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Title: The Hubble Space Telescope Fine Guidance System Operating in the Coarse Track Pointing Control Mode

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The Hubble Space Telescope (HST) Fine Guidance System has set new standards in pointing control capability for earth orbiting spacecraft. Two precision pointing control modes are implemented in the Fine Guidance System; one being a Coarse Track Mode which employs a pseudo-quadrature detector approach and the second being a Fine Mode which uses a two axis interferometer implementation. The Coarse Track Mode was designed to maintain FGS pointing error to within 20 milli-arc seconds (rms) when guiding on a 14.5 Mv star. The Fine Mode was designed to maintain FGS pointing error to less than 3 milli-arc seconds (rms). This paper addresses the HST FGS operating in the Coarse Track Mode.

An overview of the implementation, the operation, and both the predicted and observed on orbit performance is presented. The discussion includes a review of the Fine Guidance System hardware which uses two beam steering Star Selector servos, four photon counting photomultiplier tube detectors, as well as a 24 bit micro-processor, which executes the control system firmware.

Unanticipated spacecraft operational characteristics are discussed as they impact pointing performance. These include the influence of spherically aberrated star images as well as the mechanical shocks induced in the spacecraft during and following orbital day/night terminator crossings. Computer modelling of the Coarse Track Mode verifies the observed on orbit performance trends in the presence of these optical and mechanical disturbances. It is concluded that the coarse track pointing control function is performing as designed and is providing a robust pointing control capability for the Hubble Space Telescope.

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## Introduction

The Hubble Space Telescope (HST) fine guidance control is performed by the Fine Guidance Sensors (FGSs) under the control of computer firmware which is implemented in the Fine Guidance Electronics (FGEs). For any given telescope observation, two of the three fine guidance systems provide pointing control such that the target being studied is maintained in the desired Science Instrument (SI) aperture. Figure 1 illustrates the HST Field of View (FOV) including the FGSs and the SI locations in that field. Selection of guide stars in any two FGSs can support three axis pointing control.

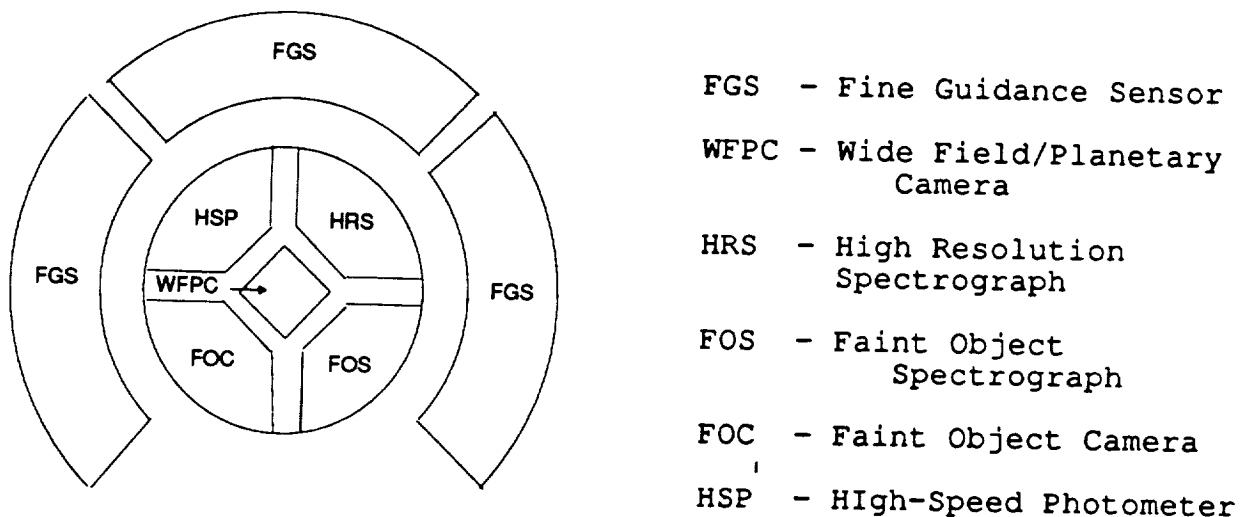


Figure 1. Hubble Space Telescope Field of View

Guidance control is achieved by locking onto a dominant guide star with one FGS and then locking on the non-dominant guide star with a second FGS. The dominant guide star is used to control pitch and yaw while the non-dominant guide star is used to control roll in the telescope. The HST Pointing and Control System (PCS) orients the guide stars in the FGS FOV such that the line of sight of the telescope is coincident with the desired SI aperture. The FGSs then provide continuous guide star lock and periodic feedback to the PCS to maintain the telescope line of sight. This paper addresses one of the two FGS fine pointing control modes, the Coarse Track Mode. The Coarse Track Mode is designed to provide a pointing accuracy of 20 milli-arc seconds (rms) when viewing a 14.5 Mv star. This control mode was originally expected to be used for guidance in about 50 % of the HST science observations. In fact, it is now used for about 70 % of all HST science observations because of its inherent ability to maintain lock under adverse dynamic disturbance conditions which occur during day-to-night and night-to-day orbital transitions.

## Coarse Track Control Implementation

Figure 2 shows the major functional components used to implement the Coarse Track Control Mode. The optical path includes a flat pick-off mirror located in the HST radial field which diverts a portion of the telescope FOV into the FGS Radial Bay Module optical path. An aspheric collimating mirror provides magnification and collimation of the beam. The beam is then relayed to the "A" Star Selector assembly which includes two flat deviation mirrors and a integral five element refractive corrector group. Next it passes through the four "B" Star Selector flat deviation mirrors and is directed to a Polarized Beam Splitter which produces X and Y orthogonal outputs. The orthogonal beams then pass through individual Koesters prisms and the resulting beams are re-imaged. Photon flux is measured using four photomultiplier tubes (PMTs); two in each axis. The PMTs and associated signal processing hardware convert the impinging photon flux into digital counts. The flux measurements in each of the four PMTs are then used to perform a pseudo-quadrature line of sight pointing error estimate and a feedback signal is generated to null out pointing errors.

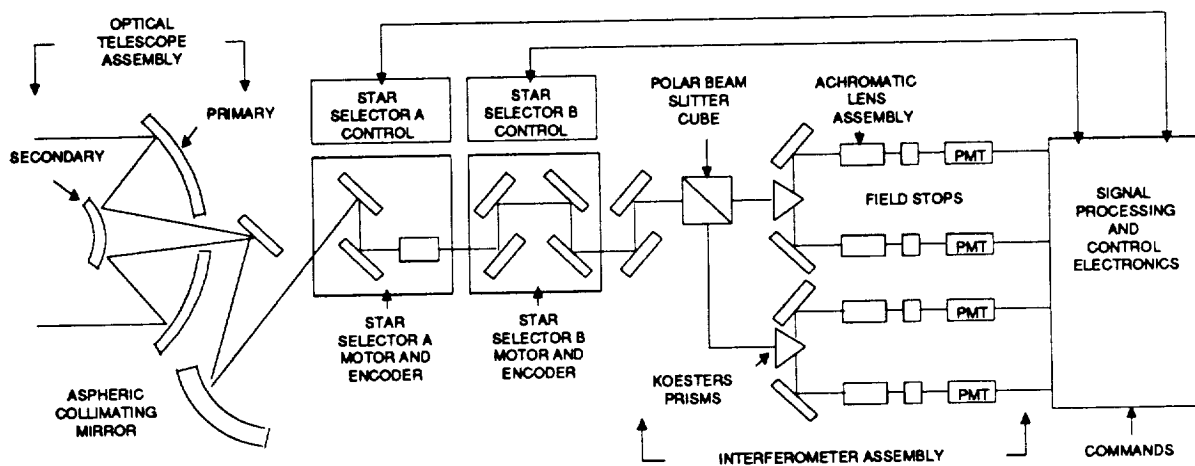


Figure 2. Functional Optical Path Diagram for Coarse Track

The Star Selector servos can be controlled in such a manner that the flux from any star in the FGS FOV can be directed to the fixed position PMTs. The control algorithms are executed in a 24 bit micro-computer located in the FGE. The FGE controls the initial guide-star acquisition following the coarse positioning of the telescope by the PCS hardware. The acquisition is accomplished during a Spiral Search Mode which creates an spiral search pattern in the proximity of the guide star. The FGE, by automatically monitoring the PMT counts and comparing them to the expected counts based on a priori knowledge of the guide star magnitude, accomplishes guide star detection. At this point a control mode transition occurs which establishes the Coarse Track Mode.

Figure 3 shows the fundamental relationships between the Star Selector servo rotational positions and the resulting pointing within the FOV.

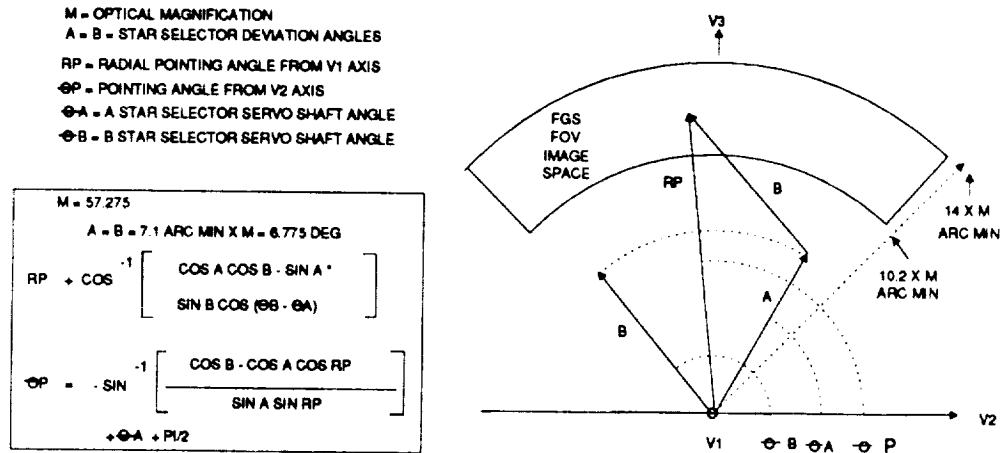


Figure 3 Star Selector Servo Pointing Relationships

Figure 4 illustrates the Search Mode to Coarse Track Mode transition as well as the coarse track guide star lock scenario in terms of the servo generated beam steering trajectories. The coarse track portion of the trajectory is controlled by the FGE and is basically an incremental nutation about the estimated line of sight of the guide star.

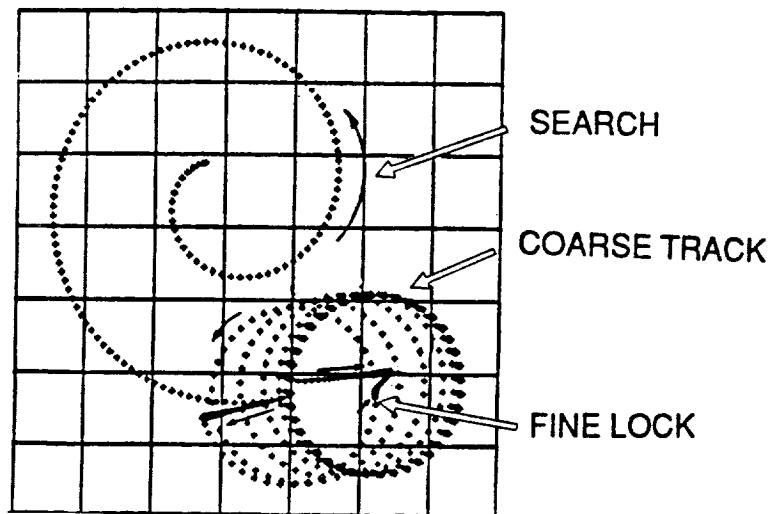


Figure 4 Search Mode and Coarse Track Guide Star Acquisition

### Coarse Track Control Algorithms

The Coarse Track control algorithm operates in a manner similar to a quadrature detector in that it measures photon energy in four

quadrants as the star image is nutated in a circular pattern in and out of the square field stops of the FGS PMT sensors. Figure 5 shows the nutation pattern which consists of 40 discrete points on the nutation circle. The pattern is created once per second by commanding the two FGS Star Selector Servos to slew the image from point to point. Photon energy is integrated during each 25 milli-second servo slew, resulting in a PMT count "I" which is the sum of the four individual PMT values. These PMT measurements are used in the error signal control equations to adjust the FGS pointing angle toward the line of sight of the star.

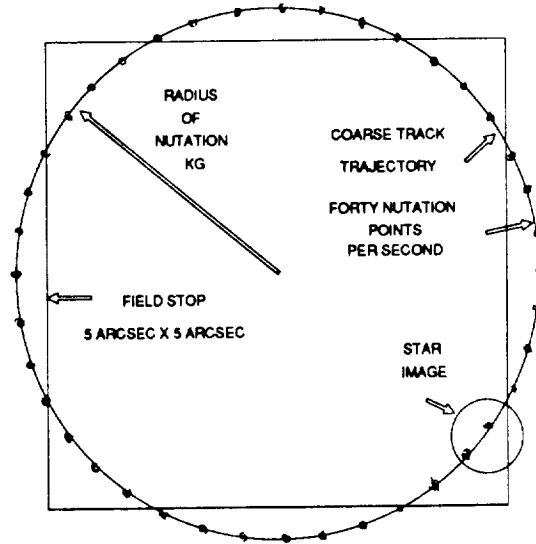


Figure 5 Coarse Track Nutation Trajectory at Null

The basis for generating the Coarse Track error is the prediction of the displacement of the nutation center from ideal and the subsequent adaptation of the center position to attempt to null the pointing error. Equation 1 is the static error equation for the X direction (Y is similar) which goes to zero when each of the four quadrants have identical intensities.

$$EX = I(X) / \text{SUMA} \quad \text{EQ 1}$$

$$\text{Where: } I(X) = -[I(1) + \dots + I(10)] + [I(11) + \dots + I(20)] \\ + [I(21) + \dots + I(30)] - [I(31) + \dots + I(40)]$$

$$\text{SUMA} = [I(1) + I(2) + \dots + I(40)]$$

Equation 2 illustrates the dynamic update to the iterative error equation which is done at each nutation point.

$$E5 = [I(X) + I(5) - I(5)'] / [\text{SUMA} + I(5)' - I(5)] \quad \text{EQ 2}$$

Where: I(X) is the computed I(X) value for nutation point 4  
 SUMA is the resultant SUMA at nutation point four  
 I(5) is the I(5) from the previous nutation cycle  
 I(5)' is the current I value measurement

The numerator is updated based on the difference between the previous  $I(5)$  and the current  $I(5)$  intensity. The SUMA value is adjusted to maintain a normalized error value. In a noise free system, the control algorithm will drive the X and Y errors to zero resulting in perfect alignment of the center of nutation with the guide star line of sight.

The actual performance of the Coarse Track control mode is influenced and limited by both Poisson noise in the intensity measurements and the dynamics of the overall telescope assuming other error sources are small. Photon noise impacts the rms pointing error in proportion to the square root of the intensity  $I$  where  $I$  represents the average photon count for a specific star magnitude  $M_v$ . The error equation will always have a residual value and its rms amplitude will be a function of the intensity of the star image. The optimum operation of the algorithm occurs when the image spot size is small enough to permit 100% of the photons to fall at times completely inside or completely outside of the image detector field stops. This maximizes the signal-to-noise ratio as well as the quadrature signal discrimination. This optimum condition is currently not met in the HST due to spherical aberration of the star image (see figure 6) which in effect spreads the image intensity over a large spatial domain. This effectively diminishes both the signal to noise ratio and the quadrature signal discrimination performance.

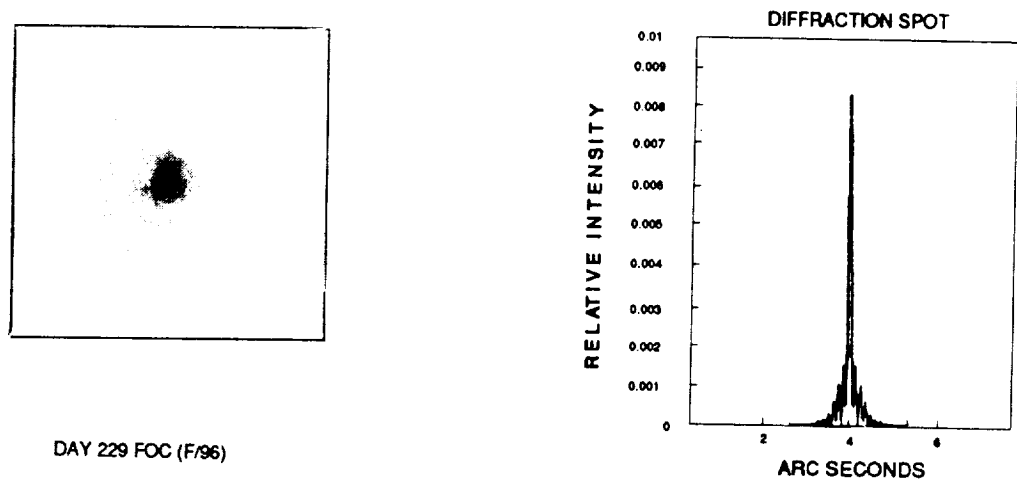


Figure 6 The Spherically Aberrated Image and Energy Distribution

The coarse track algorithms also control dynamic servo system response performance. The predicted on orbit dynamic disturbances were expected to be minimal based on an evaluation of disturbance levels of the various moving parts on the telescope. In reality, significant thermally-induced mechanical vibrations or "shocks" occur in the orbiting telescope. These mechanical shocks impact coarse track performance in that the basic control recovery

can take up to ten to fifteen seconds or longer if the disturbance causes a temporary but significant change in the line of sight of the telescope.

The Star Selector servo control implementation was designed to permit a limited amount of adjustment in the servo control loop performance characteristics. Two up-link parameters, KG (radius of nutation) and KJ(closed loop gain) are programmable. Figure 7 illustrates the on-axis transfer function for various values of KG. Large KG values maintain a saturated error signal closer to the null region and offer higher gain in the null transition region. Large disturbances are corrected faster by the selecting a higher KG value. KJ controls the closed loop servo gain and transient response. Figure 8 shows the closed loop transient response as a function of KJ with KG set to the default value of 2.68 arc seconds (object space). Increasing KJ much above 0.05 arc seconds results in close loop instabilities which must be avoided when attempting performance optimization. The nominal (default) settings of KG = 2.68 arc seconds and KJ = 0.026 arc seconds were selected for orbital use prior the HST launch. The KG value was selected to provide a radius of nutation which results in the star image being inside the field stops 50 % of the time and outside 50% of the time. This provides good signal discrimination in each quadrant. KJ was selected to provide a damped response to avoid extending the transient settling time caused by ringing when higher values are selected. The observed orbital coarse track servo performance is moderately degraded when compared to the predicted performance. The coarse track control sensitivity is within about 0.5 to 0.8 Mv of the diffraction limited performance. A computer model has been developed to verify that this decreased sensitivity is attributed to the aberrated star image.

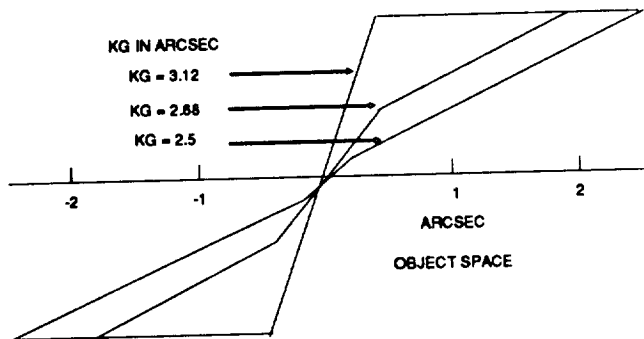


Figure 7 On Axis Open Loop Transfer Function

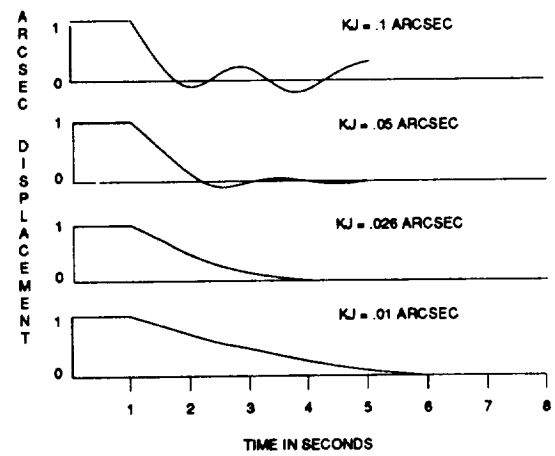


Figure 8 Close Loop Transient Response

## Computer Modelling

Figure 9 shows a top level flow diagram for the coarse track control computer simulation model. User inputs include star magnitude, KG(radius of nutation), KJ (closed loop gain), nutation center offset, image spot size, and signal amplitude distribution. A 100 point star image is used to simulate the image energy distribution. The program outputs include the nutation point (1-40) being operated on, the PMT counts at each point, X and Y coordinate error values, X and Y center values, X and Y rms squared error values, and graphical plots of selected parameters versus time. Using this model, simulations have been performed for both predicted coarse track performance and the on-orbit performance with a diffuse image.

### PROGRAM INPUTS INCLUDE:

STAR MAGNITUDE  
 KG - RADIUS OF NUTATION  
 KJ - GAIN  
 CENTER OFFSET  
 SPOT SIZE  
 SPOT ENERGY DISTRIBUTION

### PROGRAM OUTPUTS INCLUDE:

NUTATION POINT (1- 40)  
 PMT COUNTS  
 DELTA X  
 DELTA Y  
 CENTER X  
 CENTER Y  
 X RMS SQUARED ERROR  
 Y RMS SQUARED ERROR  
 NORMALIZED ERROR DENOMINATOR  
 NORMALIZED X ERROR  
 NORMALIZED Y ERROR

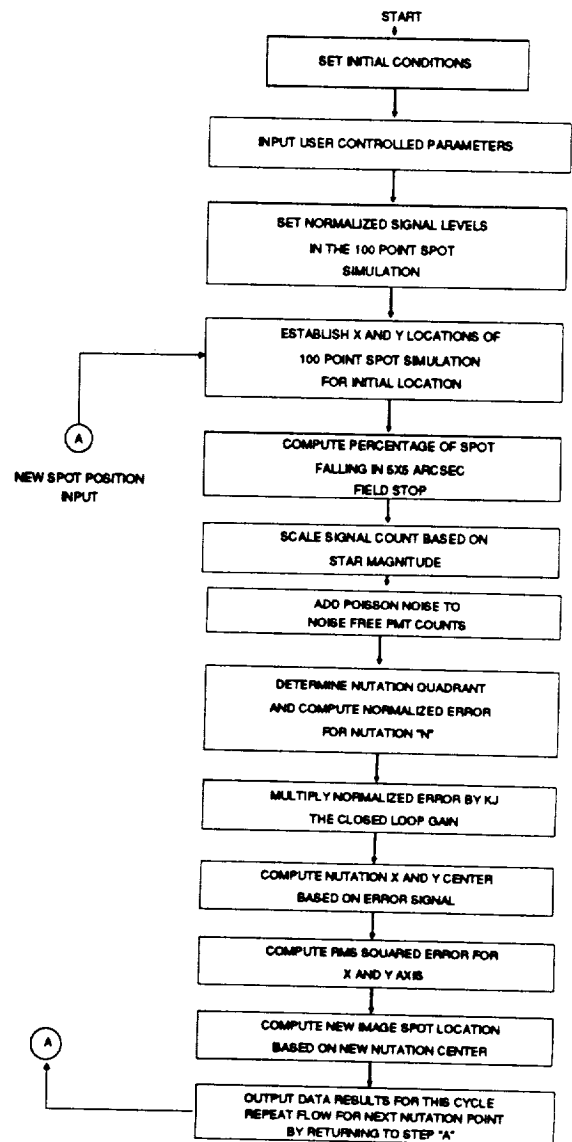


Figure 9 Coarse Track Computer Simulation Model



Figure 10 shows the impact of the diffuse star image on the open loop transfer function. Error signal gain is reduced for all values of KG when compared with figure 7. Figure 11 illustrates the impact of the diffuse star image on the closed loop rms pointing error. With a diffraction limited spot, there are sharp cut off points defined by the 5X5 arc second field stops i.e. at KG setting of less than 2.5, the image center can move within the field stop and at times provide no error feedback; likewise when the radius of nutation is greater than 3.54 arc seconds the image can be outside of the field stop resulting in loss of feedback. For a diffuse image with the energy spread over a larger area, the modelling shows a general flattening of response of the pointing control error for all KG radius values. The rms error increases under these conditions. The relatively flat response suggests that performance cannot be significantly improved by adjusting KG, the coarse track radius of nutation. This has been demonstrated by on orbit testing (Bely and Liu).

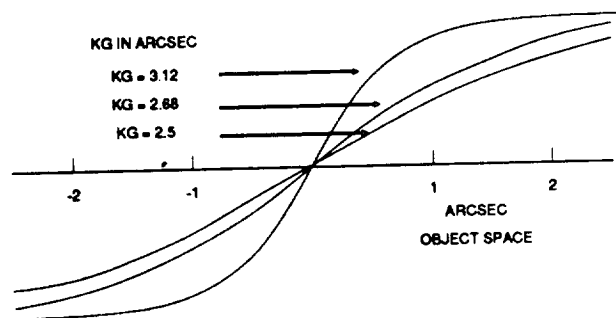


Figure 10. The Open Loop Transfer Function with a Diffuse Star Image

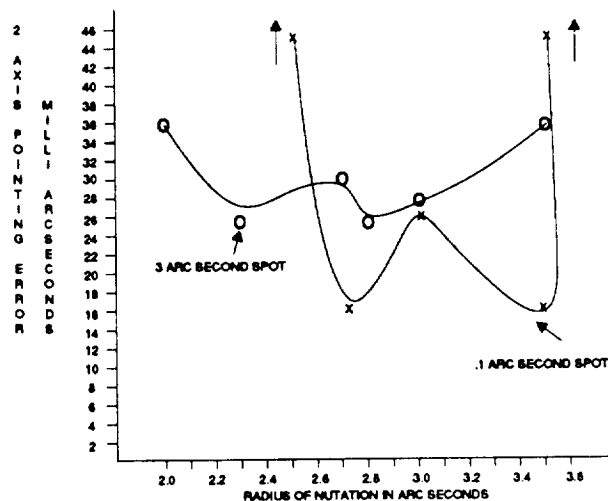


Figure 11. The Impact of a Diffuse Star Image on RMS Pointing Error

In order to gain further insight into the coarse track control characteristics, several simulations were run using the computer model. Parameters including star magnitude (Mv), image spot size, as well as KJ and KG were varied and the resultant servo response was plotted versus time. Figure 12 demonstrates the response for a high intensity star magnitude (11Mv) with the KG and KJ set to default. The diffuse image (3.0 arc seconds) and the diffraction limited image (0.1 arc second) conditions are shown to have similar rms errors and good overall settling trends. This is due to the fact that the Poisson noise is a small percentage (about 2%) of the signal in both cases, resulting in low rms errors.

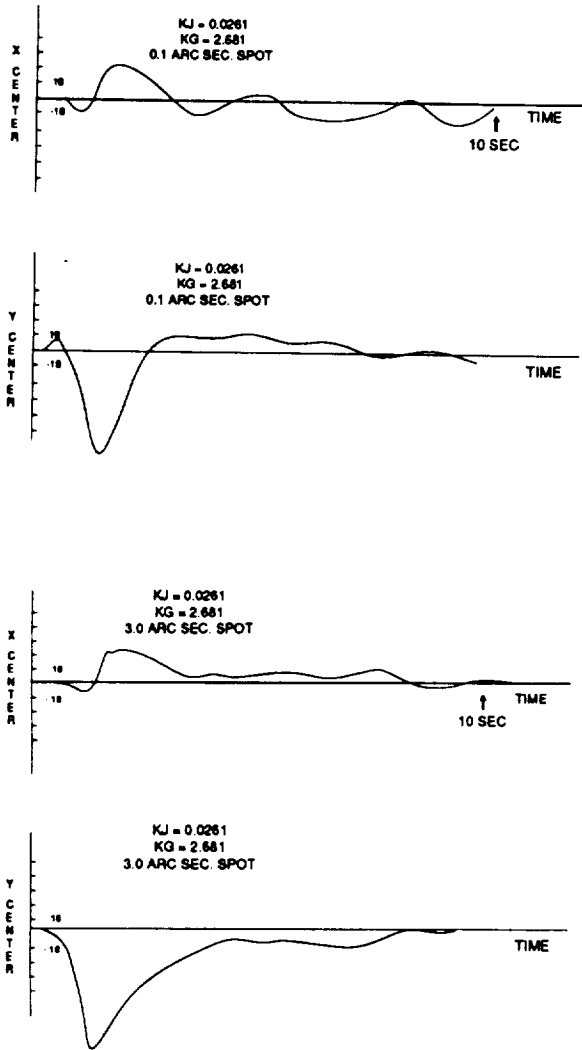


Figure 12 Coarse Track Settling for a Diffraction Limited and a Diffuse Star Image (11Mv)

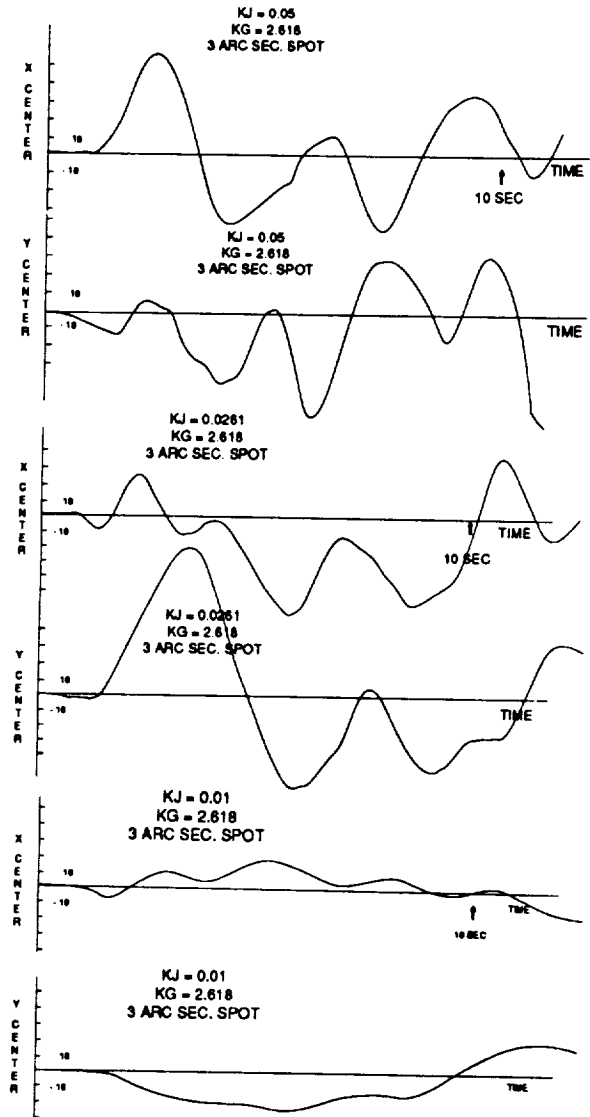


Figure 13 Coarse Track Settling for a Diffuse Star Image (14.5 Mv) for various KJ values

Figure 13 provides typical coarse track performance for a 14.5 Mv (fine guidance design limiting magnitude) star with a spot size of 3.0 arc seconds and various closed loop gains ( $KJ = 0.05, 0.0261,$  and  $0.01$  arc seconds). Since the signal to noise level ratio is quite poor with the diffuse image, any attempt to improve loop response by increasing  $KJ$  results in servo loop hunting. The loop is unlikely to settle over time since the noise constantly injects erroneous inputs at each of the 40 coarse track algorithm sample points. The higher closed loop gain emphasizes these random noise excursions. It will be noted that reducing  $KJ$  to  $0.01$  attenuates the effects of noise, but when the servo operates at this value dynamic response is severely impacted. Spacecraft disturbances cannot be followed with any fidelity in this case.

Figure 14 indicates the impact of changing KG, the radius of nutation. The star magnitude is once again set to 14.5 Mv and KJ is set to the default. Small values of KG (2 arc seconds) and large values of KG (3.5 arc seconds) result in responses which do not converge in an orderly manner. Rms errors can be large and biases can persist which will look like shifts in the average center position over time. For KG values of 2.3 arc seconds and 2.8 arc seconds, a slight improvement in rms pointing error (about 4 milli-arc seconds) occurs when compared with the case where the default parameters are used (see figure 13). Changing KG will not produce a significant performance improvement under the conditions of a spherically aberrated image. In this respect, the only approach to making inroads into improving rms pointing is to make use of high intensity guide stars whenever possible.

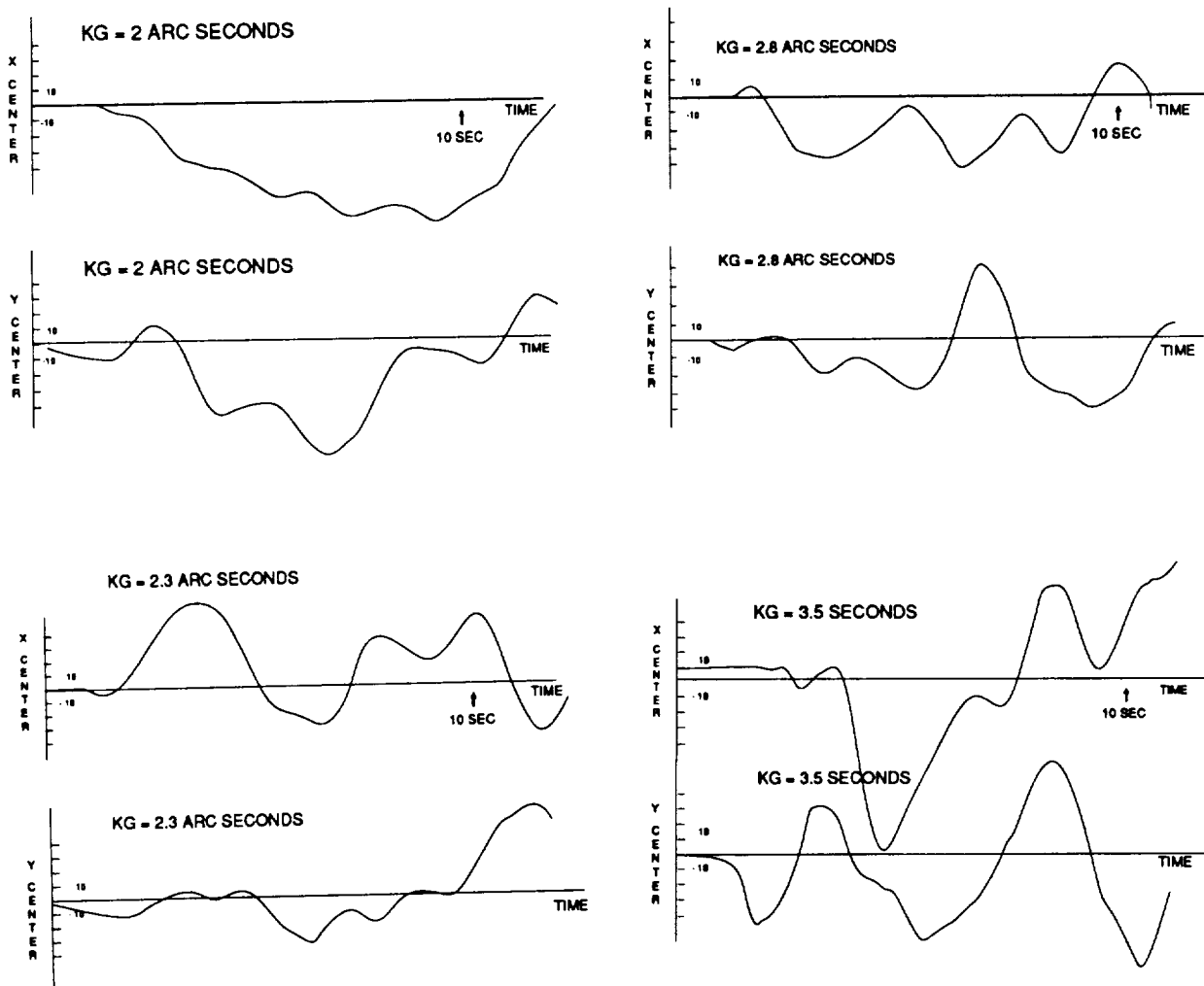


Figure 14. Coarse Track Response for Various Values of KG

Other modelling results indicate the following trends:

Figure 15 illustrates the general relationship of the quadrature modulation versus image size. It will be noted that significant modulation amplitude reduction occurs as the image size increases. The overall peak signal amplitude is also reduced if a symmetrical modulation (50% in and 50% out) is to be achieved. This condition results in decreased signal to noise as well as poorer quadrature discrimination.

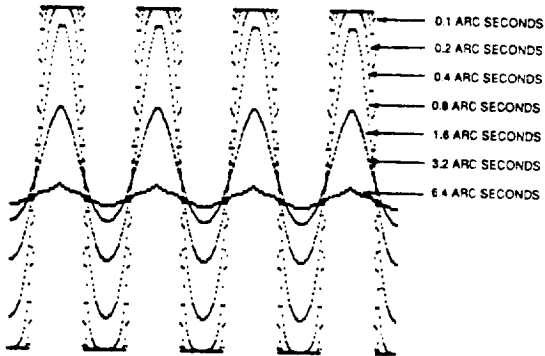


Figure 15. Quadrature Modulation Versus Image Size

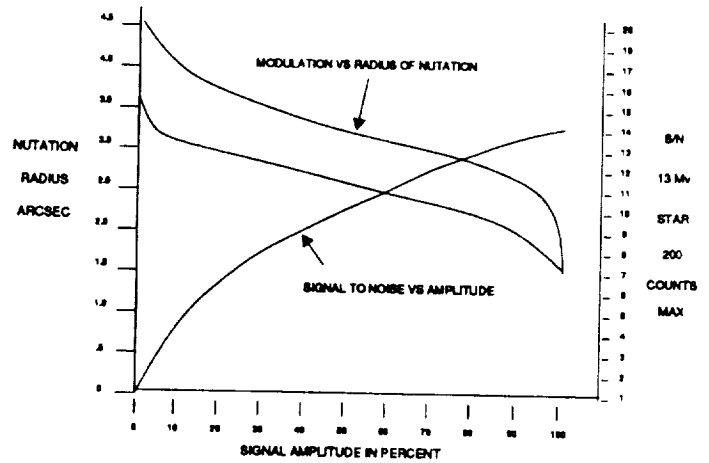


Figure 16. Relationships Between Signal Modulation, S/N Ratio and Radius of Nutation

Figure 16 illustrates the general relationships between signal modulation, signal amplitude and radius of nutation KG. Ideally, selection of the maximum modulation would provide the best control. With a diffuse image, a compromise must be made. Selection of the maximum signal amplitude, in an effort to achieve maximum signal to noise ratio, results in a very limited signal modulation level. At best, selection of a KG radius of nutation in the 2.5 to 3.0 arc second range results in reasonably good signal amplitude and modulation. The default KG value of 2.68 arc seconds is not an unreasonable choice even for the case where the star image is diffuse.

Figure 17 provides predicted (RMS) coarse track performance with and without spherical aberration of the star image. Attempts to improve control performance by increasing KJ, the closed loop gain, in the presence of a diffuse image in general has a deleterious impact. While response time is improved somewhat, the impact of Poisson noise is increased particularly for dim guide stars. RMS jitter is increased.

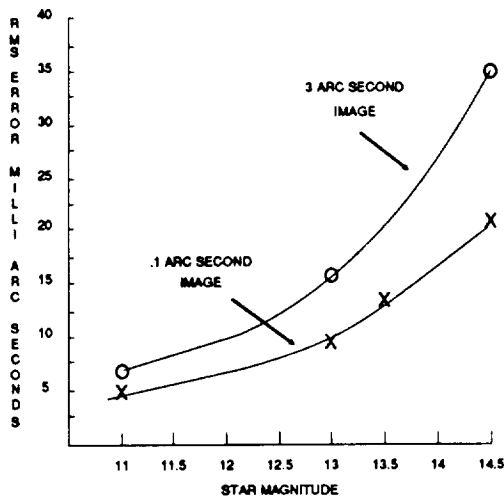


Figure 17. Coarse Track RMS Pointing Jitter Versus Image Size

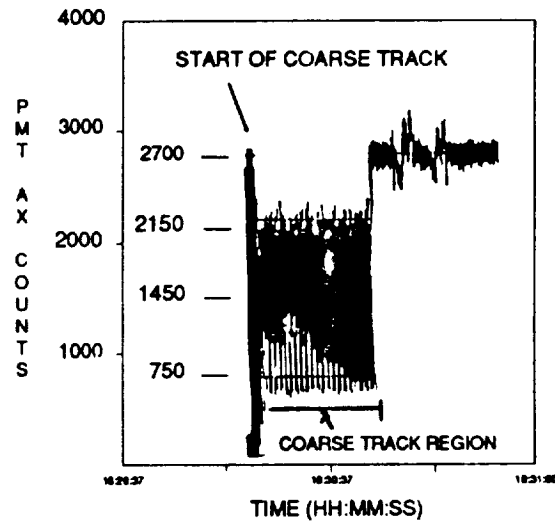


Figure 18. On-Orbit PMT Counts Versus Time

### On-Orbit Performance

Typical on-orbit observed pointing jitter is on the order of 10 to 20 milli-arc seconds (rms) for 11 Mv stars, 20 to 45 milli-arc seconds for 13.8 Mv stars and 30 to 60 milli-arc seconds for 14.5 Mv stars. Figure 18 illustrates the observed decrease in sensitivity in both PMT count amplitude and depth of modulation in the coarse track control mode. Peak PMT signal amplitudes reach only 60 to 70 % of the expected amplitudes. Good correlation between the simulations and the observed performance implies that the HST Fine Guidance Sensors are performing nominally in the presence of a spherically aberrated image.

The influence of higher than expected vehicle vibrations caused by thermally induced shocks from the spacecraft solar array panels result in hunting in the control loop as it attempts to maintain the pointing line of sight. The coarse track control has been shown to be quite robust in the sense that it can maintain lock on the guide stars even during the significant disturbances which occur during day/night thermal transitions. This has permitted longer science

observations that would likely have been impossible if only the FGS Fine Lock capability had been implemented. It is expected that, with the replacement of the solar panels on the future repair mission to HST, overall HST orbit-to-orbit pointing stability will be significantly improved. This should also improve the Fine Lock control performance which is designed to provide pointing control in the 3 milli- arc second range when the vehicle disturbances are low.

### Conclusions

In spite of un-anticipated HST anomalies including spherical aberration in the primary mirror and significant mechanical "shocks" from the Solar Panels, the Fine Guidance Systems are performing reliable pointing control in Coarse Track Mode. A large percentage of the planned HST science observations are being accomplished using this robust pointing control mode. The fine guidance system implementation using quadrature centroiding principles coupled with the beam steering servos and the associated control algorithms demonstrates a sound design concept for highly accurate pointing control of earth orbiting spacecraft.

### Acknowledgements

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Reference: Bely,P. and Liu, 1991, Space Telescope Science Institute Memorandum