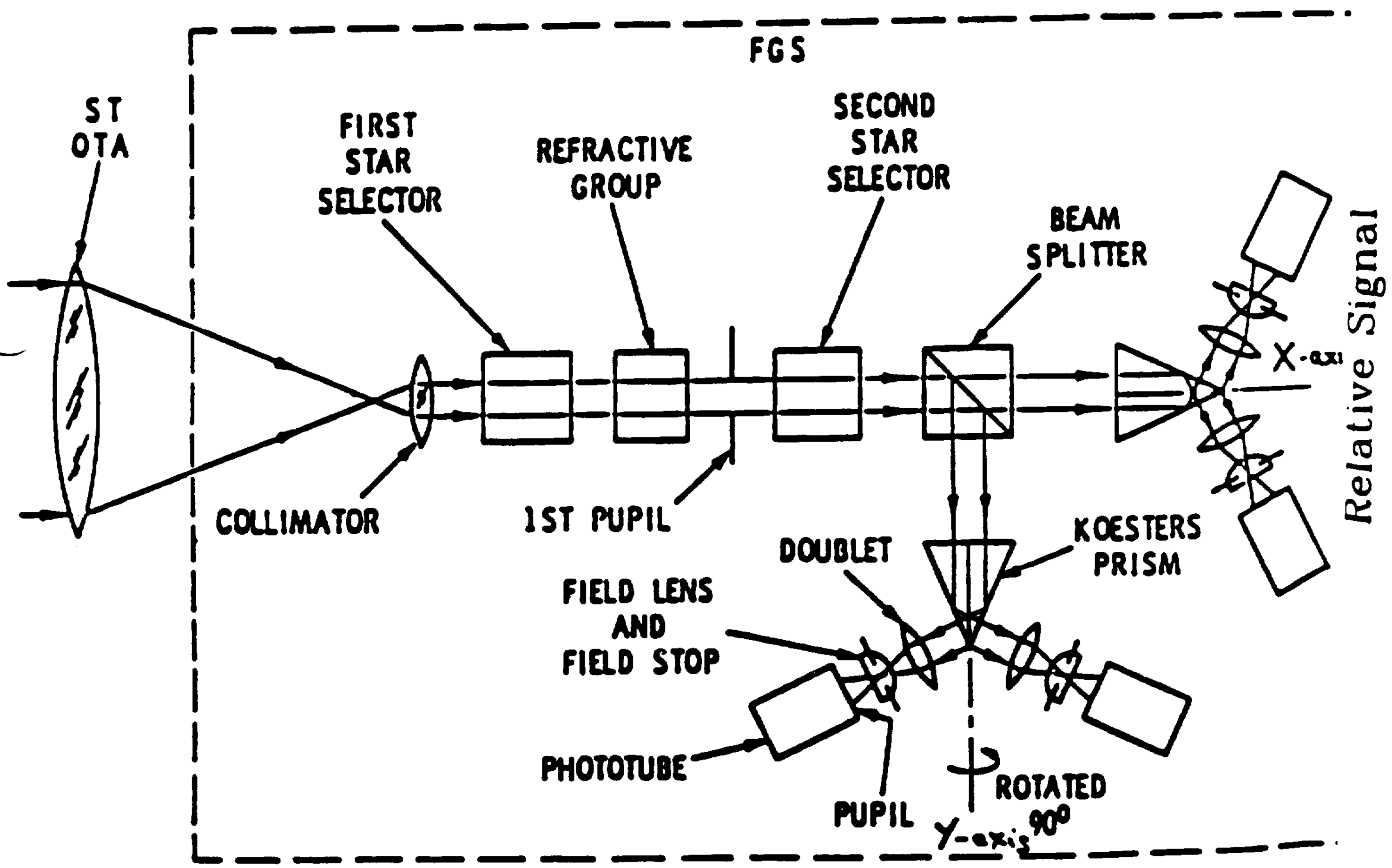
**Figure 1**: The star selectors are represented by two lever arms, each of 7.1 arcmin on the sky. The angles $\theta_A$ and $\theta_B$ are determined by means of optical disc shaft encoders. $\Delta\theta_A$ and $\Delta\theta_B$ are the basic measurements used to perform differential astrometry when the fine error signals are at null in both interferometer axes. The spherical polar coordinates $\rho$ and $\phi$ are one way to map the HST field-of-view.



### 7.3.3 Schematic Diagram of the FGS

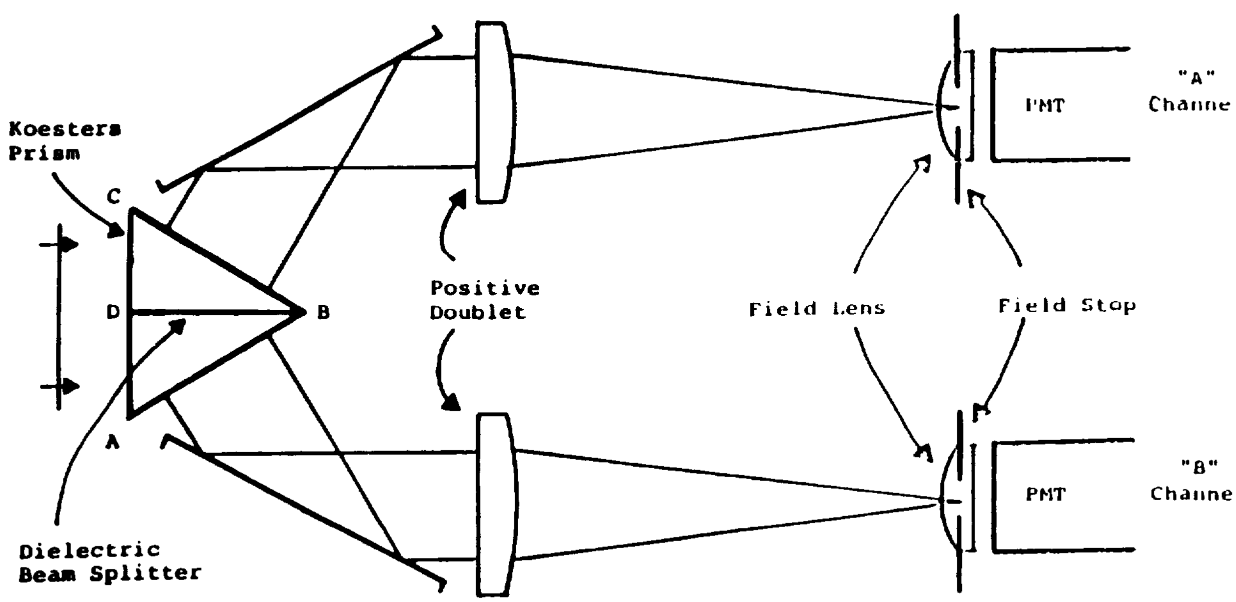
**Figure 3**: The Optical Telescope Assembly and the aspheric collimator are represented in transmission (as lenses). The filter wheel is not indicated and is located between the second star selector and the beam splitter. Note the two orthogonal axes X and Y of the interferometer provided by the beam splitter.

SIMPLIFIED FGS OPTICAL SCHEMATIC



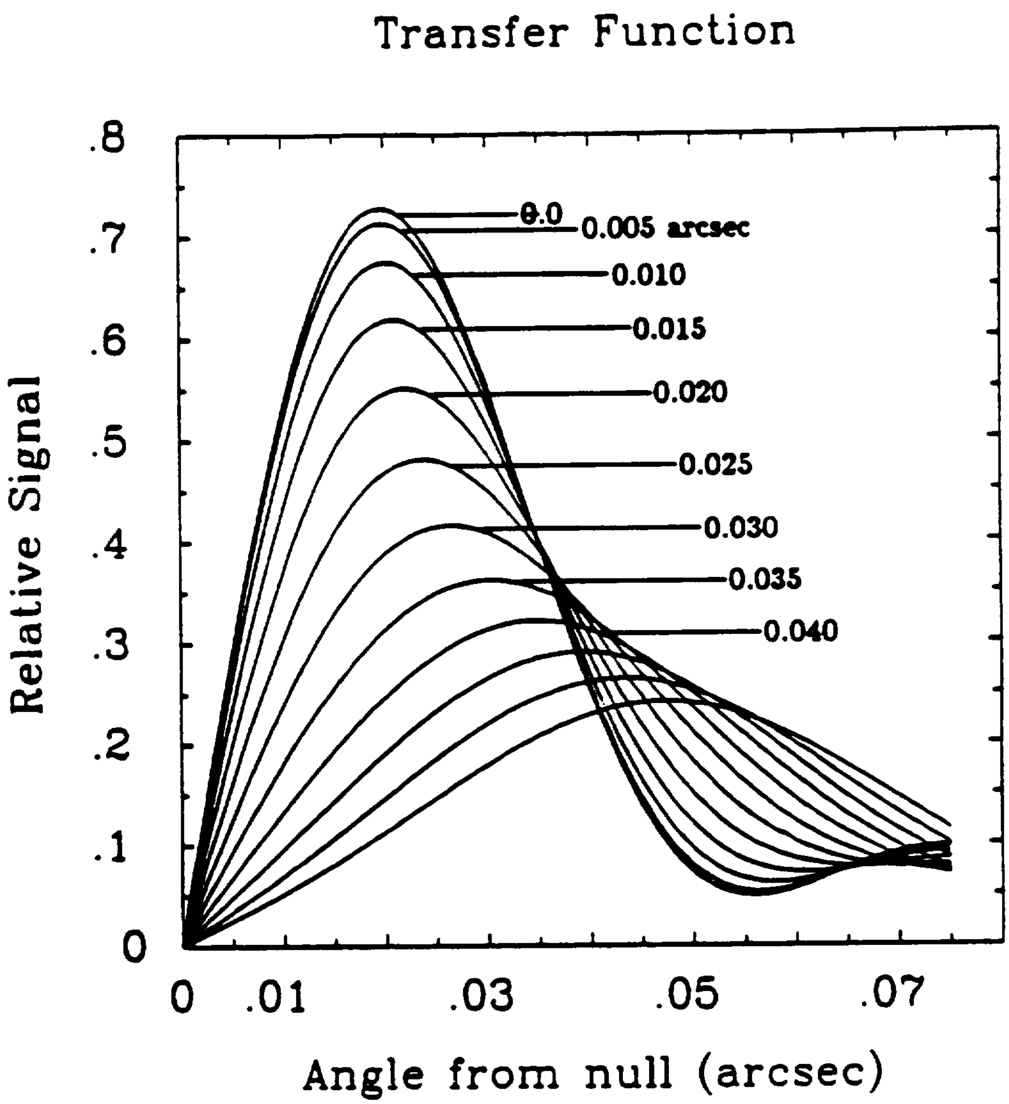
### 7.3.5 Koesters' Prism and Photomultiplier Tube Assembly

**Figure 5**: Schematic diagram of the two Koesters' prism/photomultiplier tube assemblies per FGS.



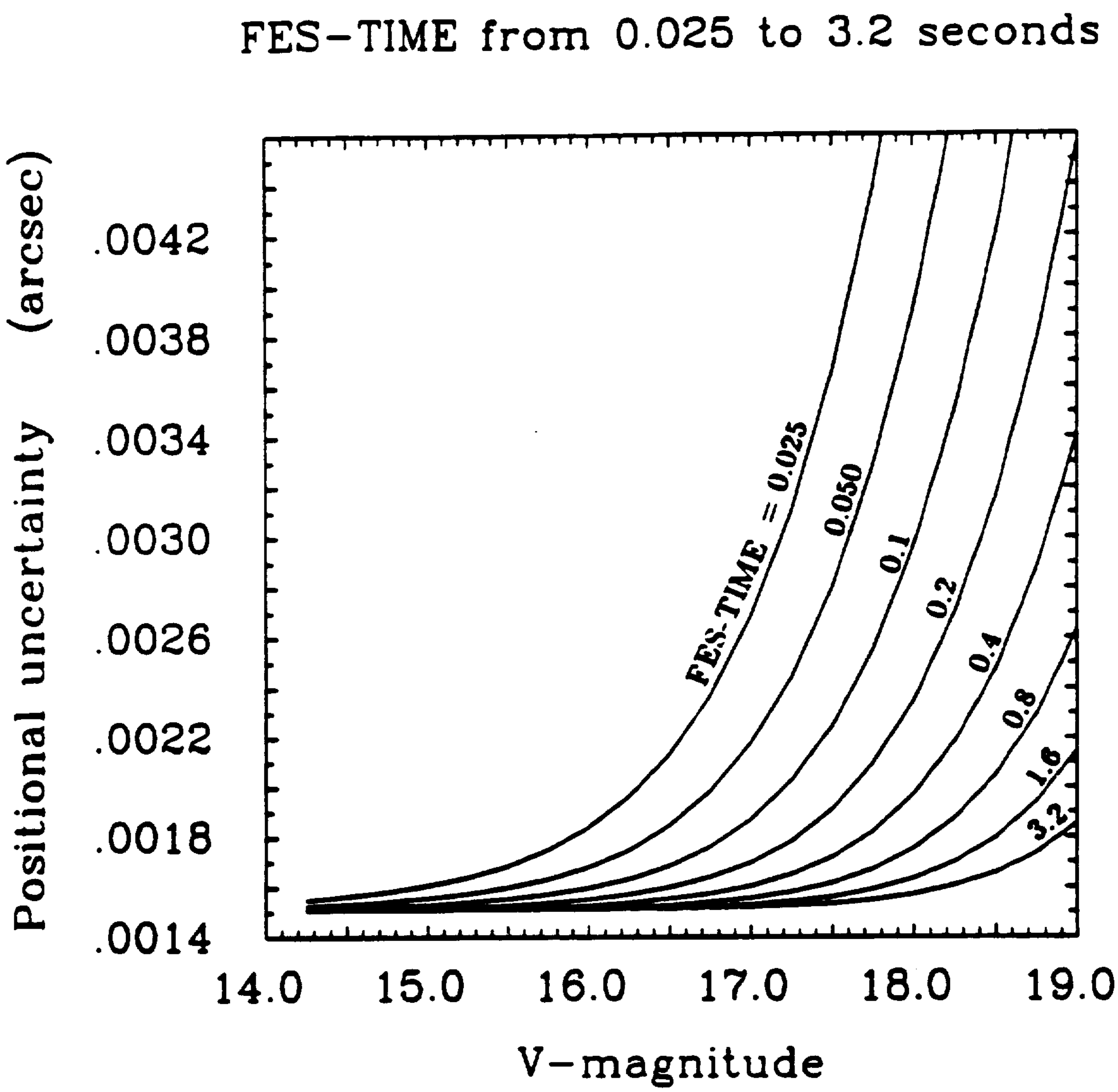
7.3.7 The Transfer Function for Sources of Different Radius

**Figure 7**: Targets of apparent size larger than 0.05 arcsec do not provide good fringe visibility. The transfer function is modulated by the source apparent diameter. The maximum and the slope at the origin are reduced, the peak offset is increased.



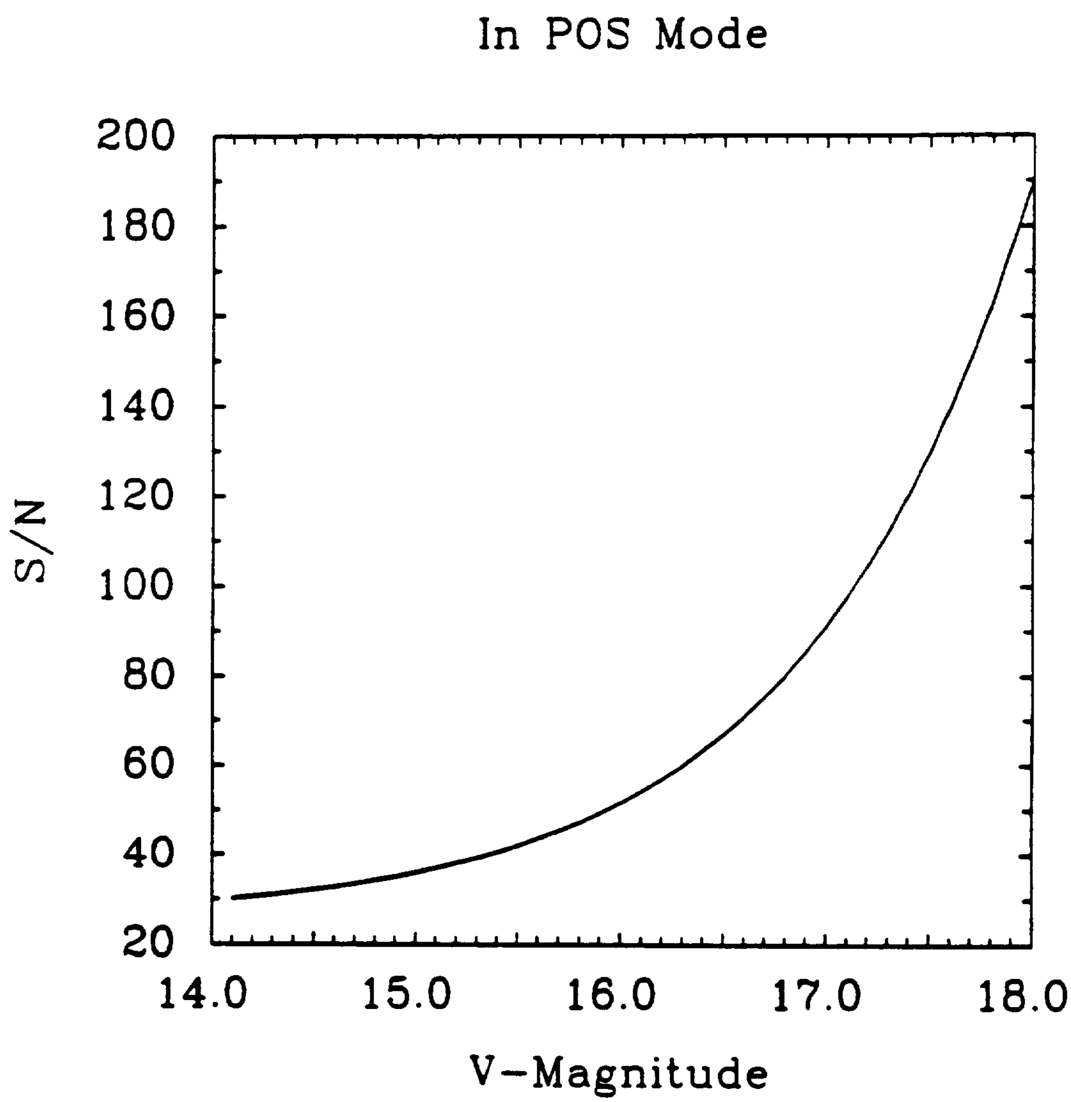
7.3.9 Effect of FES-TIME on the Positional Uncertainty for a Target

**Figure 9**: FES-TIME has to be selected among eight possible values in order to produce a NEA smaller than 0.000615 arcsec, (see Eq. (3)).



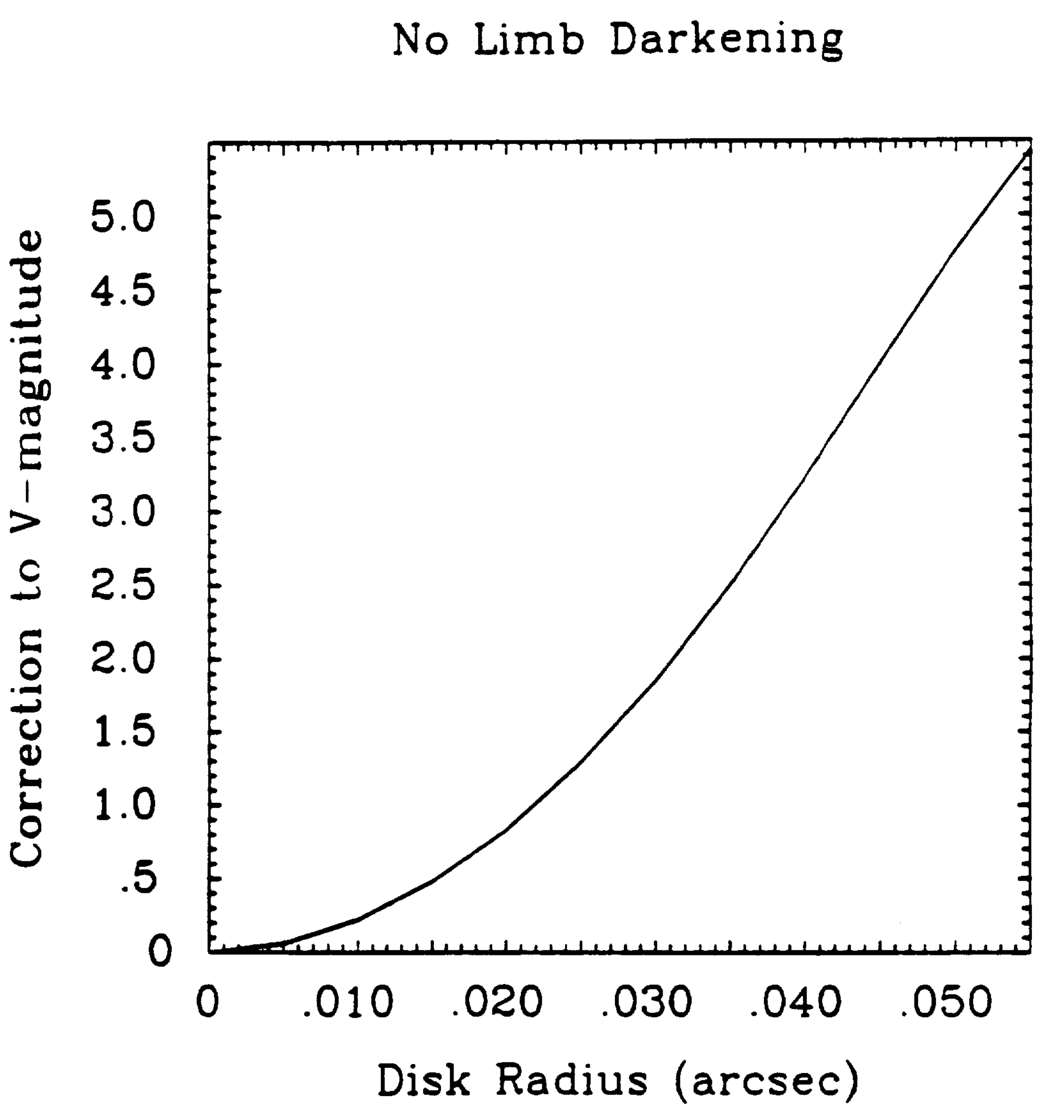
7.3.11 S/N in POS Mode

**Figure 11**: Minimum S/N in order to reach half the least significant bit of the encoder readings over 32 readings in POSition mode. The signal is integrated over the 5 by 5 arcsec square aperture, but the interference fringes are visible in a range of ±0.04 arcsec.



7.3.13 Correction to Visual Magnitude

**Figure 13**: A correction must be added to the target apparent visual magnitude in order to compensate for the reduced visibility of the interference fringes due to an extended apparent size at a constant luminosity (no limb darkening). The corrected magnitude can then be used as input to Figure 7 in order to determine the FES-TIME.



7.3.15 <u>Scan of a Transfer Function</u>

**Figure 15**: Transfer function for a very close binary system with two components of the same magnitude; $\alpha$ is the angular separation of the two components. The slope of the curve at the origin is reduced.