An Investigation of the Absolute Proper Motions of the SCUSS Catalog

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ABSTRACT. Absolute proper motions for ~7.7 million objects were derived based on data from the South Galactic Cap u-band Sky Survey (SCUSS) and astrometric data derived from uncompressed Digitized Sky Surveys that the Space Telescope Science Institute (STScI) created from the Palomar and UK Schmidt survey plates. We put a great deal of effort into correcting the position-, magnitude-, and color-dependent systematic errors in the derived absolute proper motions. The spectroscopically confirmed quasars were used to test the internal systematic and random error of the proper motions. The systematic errors of the overall proper motions in the SCUSS catalog are estimated as −0.08 and −0.06 mas/yr for $\mu_\alpha \cos \delta$ and $\mu_\delta$, respectively. The random errors of the proper motions in the SCUSS catalog are estimated independently as 4.2 and 4.4 mas/yr for $\mu_\alpha \cos \delta$ and $\mu_\delta$. There are no obvious position-, magnitude-, and color-dependent systematic errors in the SCUSS proper motions. The random error of the proper motions goes up with the magnitude from about 3 mas/yr at $u = 18.0$ mag to about 7 mas/yr at $u = 22.0$ mag. The proper motions of stars in SCUSS catalog are compared with those in the SDSS catalog, and they are highly consistent.

Online material: color figures

1. INTRODUCTION

A catalog of proper motions in the International Celestial Reference System (ICRS), with precise positions and proper motions as well as deep limiting magnitude, is important for research on the Galactic structure, Galactic kinematics, and stellar populations.

There are two methods to determine the absolute proper motions of stars based on the hypothesis that the proper motions of background galaxies are zero. One is that all the observations obtained in different epochs are transformed into one reference position system using galaxies, and absolute proper motions are calculated directly. For example, Munn et al. (2004) took this method to construct the improved SDSS proper motion catalog combining USNO-B (Monet et al. 2003) and SDSS (Gunn et al. 1998; York et al. 2000; Lupton et al. 2001; Stoughton et al. 2002). The basic procedure in this work is as follows. For each object from USNO-B, the nearest 100 galaxies (classified as galaxy by SDSS morphological classification) detected in both SDSS and USNO-B were selected.10 Then the mean offsets in right ascension and declination between the SDSS and USNO-B positions were measured from the 100 nearest galaxies, and were added to the USNO-B position of this object. Finally, the proper motions of objects in SDSS were computed using a linear fit with the recalibrated USNO-B positions and the SDSS positions at different epochs.

The other method to determine absolute proper motions is to take a novel calibration method which iteratively uses the stellar sources and galaxies on each position system to eliminate all systematic errors between different position systems. Absolute Proper Motions Outside the Plane (APOP) adopted this technique with the Guide Star Catalog II (GSC-II) Schmidt plate data (Qi et al. 2012; Lasker et al. 2008). Meanwhile, the APOP

10 Please see http://www.sdss.org/dr1/products/catalogs/flags.html.
used the measured coordinates \((x, y)\) of objects instead of equatorial coordinates to calculate the absolute proper motions. The principal calibration steps for APOP are as follows.

1. Removing the position-dependent systematic errors (PdE) with a moving-mean filter using good-quality stellar objects;
2. Selecting galaxies from nonpoint-like sources (nonstars) via their common null-motion characteristics;
3. Calibrating magnitude- and color-dependent (MdE and CdE) errors and the residual PdE of all objects with respect to the galaxies selected above;
4. Calculating absolute proper motions from all-epoch plate data with a linear fit.

The construction of the latest version of APOP catalog and evaluation of the catalog are described in detail by Qi et al. (2014). In this article, we take almost the same method and pipeline as APOP to derive absolute proper motions.

The SCUSS (H. Zou et al. 2014, in preparation; X. Zhou et al. 2014, in preparation; Jia et al. 2014) is a \(u\)-band (3538 Å) imaging survey using the 2.3 m Bok telescope. The survey covers about 5000 square degrees. Most of the SCUSS fields were observed twice in the course of survey from 2010 to 2013. It is difficult to measure accurate proper motions for the SCUSS objects from the SCUSS data only. In this article, we construct a SCUSS proper motion catalog by combining the SCUSS data with the GSC-II Schmidt plate data. The GSC-II Schmidt plate data is an all-sky astrophotometric database which was derived from the digitization of the Palomar and UK Schmidt surveys. The GSC-II contains astrometry, photometry, and classification for objects down to the limiting magnitude of the plates.

This paper is organized as follows. In § 2, we summarize the SCUSS program and GSC-II project that are used to derive the SCUSS proper motion catalog. § 3 describes the construction of the SCUSS proper motion catalog. In § 4, quasars are used to perform internal test of the proper motions. We compare the catalog with the SDSS proper motion catalog in § 5. We summarize the paper in § 6.

2. DATA

2.1. The SCUSS Program

The SCUSS is a \(u\)-band imaging survey with an effective wavelength of \(\sim 3538 \text{ Å}\) and a bandwidth \(\sim 345 \text{ Å}\). This \(u\)-band filter is slightly bluer than the SDSS \(u\)-band filter. The imaging depth is \(\sim 23.5 \text{ mag}\), roughly 1.5 mag deeper than that of the SDSS imaging survey. The SCUSS project began its observations in 2010 September and ended in 2013 October. It covers a total 5000 square degrees. Proper motions are measured with respect to a reference frame of galaxies. Hence, the accuracy of star/galaxy classification affects systematic error of the proper motions. The SCUSS proper motion catalog covers 3700 square degrees (Galactic latitude \(b < -30^\circ\) and Equatorial latitude \(\delta > -10^\circ\)). In this area, the accuracy of star/galaxy classification is reliable. The spatial distribution of the SCUSS proper motion catalog is shown in Figure 1. Most of the images in this area were taken with seeing \(< 3''\) and sky background \(< 500 \text{ ADU}\).

The description of reduction of the SCUSS data can be found in H. Zou et al. (2014, in preparation). Photometry was done using SExtractor (Bertin & Arnouts 1996). The measured \(x\)
and $y$ positions were calculated by applying SExtractor to sources brighter than 1σ of the background level. External astrometric errors were determined by cross-matching the SCUSS sources to the UCAC4 sources (Zacharias et al. 2013). Over the whole survey, the mean offsets of right ascension and declination between the SCUSS and UCAC4 are $\Delta \alpha = -0\rlap{.}007 \pm 0\rlap{.}008$, $\Delta \delta = -0\rlap{.}007 \pm 0\rlap{.}007$, respectively. In this work, we will construct a proper motion catalog using the measured coordinates ($x$, $y$), the celestial coordinates ($\alpha$, $\delta$), the $u$-band magnitudes from SCUSS, and the star/galaxy morphological classifications from SDSS for objects on SCUSS images. The basic information for each frame including plate size and scale as well as observation time is also needed in the process of calculation of proper motions.

### 2.2. Astronomic Data from GSC-II

GSC-II (Lasker et al. 2008), as first epoch data to obtain the proper motions of SCUSS, was originally taken from the survey plates observed by the Palomar Schmidt telescope and the UK Schmidt telescope. Each individual plate was digitized by the Guide Star Automatic Measuring Machine (GAMMA) and was processed through image processing and plate calibration. The final products were stored in the COMPASS database (Lasker et al. 2008). GSC-II contains astrometry, multiband photometry ($R_F$, $B_J$, $I_N$), and star/nonstar classification for objects down to the limiting magnitude of the survey plates. For stellar sources, the all-sky average absolute position error per coordinate ranges from 0.2° to 0.28° depending on magnitude. Stellar photometry is determined to 0.13–0.22 mag as a function of magnitude and photographic passbands ($B_J$, $I_N$).

Outside of the Galactic plane, the catalog is complete to magnitudes from SCUSS, and the star/galaxy morphological classifications from SDSS eventually affect the error of the proper motions. In our work, most of the SCUSS survey are covered by the SDSS, were chosen as reference plates. The star/galaxy classifications of sources play an important role in the calculation of the proper motions. However, in GSC-II, the probability of stars correctly classified drops with magnitude from better than 90% at $R_F = 18.0$ mag to less than 50% at $R_F = 20.0$ mag, while the percentage that a galaxy is classified as nonstar remains above 90% for all the magnitude range.

3. CONSTRUCTION OF THE SCUSS PROPER MOTION CATALOG

Two major aspects determine the final accuracy of absolute proper motions. One is the measured uncertainties of object positions on the images of all epochs, and the other is the systematic error between different images. The latter requires unifying images in different epochs and different bands to one reference system (Qi et al. 2012).

The general steps of the construction of the SCUSS proper motion catalog are similar to those of APOP. Relevant equations and details are recommend to see the paper of Qi et al. (2014). A few steps are slightly different. The steps are summarized as follows.

1. Extract all the GSC-II plates and SCUSS images in the same sky field.
2. Compare GSC-II reference plates with the SDSS, update the star/nonstar classification in GSC with star/galaxy in the SDSS.
3. Reject the synthetic double stars (stars with the same ID) in each GSC-II plate.
4. Find common objects between the program images and the reference plate.
5. Smooth out position-dependent difference between each image pair using stars with small measuring error.
6. Regenerate the $x$, $y$ of all the objects on program plates using galaxies and remove the MdE, CDE, and residual PdE of proper motions.
7. Calculate the absolute proper motions and new positions in a given epoch using all the images.

The plates, which are from GSC-II with good quality and overlap with the SCUSS, were chosen as reference plates. The star/galaxy classifications of sources play an important role in the calculation of the proper motions. However, in GSC-II, the probability of stars correctly classified drops with magnitude from better than 90% at $R_F = 18.0$ mag to less than 50% at $R_F = 20.0$ mag, while the percentage that a galaxy is classified as nonstar remains above 90% for all the magnitude range. Outside of the Galactic plane, stellar classification is reliable to at least 90% confidence for magnitudes brighter than $R_F = 19.5$ mag (Lasker et al. 2008). The low accuracy of star/nonstar classification of the fainter objects of the GSC-II reference plates eventually affect the error of the proper motions.

### Plate Information from GSC-II

| Survey     | Epoch     | Band   | Depth | Plates used | Sky coverage |
|------------|-----------|--------|-------|-------------|--------------|
| Pal-QV     | 1983–1985 | $V_{12}$ | 19.5  | 103         | $\delta \geq 0^\circ$ |
| SERC-EJ    | 1979–1988 | $B_J$   | 23.0  | 72          | $-15 < \delta \leq 0$ |
| POSS I E   | 1950–1958 | $E$     | 20.0  | 144         | $\delta \geq -30$ |
| POSS II O  | 1950–1958 | $O$     | 21.0  | 143         | $\delta \geq -30$ |
| POSS II I  | 1987–2000 | $B_J$   | 22.5  | 141         | $\delta \geq 0$ |
| POSS II F  | 1987–1999 | $R_F$   | 20.8  | 141         | $\delta \geq 0$ |
| POSS II N  | 1989–2002 | $I_N$   | 19.5  | 139         | $\delta \geq 0$ |
| SERC ER    | 1990–1998 | $R_F$   | 22.0  | 93          | $-15 < \delta \leq 0$ |
| SERC I     | 1990–2002 | $I_N$   | 19.5  | 93          | $\delta \leq 0$ |
4. PROPERTIES OF SCUSS PROPER MOTION CATALOG

The SCUSS proper motion catalog contains the equatorial coordinates ($\alpha$, $\delta$), the absolute proper motions ($\mu_\alpha \cos \delta$, $\mu_\delta$), and the SCUSS $u$-band magnitudes for about 7.7 million objects. The proper motions of quasars cannot be detected by present astrometric observation in the optical band, so the intrinsic proper motions of quasars can be considered as zero (Wu et al. 2011). Therefore, the measured proper motions of quasars can be used to derive the systematic and random error of the proper motion.

We choose the spectroscopically confirmed quasars from SDSS DR9 (Ahn et al. 2012). A total of 22,831 common quasars among the SDSS and SCUSS catalog are selected as a quasar sample. The Gaussian function is used to fit the distribution of the quasar proper motions to derive the systematic and random error. The systematic error of proper motions is derived from the mean proper motion of the quasar sample. The dispersion of the proper motions of quasars can be considered as the random error of proper motions. Figure 2 displays the histograms of the measured proper motions in right ascension $\mu_\alpha \cos \delta$ (upper) and in declination $\mu_\delta$ (lower) for all SDSS spectroscopically confirmed quasars in SCUSS proper motion catalog. The random errors of the proper motions are 4.2 and 4.4 mas/yr in $\mu_\alpha \cos \delta$ and $\mu_\delta$, respectively. The systematic error of $\mu_\alpha \cos \delta$ is about $-0.08$ mas/yr and the systematic error of $\mu_\delta$ is about $-0.06$ mas/yr. Next, all the 22,831 quasars are

4.1. Influence of the Position on the Proper Motion

The scatters of $\mu_\alpha \cos \delta$ (upper) and $\mu_\delta$ (lower) of the selected quasar sample as a function of $\alpha$ and $\delta$ are shown in Figures 3 and 4, respectively. In order to derive the position-dependent error of the proper motions, quasars are divided into different position groups with a group size of $5^\circ$ (in declination) and $10^\circ$ (in right ascension). In Figures 3 and 4, red points and red error bars show the systematic and random errors of the quasar proper motions in different groups. As mentioned above, the systematic and random errors correspond to the mean and dispersion of the best-fit Gaussian function of the distribution of proper motions for quasar groups.

Figure 3 shows that, for $\mu_\alpha \cos \delta$, there is no significant dependence of the systematic or random errors in the $\alpha$ direction. The systematic errors of $\mu_\alpha \cos \delta$ for quasar groups are small and fluctuate around zero. The random errors of $\mu_\alpha \cos \delta$ are about $4$ mas/yr. In addition, there is also no significant dependence of the errors of $\mu_\delta$ in $\alpha$ direction. The systematic errors of $\mu_\delta$ fluctuate around zero. The random errors of $\mu_\delta$ are around $4$ mas/yr and do not significantly change with $\alpha$. From Figure 4, we can see that there is no significant relation between error (systematic and random error) of proper motions and $\delta$. The absolute values of systematic errors of $\mu_\alpha \cos \delta$ and $\mu_\delta$ for most quasar groups are less than $0.1$ mas/yr and fluctuate around zero. The random errors of proper motions are about
4 mas/yr. So, from Figures 3 and 4, we can see that the PdE of SCUSS proper motion catalog is well eliminated and the random errors of the proper motions do not significantly change with position.

4.2. Influence of the Magnitude and Color on the Proper Motion

Figure 5 shows the histogram of SCUSS $u$-band magnitude distribution of quasar sample. The quasar sample covers the SCUSS $u$-band magnitude from 16.0 to 24.0 mag. Quasars are divided into different magnitude groups with a group size of 1 mag. Figure 6 shows the scatters of $\mu_\alpha \cos \delta$ (upper) and $\mu_\delta$ (lower) for quasar sample as a function of the SCUSS $u$-band magnitude. In Figure 6, the red points and red error bars show the systematic and random errors for quasar groups. From Figure 6, we can see that no MdE of the proper motions is found. The systematic errors of $\mu_\alpha \cos \delta$ and $\mu_\delta$ are both small. The random error of proper motions increases from the brightest end of the magnitude group to the faintest end of the magnitude group. For $\mu_\alpha \cos \delta$, the random error goes up from 2.5 mas/yr for quasars brighter than $u = 18$ mag to 7.5 mas/yr for quasars fainter than $u = 22$ mag. For $\mu_\delta$, the random error goes up from 2.6 mas/yr for quasars brighter than $u = 18$ mag to 7.1 mas/yr for quasars fainter than $u = 22$ mag. The increasing of the random error may be caused by the large measuring errors of the fainter sources on image. $\sigma_\mu = a + b \times \exp(-m/c)$ is used to describe the random error of proper motions as a function of magnitude, where $\sigma_\mu$ is the random error of proper motions, $a$, $b$, and $c$ are the unknown parameters to be fitted, and $m$ is the SCUSS $u$-band magnitude. Table 2 lists the best-fit parameters for proper motions in right ascension and declination.

From Figure 6, we can see that no MdE of the proper motions is found. The systematic errors of $\mu_\alpha \cos \delta$ and $\mu_\delta$ are both small. The random error of proper motions increases from the brightest end of the magnitude group to the faintest end of the magnitude group. For $\mu_\alpha \cos \delta$, the random error goes up from 2.5 mas/yr for quasars brighter than $u = 18$ mag to 7.5 mas/yr for quasars fainter than $u = 22$ mag. For $\mu_\delta$, the random error goes up from 2.6 mas/yr for quasars brighter than $u = 18$ mag to 7.1 mas/yr for quasars fainter than $u = 22$ mag. The increasing of the random error may be caused by the large measuring errors of the fainter sources on image. $\sigma_\mu = a + b \times \exp(-m/c)$ is used to describe the random error of proper motions as a function of magnitude, where $\sigma_\mu$ is the random error of proper motions, $a$, $b$, and $c$ are the unknown parameters to be fitted, and $m$ is the SCUSS $u$-band magnitude. Table 2 lists the best-fit parameters for proper motions in right ascension and declination.

The scatters of $\mu_\alpha \cos \delta$ (upper) and $\mu_\delta$ (lower) for quasars as a function of SDSS $g - r$ color are shown in Figure 7. Quasars with $g - r$ color of between $-0.25$ and $1.75$ are divided into different color groups with a group size of 0.3. There is no relation between error of proper motions and color. The absolute values of systematic errors of $\mu_\alpha \cos \delta$ and $\mu_\delta$ are around...
0.1 mas/yr. The random errors of \( \mu_\alpha \cos \delta \) and \( \mu_\delta \) are both about 4.0 mas/yr. The CdE of SCUSS proper motion catalog is well eliminated. The random error of SCUSS proper motion catalog does not significantly change with color.

### 5. COMPARISON OF PROPER MOTIONS BETWEEN SCUSS AND SDSS CATALOG

Comparing the SCUSS proper motion catalog with other catalogs can estimate the external error of proper motions. The SDSS proper motion catalog (Munn et al. 2004, 2008; Ahn et al. 2012) covers most of the SCUSS fields. We compare the proper motions between SCUSS and SDSS catalog. The SDSS proper motion catalog is derived by combining SDSS and recalibrated USNO-B astrometry. For SDSS proper motion catalog, the random errors in right ascension and declination are about 4.2 mas/yr and 3.7 mas/yr, respectively (Munn et al. 2004). The median proper motion for all the quasar sample is about 0.2 mas/yr, but the systematic errors can be larger by a factor of 2–3 in small sky patches (Bond et al. 2010; Ahn et al. 2012).

#### TABLE 2

| Type of \( \sigma_{\mu} \) | a     | b    | c    |
|--------------------------|-------|------|------|
| \( \mu_\alpha \cos \delta \) | -4.78 | 1.08 | -9.47 |
| \( \mu_\delta \)         | -4.77 | 1.23 | -10.07 |

The common stars between SCUSS catalog and SDSS catalog are selected and divided into different position (\( \alpha, \delta \)) and magnitude groups. The means and the dispersions of differences of proper motions in different common star groups are derived. The mean differences of proper motions as a function of \( \alpha \) are

![Fig. 7.](image1)  
**Fig. 7.**—The scatter of proper motions \( \mu_\alpha \cos \delta \) (upper) and \( \mu_\delta \) (lower) for SDSS spectroscopically confirmed quasars in SCUSS catalog as a function of the SDSS \( g - r \) color from -0.25 to 1.75. The systematic and random errors for quasar groups are shown as red points and red error bars. See the electronic edition of the *PASP* for a color version of this figure.

![Fig. 8.](image2)  
**Fig. 8.**—The mean differences of proper motions \( \mu_\alpha \) (upper) and \( \mu_\delta \) (lower) of common stars between SDSS and SCUSS as a function of \( \alpha \). The typical dispersion of differences of proper motions is about 5 mas/yr. See the electronic edition of the *PASP* for a color version of this figure.

![Fig. 9.](image3)  
**Fig. 9.**—The mean differences of proper motions \( \mu_\alpha \) (upper) and \( \mu_\delta \) (lower) of common stars between SDSS and SCUSS as a function of \( \delta \). The typical dispersion of differences of proper motions is about 5 mas/yr. See the electronic edition of the *PASP* for a color version of this figure.
plotted in Figure 8. The upper panel shows the mean differences of \( \mu_\alpha \) of stars and the lower panel shows the mean differences of \( \mu_\delta \) of stars. Figure 8 shows that, for many regions, the mean differences of proper motions between SDSS and SCUSS are small. From the upper panel of Figure 8, we can see that, in the region 60° < \( \alpha < 70^\circ \), the absolute values of mean differences of \( \mu_\alpha \) of common stars are about 1.5 mas/yr. The lower panel shows that, in the region 0° < \( \alpha < 10^\circ \), 60° < \( \alpha < 70^\circ \), 310° < \( \alpha < 320^\circ \), and 320° < \( \alpha < 330^\circ \), the absolute values of mean differences of \( \mu_\delta \) of common stars are about 1.0 mas/yr. However, in the region \( \alpha = 320^\circ \), the absolute value of mean difference of \( \mu_\delta \) of stars reaches about 3.5 mas/yr. In most regions, the mean differences of the proper motions are smaller than the random errors of SDSS and SCUSS proper motions. The means and dispersions of differences of proper motions as a function of \( \delta \) are plotted in Figure 9. From Figure 9, we can see that the mean differences of proper motions between SDSS and SCUSS are small. The absolute values of mean differences are less than 0.5 mas/yr.

The means and dispersions of differences of proper motions as a function of SCUSS \( u \)-band magnitude are plotted in Figure 10. Figure 10 shows that, in the magnitude range \( u > 17 \) mag, the mean differences of proper motions between SDSS and SCUSS are small and the dispersion of the differences of proper motions increases with magnitude.

6. CONCLUSION

The absolute proper motions of the SCUSS program are computed by combining the SCUSS and GSC-II. The basic method of calculation of absolute proper motions follows that of APOP. The measured coordinates \((x, y)\) of objects instead of equatorial coordinates are used to calculate the absolute proper motions. The stellar sources with good imaging quality are used to eliminate the PdE between the reference and program image. The galaxies with good imaging quality are used to eliminate the MdE, CdE, and the residual PdE.

The 22,831 common quasars among SCUSS and SDSS are selected to test the properties of SCUSS proper motion catalog. The systematic errors of the proper motions are \(-0.08\) and \(-0.06\) mas/yr in \( \mu_\alpha \cos \delta \) and \( \mu_\delta \). In addition, the random errors of the proper motions are 4.2 and 4.4 mas/yr in \( \mu_\alpha \cos \delta \) and \( \mu_\delta \). We made a detailed analysis of the obtained proper motions in order to determine the position-, magnitude-, and color-dependent errors of the proper motions. Finally, we find that the PdE, MdE, and CdE of SCUSS proper motion catalog are small. The position- and color-dependent random errors remain about the same. The random errors of \( \mu_\alpha \cos \delta \) and \( \mu_\delta \) increase with magnitude. Beyond that, no significant relations between errors (systematic and random) and the position, magnitude, and color are found.

The common stars between SCUSS and SDSS catalog are selected. The means and dispersions of differences of proper motions between SCUSS and SDSS are derived. The mean differences of proper motions between SDSS and SCUSS as a function of \( \alpha \) are small except for some regions. There is no relation between the mean differences of proper motions and \( \delta \). The mean differences of proper motions are small in magnitude region \( u > 17 \) mag.

The SCUSS proper motion catalog with small systematic error and low random error can be used for many astronomical studies such as the Galaxy disk kinematics, substructure of the Galaxy, and Galaxy rotation curve.

The release of the SCUSS proper motion catalog is in preparation. The final version of the SCUSS proper motion catalog will be available when the SCUSS data becomes public. If you need a preliminary version of SCUSS proper motion catalog, you can email Xiyan Peng (xypeng@bao.ac.cn).

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