Absolute Proper motions Out side the Plane(APOP)
A step towards the GSC2.4

Qi et al. [1,2,3]

ABSTRACT

The calibration and removal of systematic errors for absolute proper motions (μ_α, μ_δ) using digitized sky survey Schmidt plate data is presented. The first version of this kind of catalog was achieved based on plate data that out side the galactic plane $|b| \geq 27^o$, resulting in a zero point error less than ± 0.3 mas/yr, and the accuracy is better than ± 4.5 mas/yr for objects bright than $R_F = 18.5$, and rises from 4.5 to 9.0 mas/yr for objects with magnitude $18.5 < R_F < 20.5$. The systematic errors of absolute proper motions related to the position, magnitude and color are practically all removed. The calibration of the positions (α, δ) is also introduced briefly. The sky cover of this catalog is 22,525 square degree, the mean density is 6444 objects/sq.deg and the magnitude limit is around $R_F = 20.5$. This work shows the possibility for improving the proper motions and positions of the GSC 2.3 catalog. This effort also give an idea for GAIA to dispel the magnitude- and color-dependent systematic errors in its proper motions reduction and link them onto an intertial system vi the extragalactic sources like galaxies and quasars, thus also on the ICRS.

Subject headings: astrometry – catalogs – absolute proper motions–classification

1. INTRODUCTION

The GSC catalog is an all-sky database of objects derived from the uncompressed Digitized Sky Surveys that the Space Telescope Science Institute has created from the Palomar and UK Schmidt survey plates and made it available to the community. The GSC was primarily created to provide guide star information and observation planning support for Hubble Space Telescope, and the latest version GSC2.3(Lasker et al. 2008), is already employed at some of the ground-based new-technology telescopes such as GEMINI, VLT, TNG and LAMOST. However there are systematic astrometric errors as well as relatively large random errors in GSC2.3 which will limit the scientific achievements(Lasker et al. 2008), e.g. the research of the local dynamical structure of the Galaxy. Various experiments(Tang et al. 2007) have indicated that the astrometric accuracy of GSC catalog can be improved further by improving the methods used and this will expand the application of the catalog not only operationally, but also in the astrophysically. For Galactic research the absolute proper motions of stars are more important than the positions. These offer the fundamental parameters for research on the structure, movement and evolution of the Galaxy. Therefore, the recalibration of the proper motions of the GSC catalog is highlighted in this paper, and the recalibration of the positions is also introduced briefly.

Considering the proper motions of galaxies can be assumed to be zero, there are two ways to determine the absolute proper motions of stars based on the background galaxies. One is direct way, i.e. all the observations obtained in different epochs are transformed into one (reference) epoch position system by galaxies, and then the absolute proper motions are calculated directly; or all the

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observations are first transformed into one (reference) epoch position system by stars, the relative proper motions are calculated, and then the absolute proper motions are obtained by adding the shift of the galaxies between the different epochs. Since the GSC classification is not sufficiently precise and the positional accuracy of the galaxies is worse than stars, the second way is adopted in this paper.

However, interstellar extinction means that as we approach the galactic plane the number of observable galaxies drops to zero. So the method introduced in this paper applies to the regions where there are enough galaxies observed, e.g. the regions of the galactic latitude $|b| \geq 27^o$, see Fig. 1 for the sky cover of this catalogue-Absolute Proper motions Out side the Plane (hereafter we named it APOP as brevity).

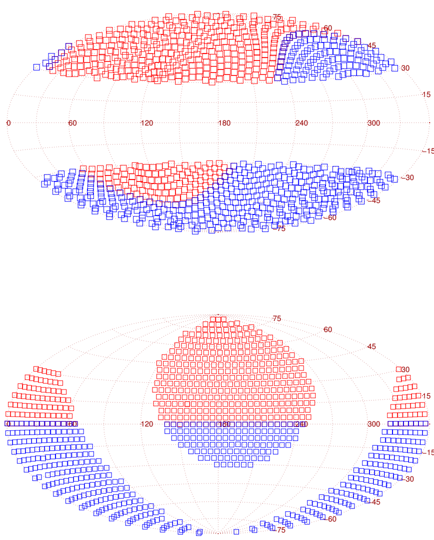

Fig. 1.— The sky distribution of Schmidt plates used in the catalogue APOP. There are 4239 plates used in the reductions. The total area covered by this catalogue is 22,525 deg^2. The top figure is presented in Galactic coordinate system with the Aitoff projection and the bottom is in Equatorial coordinate system. The blue squares are plates with equatorial coordinates $\delta < 0^o$, and the red ones are for $\delta \geq 0^o$.

In the 2nd section of this paper, the plate data used are introduced; In the 3rd section, the principle and the processing pipeline of calibrating the absolute proper motion are highlighted, as well as the detection and removal of the varied systematic positional errors that are dependent on the position, magnitude and color of the object on the plate (hereafter **P.d.E.**, **M.d.E.** and **C.d.E.** for brevity.). In the 4th section, the anticipated precision is estimated theoretically, and the internal and external precisions are presented.

2. PLATE DATA

The plate data come from COMPASS data-base established by GSC-II project(Lasker et al. 2008), which contains digitized all sky survey Schmidt plate data in different epochs and different optical bands. These data include the basic information for each plate, such as telescope name, plate size and scale, observation time, site and weather condition. They also give the astrometric and photometric results of each object including the measured coordinates, the equatorial coordinates referring to Tycho-2 and ACT catalog, magnitude and classification (star or non-star) etc. The cross identification parameter of each object between different plates is also included. The digitized resolution of most plates is 15 μm/pixel (1 arcsec/pixel), while some other plates is 25 μm/pixel (1.7 arcsec/pixel). The average accuracy of the measured coordinates are about 0.12-0.22 pixel (Spagna et al. 1996); the average photometric accuracy is about 0.13-0.22 magnitude; and reliability of the classification is about 90% (Lasker et al. 2008), but the classification is limited to star or non-star without the galaxy class. This introduces an inconvenience for the calculation of the absolute proper motion, so we have to select the galaxies from non-stars using a new method.

3. CATALOGUE CONSTRUCTION

There are several factors that determine the final precision of the absolute proper motion, first is the measuring error of the images on plates of all epochs, second is the epoch interval of plates which are used to calculate the absolute proper motion, third is how to unify plates in different epochs and different colors to one reference system(i.e. the reference plate). Since the first two factors are objective which are decided by the plates themselves, while the last factors are more important because with better solutions of this factors, the better proper motions can be obtained by all plates in different epochs.

It is well known that because of the combined influence of the atmosphere (differential refraction, dispersion, extinction etc.), telescope (guiding errors, distortion of field of view etc.), photographic plates (uneven response of bending stress, size and distribution of emulsion, low quantity efficiency etc.), plate scanner (digitizing errors), the positions of the images of stars in digitized data have varied systematic errors that are dependent on the position, magnitude and color of the object on the plate (Evans and Irwin 1995) (Tang et al. 2007) (Spagna et al. 1996). Therefore, the proper motions, which come from the positions of different epochs, will suffer from such systematic errors. One point should be mentioned, from the point of view of astrophysics, proper motions of stars are functions of position, magnitude and color of the stars. Statistically, faint and red stars are further than bright and blue stars, so the proper motions of the former are smaller than the later. It is necessary to keep in mind that when eliminating the systematic errors mentioned above, the part of proper motions which related to astrophysical characteristics should not be eliminated as well, otherwise the proper motion data will lose its astrophysical value.

3.1. Principle of calibration

Here the calibration of the absolute proper motions bases on the hypothesis that the objects (stars and galaxies) with close positions, magnitudes and colors have similar systematic errors; the absolute proper motions of galaxies are always zero and not dependent on their positions on plates, magnitudes and colors. Based on this assumption and considering the available plate data, the basic idea of this work is that the plates with good quality are chosen as reference plates (e.g. the 2nd epoch plates), and the stellar objects(i.e. objects classed as stars in COMPASS)with good imaging quality on the reference plates are used to unify the program plates to reference plates; a new kind of moving-mean method is adopted to remove the **P.d.E.** via stellar objects; galaxies are chosen from the non-stars utilizing the motion characteristics of galaxies, and then the **P.d.E.**, **M.d.E.** and **C.d.E.** of all objects are removed by referring to those galaxies; finally, the absolute proper motions of stellar objects are calibrated by combing all of the plate data in different epochs and colors.

Relevant mathematics equations are derived as follows:

For each objects, the systematic difference of positions between the reference and the program plates can be shown in the following two equations (Y directions is almost similar to X direction in most cases, so we take X direction as an example here):

$$\begin{aligned}\Delta x_s = x_1 - x_2 = \\ \mu_x \times \Delta t + D(x_2, y_2) + E(m_2, c_2, x_2, y_2)\end{aligned} \quad (1)$$

$$\Delta x_g = D(x_2, y_2) + E(m_2, c_2, x_2, y_2) \quad (2)$$

Here, $\Delta x_s, \Delta x_g$ represent the positional difference of stars and galaxies respectively, μ_x is the absolute proper motion of stars, Δt is the epoch interval between the reference and progam plate, D is the **P.d.E.**, and E is the combined factor of **M.d.E.** and **C.d.E.**. The absolute proper motions μ_x for each star can be divided into the average proper motions $\bar{\mu}_x$ for all stars and the remaining proper motions$d\mu_x$. After the systematic error D is removed by using stars, the average proper motions$\bar{\mu}_x$is also removed, meanwhile all the galaxies get a pseudo proper motions$-\bar{\mu}_x$. Then, the position difference $\Delta x'_s, \Delta x'_g$ of stars and galaxies between the reference and the program plates can be expressed as

$$\mu_x = \bar{\mu}_x + d\mu_x \quad (3)$$

$$\begin{aligned}\Delta x'_s = x_1 - x'_2 = \Delta x_s - (D + \bar{\mu}_x \times \Delta t) \\ = d\mu_x \times \Delta t + E\end{aligned} \quad (4)$$

$$\Delta x'_g = \Delta x_g - (D + \bar{\mu}_x \times \Delta t) = -\bar{\mu}_x \times \Delta t + E \quad (5)$$

Utilizing the characteristic that a pseudo proper motions $-\bar{\mu}_x$ is added to all galaxies, the real galaxies can be selected by fitting equation (3) with $\Delta x'_g$, and then by using the real galaxies, the average proper motions $\bar{\mu}_x$ and the **M.d.E.** and **C.d.E.** can be calculated and corrected. After this stage, the position difference $\Delta x''_s, \Delta x''_g$ of stars and galaxies between the reference and the program plates can be expressed as

$$\begin{aligned}\Delta x''_s = x_1 - x''_2 = \Delta' x_s - \Delta' x_g \\ = d\mu_x \times \Delta t + E - (-\bar{\mu}_x \times \Delta t + E) \\ = (d\mu_x + \bar{\mu}_x) \times \Delta t \\ = \mu_x \times \Delta t\end{aligned} \quad (6)$$

$$\Delta x''_g = \Delta' x_g - \Delta' x_g = zero \tag{7}$$

Finally, with all the plate data which has been transformed into one position system, a linear fitting is performed to get the absolute proper motions (and new measured coordinates) for all objects as follows

$$\begin{cases} x_t = x_0 + \mu_x (t - t_0) \\ y_t = y_0 + \mu_y (t - t_0) \end{cases} \tag{8}$$

Where x_t, y_t is the measured coordinates at epoch t, the unknown μ_x, μ_y is the absolute proper motions in measured coordinates system, and the unknown x_0, y_0 is the new measured coordinates at the given epoch t_0.

x_0, y_0 are the adjustment results of combing all plate data in different epochs and colors, which can decrease the influence of the random errors of measured coordinates greatly. So it can improve the accuracy of position of the existing GSC catalog. However, what the above work does do is remove the systematic errors between the reference and the program plates. This does not improve the absolute positional accuracy of an object. The absolute positions on the reference plate will still be affected by the **P.d.E.**, **M.d.E.** and **C.d.E.**. At present, UCAC3 catalog (Zacharias et al. 2010) is a representative in this system, so UCAC3 catalog is chosen as the reference catalog to realize the transformation between the measured and celestial coordinates.

The transformation between the measured coordinates x, y and celestial standard coordinate ξ, η can be expressed as

$$\begin{cases} \xi = ax + by + c + \varepsilon(x, y) \\ \eta = a'x + b'y + c' + \varepsilon'(x, y) \end{cases} \tag{9}$$

Here a, b, c, a', b', c' are the coefficients of the linear terms of the plate model(i.e. equation(9)), which represent axis direction, scale and origin difference between the measured and standard coordinate system, and $\varepsilon(x, y), \varepsilon'(x, y)$ are all the high order terms.

Do a differential to equation (9) (Neglect the infinitesimals after the differential) and then divided by the epoch interval Δt, we can get the proper motions in the standard coordinate system.

$$\begin{cases} \mu_\xi = \frac{\Delta \xi}{\Delta t} \simeq a\frac{\Delta x}{\Delta t} + b\frac{\Delta y}{\Delta t} = a\mu_x + b\mu_y \\ \mu_\eta = a'\mu_x + b'\mu_y \end{cases} \tag{10}$$

For the objects on the plate, there is a precise geometrical relationship between the standard coordinates and equatorial coordinates i.e.

$$\begin{cases} \tan(\alpha - \alpha_0) = \frac{\xi}{\cos\delta_0 - \eta\sin\delta_0} \\ \tan(\delta) = \frac{\eta\cos\delta_0 + \sin\delta_0}{\cos\delta_0 - \eta\sin\delta_0}\cos(\alpha - \alpha_0) \end{cases} \tag{11}$$

Where α_0, δ_0 are the equatorial coordinates of the tangent point. As the proper motions of objects is small, for convenience, we take the position in the first epoch as a hypothetical tangent point, and then equation (11) can be simplified to equation (12).

$$\begin{cases} \alpha - \alpha_0 \simeq \frac{\xi}{\cos\delta_0 - \eta\sin\delta_0} \simeq \frac{\xi}{\cos\delta_0 - 0} \\ \delta \simeq \frac{\eta\cos\delta_0 + \sin\delta_0}{\cos\delta_0 - \eta\sin\delta_0}\cos(\alpha - \alpha_0) \\ \quad \simeq \frac{\eta\cos\delta_0 + \sin\delta_0}{\cos\delta_0 - 0} \times 1 \end{cases} \tag{12}$$

Do a differential to equation (12) and divided by the epoch interval Δt, then we can get the proper motions in celestial reference coordinate system i.e.

$$\begin{cases} \mu_\alpha \simeq \frac{\mu_\xi}{\cos\delta} \\ \mu_\delta \simeq \mu_\eta \end{cases} \tag{13}$$

3.2. Processing pipeline

We write a package of FORTRAN programs based on the above ideas for calibrating the absolute proper motions via the database COMPASS. The flowchart (Fig. 2) summarizes the steps and techniques used to remove the varied systematic errors and to acquire the absolute proper motions. The following sections are the detailed descriptions of the key steps refer to the flowchart.

From **Step 1** to **Step 3**, all of the plate data that have overlap regions with the reference plate are extracted from the COMPASS database and the objects on an arbitrary program plate are cross-matched with the reference plate using the catalog ID. Here we keep the closest one for the multi-counterparts between a plate pair and only use the objects which have counterparts on all the plates to calibrate the absolute proper motions.

In **Step 4**, A new moving-mean is applied to the plates for removing the mean shift (P.d.E. and the mean proper motions of stars) in x and y between the program plate and reference plate. Only the stellar objects are used in this filter method, but it has been applied to non-stars(contain the

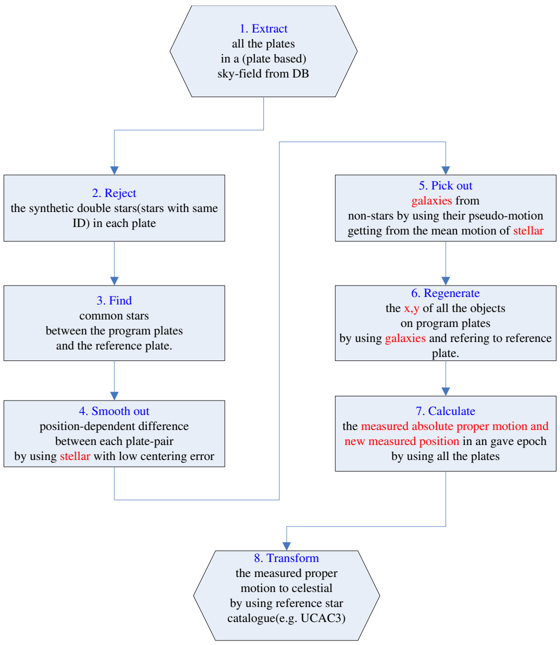

Fig. 2.— Flowchart of the processing pipeline

real galaxies and other extended objects). In order to get a more accurate coordinate transformation, we'd better select the stellar objects with middle magnitude as the reference stars, cause the measuring errors of these objects are lower than those with very bright or very faint magnitude. In the programs, we use stellar objects for $(m_{\rm lim} - 4.5) \le m \le (m_{\rm lim} - 2.0)$ as the reference stars. Where $m_{\rm lim}$is the limiting magnitude of the plate and m is the magnitude of the object. This could provide at least 500 stars degree^{-2}well-distributed on the plate. There are several methods for removing the P.d.E., such as Global plate solution(i.e. only using polynomials), MASK and IOC(Bucciarelli et al. 1993) etc.. But all of these methods are with some defects: it's difficult to fit the intricate distortion by using the Global plate solution method; the number and size of the grids and the number of reference objects in each grid will both affect the effect of the MASK method; there will be a boundary effect when using the IOC method.

Algorithms of our method (named it as Moving Sub-plate method) :

First, transforming the measured coordinates $x_n, y_n (n = 2, ..., N)$ on the program plates to the corresponding coordinates x_1, y_1 on the reference plate using cubic polynomials(see equation (14)). This will remove most of the large scale errors(e.g. spherical deformation).

$$\begin{cases} x_1 = f(x_n, y_n; F) \\ y_1 = g(x_n, y_n; G) \end{cases} \tag{14}$$

Where f,g are the complete cubic polynomials, F,G contain the 15+15 coefficients.

$$\begin{cases} \Delta x = a x_n + b y_n + c \\ \Delta y = a' x_n + b' y_n + c' \end{cases} \tag{15}$$

Where $\Delta x, \Delta y$ are the residuals after using the cubic polynomials, a, b, c, a', b', c' are the coefficients of the six linear term allow for zero point, rotation, and scale difference.

Second, finding out M ($M \ge 3$) reference stars surround the program object (here and now we prefer let M=10), fitting the equation (15) by using these M reference stars to represent the relationship between the residuals $\begin{cases} \Delta x = x_1 - x_n \\ \Delta y = y_1 - y_n \end{cases}$ and the measured coordinates x_n, y_n on the program plate. Then applying this relationship to the program object. This will remove most of the small scale errors dependent on the measured coordinates (See Fig. 3).

And comparing to other method, using this method means to run a separate sub-plate solution for each object on the program plate, the size of the sub-plate will vary automatically and do not have to consider how to give the weight for difference reference points (e.g. weightings in the MASK method).

After step 4 the mean 'proper motion' of the stellar objects is zero, while that of all galaxies is(or should be) non-zero.

In **Step 5** we use all of the non-stars to fit the equation (16) and do iterations until the residuals of the object are less than 2.6 root-mean-square error(a strict criterion) which can help us to pick out the real galaxies(or non-star objects with proper motion equal to zero) from the non-stars. Fig. 4 shows the mean 'proper motion' of galaxies picked out from non-stars after Step 5.

In **Step 6** We apply the transformation (i.e. equation (16)), which is defined by those real galaxies, to all the objects on the program plate, thus all of the P.d.E., M.d.E. and C.d.E. between

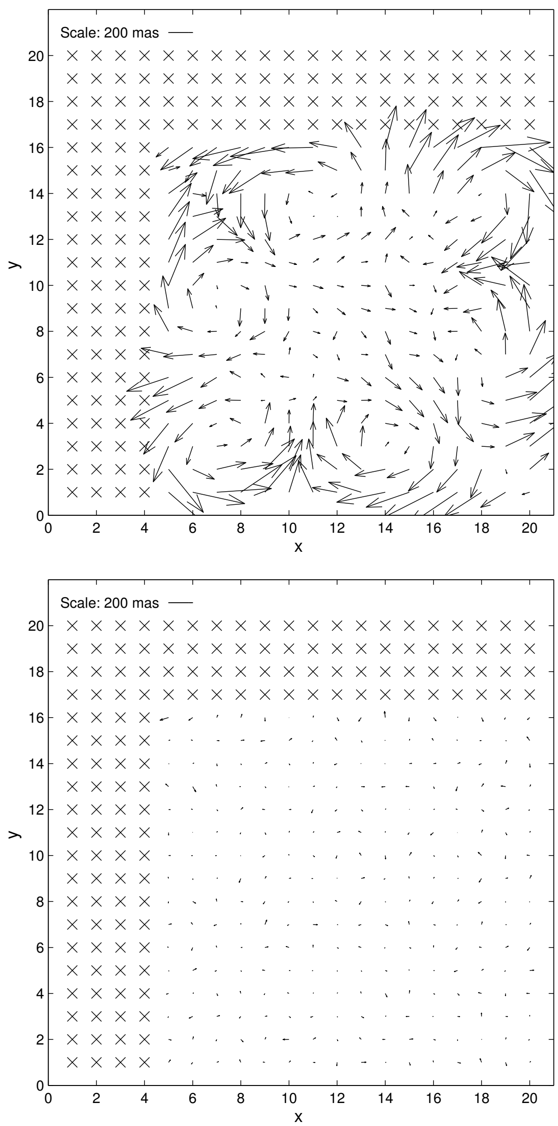

Fig. 3.— The upper figure shows the P.d.E. as a function of plate position after the cubic polynomials fitting. The vector represents the magnitude and direction of the average residual for that region of the plate. The data shown here comes from the plate XP715(epoch=1996.3, l = 266.9^o,b = 69.2^o) and XE494(epoch=1955.3). The lower figure shows the same data as in above after applying the Moving Sub-plate method. No observable P.d.E. remains after this step. The marker '×' indicates there are no common stars in this region.

the program and reference plates will be removed.

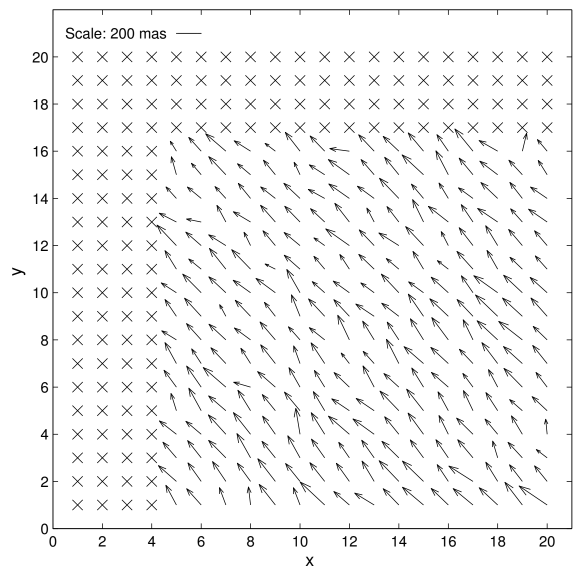

Fig. 4.— Shows the mean 'proper motion' of galaxies as a function of plate position

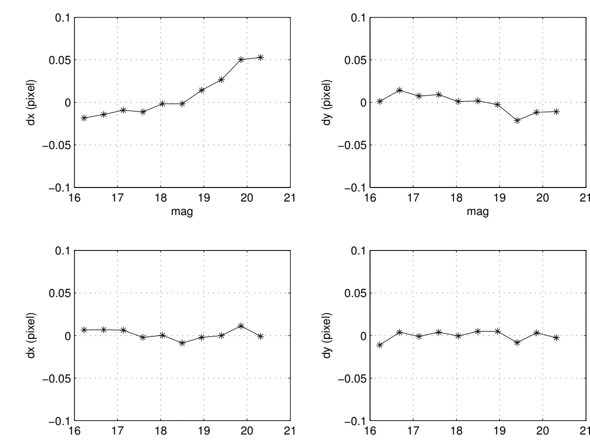

Fig. 5.— Shows the mean residuals of the galaxies as a function of magnitude after step 6. The upper two figures are the results without magnitude term, while the lower are results with those terms.

At the same time we also return the mean proper motion to stellar objects and set that for galaxies as zero. From the diagrams Fig. 5 and Fig. 6, we could find that nearly all the M.d.E. and C.d.E

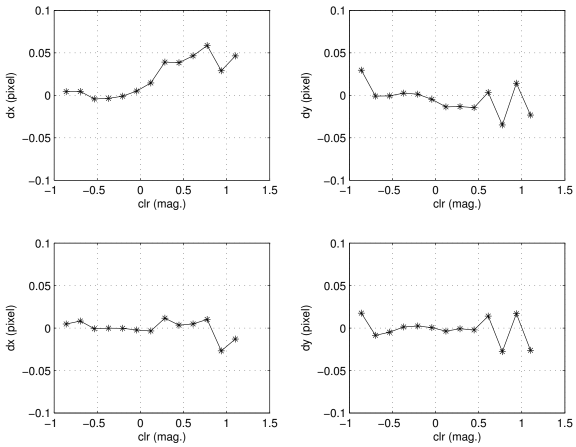

Fig. 6.— Shows the same data as Fig. 4, but as a function of color.

have been removed.

$$\begin{cases} x_1 = ax_2 + by_2 + c + \\ dm + emx_2 + fmy_2 + gm^2 \\ +hC + iCx_2 + jCy_2 + kC^2 \\ y_1 = a'x_2 + b'y_2 + c' + \\ d'm + e'mx_2 + f'my_2 + g'm^2 \\ +h'C + i'Cx_2 + j'Cy_2 + k'C^2 \end{cases} \quad (16)$$

Where x_2, y_2 are the measured coordinates of non-stars on the program plate, x_1, y_1 are the corresponding coordinates on the reference plate, m and C are the magnitude and color(magnitude difference between the reference plate and program plate).

In **Step 7** we use all of the plates after Step 6 to fit the equation (8), and then get the absolute proper motions and the new measured coordinates at a given epoch, here we set the J2000.0 as the given epoch.

In **Step 8** we choose a reference catalogue(here and now we prefer UCAC3 catalog) and use equation (9), (10) and (13) to transfer the measured coordinates to celestial coordinates, i.e get the absolute proper motions and positions in the celestial reference system. Before doing this, we will take a special handing of the reference catalogue, to minimize the influence of its proper motions on our results. What we do are:

1). Transforming the positions of reference star at its catalog epoch(normally J2000.0) to its observational epoch, where the positional error has its smallest value, by using its own catalogue values. For UCAC3 we have to use the central epoch as the observational epoch, which is close to the former, because there is no observation epoch data in UCAC3.

2). Using our absolute proper motions of this star to calculate the new positions from the observational epoch to the given epoch as mentioned in Step 7 .

Therefore, the influence caused by the proper motion in reference catalog on our objects will be reduced to minimum.

4. CATALOGUE ACCURACY

Before we do the statistics base on the final results, we could theoretically estimate the range of accuracy of the absolute zero point of proper motions and the overall accuracy of the absolute proper motions. These will give us a judgment criterion for the final results. For the absolute zero point, we could refer to this equation

$$\sigma_{zero} = \frac{\sqrt{2}\sigma_g}{\Delta t \sqrt{N_g}} \quad (17)$$

where σ_g is positional measuring error of galaxies, $\sqrt{2}$ means the error is affected by both 1st and 2nd epoch, N_g is the number of galaxies used in setting the reference frame and Δt is the baseline over which the proper motions are measured. The range of positional measuring error of galaxies is about $0.''2 < \sigma_g < 0.''5$ for objects bright than $R_F = 20.0$, the number of galaxies is $8000 < N_g < 20000$ and the baselines range is $25 < \Delta t < 45$ years. This corresponds to a range of zero-point error of $0.05 < \sigma_{zero} < 0.3$ mas/yr.

We could theoretically estimate the range of overall accuracy of absolute proper motions with the equation

$$\sigma_\mu = \frac{\sqrt{2}\sigma_s}{\Delta t \sqrt{N_{obs}}} \quad (18)$$

where σ_s is positional measuring error of stellar objects, $\sqrt{2}$ means the error is affected by both 1st and 2nd epoch, N_{obs} is the number of observations of a star and Δt is the baseline over which the proper motions are measured. The range of positional measuring error of stellar objects is about $0.''2 < \sigma_g < 0.''3$ for objects bright than $R_F = 20.0$, the number of observations is about $6 < N_{obs} < 15$ and the baselines range is

$25 < \Delta t < 45$ years. This corresponds to a range of overall error of $1.6 < \sigma_\mu < 9.2$ mas/yr.

We have carried out the reductions on all the plates with $|b| \geq 27^o$ and done the error analysis to certify the reliability of the calibration software and the qualities of the catalogue APOP. The final results are all in the range of estimates mentioned above.

4.1. Internal accuracy

For each object, we could obtain the calibrated absolute proper motions and positions by fitting the equation (8) with all its measures in different epochs and colors. Meanwhile, we could also get the formal errors(i.e. the median standard errors) of the calibrated parameters ($\mu_{\alpha*}$, μ_δ, α, δ) combining the equation (9) and (10), which could be as an internal check of the qualities of the catalogue APOP. Figure 7 displays the results.

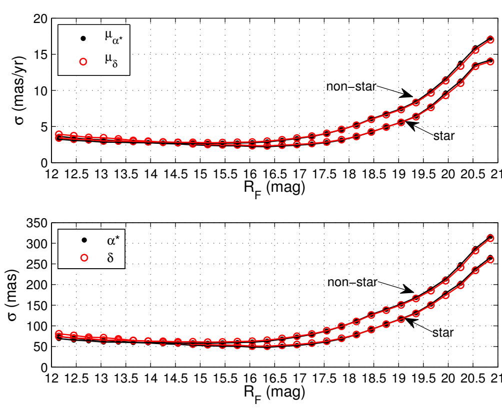

Fig. 7.— Shows the mean formal errors of the absolute proper motions ($\mu_{\alpha*}$,μ_δ) and positions (α,δ) of stars and non-stars as a function of R_F magnitude in catalogue APOP. The magnitude bin for this statistics is 0.3 mag, which make sure there are at lest 100,000 objects in each bin. The marker $*$ followed the μ_α and α means projecting them onto the the great circle direction (i.e times the cos δ). **Top:** the formal errors of absolute proper motions, the unit is milli-arcsec per year (mas/yr); **bottom:** the formal errors of positions, the unit is milli-arcsec (mas).

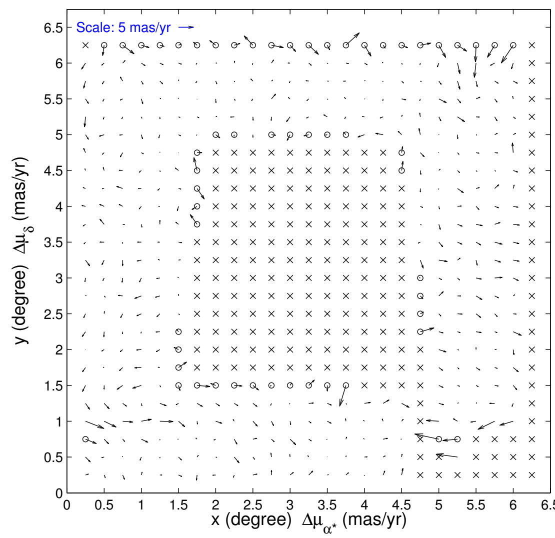

Fig. 8.— Shows the differences of the absolute proper motions ($\Delta\mu_{\alpha*}$,$\Delta\mu_\delta$) of all the common objects in the overlap area between the reference plates as a function of the measured coordinates on one(the central) reference plate. The size of each bin for this statistics is 0.25×0.25 $degree^2$, which make sure there are about 300 objects in each bin. The marker '×' indicates there are no common stars in that bin, and the marker '∘' indicates the number of the common objects is less than 100, which means the statistics is not reliable for that bin. The '↗' indicates the modular and direction of the differences of the absolute proper motions, its scale(5 mas/yr) is plot at the left top of the figure.

We could find that the mean formal errors are consistent very well in the direction of right ascension and declination for all the calibrated parameters, despite we did the least square fitting on those two directions separately. For star objects, the internal accuracy of absolute proper motions is better than ± 4.3 mas/yr for objects bright than $R_F = 18.5$, goes up to 9.5 mas/yr at $R_F = 20.0$ and rises from 10 to 14.2 mas/yr for objects with magnitude $20.0 < R_F < 20.8$. The internal accuracy of positions for star objects is better than ± 100 mas for objects bright than $R_F = 18.5$, increasing from 180 to 260 mas for objects with magnitude $20.0 < R_F < 20.8$. The offset between the star and non-star objects is agree with the fact that the measurement errors are larger for non-star objects(most of which the shape and energy distribution curve is much irregular) than star objects(almost all is point source with regular shape) by a factor 1.5.

It should be mentioned that compared to the theoretical estimation (§ 4), objects close to the magnitude limit (i.e $20 < R_F < 21$) could give an underestimated error due to the unexpected poor measurement in position and photometry. Thus those objects which are faint than $R_F = 20.0$ in APOP should be used carefully, both for their positions and the absolute proper motions.

The internal accuracy could also be estimated if multiple measures of one object are available. For instance, the objects in the overlap region between the adjacent reference plates. The Figure 8 displays the mean offset between the absolute proper motions calibrated on two adjacent reference plates. The data is plot base on the central reference XP216($l = 151.4^o$,$b = 62.8^o$) which have a typical $1.5^o \times 6.5^o$ overlap region with its four adjacent plates XP215(left), XP217(right), XP170(top) and XP266(bottom). It's hard to find a distinct offset for all the four overlap regions, but could see that there are offsets about 1.8 mas/yr in some small regions particularly at the bottom left of that figure. Such offsets are very likely caused by the uncertainty in the correction to absolute zero point by the galaxies, which is estimated to be not larger than 0.3 mas/yr for each reference plate. The other possible reason is in the process of removing the **P.d.E.** by the stars and the exact cause of the problem is still in dispute.

4.2. External accuracy

Quasi-stellar objects (QSOs) have stellar-like images and since they are extragalactic, their proper motions could be considered as zero. Thus the dispersions of their measured proper motion will be a very good measure of the zero point and overall accuracy of absolute proper motions of the stellar objects. Here we use them as an independent and direct determination of the qualities of this APOP catalogue.

The Large Quasar Reference Frame (LQRF) (Andrei et al. 2009) is chosen as the source list for known QSOs. The distribution of QSOs in that catalogue is not uniform, most of the objects are located at the SDSS regions(See Fig. 9). But fortunately they are spectroscopically confirmed with the observations of SDSS, so people could consider most of them are real QSOs and thus the statistics results based on them are reliable. Figure 10, Figure 11 and Figure 12 show the statistics results and indicate that there is a very good agreement between the external and theoretical error estimates of proper motions for the magnitude range $R_F < 20.5$. As a verification of the internal estimates, Figure 13 shows the formal errors of positions (α,δ) of QSOs as a function of magnitude, and indicate that they are consist with the ordinary star objects.

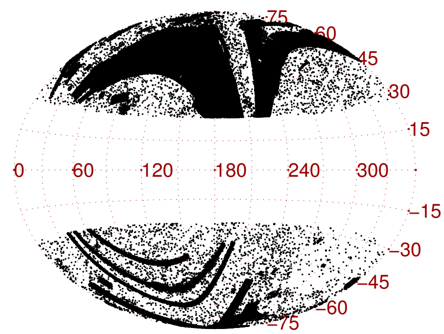

Fig. 9.— Shows the distribution of 108,521 QSOs found in the APOP catalogue(via cross-matching with the LQRF catalogue) and is presented in Galactic coordinate system.

5. CONCLUSIONS AND FUTURE WORK

The main results of our study and problems we met are as follows.

(1) The principle and techniques for the reduction of absolute proper motions were described in details, with emphasis on the techniques for detection and removal of P.d.E., M.d.E. and C.d.E..

(2) The catalogue APOP was achieved based on the plate data out side the galactic plane $|b| \geq 27^o$ in COMPASS database maintained by OATo. The internal and external accuracies of this new catalogue appear to be consistent with what should be expected. The overall accuracy of the absolute proper motions is around 3 to 9 mas/yr, with an error in the absolute zero point better than 0.3 mas/yr, which proves the feasibility and reliability of the method and principles.

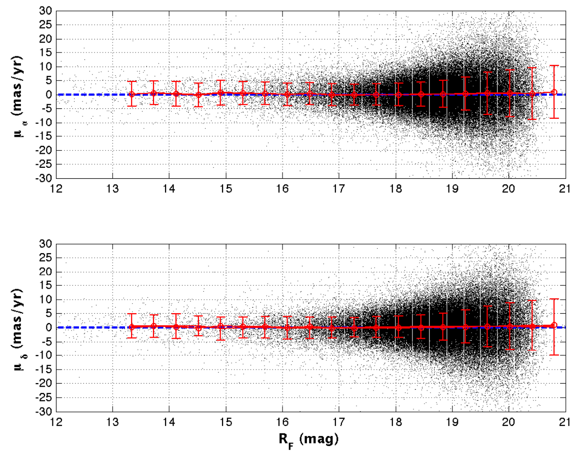

Fig. 10.— Shows the distribution of absolute proper motions ($\mu_{\alpha*}$, μ_δ) of QSOs as a function of magnitude, and plot with their systemic and random values(or call it errors). The blue dash line indicates the desired zero point of the absolute proper motions. The red line and circle indicates the mean of μ_α and μ_δ of QSOs in that magnitude bin and the red error-bar shows their median standard error(the random errors).

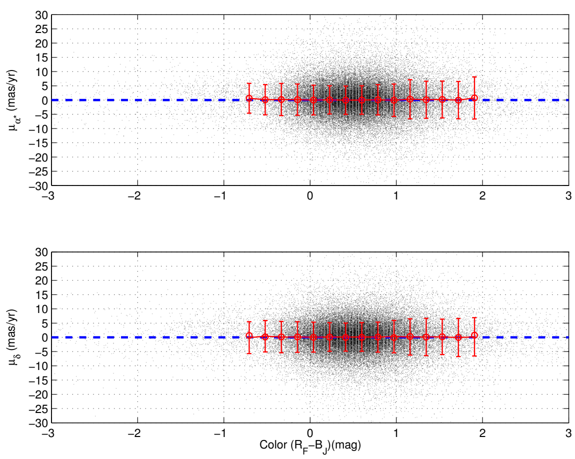

Fig. 11.— Shows the absolute proper motions of QSOs as a function of color.

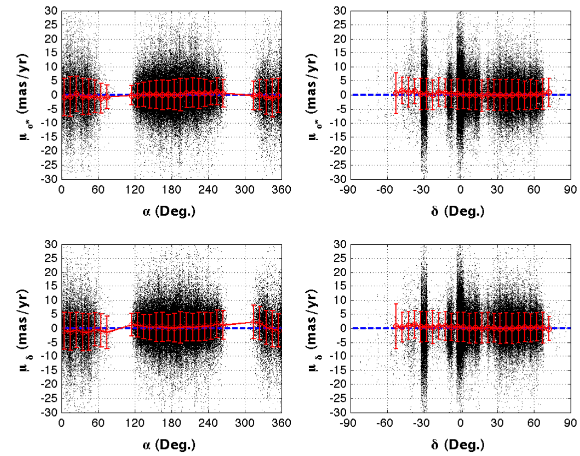

Fig. 12.— Shows the absolute proper motions of QSOs as a function of α and δ.

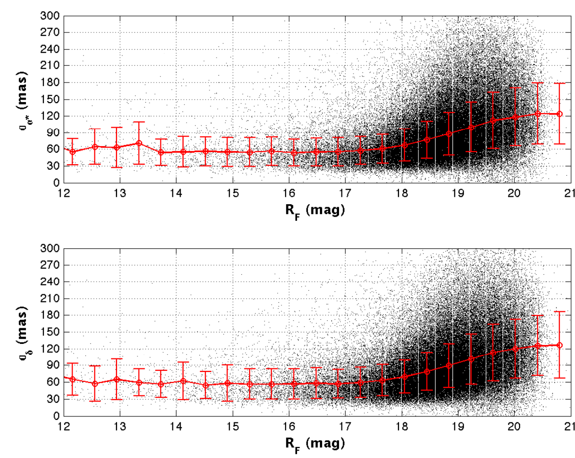

Fig. 13.— Shows the formal errors of positions parameters of QSOs as a function of magnitude.

(3) A new method of source classification was presented, which picks out galaxies from non-stars by using their pseudo-motion getting from the mean motion of stellar. This provided us a new index among other astrophysical indexes.

(4) Other work (Lasker et al. 2008), has shown that there is an offset in magnitude system between stars and galaxies. To some extent, this will reduce the effect of removing the M.d.E. and C.d.E. by using galaxies. We are doing some exploratory investigation to relieve these bad effects. Fortunately, the GSCII team also plans to update the photometry in COMPASS database. We should note that the values of M.d.E. and C.d.E. can be considered small comparing to the total systematic error and the corresponding systematic effects are smaller than 0.4 mas/yr mag-1 and 0.2 mas/yr mag-1 respectively in this work.

6. ACKNOWLEDGMENTS

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REFERENCES

Lasker et al., 2008, AJ, 136:735-766

Tang Z.H., Qi Z.X.,et al., 2007, IAU symp. 248

N. Zacharias et al., 2010, AJ, 139 2184

A. Spagna et al., 1996, A&A, 311, 758-777

Evans D. W. and Irwin M., 1995, MNRAS, 277, 820-844

Bucciarelli B., Taff L. G., Lattanzi M. G., 1993, J. Statist. Comput. Simul., 48, 29

Andrei et al., 2009, A&A, 505, 385-404

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