TESTING SCHMIDT PLATES FOR ASTROMETRIC PURPOSES

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ABSTRACT. The Guide Star Selection System for the Space Telescope is being developed to find positions (± 0.25 arcsec) and magnitudes(± 0.4 mag) for guide star pairs for every possible ST target. The data available for the astrometric portion of this task are measurements (±1 μm) of plate surveys from the Palomar and UK schmidt telescopes and positional data from the AGK3 and the SAOC. Astrometric testing to date has concentrated on whole plate reductions in the area of the astrometric standard region in Praesepe. Described here are the test procedures derived to measure the effect of the astrometric accuracy of the guide star positions on ST pointing success. The most critical item in the pointing procedure is that the separations of the guide stars and the target over the ST field of view (28 arcmin diameter) be well-known. Any small zero-point shift or rotation of the field relative to the absolute system is tolerable.

1. INTRODUCTION

One of the earliest responsibilities of the Space Telescope Science Institute (ST ScI) is the establishment of the Guide Star Selection System (GSSS) and the construction of the Guide Star Catalog (GSC). This system is described briefly by Russell (1986) elsewhere in these proceedings. The specifications for the GSSS include relative positions with one sigma errors of 0.33 arcsec for the target and several guide star pairs and photometry for the guide stars with errors of 0.4 mag in the bandpass of the ST fine guidance sensors. The 0.33 arcsec error will include error due to the stars' proper motion, since the catalog will be constructed from single epoch plates. Of the 0.33 arcsec error specification, 0.25 arcsec is allowed for the accuracy of the positions at the plate epoch. The GSC is planned as a finding list of possible guide stars which can be used for planning and scheduling and also for low accuracy pointings. The specifications for the entries in the GSC are at least ± 1.2 arcsec in position and 0.7 mag for the photometry. These are the limiting values; GSSS operation will be simplified with any increase in the accuracies in the GSC. The catalog should contain in excess of thirty million stars, the sky nearly complete to visual magnitude 15.

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Of fundamental importance in the astrometry for the GSSS is knowledge of the plate scale; its accuracy is more important than error in translation or rotation of the field. And the scale must be absolute; the GSSS positions must predict the relative separations on the "real" sky, not relative to another plate. However the separations must be within tolerance for only the Space Telescope (ST) field of view, i.e. 28 arcmin diameter. It is also important to be able to test for any magnitude terms in the plate modeling. The range of visual magnitude for the guide stars is 9.0 to 14.5, while that of the reference stars is generally brighter and that of the ST targets generally is expected to be fainter. The main purpose of this paper is to describe special testing techniques which can give information on the reliability of the plate modeling, and position separations, across areas the size of the ST field of view. These special Guide Star Separation (GSSep) tests are described here and sample results are shown.

2. POINTING SPACE TELESCOPE

The field of view of Space Telescope is shown in Figure 1; it is circular with a diameter of 28 arcmin. Three-quarters of the outer perimeter is occupied by the three fine guidance sensors (FGSs), with a field width of 4.3 arcmin. To point the ST one guide star each must be acquired by any two of these sensors. The first guide star is acquired and used to set the pitch and yaw of the satellite while the second is acquired and used to set the roll angle. The roll angle is determined by the date of the observation so as to maintain optimum orientation of the solar panels and thus assure the power levels onboard the spacecraft. Although the roll angle can be set at less than optimum values for special observations, this will not happen routinely. Using the predicted relative positions of the target and guide stars provided by the GSSS, the guide stars are positioned within the field of view so that the target should be in the desired aperture. The fields of view of the other scientific instruments are arranged within those of the fine guidance sensors. This inner region is divided into 5 areas containing the Faint Object Spectrograph (FOS), the High Resolution Spectrograph (HRS), the High Speed Photometer (HSP), the Faint Object Camera (FOC) and the Wide Field/Planetary Camera (WF/PC), which occupies the central region of the focal plane.

Each instrument has an acquisition aperture which is used to assure that the target is within the field of view; if a smaller aperture is desired then the telescope is offset from the acquisition aperture. The smallest acquisition aperture of the ST scientific instruments is that of the the HRS. It is 2 arcsec square and this area, then, determines the positional precision needed for GSSS operation. The second smallest aperture is that of the FOS, which is 4.3 arcmin square. A full description of the instruments, their apertures and modes, is contained in the book edited by Hall (1982).

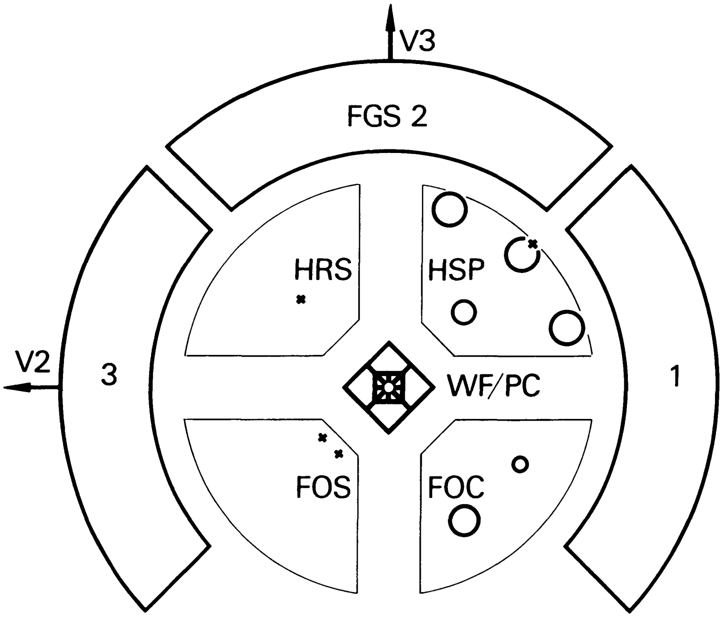

Figure 1

The Space Telescope field of view. Shown is the placement of the fine guidance sensors and the apertures of the five scientific instruments.

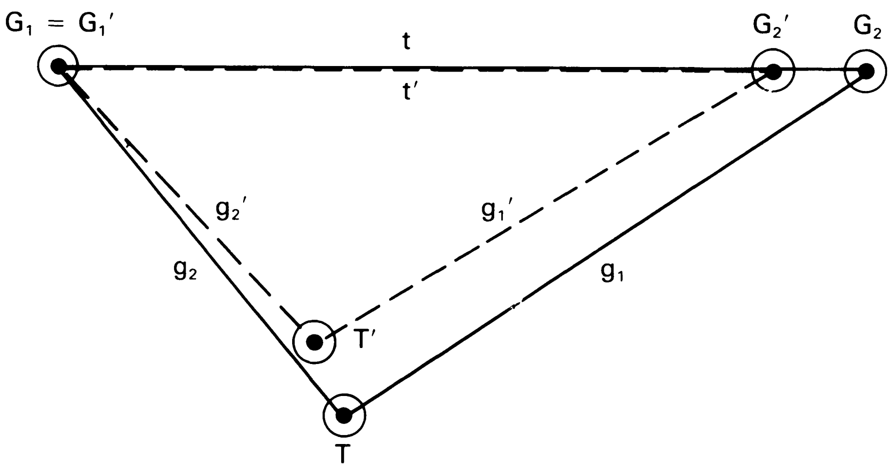

Figure 2

The geometry of the pointing triangle. The points G_1, G_2, and T are the predicted positions of the two guide stars and the target, respectively. The points G_1', G_2', and T' are the actual positions of the same three objects on the sky. The relative placement of the two pointing triangles, the predicted defined by the solid lines and the actual by the dashed lines, is defined by the pointing operation of the ST.

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The geometry of a target acquisition is illustrated in Figure 2. The "pointing triangle" -- two guide stars and a target -- is shown as that connected by the solid lines, where the guide stars are G_1 and G_2 and the target is labelled T. These are the positions predicted for the three objects by the GSSS. The positions G_1', G_2' and T' connected by the dotted lines are the true positions of the objects as found at the time of ST pointing. The coincidence of G_1 and G_1' and the common orientation of the lines G_1-G_2 and G_1'-G_2' are results of the pointing method used for the ST.

Because of the method of acquiring the target, the orientation of the pointing triangle on the sky is defined relative to the predicted one, so that small errors in zero point and orientation between the triangles can be ignored. (This is of course not the case in trying to acquire solar system members or other objects as targets for which only the coordinates on an absolute system are known instead of the positions relative to the guide stars. These are not included in the the present discussion.) The only concern is that the separations within the triangle be correct, i.e. that the scale of the relative positions be that of the absolute system and that the relative positions be accurate over the 28 arcmin field of view. These special requirements were the impetus for the creation of the GSSep tests.

3. INTRODUCTION TO GSSS ASTROMETRY

The right ascensions and declinations of the guide stars are determined from plates taken specifically for this purpose with the 1.2 meter Schmidt telescope at Palomar Observatory and the U. K. Schmidt telescope at Siding Springs, Australia. Both telescopes have a plate scale of 67 arcsec/mm, use 14-in square plates and thus have a field of view of 6.4 x 6.4 deg. The entire sky is covered with about 1500 recent epoch plates taken at the two facilities and stored at the Space Telescope Science Institute in Baltimore, Maryland. The plates are scanned in Baltimore with two PDS microdensitometers, which are equipped with Hewlett-Packard laser interferometers. The scan data for each star is centroided and potential guide stars' measured coordinates are determined.

The astrometric reductions from plate measurements to standard coordinates are accomplished using plate constant reductions and large survey catalogs. The major catalogs available are the SAOC and the AGK3. The first GSSS astrometric tests are to choose the best combination of plate model and catalog for each telescope, which simultaneously determines the best estimates of the accuracy of the final GSSS procedures and that of the GSC. The principal criterion for the choice is that the reduction give the best results in the guide star separation tests, even though the possibility exists that what is chosen may have larger formal or systematic errors than some other combination.

Why not use just the formal errors of the plate constant solutions as the criteria for the selection of the plate model and catalog? The problem with this approach is two-fold. The formal errors of the catalogs are much larger than the estimated internal accuracy of the Schmidt plates (see below). Also the catalogs' star density and magnitude range could not produce a realistic estimate of the accuracy of the guide star and target positions. The formal errors produce an estimate only of how well the reference star positions are modeled, not an estimate of the suitability of the catalog/plate model to produce the best positions for guide star selection. These problems would be resolved with more accurate and more complete catalogs, but none are available. Only a few such catalogs over a small areas of the sky exist.

4. PREVIOUS SCHMIDT PLATE ASTROMETRIC STUDIES

Schmidt plates rarely have been used for astrometric programs, although Konig (1962) states that good results are possible since one can easily measure the curvature of the field. Dieckvoss (1972), in referring to earlier work by himself and deVegt (1966), discourages performing least squares solutions over the whole field of the Bergedorf Schmidt telescope and describes successes by dividing each plate into several smaller sub-regions. The mean errors obtained for their telescope for relative positions between two plates is 0.15 arcsec. Luyten and LaBonte (1972) reach much the same conclusions. They describe whole plate reductions of eight plates from the Palomar Schmidt to the SAOC which give average errors of 0.91 arcsec in xi and 0.82 arcsec in eta. They suggest that their results could be improved using a better plate model, since they used only four plate constants per coordinate.

Several of the early analyses show that Schmidt plates, because they are bent during exposure and measured flat, suffer not only from curvature of field but also from elastic deformations and/or irregular emulsion shifts. Many investigators report large differences between internal (plate to plate) and external (plate to catalog) mean errors indicating the presence of systematic errors, possibly due to these causes among others. Bru and Lacroute (1972) describe plates taken with Schmidt telescopes on which opaque reseau marks placed in the focal plane are exposed. Fresneau (1978) makes an extensive study of Palomar Schmidt plates with grid lines exposed on the plates by Lacroute. His solutions are iterated based on a technique which tests the vector residuals for randomness. Earlier investigators had observed sharp decreases in the rms error of solution occurring at the boundary of and inside a central region of the plates about 4 by 4 deg. Fresneau concludes that elastic deformations and emulsion shifts are probably not the cause of this abrupt change. The errors on the outer regions of the plate indeed indicate the presence of systematic errors and therefore the plate model is very important. This important investigation gives an internal error of about 0.15 arcsec, and Fresneau suggests that therefore the external error should be close to the error of the star catalog used for the reduction, since these errors are usually larger than 0.15 arcsec. Anderson (1971) also found a significant improvement in the positional accuracy of the

Brorfelde Schmidt telescope by limiting the field size to the central portion of the plate. In contrast to the requirements of the Guide Star Catalog, Anderson can ignore stars near the edge of the plate where he expects emulsion shifts (and hence systmatic errors) to be large. (See also discussion of Schmidt astrometry by de Vegt, 1979.)

The above selections from the literature are typical. Schmidt plates have not been used routinely for astrometry, but usually for a few selected fields and most often for small regions in the center of the plate. The GSSS must be able to perform in any area of the sky and, because of the limited overlap of the Schmidt surveys, 0.4 deg for the Palomar and 1.4 deg for the U.K. Schmidt, will not be able to exclude any area of the plate, even using the near edges for astrometry of ST fields of view which straddle plate boundaries. The only good news in what sounds like an impossible problem is that, according to the GSSS requirements described above, systematic errors which do not change significantly over distances of one-half degree or less generally will not affect the GSSS performance. In the plate modeling for the Guide Star Catalog, we must consider, in addition to the geometric terms of a plate model, the magnitude and color terms. Magnitude terms may be introduced both at the telescope and during the measuring process. Since the magnitude range of the comparison catalogs is limited, magnitude terms determined by the plate models may not adequately represent those terms for the fainter guide stars and still fainter targets. Color terms cannot be included because there is no way of determining the colors of the stars from just one Schmidt plate. Some preliminary work suggests that color terms are present, but weak enough that they can be ignored.

To choose which plate model/catalog combinations are the correct ones, we begin with the standard astrometric tests. These include 1) a comparison between various models of the values of the plate constants and their associated standard errors; 2) an inspection of the residuals for correlations with position, magnitude, etc; 3) an examination of the vector plots of residuals for patterns or randomness; and 4) a search for correlations of parameters and/or residuals. If more than one catalog is available, one can perform useful comparisons between reductions to each catalog. To first order, plate reductions are "good" if the standard error of the residuals is comparable to the expected error of the catalog and if the residuals are random. The plate constants and their errors should be close to "expected" values. The correlations between residuals and parameters should also be small. These criteria help identify bad measurements and identify the major plate constants. However, as the solutions stabilize, these criteria give ambiguous comparisons between models, or, at best, suggest that several different plate models are equally good. This is when the GSSS specific tests are appropriate.

5. GUIDE STAR SEPARATION TESTS

An external check on a plate reduction cannot be done without having a second, high accuracy catalog available as a standard to provide the

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"true" positions of the stars. The two catalogs should be independent. The constraints on precision needed for the guide star catalog suggest the following requirements for the standard catalog.

1. extremely small or non-systematic errors
2. the standard error in star positions at the epoch of the ST ScI plates (about 1983) be smaller than that expected from the plates themselves (less than 0.15 arcsecs, based on previous studies)
3. a wide range of magnitudes covering the range of survey catalog magnitudes, 8 to 10 and brighter; guide star magnitudes 9 to 15; and target magnitudes as faint as possible
4. a star density appropriate to do reasonable statistics predicting guide star performance
5. an area of sky approximately equal to or larger than that of a survey plate
6. an area of sky accessible to both telescopes

The Astrometric Standard Region, centered on the Praesepe star cluster (Russell, 1976; 1986, see elsewhere in these proceedings), meets 5 of these 6 criteria; it covers a region of the sky only 3 by 4 degrees. Because of its smaller size, it is used for testing by considering for each telescope two or more plates taken with different centers so that the Praesepe cluster occurs in different positions on the Schmidt plate. It includes 408 stars, magnitude range 6 to 16th, colors -0.3 to 1.6, and at declination 20 deg is accessible to both telescopes.

Later testing for the Palomar plates will be done using use the catalog by Diekvoss (1970) centered in the Alpha Persei star cluster. It has the advantage of covering a larger region, 5 x 5.5 deg, but has a limiting magnitude of 12.2 and is accessible only to the Palomar Schmidt. Other standard catalogs for testing the southern plates have not been found yet.

Consider the pointing triangle (Figure 2) which has two guide stars (G_1 and G_2) and a target (T) at its three vertices. Let the vertex angles of this triangle be given these names (G_1, G_2, T) and the sides opposite these vertices be g_1, g_2, and t respectively. Further define three unit vectors

$$\hat{u} = (\cos\alpha_1\cos\delta_1,\ \sin\alpha_1\cos\delta_1,\ \sin\delta_1)$$

$$\hat{v} = (\cos\alpha_2\cos\delta_2,\ \sin\alpha_2\cos\delta_2,\ \sin\delta_2)$$

$$\hat{w} = (\cos\alpha_T\cos\delta_T,\ \sin\alpha_T\cos\delta_T,\ \sin\delta_T)$$

where the subscripts 1 and 2 refer to G_1 and G_2, respectively. The side g_1 is obtained from

$$\sin g_1 = \text{signum}\,(\alpha_T - \alpha_2)\ |\hat{v} \times \hat{w}|$$

Cyclic permutations will give g_2 and t. The vertex angle G_1 is obtained from

$$\sin G_1 = \frac{\hat{u} \cdot (\hat{v} \times \hat{w})}{\sin g_2 \sin t}$$

$$\cos G_1 = \frac{(\hat{u} \times \hat{v}) \cdot (\hat{u} \times \hat{w})}{\sin g_2 \sin t}$$

Cyclic permutations of this formula will give G_2 and T.

The above formulae for the angles and sides can be calculated for the positions from the plate reduction (G_1, G_2, T, g_1, g_2, t) or for the standard catalog, which we assume to be the true positions, the quantities (G_1', G_2', T', g_1', g_2', t') from Fig 2. Define separation differences

$$\Delta g_1 = g_1 - g_1'$$

$$\Delta g_2 = g_2 - g_2'$$

$$\Delta t = t - t'.$$

If there is an error in scale, ΔS, it will affect the separation between two stars according to the formula

$$\frac{\Delta S}{S_o} = \frac{\Delta g_1}{g_1'} = \frac{\Delta g_2}{g_2'} = \frac{\Delta t}{t'}$$

where S_o is the true scale.

5.1. One-Dimensional Guide Star Separation Tests

The initial guide star separation tests were only in one-dimension, i.e. considering only the separation of the guide stars, the Δt defined above. For each plate solution the following procedure was followed:

1) identify all possible guide stars pairs from the standard catalog stars measured on the plate, i.e. all pairs which had a separation of 6 to 28 arcmin
2) calculate $\underline{\Delta t}$ for all pairs
3) calculate $\overline{\Delta t}$, the mean Δt, and σ_1, the standard deviation for the distribution of Δt for all pairs

The center square-degree of the Praesepe standard catalog has a high density to allow for testing small fields. Within this area more than 3000 pairs of stars qualify as guide star pairs, which completely dominates the test results. Thus in most of the tests the inner one-deg circle is not included.

If $\overline{\Delta t}$ is strongly positive or strongly negative, it suggests that there is a systematic error in the plate scale. σ_1 reflects this and the other errors in the plate reduction, assuming the errors of the standard catalog are much smaller. The specifications for the GSSS are that ST pointing have a success rate of 99% in the smallest acquisition aperture, the 2 arcsec one of the HRS. Thus in addition to the statistics calculated above, we plotted a histogram of the differences in separations, Δt, and calculated the actual percentage of separations which were greater than $\pm$ 1 (for the HRS) or $\pm$ 2 arcsec (for the FOS) from the standard catalog separation. Figure 3 shows an example histogram for the one-dimensional GSSep tests for one of the plate modeling experiments.

The best separation tests are not always associated with what one might judge to be the best plate reduction based on the routine astrometric procedures already described. This may be the fault of the catalogs, which do not have the accuracy to support the complex plate modeling which the Schmidt plates require. Another explanation may be that there are weak magnitude terms in the plate model which are not evident for the reference star solution, but do effect the GSSep results. A more thorough understanding of the errors in plate modeling seems required to explain this apparent discrepancy.

The one-dimensional GSSep test really checks only the accuracy of the separation of two stars, while the actual pointing of the ST is affected by the separations among three objects -- the two guide stars and the target. Two-dimensional separation tests are based on the positions of all three objects.

5.2. Two-Dimensional Guide Star Separation Tests

The two-dimensional separation tests are based on the simulation of the ST pointing algorithm, illustrated previously in Fig. 2. When the positional error in all of the objects is considered, the error in pointing is the length of the line T-T'. This can be calculated from the length of the sides g_2 and g_2' and the angle between them. Because of the coincidence of lines G_1-G_2 and G_1'-G_2', the latter angle is just

$$\Delta G_1 = G_1 - G_1'.$$

Then from the law of cosines, the displacement of the target is

$$(T - T')^2 = (g_2)^2 + (g_2')^2 - 2\, g_2\, g_2' \cos \Delta G_1.$$

The procedure for two-dimensional separation tests includes

1) all possible triplets of standard catalog stars within an area the size of the ST field of view are identified -- the center of the cluster may be excluded so as to not bias the statistics
2) calculate (T - T') for each each pointing traingle

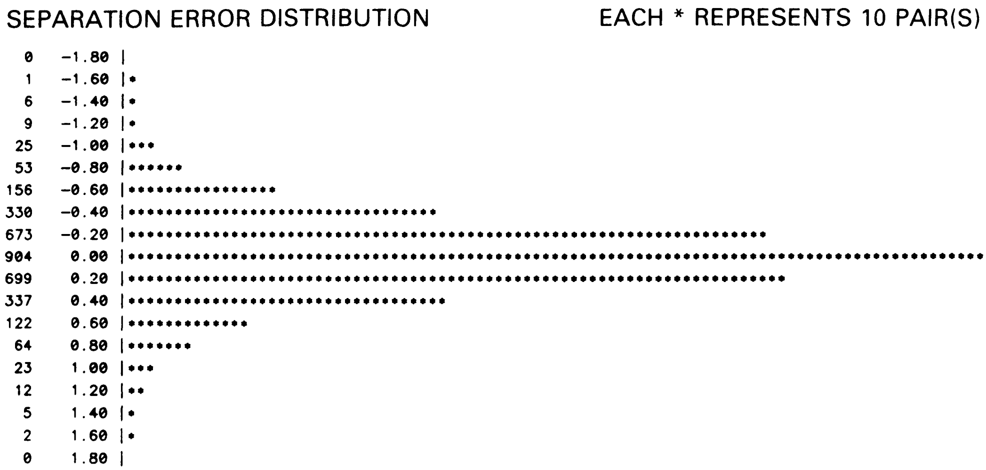

Figure 3

The histogram from a sample one-dimensional GSSep test. The left-hand column of numbers gives the number of guide star separations included in that bin of the histogram. The right-hand column gives the limit of the bin in arcsec.

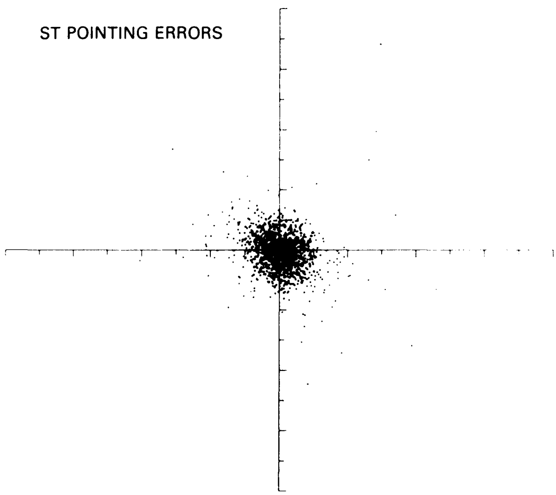

Figure 4

A scatter plot from a two-dimensional GSSep test. Each point represents the actual position of the target based on a simulated pointing the ST. The predicted position of the target is the center of the coordinate system included in the plot. Each tick mark represents 0.5 arcsec, so that the scatter plot includes the area within +/- 4 arcsec of the predicted target position.

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3) calculate the position angle of the displacement from the line $G_1'-T'$
4) calculate the mean and standard deviation of the displacements $(T - T')$
5) check the distribution of position angles for randomness

As in the case of the one-dimensional tests, a histogram of the offsets from the true position of the target is plotted and the percentage of successful pointings in the HRS and FOS are calculated. Figure 4 is an example scatter plot of the results of a two-dimensional pointing simulation. So far the tests have shown that the SAOC and the AGK3 will point the ST successfully for about 95% of the HRS targets and about 99% of those for the FOS. With the help of the guide star separation tests plate models have been defined which are able to meet these criteria for all of the Schmidt plate area except for the extreme edge regions. This does not mean that there are no systematic errors in the plate solutions, only that there are none which will affect the ST pointing accuracy for objects from the same plate solution.

6. SUMMARY

The guide star separation tests have proven very valuable for assessing the best plate models and catalogs for the operation of the Guide Star Selection System and the construction of the Guide Star Catalog. These are the most effective way to determine the overall system accuracy and to check for magnitude and color effects, all considering the special requirements of the Space Telescope operations.

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Discussion:

MURRAY: I have some interesting data on the temperature variation of the scale value of the UK Schmidt from the South Galactic Cap work.

WILLIAMS: The SRC plates use J emulsions. I have seen a small linear color term in the SRC plates. Unfortunately, we cannot use color terms in the reductions for guide stars. Interestingly, when color terms or magnitude terms are included in the reductions for test plates, although the solution improves, the separation tests get worse.

ARGUE: Yesterday Dr. Walter reported that he and West, using Perth 70 to calibrate ESO Schmidt plates over the entire field, obtained precisions of the order $0''.2$.

WILLIAMS: Using Russell's Praesepe Catalog and measuring the cluster in the middle $4^{\circ} \times 3^{\circ}$ of the Schmidt plate we can obtain a solution with a standard deviation of $0''.1$. This may represent the limiting accuracy of the center of these plates. With the SAOC or AGK3 catalogue, measuring the entire plate, the best reductions we have made produced standard deviations between $0''.3$ and $0''.4$. This may represent the limitation of the catalogues in this region. The Perth 70 catalogue gives a good solution, but it contains more of the brighter stars. We need a catalogue with more of the fainter stars for the purposes of Space Telescope.