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THE GUIDE STAR CATALOG, VERSION 1.2: AN ASTROMETRIC RECALIBRATION AND OTHER REFINEMENTS

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ABSTRACT

A collaboration between the Space Telescope Science Institute (STScI) and the Astronomisches Rechen-Institut has produced an astrometric re-reduction of the Guide Star Catalog (GSC) published by Lasker et al. This version, GSC 1.2, has dramatically reduced the systematic errors present in the GSC 1.1. As shown by Taff et al., the positions in the GSC 1.1 are affected by plate-based systematic distortions that are largest at the plate edges (1″.0 in the north and 1″.2 in the south). In addition, Morrison et al. have shown that these positions also suffer from systematic errors which are a function of magnitude and radial distance from the plate center. This effect is small for radii under 2°.7 from the plate center, then rapidly increases, producing an average offset of the faint stars (15 mag) versus the reference stars (10 mag) of 0″.9 at the plate edges. Since the magnitude term was similar for the two main plate collections comprising the GSC, which were taken with different telescopes, exposure times, emulsions, and filters, we believe this effect is common to fast wide-field-of-view Schmidt plates. In this paper we report on the astrometric quality of the GSC 1.2 and present the method we developed (for large plate collections) to quantify and reduce the positional errors which are dependent on location on the plate and magnitude. Instruction for obtaining the catalog may be obtained from the STScI World Wide Web site, or the user can obtain the catalog directly from CDS (Centre de Donneés astronomiques de Strasbourg). This version of the catalog has not been installed in the *HST* Guide Star Selection system. Therefore this version *must not be used for HST observation planning.*

Key words: astrometry — catalogs — methods: data analysis — surveys

1. INTRODUCTION

The Guide Star Catalog (GSC 1.0, dated 1989 June 1; Lasker et al. 1990; Russell et al. 1990; Jenkner et al. 1990) was constructed to support pointing and target acquisition for the *Hubble Space Telescope* (*HST*). The Guide Star Catalog contains approximately 19 million stars and other objects in the sixth to fifteenth magnitude range, primarily determined from an all-sky, single-epoch collection of 6°.4 × 6°.4 Schmidt plates. The Schmidt plates for north of +6° consists of a 1982–1984 epoch "Quick V" survey (IIa-D, 20 minute exposure) obtained from the Palomar Observatory. The southern fields consist of 50–75 minute exposure IIIa-J Schmidt plates, from the UK SERC J/EJ survey (epoch 1975–1988) and a supplemental 4 minute IIa-D southern Galactic plane extension (epoch ≈ 1988). Both observatories used 14 inch (35.5 cm) square plates taken with 1.2 meter Schmidt telescope with a plate scale of 67″ mm^{-1}. The northern survey was grid of 618 plates taken with 6° centers, while the long exposure southern survey contained 802 plates taken with 5° centers. The southern short exposure extension consists of 94 Schmidt plates. All the plates were digitized at the Space Telescope Science Institute into 14,000 × 14,000 rasters at a 25 μm sampling interval using two modified PDS microdensitometers. For more information on the plate material and processing of these digitized images, see Lasker et al. (1990).

For the last decade the GSC, together with the set of 1514 digitized Palomar and UK Schmidt plates from which it was constructed, has come to be used for numerous other purposes, for example, the fainter elements of the Tycho input catalog (Egret et al. 1992), observation planning for fiber optic spectrographs, preparation of finding charts, and operation of ground-based telescopes. Despite the successful pointing and tracking of *HST* and the widespread acceptance of the GSC for other applications, the initial GSC, version 1.0, had a number of deficiencies. Improvements to the precision and reliability of the catalog were seen as having significant impact both in *HST* operational efficiency and in the various other applications to which the community applies the GSC. Thus, an improved version of

[1] This project was completed while the author was on a National Science Foundation Fellowship.

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the catalog, version 1.1, was created and distributed on the CD-ROM, dated 1992 August. The corrected defects included spurious entries (principally due to false detections on the diffraction spikes of bright objects), grossly incorrect entries for the brighter stars ($V < 7$) because they were produced from heavily over-exposed Schmidt images, and different entries for the same object having more than one name because of blend-resolution difficulties, as well as astrometric errors at the plate edge. However, the GSC 1.1 still suffered from serious shortcomings. These include photometric systematic errors due primarily to plate nonuniformity and image-processing deficiencies, as well as astrometric systematic errors due to deficiencies using global polynomial plate-models for Schmidt plates and in the astrometric quality of the reference catalogs. Section 2 of this paper discusses the astrometric systematic errors present in the GSC 1.1.

This paper reports on the third release of the GSC, version 1.2. GSC 1.2 is an astrometric recalibration of the GSC 1.1 using improved reduction techniques for Schmidt plates. *However, since this version has not been installed in the HST Guide Star Selection System it should not be used for planning HST operations. The observer should continue to use GSC 1.1.* Section 3 of this paper discusses this astrometric recalibration. Since the majority of the work in creating this catalog was done before the Tycho and *Hipparcos* catalog were readily available, this version of the GSC is on the system defined by the Positions and Proper Motions catalog (FK5). The thrust of this paper is to report on the techniques we used to reduce the positional systematic errors which have plagued the GSC. These are general techniques and can be used to reduce similar wide-field-of-view Schmidt plates.

Currently, the STScI is creating the GSC 2 (McLean et al. 1998), which contains the plate material the GSC 1.0 is based on, plus Schmidt plates for other epochs and bandpasses: Palomar Observatory Sky Survey I and II (POSS I, Minkowski & Abell, 1963; POSS II, Reid et al. 1991), and the SERC/UK Schmidt surveys (Morgan et al. 1992). This catalog will be tied to the International Celestial Reference Frame (ICRF) and will contain positions, proper motions, and colors for all objects down to 18 mag with a complete reprocessing of the GSC 1.0 plate material. Therefore, corrections to the known systematic errors in plate nonuniformity and image-processing deficiencies in photometry in the GSC 1.2 and the reduction of the catalog onto the ICRF will be deferred until the release of the GSC 2. *An initial* public release of the GSC 2 is anticipated in 2001, with a final release in 2002. Depending upon the requests from the astronomical community some copies may be available with a set of DVDs.

2. GENERAL PROPERTIES OF THE GSC 1.0 AND GSC 1.1

The astrometry of the GSC 1.0, which remained unchanged in version 1.1, is based on a general third-order polynomial solution. The reference catalogs used for this reduction and their properties are summarized in Table 1.

Several early investigation (Dieckvoss 1960; Anderson 1971; Dodd 1972; Fresneau 1978; de Vegt 1979) have demonstrated the difficulties that arise in the reduction of wide-field-of-view Schmidt plates. As clearly stated by de Vegt (1979), "the main disadvantage of the classical Schmidt telescope with respect to astrometric applications is the deformation of the plate and emulsion in the curved plate holder necessary during exposure and its rebending to a plane during processing and measuring. For this purpose only very thin plates can be used, which provide an unfavorable metric stability and surface flatness as compared with micro-flat, thick plates customary in astrometry with other types of telescopes." The results of these early studies and other more recent studies (Taff 1989; Taff, Lattanzi, & Bucciarelli 1990a) have demonstrated that wide-field-of-view Schmidt plates reduced solely with a global plate model suffer from plate-based position-dependent systematics errors. These types of systematics can be detected from the residuals in the overlapping area of a plate pair (i.e., the residuals obtained from the same GSC star located on more than one plate). In fact, such deficiencies in the GSC 1.0, were initially noted in the plate overlap areas (e.g., Fig. 9 in Russell et al. 1990), and rigorously quantified in a subsequent study by Taff et al. (1990b). Figure 1*a* demonstrates the typical astrometric residuals in the overlapping areas of a plate pair from the GSC 1.1C.

TABLE 1

REFERENCE CATALOGS USED FOR THE GSC 1.0

Catalog	GSC Plate centers (deg)	Precision at 1980 (arcsec)
AGK3......	$\delta \geq 2$	0.33
SAOC......	$0 \geq \delta \geq -60$	0.79
CPC........	$-65 \geq \delta$	0.57

Taff et al. (1990a) developed a powerful technique to determine and correct for systematic trends left in the residuals after a standard global least-squares reduction by using the residuals of the reference stars for an ex posto facto correction. They superposed the reference star residuals from hundreds of different plates, but from the same telescope, and then binned and averaged the residuals in the Schmidt plate reference frame. A 3×3 moving average technique was then used to smooth over the noise. The resulting signal represents the mean deformation that is common to a set of plates. An adjustment to each star's position on the plate can then be made by applying the appropriate average residual from the residual map. This residual map is called a *mask*, and this technique is commonly referred to as the mask method.

We have used this mask technique to detect and quantify the systematic errors in the GSC 1.1. Since the GSC 1.1 does not contain proper motions, we constructed residual maps using an independent high-quality approximately coeval set of positions from the Carlsberg Meridian Circle Catalogs (CMC; Carlsberg Consortium 1989, 1991, 1992). These catalogs are useful for estimating the astrometric quality of the GSC because they uniformly cover most of the sky north of declination $-45°$ down to 15 mag (with the majority of the objects in the 8 to 12 mag range) and typically have positional precisions at the GSC plate epochs of $0\farcs15$ in the northern hemisphere and $0\farcs16$ in the northern part of the southern hemisphere.

After computing the difference between the stars found on the GSC 1.1 and CMC and binning and averaging these values on the GSC Schmidt plate coordinate system, we obtained detailed maps of the scale and direction of the remaining residuals. Figure 2 is a mask constructed with the CMC. Figure 3 contains the results of binning the difference between the GSC 1.1 and CMC positions according to the

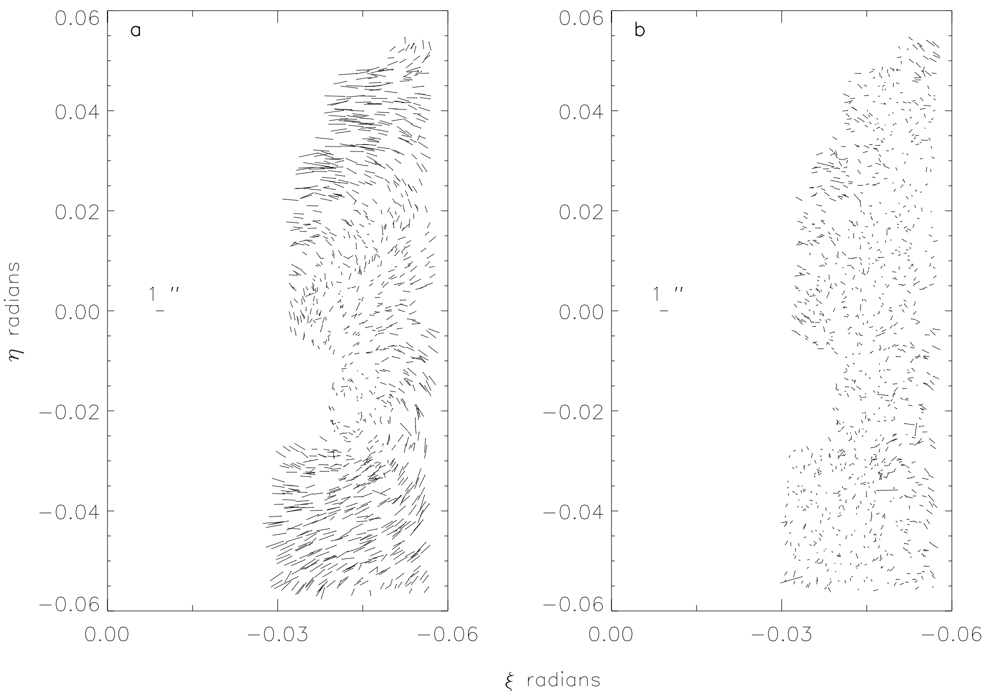

FIG. 1.—Overlapping plate residuals from plate 0019 and plate 04JJ. Results using the GSC 1.1 on left and the GSC 1.2 on right.

star's distance from the center of the plate in 0°.3 bins and then averaging the values within each annulus.

Both Figure 1*a* and Figure 2 demonstrate the strikingly clear swirl pattern of systematic errors remaining in the GSC 1.1. Also, Figures 2 and 3 show the well-known fact that the GSC 1.1 has mean positional errors that are smallest at the plate center and increase rapidly towards the edges (1″.0 in the north; 1″.2 in the south). The systematic errors are relatively stable from plate to plate. This global pattern of positional errors is a consequence of an insufficient plate modeling caused by a combination of factors, such as the physical deformation of the plate from the bending and unbending of the plate, Schmidt optical aberrations, and, finally, the characteristics of the image formation and the algorithm that describes the properties of the image (i.e., location of center and size of the image). Most of the above effects are not understood well enough (from an engineering/physics standpoint) to be adequately incorporated into the model. Though a few groups have studied the effects of the bending and unbending of the plates (Shepherd 1953; Dieckvoss 1960; Dieckvoss and de Vegt 1966), no satisfactory method has yet been found to correct the positions resulting from these plate deformations. As shown by Figure 3, the GSC 1.1 positional errors also have a north-south asymmetry that is attributed to a combination of the less accurate catalogs in the south. Yet more important, the southern plates had an exposure time a factor of 3 times longer than the northern plates, thereby creating larger

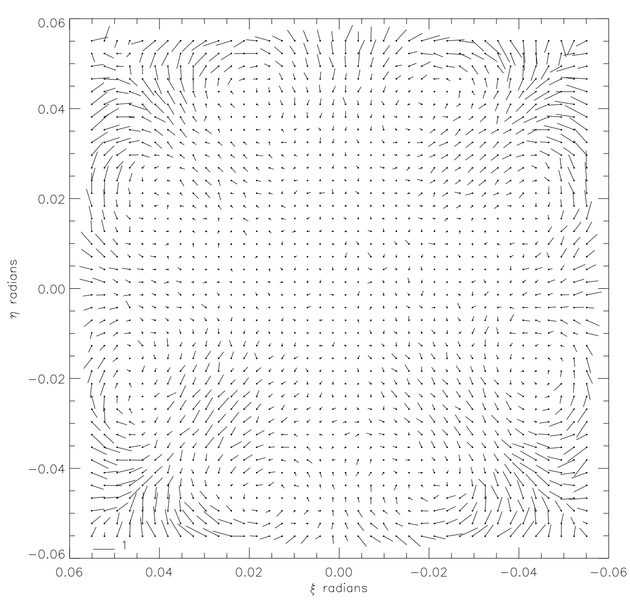

FIG. 2.—Binned and averaged astrometric residuals between positions in the CMC and the GSC 1.1 for the northern hemisphere. The average number of matches per bin point is 32. (Note the 1″ scale given in the bottom left.)

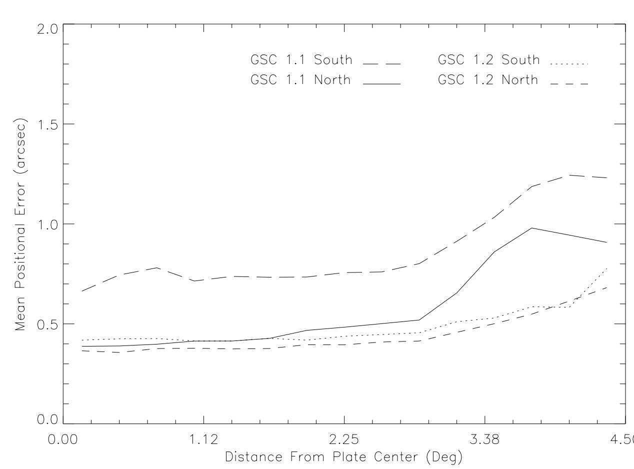

FIG. 3.—Mean positional error vs. distance from the plate center between the GSC and the CMC positions.

images, while they were still processed (measured and centroided) with the same techniques.

The positions in the GSC 1.1 also suffer from systematic errors that are a function of magnitude and radial distance from the plate center, i.e., computationally analogous to the coma term in astrographic work (Morrison et al. 1996). The effect is small for radii under 2°.7 from the plate center, then rapidly increases. The average offset of the faint stars (15 mag) versus the reference stars (10 mag) is 0″.2 to 0″.3 at a radius of 3°.0 and increases to 0″.8 to 0″.9 at the corners (radius of 4°.2).

3. NEW REDUCTION

The reference material for this re-reduction was the Positions and Proper Motions catalog (PPM; north: Röser & Bastian 1991; south: Bastian, Röser, & Yagudin 1993; 90,000 stars Supplement to the PPM catalog: Röser, Bastian, & Kuzmin 1994) and the Astrographic Catalogue (AC). A significant improvement in the positions came from the use of denser (AC) and more precise (PPM) reference material. Their properties are summarized in Table 2. The PPM positions have significantly better precision at the mean GSC plate epoch (1980) than those used to reduce the GSC 1.0 (Table 1). The AC does not contain proper motions, so its precision at the mean GSC plate epoch cannot be determined. However, our method of reduction does not require the reference catalog to be placed at the epoch of the plate material. We will describe this method in detail in §§ 3.2 and 3.3.

Over the last few years there has been considerable progress in developing successful algorithms for obtaining astrometric quality positions from Schmidt plates which compensate for deficiencies of the polynomial approach. Because the errors are stable on the average and vary slowly over small distances (Taff et al. 1990b), a number of astrometric recalibration techniques using *local solutions* have been proposed, i.e., the *mask* method, which is based on the plate-to-plate stability of the errors (B. J. McLean 1988, private communication; GSSS Development Internal Document; Taff et al., 1990a), the *subplate* method, which uses small piecewise overlapping linear solutions (Taff 1989), and the *collocation* method, which constructs an optimal filter based on the image covariance (Bucciarelli, Lattanzi, & Taff 1993). In addition, a number of other conceptually simpler filters have been studied; one based on the *method of infinitely overlapping circles* (Morrison, Smart, & Taff 1998) and another with a nonoptimum square-wave *filter* (Röser, Bastian, & Kuzmin 1995).

As shown by Figures 1*a*, 2, and 3, the positional systematic errors in the GSC 1.1 have a complicated structure, and we do not know of a single technique which adequately removes them while also removing the magnitude-dependent systematic errors. Therefore, our astrometric recalibration of the GSC evolved into a three-step process.

TABLE 2

REFERENCE CATALOGS USED FOR THE GSC1.2

Catalog	GSC Plate Centers (deg)	Precision (arcsec)
PPM North......	$\delta \geq 3$	0.23 (at 1980)
PPM South	$\delta \leq 0$	0.09 (at 1980)
AC	All sky	0.30 (at 1906)

Step 1 removed a portion of the position-dependent systematics and the majority of the zonal systematics caused by the original reference material. Step 2 removed the bulk of the magnitude-dependent positional errors, while step 3 removed the mean of the position-dependent systematics common to a set a plates.

3.1. *Step 1: The Filter Method*

The starting point for the new reduction was to correct the positions in the GSC 1.1 by the use of a filter technique. In this type of reduction, a filter of a chosen size and shape, along with an appropriately determined weighting function, is used to transform the plate-based system to a system defined by the reference catalog and hence remove or reduce the small-scale local systematic differences between the two systems in the process. The method of using a filter to correct systematics on individual Schmidt plates has been studied by many groups, including Dodd (1972), Fresneau (1978), Bucciarelli et al. (1993), and Morrison et al. (1998). The filter method we use is a general technique, which, when used in combination with a dense reference catalog, can reduce small-scale systematics found in the positions of star catalogs. The reference catalog for this method was the PPM and the filter's shape was a circle, which varied in size to contain approximately 30 reference stars ($\approx 2° \pm 1°$ diameter). Basically, the corrections necessary to transform the positions in the GSC 1.1 onto the system defined by the PPM catalog were found by drawing a circle around each GSC star, finding all the PPM reference stars in the circle, and then calculating the average of the differences between the positions from the GSC and PPM contained in the circle. This correction, the average difference, is then applied to the central GSC star. This process is continued for all the GSC 1.1 stars. The main objective of using the filter method was to place the GSC 1.1 onto the reference system defined by the PPM (FK5) and to remove the majority of the systematic errors inherent in the original reference catalogs (i.e., SAO, see Table 1). The application of this method also removed a portion of the positional errors present in the catalog as a consequence of the insufficient plate model used in constructing the GSC 1.1. Systematic errors less than the diameter of the filter could still remain. In Figure 4 we have compared the filtered positions from the deep southern IIIaJ plates with those in the PPM catalog. As one can see, the plate-based

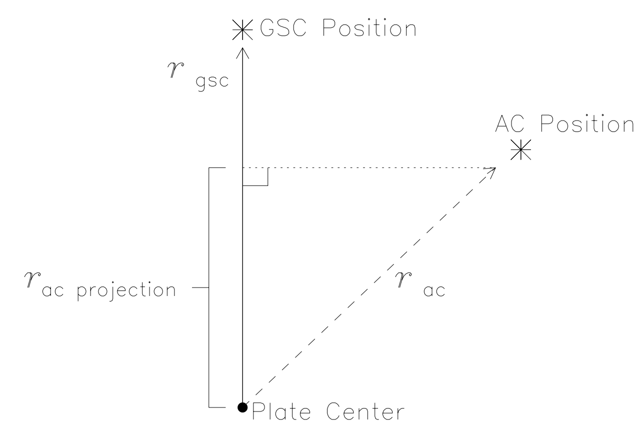

FIG. 4.—Schematic example of the differences in the GSC and AC positions for the same star projected onto the GSC Schmidt plate.

position-dependent systematics still remain, with residuals up to 0″.8 in the corners.

3.2. *Step 2: Reduction of Magnitude-dependent Errors*

Our second step, the correction for the magnitude effect, was slightly more complicated. The difficultly with trying to determine magnitude-dependent terms on plates that cover a broad magnitude range has been the lack of astrometric reference catalogs covering the same range. A dense all-sky reference catalog covering a broad magnitude range (preferably the same as the GSC, 6 to 15 mag) is needed to quantify and remove the magnitude-dependent systematics. Most reference catalogs have a limiting magnitude of $V \approx 10$ mag, whereas Schmidt plates often cover the magnitude range from 6 to 19 mag (the measured images on the GSC plates cover the range from 6 to 15 mag). Therefore, no magnitude-dependent term for the fainter stars can be reliably found by reducing the measurements based only on comparisons with reference stars. In an astrometric study on the GSC Schmidt plates Russell & Willams (1986) concluded that there may be "weak magnitude terms in the plate model," however, the determination of this dependence was hampered by the lack of suitable reference catalogs. The magnitude range and density of the PPM, Tycho, and *Hipparcos* are inadequate to support the use of these catalogs for determining a magnitude term directly. Note that the Tycho II catalog (Hoeg et al. 2000), a re-reduction of the Tycho data extending the depth of the catalog so that it is 90% complete at 11.5 mag, was not complete when this work was carried out; however, it still does not contain a broad enough magnitude range for detecting and compensating for magnitude-dependent systematics on Schmidt plates. The lack of such a modern epoch catalog forced us to adopt a rather unconventional approach by using the Astrographic Catalogue.

The Astrographic Catalogue was the first large-scale catalog produced with photographic plates. We will briefly summarize the AC project (a more complete description of the catalog can be found in Eichhorn 1974, § 5.5). The work for compiling the AC was divided among 20 observatories, and the majority of the observations were taken between 1898 and 1920. The plates were photographed so they overlapped 50% in right ascension and 50% in declination. The resulting catalog contains 10 million measurements of roughly 4 million stars with an accuracy lying between 0″.2 and 0″.4, depending on the observatory zone. It was planned to establish a complete survey down to 11 mag, but in many areas of the sky it is as faint as 13 to 14 mag (a very interesting magnitude range concerning the GSC). Therefore the AC meets the requirement of a dense catalog with a broad magnitude range. However, since the AC project was divided among twenty observatories, differences in each observatory's methods of plate processing, measurement of the images, and reduction of the measurements, and the fact that the plates were observed between 1891 and 1950 produced an inhomogeneous catalog with zonal and observatory dependent systematics. The version of the AC we used (Röser & Bastian 1991) was constructed for compilation of the PPM and is therefore on the PPM system.

As mentioned above the AC consists of only material from a single epoch (mean epoch 1903) and therefore contains no proper motions. The large epoch difference (roughly 80 yr) between the GSC and AC with neither catalog containing proper motions posed a significant problem for using the AC in a new reduction of the GSC. However, we have developed a method of reduction where this difference in the epochs is *inconsequential*.

The numerous tests we have performed on the magnitude effect have proven that the overwhelming part of it is radial. Therefore, as far as the magnitude effect is concerned, we are only interested in determining, for each GSC/AC match, the radial distance from the plate center using the GSC position, $r_{\rm gsc}$, and the corresponding radial distance using the AC position, $r_{\rm ac}$. We then calculate the difference, dr, which is simply

$$dr = r_{\rm gsc} - r_{\rm ac\ projection} , \tag{1}$$

where $r_{\rm ac\ projection}$ is $r_{\rm ac}$ projected on to the radial vector $r_{\rm gsc}$ (see Fig. 5).

The dominant factors contributing to each object's radial difference value, dr, are the Galactic, solar, and stellar motions during the 80 yr. The remaining, smaller amplitude signal is caused by the systematic and random errors in the AC and the GSC positions. If we could remove from the dr value the effects of Galactic, solar, and stellar motions along with the effects caused by the errors in the AC positions we could study the systematic errors in the GSC 1.1. We have developed a technique, similar to the mask method, where we can determine the mean magnitude-dependent systematic errors in the positions which are common to a set of plates from the dr values.

For a set of specified magnitude ranges, the dr radial difference is found for all the GSC/AC matches contained from a set of plates and then binned and averaged into thin rings (2′.7) centered on the GSC plate coordinate system. The large number of AC stars and the high degree of overlap of the AC plates resulted in roughly 4.25 million GSC/AC matches in the north and 5.33 million matches in the south. Even after binning the data according to magnitude and distance from the plate center each ring still contained an enormous number of matches (thousands). We can assume that after binning and averaging, the random

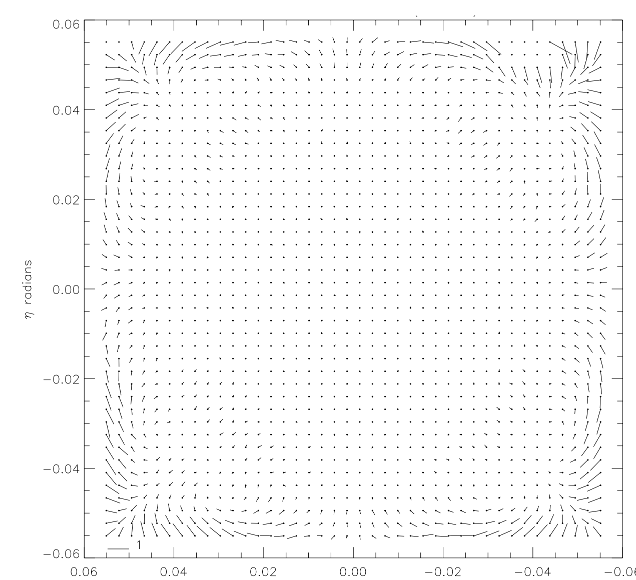

FIG. 5.—Binned and averaged astrometric residuals between positions in the PPM and *filtered* GSC 1.1 for the deep southern IIIaJ plates. Note the 1″ scale given in the bottom left. The average number of stars per bin point was 206.

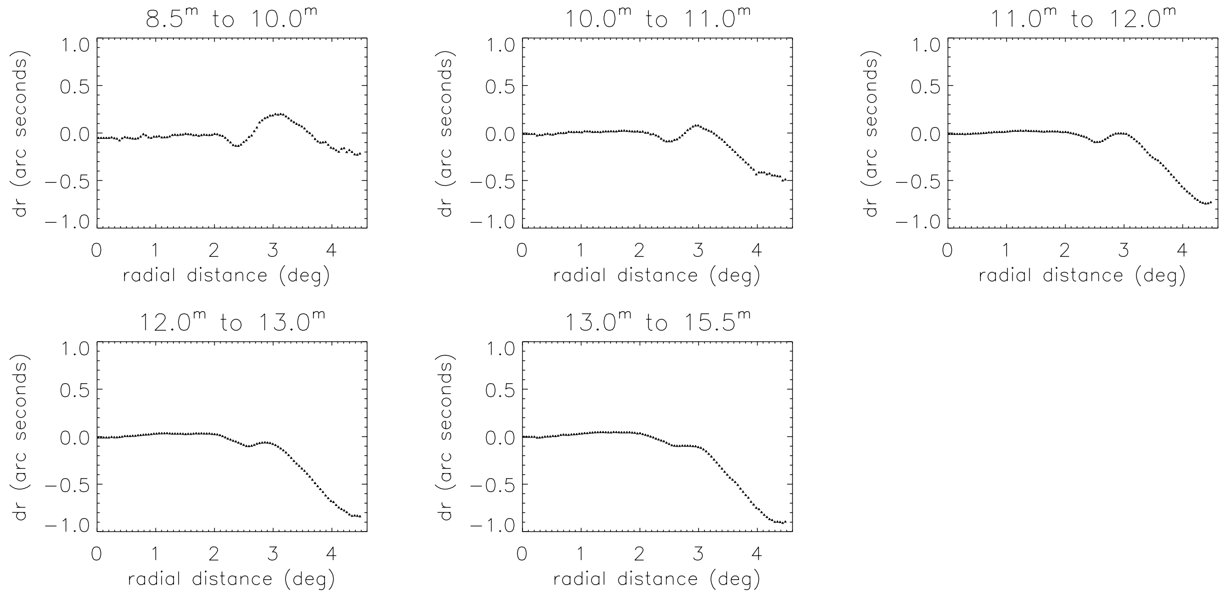

FIG. 6.—Radial magnitude effect for the deep southern hemisphere IIIaJ plates as a function of distance from the Schmidt plate center. The individual panels are binned for the indicated magnitude ranges.

errors in the AC and the GSC positions cancel out. Since we "stack" the residuals onto the GSC plate frame and the GSC and the AC plate centers are uncorrelated the systematic errors in the AC positions cancel out. Also, by assuming the peculiar motions of the stars to be random, after the binning and averaging process the effects caused by these motions cancel out. Because each bin contains thousands of matches, the effects of high proper motion stars and the effects of streaming from a cluster or other such regions, which would produce local large residuals, are damped out and do not produce any net effect. In tests for such cases we analyzed the residual vector in each bin and its associated variance within the bin and saw no obvious effects.

If we can remove the effects of the Galactic and solar motion during the 80 yr, we will have a *dr* value that is dependent only on the systematic errors in the GSC. The Galactic induced proper motion is, on the average, the same across a plate. Although a plate covering 6°.4 × 6°.4 is large in astrometric work, it is a very small section of the sky. By choosing rather narrow magnitude bins we can assume that we are sampling the same stellar population and with each bin containing tens of thousands of matches, the solar motion we are sampling in each range is nearly constant. Even though the plates are for different locations on the sky, "stacking" the plates on the GSC plate system results in a summed final Galactic and solar motion which is still constant because the sum of constant vectors is itself a constant vector.

The benefit of binning the data into thin rings is that with this geometrical configuration the motions induced by Galactic and solar motions cancel out, leaving the difference value, *dr*, as a function of the magnitude-dependent systematic errors in the GSC positions. In order to demonstrate this in Figure 6 we have shown two stars within the same narrow ring separated by 180°. For this purpose we will assume that the difference between the GSC and AC position is caused only by the Galactic and solar motion during the 80 yr time interval. The two GSC positions are located at the same distance from the plate center, but in opposite directions. Their corresponding AC positions are offset by a constant vector representing the constant vector from the Galactic and solar motions. This constant offset results in the $r_{\mathrm{ac\ projection}}$ for star B being longer than its corresponding r_{gsc} by the same amount that $r_{\mathrm{ac\ projection}}$ for star A is shorter than its corresponding r_{gsc}. In other words, $dr_{\mathrm{A}} = -dr_{\mathrm{B}}$. With each ring containing thousands of matches, after the averaging process this constant value within each annulus cancels out, leaving only the difference caused by systematic errors in the GSC positions.

Figure 7 is a plot of the *dr* versus radial distance from the plate center binned in GSC magnitude, for the long exposure IIIa-J southern plates, clearly showing a magnitude dependence. If the GSC positions were affected by position-only dependent systematics then all the plots would be identical. For all the plots, except the first magnitude region, the bins near the center of the plate have a *dr* values roughly equal to 0. This demonstrates that constant Galactic and solar motion cancels out. The filtering process in step 1 has placed the GSC onto the PPM reference system. We believe the nonzero *dr* values for the first magnitude result from a magnitude-dependent proper-motion offset between the PPM and AC systems. In any case the amplitude of the offset is less than 0″.05, well below the effects we are trying to remove.

The onset of this effect begins at about 2°.7 from the plate center, rapidly increasing with increasing distance from the plate center to produce an average offset of the faint stars from the reference stars (8 to 9.5 mag) of 0″.9 at the plate edges. It should be noted that the effects of vignetting also begins at 2°.7 from the plate center. The jump in the *dr* value between ≈2°.5 to 3°.5 from the plate center results from the complicated structure of the positional residuals, as shown in Figure 2, and persists for all the magnitude bins; however, its amplitude is diminished by the magnitude effect.

Our first magnitude bin begins at 8.5 mag because stars brighter than this magnitude are well beyond the saturation limit and produce large images on the Schmidt plates that

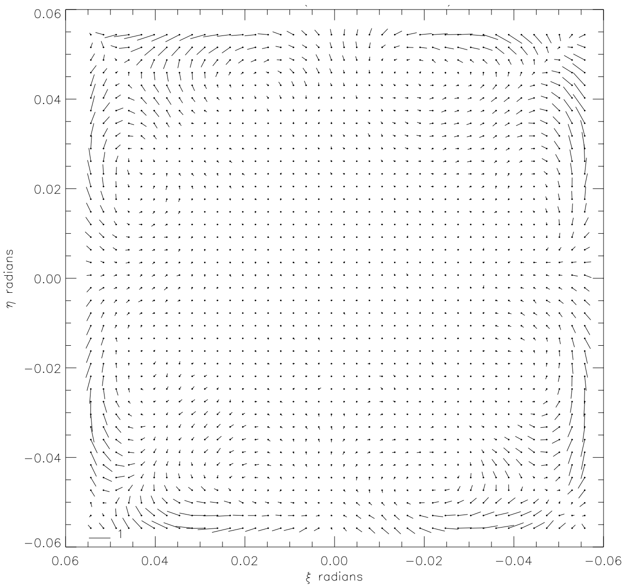

FIG. 7.—Binned and averaged astrometric residuals between positions in the AC and the GSC 1.1 after the *filtering method* and the magnitude correction have been applied to the northern Quick-V plates. The constant arising from the Galactic and solar motion during the 80 yr interval has been subtracted. In this diagram we have plotted every other point. The average number of stars per bin point was 666.

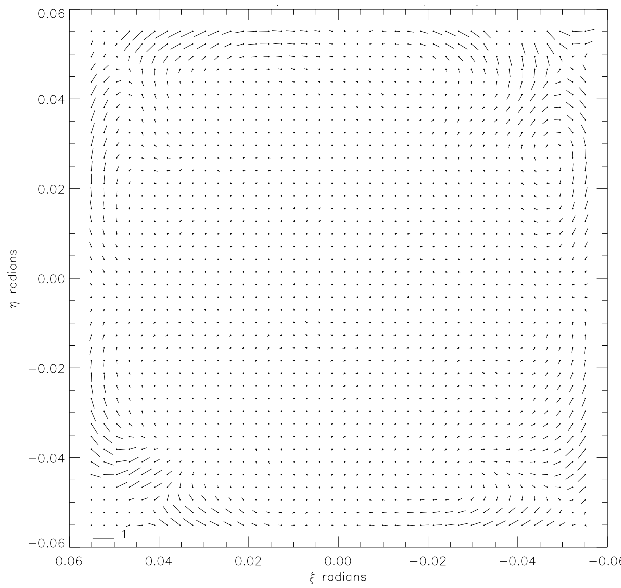

FIG. 9.—Binned and averaged astrometric residuals between positions in the AC and the 4 minute southern IIaD plates after the *filtering* was applied and the constant for Galactic and solar motion during the 80 yr interval has been subtracted. No magnitude correction was applied to these plates. The average number of stars per bin was 894.

are not suitable for astrometric testing. For the detection of the magnitude-dependent systematic errors we split the GSC plate archive into three groups: Quick-V plates from the Palomar telescope, long exposure IIIa-J (blue) plates from the UK Schmidt telescope, and short exposure (4 minute) IIa-D plates from the UK Schmidt telescope. Except for differences in the magnitudes systems, the northern plates show a similar magnitude dependence as the long exposure IIIa-J plates. No noticeable magnitude effect in the short exposure UK Schmidt plates was apparent, as was expected. The average magnitude in last bin ≈ 13.3 mag for the northern Quick-V plates and ≈ 13.5 mag for the long exposure IIIa-J southern plates. Therefore we are limited to probing the magnitude effect to these levels.

We can turn the method of detection of the magnitude-dependent positional errors as a means for reducing these errors. By using spline fits the radial difference between the GSC and AC positions as a function of distance from the plate center and magnitude, we were able to remove the majority of the magnitude-dependent positional errors.

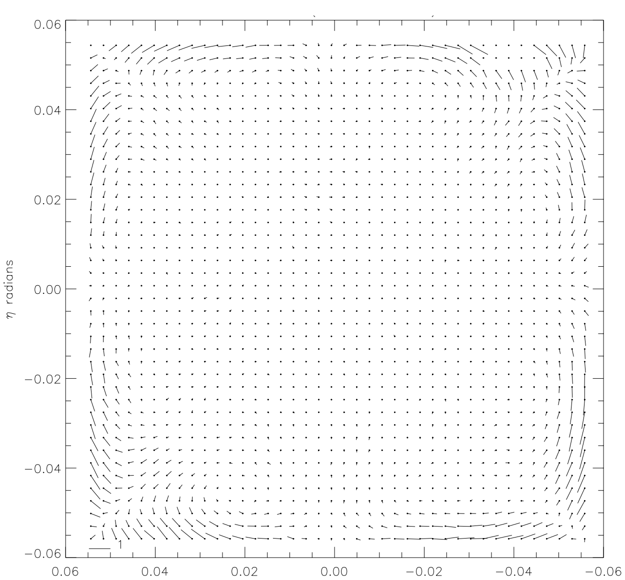

FIG. 8.—Binned and averaged astrometric residuals between positions in the AC and deep southern IIIa-J GSC 1.1 plates after the *filtering method* and magnitude correction have been applied. The constant arising from the Galactic and solar motion during the 80 yr interval has been subtracted. In this diagram we have plotted every other point.The average number of stars per bin point was 829.

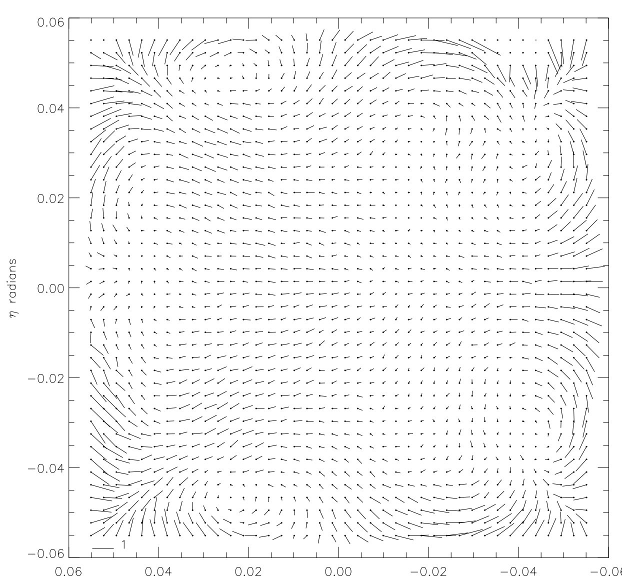

FIG. 10.—Binned and averaged astrometric residuals between positions in the PPM and the GSC 1.1 for the deep southern IIIaJ plates. The average number of stars per bin was 206.

After a series of tests, we devised a slightly different method for correcting the magnitude dependence for the faint stars for the Palomar and SERC-J plates. In the Palomar plates no extrapolation past the average magnitude in the last bin was allowed, in the SERC-J we extrapolated to 15.0 mag. It is worth noting that the method we have developed can be used to reduce the magnitude-dependent positional systematic errors common to a set of plates. This method does not handle the plate-to-plate magnitude-dependent errors (Lu et al. 1998).

3.3. *Step 3: The Mask Method*

The final correction to the GSC positions removed the plate-based position-only dependent systematics the filter method in step 1 failed to remove. This was accomplished by creating residuals maps similar to Figure 2 but with the AC. We chose Schmidt plates of similar type (exposure time, emulsion type, and telescope) and compared the GSC positions on these plates with their counterparts in the AC. These residuals were then binned according to their location on the GSC Schmidt plate reference frame, added together for a reasonably large number of plates, and then averaged. By stacking the AC plates onto the GSC reference plate frame the zonal systematics of the AC plates cancel out.

After numerous tests grouping similar GSC Schmidt plates for the construction of the residual maps, we split the plates into the same three groups we used in the analysis of the magnitude effect: the Quick-V Palomar plates, the long exposure IIIa-J UK Schmidt southern hemisphere plates, and the 4 minute IIa-D UK Schmidt southern hemisphere plates. For the Palomar Quick-V and long-exposure southern plates, we constructed a mask of 80×80 points, while for the southern short exposure plates with fewer data points we used a grid of 40×40 points. The 80×80 grid spacing allowed us to probe the residuals to a level of $4\overset{\prime}{.}8$. With the large number of matches per bin point (≈ 660 for the north, ≈ 830 for the southern IIIa-J, and ≈ 890 for the southern IIa-D plates), we can assume that each grid point contains enough matches that the peculiar motions of the stars during the 80 yr interval cancel out. The residual map we have constructed thus far represents the average systematic distortions in the GSC positions plus the constant from the 80 yr of Galactic and solar motion. As explained earlier over a $6\overset{\circ}{.}4 \times 6\overset{\circ}{.}4$ plate we can assume that the Galactic and solar induced motion is constant. The differential motion across a plate is negligible $\approx 1 - \cos(3^\circ)$. From previous studies using the PPM and CMC, we know that the residual map of distortions is nearly zero in the central region and that it follows an eightfold overlap symmetric pattern. Therefore, the average residual vector in the central portion of the mask constructed with the AC is simply the constant caused by the Galactic and solar motion over the 80 yr interval. Subtracting this value from all the grid points, leaves the mean astrometric residuals common to a set a plates which represent the scale and direction of remaining residuals (see Figs. 8, 9, 10). Comparing this mask with those created using the PPM and CMC with proper motion applied shows a similar eightfold symmetric pattern of systematics. Therefore we are confident that we have not introduced any systematics in our subtraction technique. Using these residuals masks we corrected the GSC positions by applying the correct residual vector based on the objects location on the plate.

4. FINAL RESULTS

As mentioned earlier our starting point for this reduction was the right ascensions and declinations from the GSC 1.0 catalog, not the measured x and y pixel values. Therefore we benefited greatly from the enormous effort that went into the original astrometric quality control done on each plate in the creation of GSC 1.0 (Russell et al. 1990). The magnitude correction and mask method apply corrections based on improving the majority of the plates. We were concerned that by applying this average correction to all the plates we might introduce errors for a small percentage of objects on the plates or for a large percentage of objects on a few plates. In addition, the nature of the filter method could introduce small-scale systematics if objects incorrectly matched as reference stars were used in the filter to determine the correction. For each step of the reduction we calculated the average correction applied to the objects on the plate and the standard deviation of this correction. Corrections larger than 2 σ from mean were analyzed for any unexplained irregularities. Occasionally a mismatched reference star produced a high correction. Such objects were rejected, and the reduction was repeated. The final results of this analysis revealed no irregularities in the corrections. In addition, the positions from the GSC 1.1 were compared with the positions determined from this new reduction, and no irregular residual patterns or unusually high residuals were found.

One method to judge the astrometric quality of the GSC is to plot the residuals in the overlapping area of a GSC plate pair (i.e., the residuals obtained from the same GSC star located on more than one plate). For approximately 30% of the plates (made up of plates from all three groups we split the Schmidt plates into) we compared the residuals from overlapping plates. Figure 1*a* demonstrates the typical residuals found for overlapping plate pairs in the GSC 1.1. The standard deviations of the right ascension on a great circle and declination for the 999 matched objects is $0\overset{\prime\prime}{.}99$ and $0\overset{\prime\prime}{.}62$, respectively. As seen in Figure 1*b* this new reduction of the GSC has removed a majority of the systematic errors. The standard deviations of the right ascension on a great circle and declination for the new reduction is $0\overset{\prime\prime}{.}36$ and $0\overset{\prime\prime}{.}31$, respectively (a 59% improvement).

We performed a number of tests to determine if the global pattern of systematics had been reduced by this new reduction. To check whether the position and magnitude-dependent systematics have been minimized (or eliminated) we compared our newly reduced positions with those from the CMC and PPM catalog. Though the PPM catalog was used as a reference catalog in the recalibration its role was mainly to place the GSC 1.1 on the system defined by the PPM catalog and to remove some of the zonal systematics introduced by the original reference catalogs. Its usage in the filtering process did remove some of the position-dependent systematics, however, as seen by Figure 4, plate-based systematics up to $0\overset{\prime\prime}{.}8$ at the plate-edges still remain. Therefore, comparisons between the GSC 1.2 and the PPM are useful to demonstrate that our utilization of the AC did not introduce any new systematic errors and to estimate the astrometric quality of the new reduction, especially since the CMC does not cover the entire southern sky. The results of comparing the CMC and PPM catalogs with the GSC 1.1 and 1.2 are shown in Tables 3 and 4, respectively. The tremendous improvement in the southern hemisphere

TABLE 3

RMS Results of Comparing PPM and CMC Positions with the GSC 1.1

Schmidt Survey	PPM ($V \geq 8$) R.A. cos (decl.) (arcsec)	PPM ($V \geq 8$) Decl. (arcsec)	CMC ($V \geq 8$) R.A. cos (decl.) (arcsec)	CMC ($V \geq 8$) Decl. (arcsec)
Palomar	0.46	0.44	0.48	0.48
SERC J	0.72	0.56	0.73	0.65
SERV V	0.68	0.52	0.58	0.56
All Schmidt plates......	0.65	0.54	0.57	0.54

is largely due to the use of the PPM supplement in the filtering processing. The PPM supplement contains 90,000 stars in the southern hemisphere, providing a denser set of stars with positions more precise and accurate than those originally used in the GSC 1.0. The PPM comparison shows a 47% improvement in the accuracy of the positions, while the CMC comparison shows a 27% improvement.

The results of comparing the CMC with the GSC 1.1 and 1.2 (shown in Fig. 3) demonstrate the overall reduction in the positional error and the elimination of the asymmetric north-south errors. However, there still exists a slight increase in the errors with increasing distance from the plate center beginning near a radius of 2°.7. The majority of these errors are probably due to the failure to remove all the magnitude-dependent systematic errors. The removal of the magnitude-dependent errors, of course, relies on the accuracy of the GSC 1.1 magnitudes. The GSC 1.1 magnitudes were determined using BV standards in the ninth to fifteenth magnitude range from the Guide Star Photometric Catalog (Lasker et al. 1998). The overall photometric quality varies from 0.15 mag, for stars near the standard stars to, 0.3 mag for stars far from the sequences. Also, in plate-to-plate tests about 10% of the objects have a error greater than 0.5 mag and about 1% greater than 0.9 mag. For more details concerning the photometric calibration, see Russell et al. (1990). In order to estimate how the magnitude correction is limited by inaccurate GSC 1.1 magnitudes, we reproduced the magnitude correction (Fig. 7), blurring the bright and faint magnitude limits for each magnitude range by 0.3 mag (see Fig. 11). In this figure the solid curve represents the correction for the original magnitude limits, the dotted line corresponds to the magnitude limit -0.3 mag, while the dashed line corresponds to the magnitude limit $+0.3$ mag. One thing to keep in mind is that the curves are applied using weighted spline fits. For most of the magnitudes and radial distances, the correction's dependence on an error in the GSC magnitude is negligible (much smaller than the systematics we are trying to remove). For bright stars at large distances from the plate center (greater than 3°) the astrometric correction based on magnitude does have a dependence on the error in the GSC magnitude. However this dependence is dampened by the weighted spline fitting and is estimated to be no larger than 0″.1.

By constructing a residual map from the CMC(PPM)/GSC residuals before and after the corrections are applied we can obtain a visual picture if our new reduction has eliminated the plate-based systematics. Comparing Figure 2 (precorrection) with Figure 12 (postcorrection) clearly shows we have reduced the plate-based positional systematics. The results of comparing the PPM catalog to the GSC in the southern hemisphere are shown in Figures 13 and 14. Note that a portion of the southern plates have a sensitometer wedge in the upper right hand corner of the

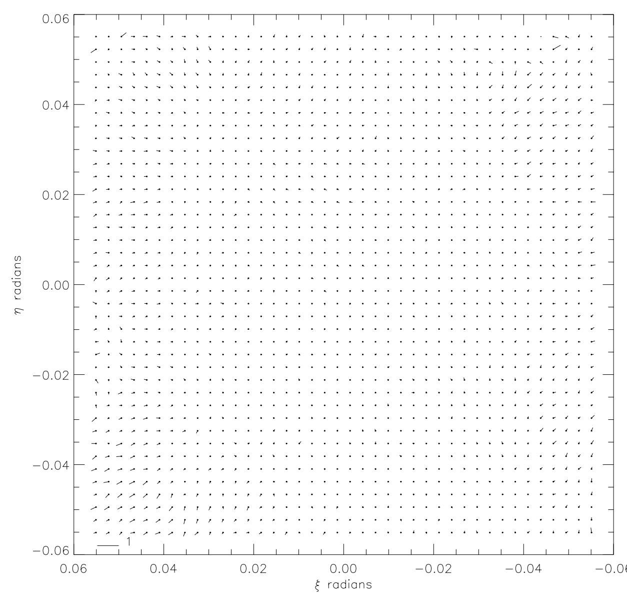

Fig. 11.—Binned and averaged astrometric residuals between positions in the PPM and the GSC 1.2 for the deep southern IIIaJ plates. The average number of stars per bin was 206.

TABLE 4

RMS Results of Comparing PPM and CMC Positions with the GSC 1.2

Schmidt Survey	PPM ($V \geq 8$) R.A. cos (decl.) (arcsec)	PPM ($V \geq 8$) Decl. (arcsec)	CMC ($V \geq 8$) R.A. cos (decl.) (arcsec)	CMC ($V \geq 8$) Decl. (arcsec)
Palomar	0.35	0.34	0.39	0.38
SERC J	0.31	0.31	0.45	0.44
SERV V	0.20	0.20	0.25	0.27
All Schmidt Plates......	0.32	0.31	0.41	0.40

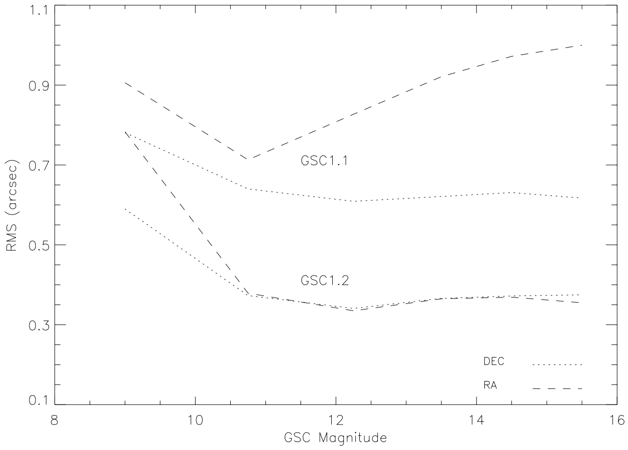

FIG. 12.—rms differences in the GSC positions measured on 55 overlapping plates in the $-30°$ zone for the GSC 1.1 and 1.2

plates, while others have a wedge in the lower left hand corner of the plate. These wedges have somewhat distorted the residuals in these regions. The failure to completely remove the magnitude effect is apparent in radial increase of the residuals.

As mentioned above, detecting magnitude-dependent systematics on data that cover as broad a magnitude range

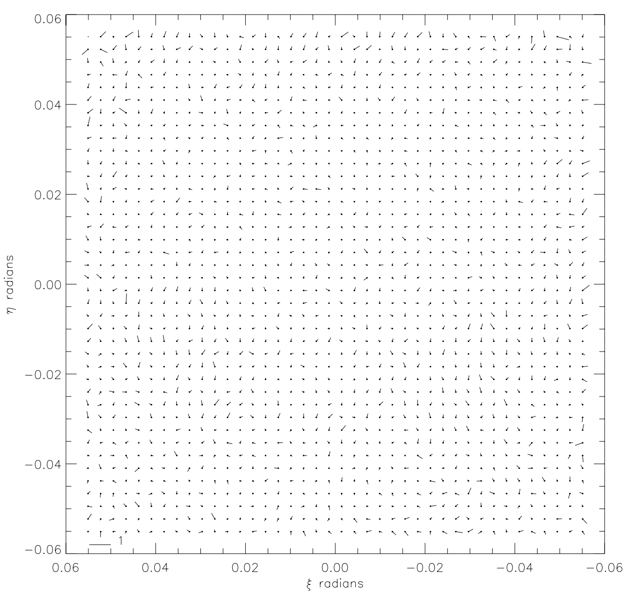

FIG. 13.—Binned and averaged astrometric residuals between positions in the CMC and the GSC 1.2 for the northern Quick-V plates. The average number of stars per bin was 32.

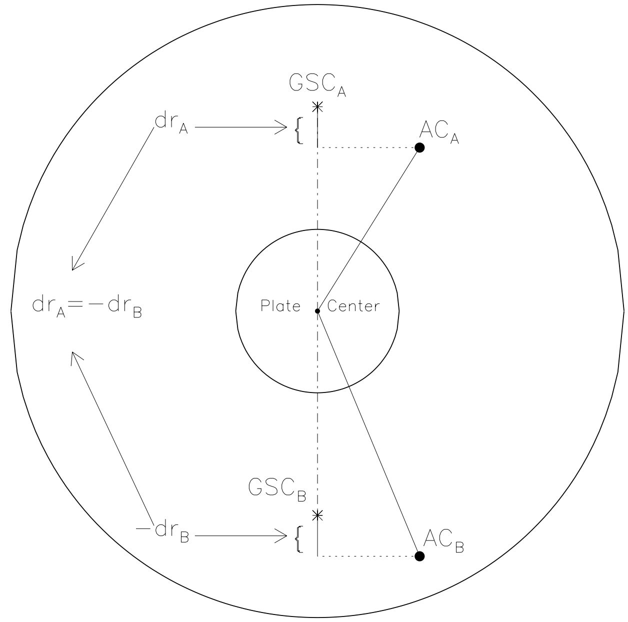

FIG. 14.—Example of the cancelation of the effects of Galactic and solar motion in the determination of the radial difference value, *dr*. Two stars, A and B, are located within the same narrow ring of radius 2'.7. For this example the difference between the GSC position and its corresponding AC position is only due to the effects of Galactic and solar motions over the 80 yr.

as the measured GSC images (8–5 mag) is difficult due to the lack of astrometric reference catalogs covering the same range. However, we can use the overlap region on Schmidt plates to search for positional systematics that depend on magnitude. For a large number of overlapping plates having the same geometric overlap configuration, the difference in positions for the same star imaged on two plates was binned in magnitude and location on each plate and then averaged. Table 5 contains the results from comparing the positions from 55 overlapping long exposure southern IIIaJ plates in the $-30°$ zone of the GSC. Because the magnitude effect is radial, vector subtraction of the residuals on plates that overlap in right ascension results in residuals only in the right ascension direction (the declination component of the residual cancels out) and vice verse for plates that overlap in declination (see Fig. 3 in Morrison et al. 1996). The right ascension residuals for the filtered GSC 1.1 steadily increase with increasing magnitude to a maximum of 1''.0 for stars fainter than 15 mag. Whereas the GSC 1.2 right ascension residuals are nearly constant (0''.35) with increasing magnitude, demonstrating the reduction of the magnitude-dependent systematics. In Figure 15 we have

TABLE 5

STANDARD DEVIATIONS OF THE COORDINATES IN ARCSECONDS FOR OVERLAPPING PLATES IN THE $-30°$ ZONE

	MAGNITUDE				
VERSION	10–11.5	11.5–13.0	13.0–14.0	14.0–15.0	15.0–18.0
Filtered GSC 1.1 R.A. cos (decl.)	0.67	0.81	0.91	0.97	1.00
Filtered GSC 1.1 decl.	0.59	0.56	0.56	0.56	0.56
GSC 1.2 R.A. cos (decl.)	0.35	0.31	0.35	0.36	0.34
GSC 1.2 decl.	0.35	0.33	0.36	0.36	0.36

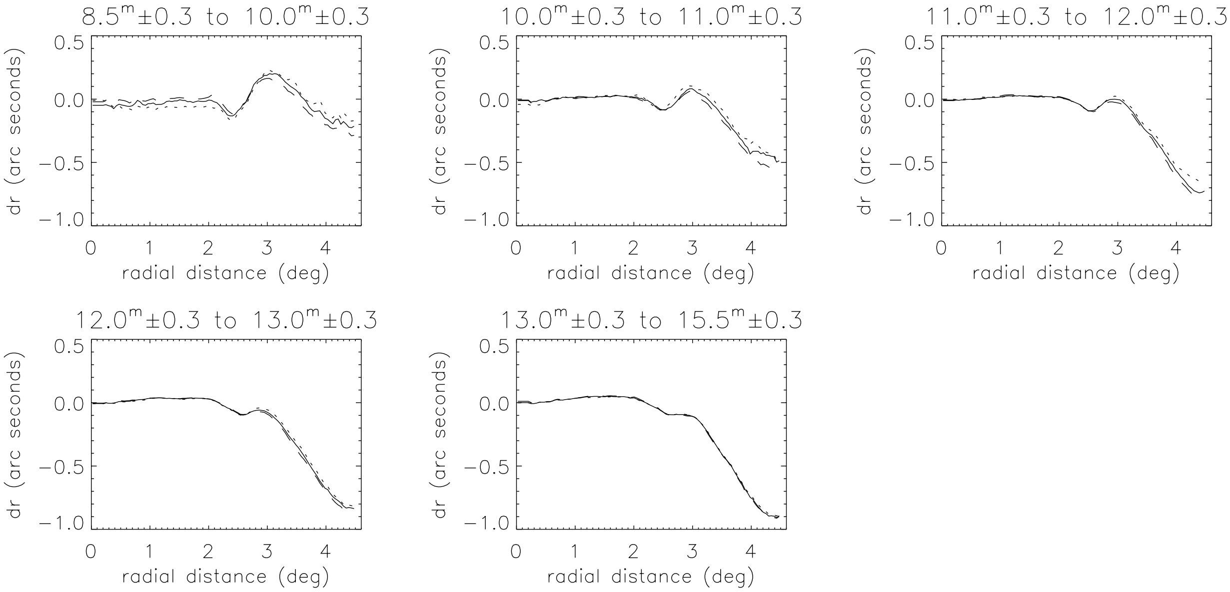

FIG. 15.—The radial magnitude effect for the deep southern hemisphere IIIaJ plates as a function of distance from the Schmidt plate center. The magnitude limits on the individual plots are blurred by ±0.3 mag (roughly the error in the GSC 1.1 magnitudes). The solid line is for the magnitude range indicated (the same as Fig. 7), the dotted line corresponds to the limits -0.3 mag, while the dashed line corresponds to the limits minus $+0.3$ mag.

plotted the rms error in positions found on overlapping plates as a function of magnitude. The radial magnitude dependence in the positions is clearly seen in the GSC 1.1 material as an increase in the right ascension rms error with increasing magnitude. For the GSC 1.2 the near constant right ascension RMS error with increasing magnitude demonstrates the reduction the magnitude dependence in the positions.

The results in Table 4 are valid for the brighter end of the GSC ($12 \geq V \geq 8$) and are biased towards the brighter magnitudes in this interval. Note that we did not remove random CMC errors from our comparisons of positional data because the CMC stars typically have positional precisions of 0″.15 in the northern hemisphere and 0″.16 in the northern part of the southern hemisphere at the epoch of the GSC plates. Because these bright stars are over-exposed on the GSC plates, this comparison is unfavorable for estimating the accuracy of the bulk of the GSC stars, which are typically fainter than $V = 12$. For this important fainter part we can judge the astrometric quality from the standard deviation of stars located on more than one the GSC plate (see Fig. 1*b* and Table 5). This standard deviation is typically 0″.35, and it involves the individual RMS errors of two GSC positions. Considering this and the fact that the comparison with other reference stars contains the mean errors in the reference catalog ($\approx$10 yr) we can infer that the overall rms error of the GSC 1.2 is better than 2″.5 per coordinate.

5. CONCLUSIONS

The strikingly clear swirl pattern of systematic errors remaining in the GSC 1.1 (Figs. 1*a*, 2, 13) have been dramatically reduced in the GSC 1.2 (see Figs. 1*b*, 12, 14). In addition, as shown by Table 5 and Figure 15, the residuals for the overlapping plate pairs show a reduction in the magnitude-dependent systematic errors. The bulk of the plate-based systematic errors were reduced by a combination of the filter and mask methods. The filter method eliminated some of the small-scale systematics on the individual plates and placed the GSC 1.1 onto the reference system defined by the PPM catalog (the FK5). The mask method eliminated the mean global positional errors common to a large collection of plates. Also using a rather unconventional approach, we have developed a method where a nonuniform, inhomogeneous, imprecise, single early-epoch reference catalog (the AC) can be a *useful* tool for removing the mean of magnitude-dependent systematics. This improved catalog can be obtained directly from CDS.[3]

The wide-field-of-view, combined with its high speed, makes the Schmidt telescope a desirable tool for astrometric investigations. However, astrometry from these telescopes is affected by complicated structures that are not well represented by global plate-modeling polynomials using the low numbers of reference stars per plate presently available. Within the last decade many methods have been developed which remove position-dependent systematic errors. In this paper we have used two such methods and shown their effectiveness in removing plate-based position-dependent systematics. In addition, we have also provided a method to test for and reduce (or remove) magnitude-dependent systematic errors found in positions determined from Schmidt plates.

6. CAVEATS

Though this new version dramatically reduces the systematic errors found in the GSC 1.1, it too has a few shortcomings. First and foremost, it is based on the system defined by the PPM and not on the system defined by *Hipparcos*. This version is only an astrometric recalibration, no photometric recalibration was performed. Though the majority of the astrometric systematic errors have been

[3] Also available via the instructions given at http://www-gsss.stsci.edu/gsc/gsc.html.

reduced, in a few cases there are still residuals on the order of 0″.5 near the plate edges. As mentioned above, the plates comprising the GSC 1.0 are a subset of the data used to compile the GSC 2, which will be on the ICRF system. We have released the GSC 1.2 to the astronomical community at large to be used until the GSC 2 or other similar catalogs are released. It must be remembered that astrometric header information in the STScI Digitized Sky Surveys is consistent with the GSC 1.1, not 1.2. Finally, since GSC 1.2 has not been installed in the *HST* Guide Star Selection system, *it must not be used for* HST *observation planning.*

7. FUTURE WORK

The Schmidt plates comprising the GSC 1.2 are being reprocessed and recalibrated for the construction of the GSC 2. Deficiencies in the GSC 1.2 related to image processing, systematic photometric errors and placement of the catalog onto the ICRF system will be addressed in the GSC 2. The low Galactic latitude southern long-exposure IIIaJ plates are being rescanned with 15 μm sampling. The GSC 2 construction pipeline has improved algorithms for determining the background sky, detecting objects, classifying, and deblending objects. The classification algorithm is plate-independent and uses decision trees based on ranked image features to classify the objects. The astrometric calibration uses global masks to correct for systematic distortions in each optical configuration and the application of filtering techniques to correct for local distortions. The GSC 2 will be on the ICRF system and the reference catalog will be the Tycho II catalog. The reference catalogs for the photometric calibration are the Tycho catalog (to tie down the bright end) and the Second Generation Guide Star Photometric Catalog (GSPC II, Casalegno et al. 1998). The GSPC II is based on CCD observations to provide a set of standard stars to at least 18 mag over the entire sky for each Schmidt plate. In addition, the improved photometric calibration techniques include the derivation of the density-to-intensity transformation for each individual plate. This enormous quantity of data will be contained in a commercial object-oriented database, which is well suited to perform global recalibrations and multiplate operations (i.e., determination of colors and proper motions) and can easily produce a catalog for export to the astronomical community.

This paper is based on data obtained at the Palomar Observatory, operated by the California Institute of Technology, and the UK Schmidt telescope, operated by the UK Science and Engineering Research Council until 1988 June and by the Anglo-Australian Observatory thereafter.

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