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The Effect of Double Stars on the Guidance System of the *Hubble Space Telescope*[1]

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ABSTRACT. The interferometric system used for the guidance of *HST* is sensitive to close binaries. Before the launch of *HST* it was believed that up to 25% of all guide-star pairs would lead to guidance failure due to duplicity. After more than 3 yr of operation the actual failure rate ascribable to duplicity is estimated to be just below 1%. A computer simulator has been developed to understand the causes of the discrepancy. The simulation indicates a failure rate of under 2% per guide-star pair, in much closer agreement with the observed performance of the guiding system. The failure criterion originally used was based on the manufacturer's expectations, and was too conservative. The proportion of binary guide stars in the critical separation range had also been somewhat overestimated.

1. INTRODUCTION

The *Hubble Space Telescope* (*HST*) performs fine guidance for astronomical observations by using attitude information from a set of gyroscopes, with periodic update from a star-based guidance system to correct for the drift of the gyroscopes. The guidance system relies on three Fine Guidance System (FGS) units which derive their error signals from stars imaged near the edge of the telescope field of view. Two of these sensors are needed at any one time, one supplying pitch/yaw information and the other roll. These FGSs, a detailed description of which can be found in Bradley et al. (1991), have two tracking modes, a coarse track mode based on image scanning and a fine mode, "fine lock," based on interferometric fringe tracking. Fine lock is the only mode capable of providing the image stability required for reaching the ultimate resolution of *HST*.

Because of the limited capture range of the fine-lock mode (about ±40 mas), guide stars are first acquired in coarse track mode and then "walked across" the fringe structure (commonly called an "S curve") until a large hump is detected, at which point the guidance servo system takes over, and brings the star to the S-curve null and automatically keeps it centered there. On close binaries the S curve can be degraded so as to render detection of the hump impossible or to create multiple nulls, causing fine tracking instabilities.

Originally the critical binary separation was believed to be in the range of 18–200 milliarcseconds (mas). Since most of that range was beyond the resolution of existing binary-star catalogs, a dedicated survey was performed several years before launch with a large ground-based telescope using the speckle technique on about 400 relatively nearby stars ranging in magnitude from 5 to 6.5 (McAlister et al. 1987). The speckle technique, which evades most of the effects of atmospheric turbulence blur, reached binary separations down to 40 mas. These data on bright, relatively nearby stars were then used to estimate the binary-star frequency and separation distribution of the much more distant typical guide stars expected to be used by *HST* (9 to 14.5 mag range). The failure rate of guide-star pairs was then estimated to be in the neighborhood of 25%, due to the frequency of close binary guide stars. (Shara et al. 1987). As a result, time was allowed in each orbit to try for three guide-star pairs in succession in order to reach a high probability of success in acquiring a pair of guide stars. The observation scheduling system was developed accordingly and was very costly in time. At 5 min acquisition time per pair, the total time allocated to guide-star acquisition represented 30% of the total target visibility period.

After several years of *HST* operation, fine-lock failures not due to previously unrecognized galaxies (which do not form fringes) or to other known causes, have been somewhat below the 1% level. As a result, guide-star acquisitions are now routinely scheduled with only one pair of guide stars instead of the three pairs thought necessary before launch. But the very low failure rate due to stellar duplicity compared to much higher rates previously estimated, raised questions of whether the operation of the guidance instruments had not been correctly understood, and whether the stellar statistical analysis obtained for nearby stars applied to the 9 to 14.5 mag range used with *HST*. This led us to develop a computer simulation of the Fine Guidance System (FGS) in order to redefine experimentally the failure criteria and to re-examine the binary statistical analysis.

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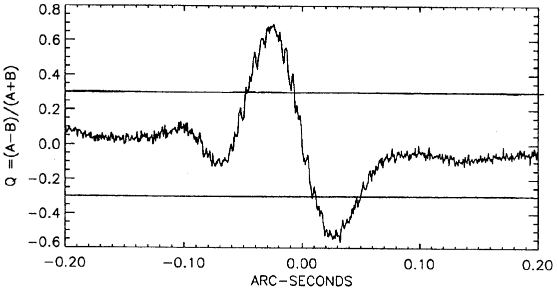

FIG. 1—An S curve obtained with a 2/3 pupil stop in FGS 3 and used for the simulation. Due to the spherical aberration in the primary mirror and misalignment errors in the FGS, full aperture S curves are degraded and are not used for guidance. In normal operation a 2/3 pupil stop is used to reduce aberrations. A threshold for fine lock at ±0.3 is illustrated. Star identification: *HST* Guide Star Catalog ID 0461901496 00h 42m 42.95s+85d 14am 14.5as J2000. 9.5 mag.

2. COMPUTER SIMULATOR

Because we suspected that the prelaunch estimates might have suffered from oversimplification in the characterization of the FGS behavior, the approach in developing the computer simulator was to be as faithful as possible to the FGS algorithm. The S curves of binary stars were synthesized from an S curve observed by *HST* from a *bona fide* single star. Photon noise and line-of-sight jitter were included and the acquisition process was a replica of the on-board software algorithms.

2.1 Generation of Binary-Star S curves

In fine-lock mode, light from the star is collimated and split into two beams, one each for the X and Y guiding axes. The beam in each axis is directed onto a Koester prism which then splits the beam into two half-circle beams and interferes them with each other. The resulting intensity in each of the two beams, measured by a pair of photomultiplier tubes for each coordinate axis, is a direct function of wave front tilt. The position error signal is obtained by combining and normalizing the intensity in the two channels, A and B, in the form $(A-B)/(A+B)$. The error signal Q as a function of wave front tilt, or "S curve," is illustrated in Fig. 1.

The shape and modulation of actual single star S curves vary with the FGS used and even depend on the position in the field of view of the same FGS. This is the result of slight differences in the alignment of the FGS internal optics which are magnified by the spherical aberration in the primary mirror. In practice the degradation is such that full aperture S curves are difficult to use for guidance. In normal guidance operation a 2/3 pupil stop (blocking out the outer edge of the primary mirror) is used to reduce aberrations. With the pupil stop in place, S curves are much more uniform throughout the guiding field, although there are still significant differences.

A representative single star S curve from a scan with the 2/3 pupil stop for astrometry purposes was adopted for the simulation (Fig. 1). The star was of visual magnitude 9.6 which is at the bright end of the guide-star magnitude range and therefore at the low end of the photon noise range for guide stars. In order to form a prototype shape upon which to superimpose computer generated noise, this S curve was then smoothed to a lower noise level without significantly altering its shape. The normalized, dimensionless error signal equation $Q=(A-B)/(A+B)$ was then solved for the number of counts from each of the two interferometer outputs A and B

$$A=0.5\times(CQ+C), \quad B=C-A,$$

where $C=A+B$ was the known total count rate generated by the magnitude chosen for the target star, allowing for the telescope and FGS throughput, and the attenuation due to the pupil stop.

The S curves for a binary along each axis were then generated for various binary separations, companion magnitudes, and position angles of the binary system with respect to the interferometer axes. The interferometer outputs A and B were calculated for each of the two companions, adding the photon noise for each, and finally adding the two S curves with a shift relative to each other by the amount of separation of the binary along the direction of each interferometer axis.

In this process of reforming the error signal, Q, the denominator was kept constant, as in the real instrument. (In the on-board calculation the denominator is set to the mean of several values of $A+B$ taken before the walkdown begins and is fixed for the remaining of the guiding period to minimize the effect of noise.) A great variety of resulting S-curve shapes are possible depending on the characteristics of the binary system. A few examples are shown in Fig. 2. One notes the two effects created by a resolved binary system: the appearance of multiple nulls and the reduced peak to peak modulation. One will also note that a fully resolved binary system has only half the peak to peak modulation of a single star (for companions of equal magnitudes). This is due to the $(A-B)/(A+B)$ normalization process: One of the two stars acts as a constant background for the other, with its flux canceled at the numerator, but added at the denominator. This phenomenon persists as long as the both stars are within the 5×5 arcsec aperture of the FGS.

2.2 Simulation of Fine-Lock Acquisition

At the start of a simulated acquisition process, the guide star is assumed to be located at the center of the FGS field of view where it would normally be found following the search and coarse track phases. As in the real hardware implementation, the field of view is then backed off by 0.6 arcsec in the 45 degree direction from the star position estimated from coarse track. The field of view is stepped towards the expected null of the S curve with an adjustable step size of 7 mas as currently set in the actual system. This "walkdown" is executed simultaneously in the two coordinates.

Telescope jitter in the line of sight was included in the fine-lock acquisition process by shifting the position of the FGS field of view center relative to the S curve as a function of time. A representative period of jitter motion data was obtained from the motion of a guide star during actual observation. The period was selected to correspond to nominal

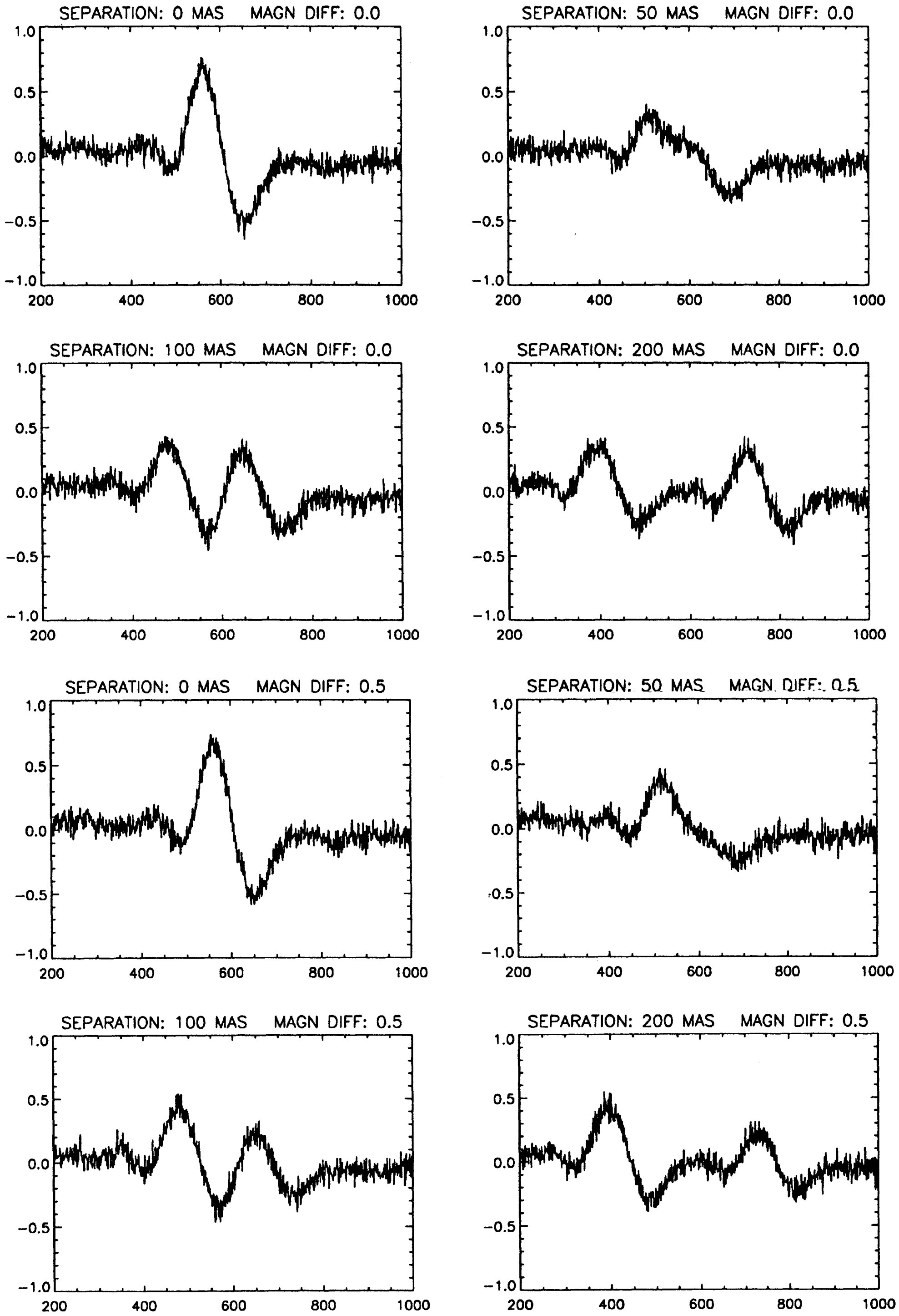

FIG. 2—Some representative synthesized double star S curves of various separations and magnitude differences. The ordinate is $Q=(A-B)/(A+B)$. The abscissa is point number. One point=0.6 milliarcsec; 800 points=0.48 arcsec.

"quiet" conditions, and specifically free of the large amplitude oscillations that occur when the spacecraft crosses the day/night terminator.

At each walkdown step, the value of the S curve in each coordinate is compared with thresholds which are commandable parameters. The thresholds are functions of guide-star magnitude and differ in the two coordinates due to instrumental differences. The same values commanded to the telescope were used in the simulator.

When walking down, the first step for which the threshold

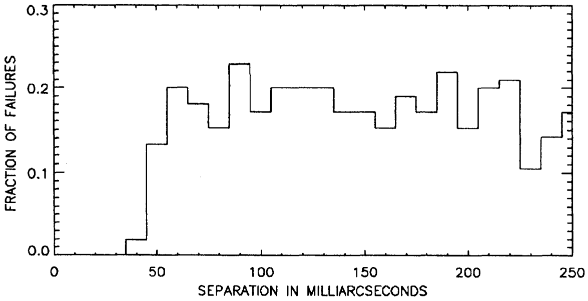

FIG. 3—The distribution of failures from the simulation as function of double star separation per 10 mas bin. All magnitude difference and position angle combinations are included. The failure rate profile for all combined magnitudes begins rather abruptly at 50 milliarcsec and remains in the 20% neighborhood up to and beyond the 250 milliarcsec shown here. The simulation was for a combined magnitude of 11, but the results are essentially the same for all guide-star magnitudes (Fig. 6).

is exceeded causes a counter to be set to one and the step size to be halved for that coordinate. If the following two steps (three adjacent steps) find Q to exceed the threshold, lock is set in that coordinate and no further stepping occurs for that coordinate. If consecutive steps are not found above the threshold, the counter is reset to zero and the step reverts to full size. The same algorithm is also at work simultaneously in the other coordinate.

As in the actual FGS algorithm, both coordinates must reach the lock criterion but not necessarily simultaneously. If one or both do not reach lock, the stepping continues through the entire S curve and until a limit in the number of steps is exceeded. If the acquisition is successful, simulated tracking commences and is continued for a maximum of 60 s, to avoid excessive computer time usage. The acquisition is deemed successful if, while under the influence of nominal line-of-sight jitter, the star is kept at the null throughout the 60 s.

3. RESULTS OF THE SIMULATOR RUNS

Runs were made with the simulator through large series of combinations of the binary-star characteristics: separation (0–250 mas), combined magnitude (9–14 as normally used for guidance), magnitude difference (0–1.5), and position angle of the binary system axis with respect to the guidance system coordinate axes. The computation steps used were 10 mas in double star separation, 0.25 in magnitude difference, and 24 degrees in position angle.

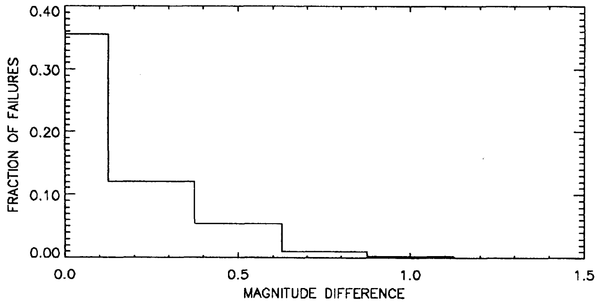

FIG. 4—Fine-lock failures in the simulator as a function of magnitude difference per 0.1 mag bin. All combinations of separation and position angle are included. Most failures occur where the two stars are of nearly equal magnitude. The failure rate drops rapidly thereafter, and is insignificant when the companion is 0.75 or more magnitudes fainter than the primary.

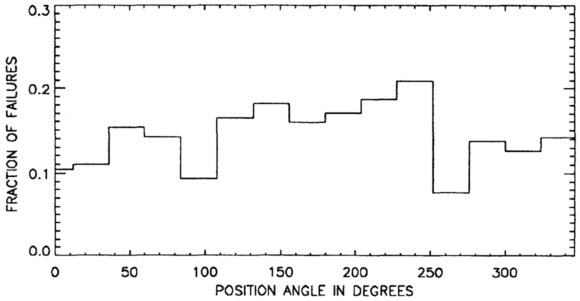

FIG. 5—Fine-lock failures in the simulator as a function of position angles per 10 degree bin. All combinations of separation and magnitude difference are included. Failures are not strongly dependent on position angle, but show some quadrant dependence.

The main statistical results of the simulation are summarized in Figs. 3 to 6. The effect of binary separation is shown in Fig. 3: failure to achieve lock only becomes significant when the double star separation exceeds 50 mas, which corresponds to the resolution of *HST*, but does not go beyond the 20% level thereafter. As one would expect, failure also depends strongly upon magnitude difference: The companion becomes insignificant for fine-lock failure when it is fainter than the primary star by 0.75 mag or more (Fig. 4). On the other hand, the failure rate is only weakly dependent upon position angle and combined brightness (Figs. 5 and 6).

Once a guide star has been acquired, about 1% of the simulated binaries were found to "lose lock" under the influence of line-of-sight jitter and S-curve distortion. Loss of lock was defined as reaching a position more than 60 mas from the null originally found on acquiring lock, and within 60 s of time (2400 steps).

4. DISTRIBUTION OF BINARY SEPARATIONS

Having characterized the response of the FGS to binary stars, it was necessary to estimate the fraction of binary

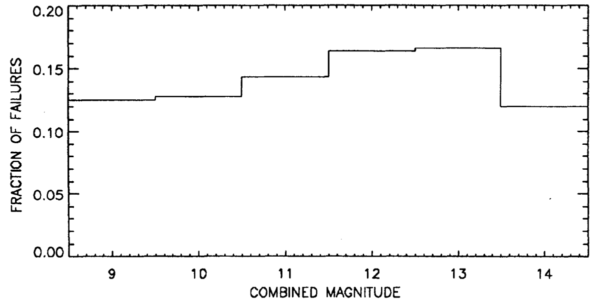

FIG. 6—Fine-lock failures in the simulator as a function of combined magnitude of the pair per 1 mag bin. All combinations of separation, magnitude difference, and position angle are included. The dependence on combined magnitude is very weak.

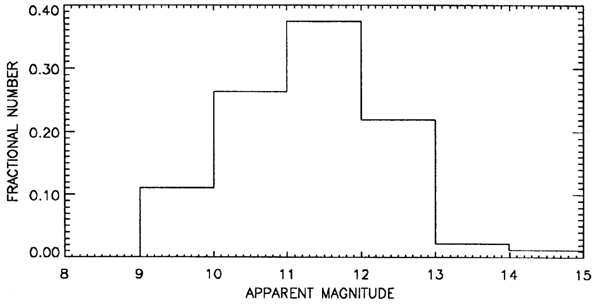

FIG. 7—The distribution of guide-star magnitudes used by *HST* for fine lock during one year of operation, from 1991.067 to 1992.067.

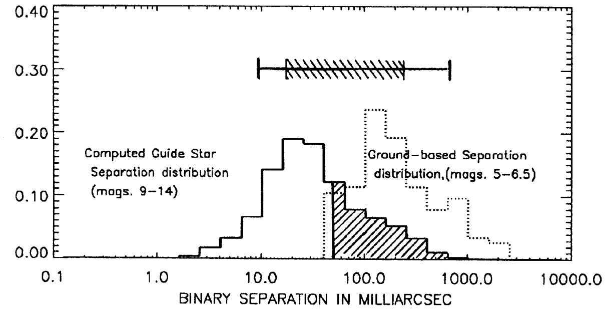

FIG. 8—The distribution of double star separations in the 5–6.5 mag range in the speckle survey (McAlister et al. 1987) and the distribution when transformed for *HST* guide stars (9–14 mag range). Most of the guide-star separation distribution falls short of the 50 milliarcsec level where duplicity causes fine-lock failures. The hatched area indicates the region of the guide-star separation distribution in which some binaries cause fine-lock failure (from Fig. 3.). The large bar indicates the separation distribution range used in the previous study, and the hatched region on the bar indicates the failure range used in that study (Shara et al. 1987).

guide stars and the distribution of their separation in the actual set of *HST* guide stars. The general principle used in the original analysis by Shara et al. (1987) was followed. A selected sample of bright stars, studied intensively for separation distribution, was shifted to distances corresponding to *HST* guide stars and the observed separation distribution was transformed to correspond to the larger distances.

In selecting the sample of stars for the survey, a distribution of spectral types and luminosity classes had been chosen to represent the distributions predicted by the galactic model of Bahcall and Soneira (1981) for magnitudes 9–14 (McAlister et al. 1987; Shara et al. 1987). However, the distance transformation in the present study was carried out with a star-by-star magnitude adjustment and convolution with other parameters, instead of a single shift for the most frequent stellar type used in the original analysis. The distribution of magnitudes for the guide stars used for fine lock was determined from those actually used for *HST* guidance during a one-year interval from 1991 September through 1992 August. The direction of pointings during that period was essentially uniform over the entire sky. The histogram of these guide star magnitudes is shown in Fig. 7.

The observed (ground-based) distribution of 5–6.5 mag binary star separations from McAlister et al. (1987) is shown by the dotted histogram in Fig. 8. Each star of this ground-based data was shifted to a series of apparent magnitudes in the guide-star range and weighted in order to reproduce the guide-star magnitude distribution. Based on the spectral type and luminosity class, a distance was estimated for each apparent magnitude, allowing for galactic absorption. The apparent binary angular separation was computed for that distance. Each star was run through a series of galactic latitudes (b) from 0 to 90 degrees. The distance above the galactic plane (z) was computed and the relative density of that particular type star at that (z) was computed and applied as a weight. A table of galactic density scale heights for each stellar type and luminosity class (Allen 1973) was used to provide a stellar density as a function of (z). The density was weighted by $2\pi\cos(b)$ to represent the area of a zone of latitude. The resulting separation distributions for all stars, from the shifted apparent magnitudes, latitude densities, and real guide-star magnitude statistics, were summed and renormalized, yielding a predicted distribution of double guide-star separations shown as a solid line in Fig. 8.

Experiments with the separation distribution generation program described above showed that the decline in density with (z) does affect the statistics of stars in the high end of the guide-star magnitude range. The distribution was relatively insensitive to variations of the interstellar absorption constants within the range of their observational uncertainty. The net result of the detailed analysis was to shift the separation distribution to smaller values as compared to the distribution based on the most frequent distance for 9–14 mag stars. The results of the detailed transformation are nevertheless limited in accuracy by all assumptions in the process and the small star sample in each spectral type and luminosity subcategory.

5. ESTIMATION OF GUIDE-STAR FINE-LOCK FAILURE RATE

Using the results of the FGS simulation, and the guide-star binary statistics derived above, the overall probability of failure of fine-lock acquisition for a guide star due to duplicity can then be estimated as follows:

(1) Probability that a guide star is binary (from speckle survey): 0.17,
(2) Probability that the separation lies in the failure range (Fig. 8); 0.29,
(3) Probability of failure in that separation range (Fig. 3): 0.18.

Multiplying the three probability factors yields

Failure rate per star: $=0.17\times0.29\times0.18 \quad =0.9\%$,
Failure rate per guide-star pair:
$1-(1-0.009)^2 \quad =1.8\%$.

This result is in relatively good agreement with the observed rate of failure from 1990 October to 1993 May which is estimated at approximately 0.7% from a list of failures not ascribable to other causes (Sturch, private communication), and from a data base count of unique guide-star pairs (Reinhart, private communication). It is difficult to assign formal errors to the quantities used above and the result should not be expected to be valid at the two place accuracy given in the calculations.

Since the above analysis a revision of binary-star statistics from speckle observations of bright stars has been made by McAllister et al. (1993) based on all speckle observations on bright stars by the authors to date. Observations of stars not in the earlier sample as well as repeat observations of many in the previous sample are included. Some of the earlier observations have not been confirmed which reduces the fraction of binaries somewhat. A comparison of Table V, from Shara et al. (1987) and Table 9, McAllister et al. (1993), shows some large changes in the spectral-type, luminosity class subcategories. As noted above, the samples in each subcategory are not large enough to provide highly accurate statistics. The percentage of binaries from all spectral types and luminosity classes in the new work is reduced from under 17% to 14%, a decrease of about 18% in factor (1) above. The reductions are primarily in the A dwarfs. Revising the binary fractions in subcategories and rerunning the convolutions to shift to guide-star magnitudes raises factor (2) above, by a few percent. The final failure rate above becomes approximately 1.5%, slightly closer to the observed failure rate. It also would have reduced the prelaunch predictions by a similar amount.

6. CONCLUSION

The primary reason for the higher estimate of failure rate made before launch lies with the criteria used to predict failure. The failure region provided by the FGS manufacturer (18–200 mas separation), started too low and was expected to be applicable to all binaries with separations falling in that separation range, and magnitude difference range up to 1.0. The simulation shows that the region of failure starts near 50 mas (with the 2/3 pupil stop in place) and that the failure rate is only partial for larger separations, and that it drops rapidly as component magnitude difference increases from zero.

A second, but lesser factor in the original overestimate is the simplification made in the calculation of the double star separation distribution. Compared to the bulk method, the star-by-star treatment through all of the variables of spectral type, luminosity class, guide-star magnitude distribution, and galactic latitude, shifts a larger fraction of binaries to greater distances than were originally calculated. Thus a larger fraction of the double star separations falls below the separation failure range.

In summary, the detailed simulation of the guiding system response to binaries together with a more detailed estimate of the binary star separation distribution predicts the low level of failure actually experienced on orbit. On the astronomical side, this result indirectly supports the binary separation statistics originally determined by McAllister et al. (1987) for stars in the 5.0–6.5 mag range. On the *HST* operational side, the results justify the current practice of not allocating time for backup guide stars, thus increasing the observing time per orbit by about 11%. Fortunately the prelaunch estimates were on the conservative side as they should have been. A failure estimate much too small would have seriously reduced efficiency of operations of *HST* for a time if a remedy had to be developed after launch.

We thank Conrad Sturch of CSC/STScI for a list of guide-star failures and for pointing out the need to consider galactic latitude effects in the statistics of faint guide stars, and Larry Taff for useful discussions. Merle Reinhart did a data base search for a count of unique guide-star pairs (not counting reserve pairs not used).

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