Improvements to Pan-STARRS1 Astrometry: II. Corrections for Differential Chromatic Refraction

RICHARD L. WHITE,1 STEPHEN H. LUBOW,1 AND BERNIE SHIAO
1Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

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ABSTRACT

In a previous paper, we applied the Gaia DR2 catalog to improve the astrometric accuracy of about 1.7 billion objects in Pan-STARRS1 Data Release 2 (PS1 DR2). We report here on further improvements made by utilizing Gaia EDR3 and correcting for the effects of differential chromatic refraction (DCR) in declination. We extend the correction algorithm in Paper 1 by iteratively subtracting color- and declination-dependent PS1/Gaia EDR3 declination residuals. We determine the astrometric improvement for ∼440 million reference objects that are point-like and cross-match to Gaia EDR3. For this set of objects, Gaia EDR3 provides a ∼3% improvement in PS1 astrometry over Gaia DR2, and DCR corrections provide an additional ∼5% improvement. DCR corrections increase substantially for objects observed away from the zenith. DCR corrections lead to an astrometric improvement of ∼30% for blue objects (0 < g − i < 1) that are 50° away from the zenith. The amplitude of systematic astrometric errors from these effects is substantially reduced to less than 1 mas for objects with PS1 colors in the range 0 < g − i < 4.5, which makes this a useful astrometric reference catalog in fields where there are few Gaia stars. The improved astrometric data will be available through the Mikulski Archive for Space Telescopes PS1 catalog interfaces.

Keywords: Surveys:Pan-STARRS1; astrometry; catalogs; proper motions; Astrophysics - Instrumentation and Methods for Astrophysics

1. INTRODUCTION

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) at Haleakala Observatory in Hawaii was used to carry out the Pan-STARRS1 survey (PS1) mainly from 2010 to 2014. PS1 covers a region north of declination −30 degrees that constitutes about 75% of the sky. This region was covered about 12 times in each of five broadband filters (g, r, i, z, y). Chambers et al. (2016) provides an overview of PS1. Data releases DR1 and DR2 have been made. DR1 (2016 December) contained only average information resulting from individual exposures. The second data release, DR2 (2019 January), contains time-dependent information obtained from individual exposures. In this paper we use data from DR2.1

In a recent paper (Lubow et al. 2021, hereafter Paper 1), we improved the astrometric accuracy of 1.7 billion PS1 objects that have more than two detections by using Gaia DR2 as an astrometric reference (Gaia Collaboration et al. 2016; Lindegren et al. 2018). A subset, consisting of about 440 million of these PS1 objects, are called reference objects. They are objects that have more than two detections, are point-like, and cross-match to Gaia. The point-like quality is determined by requiring a point-source score greater than 0.9 on a scale that ranges from 0 (extended) to 1 (point source) (Tachibana & Miller 2018, https://archive.stsci.edu/prepds/ps1-psc/). To perform the cross-matching, for each Gaia source, we determine the nearest PS1 object

1 When we refer to PS1 data products, we mean the DR2 versions unless we explicitly mention DR1.
that satisfies the detection and point-like requirements within a 2 arcsecond search radius without accounting for corrections due to proper motions and parallaxes. These PS1 cross-matched objects are the reference objects. In Paper 1, the cross-matching used Gaia DR2, while this paper uses Gaia EDR3.

In Paper 1, we found that there are spatially correlated PS1/Gaia DR2 astrometric residuals of the reference objects on the ~ 1 arcmmin scale and employed an algorithm for reducing these residuals. For each PS1 object, the algorithm applies an astrometric correction that is the median PS1 to Gaia shift of the nearest 33 reference objects, excluding the object being corrected. In addition we determined the proper motions of these PS1 objects (using only measurements from PS1) and applied similar corrections to these proper motions. The median astrometric error for the reference objects was reduced by about 33% in position to 9.0 mas and about 24% in proper motion to 4.8 mas/yr.

After applying these corrections, we found that within PS1 stripes (bands of decl. that range in size between 3 to 10 degrees) there are systematic variations of the PS1/Gaia decl. residuals as a function of the Gaia $b - r$ color. They increase with angle away from zenith as the airmass increases (scaling as the tangent of the zenith distance) and are largest for bluer colors (see Figures 18 and 19 in Paper 1). The residuals are caused by changes in atmospheric refraction with color, an effect called differential chromatic refraction (DCR).

DCR corrections have been previously made by Magnier et al. (2020), who used ground-based reference objects from 2MASS. Their corrections are included in the PS1 positions that are used as inputs to our correction algorithms. For the Magnier et al. (2020) DCR corrections, both the 2MASS astrometric reference objects and the PS1 objects experience DCR. The color difference between each PS1 object and its reference stars was taken into account in making the DCR correction. The color and declination-dependent errors described in Paper 1 are the small residual errors that remain after the corrections that were applied in constructing the PS1 catalog.

In this paper we describe improvements to the astrometry of the PS1 DR2 catalog by using Gaia EDR3 (Gaia Collaboration et al. 2021) together with DCR corrections. Some improvements occur through the use of the newer version of Gaia, which has more reference objects along with more accurate positions and proper motions. However, larger improvements are made through the DCR corrections, particularly for objects observed well away from the zenith. Since Gaia is unaffected by DCR, only the DCR effects of PS1 need to be considered. The DCR corrections we apply with Gaia are then absolute, not relative to the color of the Gaia reference objects, which provides a significant advantage compared with the original correction using 2MASS. The outline of this paper is as follows. In Section 2 we describe the correction algorithm. Section 3 describes the results of applying the corrections. Section 4 presents a detailed assessment of the errors in the corrected positions. Section 5 summarizes our results.

2. CORRECTION ALGORITHM

As in Paper 1, we apply the astrometric corrections in a database system. The PS1 database contains the tables that hold the information about detected objects, such as positions and magnitudes. Flewelling et al. (2020) and the PS1 archive documentation (https://panstarrs.stsci.edu) describe the database structure in detail. The Detection table (actually, a view or virtual table) contains positional information based on individual single-epoch exposures. The mean positions and epochs are found in the ObjectThin table, and the mean fluxes and magnitudes, both of which are determined from the Detection table measurements, are found in the MeanObject table. Stack images are produced by combining all the single-epoch exposures in a given filter to obtain a deeper image. Positional and magnitude information on each object for each filter as determined from the stack images are found in the StackObjectThin table.

To carry out both the PS1 to Gaia shift correction of nearby reference objects described in Paper 1 and the DCR correction, we first apply the Paper 1 correction. Using the color-based position residuals relative to Gaia, we then apply a DCR correction. However, these two steps alone are insufficient because the reference objects used in the first step have not been corrected for DCR. (The implications of this inconsistency are described at the end of this section.) To remedy this situation, we apply an iteration scheme that is described in Section 2.1.

For objects observed close to the meridian, refraction effects are much larger in decl. than in R.A. Most PS1 fields are, in fact, observed close to the meridian. In practice we find that the DCR corrections can be modeled as shifts in decl. only that are a function decl. and color (see Section 4 for analysis supporting this approach). These corrections are determined by the PS1/Gaia EDR3 decl. residual distributions as a function of color within each stripe. The DCR corrections are carried out in a series of nine iterations that are numbered 0 to 8. The first iteration (iteration 0) applies the correction algorithm of Paper 1 only, which made no
color corrections at all. After this iteration, the decl. residuals are determined as a function of color. These residuals are used to provide DCR corrections for iteration 1. In iteration 1, the algorithm of Paper 1 is applied with PS1 positions that are DCR corrected. The iterations continue by applying the algorithm of Paper 1 with initial PS1 positions that are DCR corrected based on the cumulative color-based decl. residuals from previous iterations.

2.1. Details of the iterative algorithm

In more detail, the steps to correct a stripe are as follows:

1. To begin iteration 0, we determine the $g - i$ color of PS1 reference objects in the stripe based on mean object information in columns $g\text{MeanPSFMag}$ and $i\text{MeanPSFMag}$ in table $\text{MeanObject}$, if available. If that color information is not available, then we use stack object information from columns $g\text{PSFMag}$ and $i\text{PSFMag}$ in table $\text{StackObjectThin}$, if that is available. If neither is available, then that reference object is removed from the list of reference objects. Only 0.07\% of the reference objects are removed (as expected, since the Gaia reference stars are usually bright enough to be detected by PS1).

2. For each reference PS1 object, we compute the Gaia R.A. and decl. at the PS1 R.A. and decl. mean detection epochs, respectively ($mdmjdra$, $mdmjddec$), of the cross-matched Gaia source by using the Gaia proper motions and parallaxes. We determine the Gaia EDR3/PS1 R.A. and decl. residuals of the reference objects that we call the initial residuals.

3. We apply the median neighbor shift correction algorithm of Paper 1 to these initial reference object residuals. After this correction we determine the post-correction residuals in R.A. and decl. between Gaia and PS1. This step completes iteration 0 for the stripe.

4. In iteration 1, we create a DCR histogram table $H$ of the post-correction iteration 0 decl. reference object residuals as a function of PS1 $g - i$ color. The histogram is stored as a database table with a row for each bin that contains the minimum and maximum color, along with the median of the decl. residuals, $\delta$decl.. There are initially 100 bins in $g - i$ with an equal number of objects for $g - i < 3.0$. The bluest (smallest $g - i$) bin is then refined by a factor of 30 to have an equal number of objects in each bin. Bins for $g - i \geq 3.0$ (very red objects) are added and contain an equal number of objects as the refined bluest bins. These refinements are done because of the relatively small number of objects outside the color range of bin 2 to 100. The maximum and minimum bin color values do not change across iterations within a stripe, but vary across stripes. For each bin (row), we store in the $\delta$decl. column the median of the iteration 0 decl. residuals for the color range in that bin.

5. In iterations greater than 1, we create a new, temporary DCR histogram table $HT$ of the decl. reference object residuals from the previous iteration as a function of PS1 $g - i$ using the same bins as used in histogram $H$. We increment $\delta$decl. in each bin of histogram $H$ by the value of $\delta$decl. in the same bin of the $HT$ histogram. To speed up convergence for objects with $g - i \geq 3.0$, we multiply the residuals in $HT$ by a factor of 1.5 and add that quantity to the $\delta$decl. value in the DCR histogram $H$.

6. For each object, we determine the bin (table row) for which its $g - i$ color lies between the minimum and maximum color in the DCR histogram. For each such object, we subtract the $\delta$decl. value for that bin from the initial decl. residual to produce DCR corrected initial residuals.

7. We apply the median neighbor shift correction algorithm of Paper 1.

8. After iteration 1, we repeat steps 5, 6, and 7 six more times for reference objects only, providing iterations 2 through 7.

9. In iteration 8, we apply step 5 for reference objects and then run steps 6 and 7 for all 1.7 billion PS1 objects with more than two detections. If PS1 $g - i$ colors are unavailable for an object, then its DCR decl. correction is set to zero. About 11\% of the objects do not have PS1 $g - i$ colors. Note that objects that do not have $g - i$ colors are typically red and so are less affected by atmospheric refraction.

10. We add the Gaia minus PS1 residuals from iteration 8 to the initial PS1 positions to produce a table of corrected PS1 positions.

2.2. Convergence of the iteration

We experimented with different numbers of iterations and found that the convergence continued somewhat up to iteration 8, especially at the red end, $g - i > 4$. Further iterations did not lead to significant improvement. In making the DCR corrections, we assume that that the objects are observed on or close to the meridian. Consequently, we did not apply DCR corrections to R.A., which would be largely unaffected by DCR. Instead, for R.A., we only used the median neighbor shift correction algorithm of Paper 1. Proper motions do not benefit from DCR corrections, assuming that the object color does not change across epochs of observations (and that our assumption that objects are observed as they transit the meridian is correct). We therefore only applied the
Mean color of PS1/Gaia reference stars

Figure 1. Mean $g - i$ color of PS1/Gaia reference stars as a function of R.A. and decl. The lower decl. limit of the PS1 survey is $\delta = -30^\circ$. Over most of the sky the color is relatively uniform, but dust absorption in the plane of the Galaxy leads to extremely red mean colors. Note also the blue halo slightly off the plane, which is the population of younger stars near the plane peaking out above the edge of the dust. The blue spots at higher latitudes are globular clusters. These color differences lead to the need for an iterative solution to the DCR correction. The object density is much higher in regions of unusual color, so the effect of color variations on the convergence is large despite the small sky area covered by the plane.

median neighbor shift correction algorithm of Paper 1 with Gaia EDR3 to the proper motions.

Notice that the algorithm above does not iterate on the median neighbor shift corrected positions. Instead, it starts each iteration with DCR corrections to the initial (not median neighbor corrected) positions of the PS1 objects. The reason is that we found that iterating on the median neighbor corrected positions can sometimes lead to instability, resulting in a lack of convergence.

The DCR histograms are constructed for reference objects within a stripe, leading to corrections that are constant across the stripe for objects of a given color. We experimented with interpolating the corrections as a function of decl. within the stripe using the corrections from neighboring stripes. However, that refinement did not lead to better astrometric accuracy and consequently we did not adopt that approach.

We discuss here the need for the iteration between the median neighbor shift correction of Paper 1 and the DCR correction. The iteration is needed because reference star and object colors vary systematically as a function of position on the sky (see Fig. 1). That means, for example, that many of the red objects (near the Galactic plane) also have red reference stars. That makes the initial positions (with no DCR corrections) more accurate for those objects. But it also means that our DCR correction in the first iteration underestimates the true amplitude of the DCR bias. An isolated red star far from the Galactic plane (with average color reference stars) therefore has a larger error than is estimated from the measured mean error for stars of that color over the sky (which is dominated by stars in the plane). After repeated iterations, the model for the “true” DCR correction gradually improves, leading to more uniform residual errors over the sky.

2.3. Database implementation

The above steps were carried out in a Microsoft SQL Server database using the JHU spherical library (Budavári et al. 2010) for finding nearest neighbors and using Common Language Runtime (CLR) functions for computing the median values and Gaia parallax shifts. The running time for all PS1 objects we consider was about 10 days.

3. RESULTS

Figure 2 plots the number distribution of reference objects by color for Stripes 2, 16, and 30. Stripe 2 is about $47^\circ$ in decl. south of the zenith, while Stripe 30 is about $47^\circ$ in decl. north of the zenith. Stripe 16 crosses the zenith. More than 98% of the reference objects lie in the color interval $0 < g - i < 4.5$. There is a more rapid decline in the blue end end than in the red end.

The left column of Figure 3 plots the Gaia EDR3 minus PS1 decl. residuals as a function of PS1 $g - i$ color that result from applying our algorithm. The results are plotted for iterations 0, 1, 2, and 8. The right column is a more detailed view of the residuals for iteration 8. As expected, the initial decl. residuals in iteration 0 (before DCR correction) are much smaller for Stripe 16 because fields in that region are generally observed closer to the zenith and have positions that are only weakly
affected by refraction. The initial (iteration 0) residuals in Stripes 2 and 30 are comparable in absolute value as would be expected for refraction by similar amounts. These residuals are of opposite sign, as is also expected by the effects of refraction north and south of the zenith.

In the color interval $0 < g - i < 4.5$ that contains more than 98% of the objects, the iteration 0 residuals in Stripes 2 and 30 reach about 20 mas at the blue end, but are generally reduced well below 1 mas by iteration 8. Outside this color interval, there is considerable scatter even for iteration 8, especially for the blue end where $g - i < -0.5$. We investigated whether the large scatter in the blue end could be due to stellar variability. The PS1 observations of the same object in different filters were typically separated by months to years, while they were nearly simultaneous with Gaia. Therefore a given variable PS1 object could have errors in colors due to the magnitude changes in the different filters measured at different epochs. Such errors should not occur with Gaia colors. It is also possible that the scatter is due to other inaccuracies in PS1 photometry. To test these possibilities, we applied the correction algorithm using Gaia $b - r$ colors instead of PS1 $g - i$ and obtained a roughly similar level of scatter at the blue end where $b - r < 0$. Note that our algorithm relies on PS1 colors rather than Gaia colors for the correction because we need to compute corrections for PS1 objects that do not have Gaia matches.

That suggests that variability is a less likely explanation than other sources of scatter in the PS1 colors. We have found that extremely blue objects with $g - i < -0.5$ are concentrated heavily in the middle of the Galactic plane, where crowding makes their photometry, astrometry and colors all unreliable. Even “normal” blue objects with $0 < g - i < 1$ are rare in this region due to heavy dust reddening. The DCR correction (and indeed all properties) of objects with those extreme colors should be considered highly uncertain. That is very likely to be the source of the large scatter in the mean DCR correction for the bluest objects. We are investigating whether the catalog data for these objects might be improved in a future reprocessing of the PS1 survey data, but for now users of PS1 DR2 should be skeptical of objects in the crowded Galactic plane that are outliers in their colors or other properties.

Figure 4 compares the distributions of PS1/Gaia residuals for R.A. and decl. at iterations 0 and 8. The DCR corrections lead to reductions in the decl. residuals from iteration 0 (orange lines) to iteration 8 (red lines). Ideally, the residual distributions of R.A. (purple lines) and decl. would be identical. But due to DCR effects that are stronger in decl. than R.A., their distributions differ significantly before the DCR correction. In the case of Stripe 16, all three distributions overlap to the extent that they are indistinguishable on the plot because that stripe is only very slightly affected by refraction. In Stripes 2 and 30, we see that the R.A. residual distribution is much more peaked than the decl. for iteration 0, where no DCR corrections have been made.

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For iteration 8 the decl. distribution is much closer to the R.A. distribution. For Stripe 2 the ratio of the peaks in the decl. distribution to the R.A. distribution for iteration 0 is 0.70 and for iteration 8 is 0.93. For Stripe 30 the ratio of the peaks in the decl. distribution to the R.A. distribution for iteration 0 is 0.73 and for iteration 8 is 0.92. So the difference between the peaks is reduced by more than a factor of 3 from iteration 0 to iteration 8.

It is uncertain what is responsible for the remaining ~8% difference between the peaks of the R.A. and decl. distributions for iteration 8. One possibility is that it is due to fields being observed off the meridian. Fields observed on the meridian have DCR shifts that are purely north-south with an amplitude determined by the object’s color. Fields observed off the meridian have shifts in both decl. and R.A. with relative amplitudes that depend on the hour angle of the observation. Due to
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Figure 4. Plot of the distributions of Gaia EDR3 minus PS1 residuals $\delta$RA (purple), $\delta$decl. for iteration 8 (red), and for iteration 0 (orange) in Stripes 2, 16, and 30. The bin size is 0.1 mas. R.A. residuals do not change across iterations. The R.A. and decl. distributions are much more similar after the DCR correction.

In interpreting Figure 5, we should keep in mind that Stripe 2 covers a region near the Galactic center, resulting in the most crowding of the three plotted stripes, and is well off the zenith, resulting in DCR effects. Stripe 16 passes through the zenith and has the smallest DCR effects. Stripe 30 is the least crowded but is well off the zenith, resulting in DCR effects. The residuals for the uncorrected case in Stripe 2 (solid blue line) generally increase monotonically with magnitude. The iteration 0 corrections do not provide much reduction of residuals much (although they can certainly affect individual objects).

In most cases, the residuals in Figure 5 are minimized at an intermediate magnitude of about $i = 17$ mag, as discussed in Paper 1. The residual increase at the bright end is likely due to effects of saturation (for the brightest stars) and to the Koppenhöfer Effect (Magnier et al. 2020), which generates brightness-dependent position errors in the PS1 detectors. The increase at the faint end is due to the decrease in the signal-to-noise ratio.
and plane. A tighter point-source restriction excludes some objects where the PS1 astrometry is affected by blending, leading to better astrometric residuals. Stripe 30 does not show much astrometric improvement for the very point-like sources (small differences between the solid and dashed lines of the same color) because it is located far from the Galactic plane and is affected less by crowding. The distributions for the very point-like reference objects (dotted lines) in Stripe 2 are much more similar to the corresponding distributions in Stripe 30 than the less point-like cases (solid lines). For Stripe 2 objects at 17 mag, the uncorrected residuals (solid blue line) decrease by about a factor of 3 for the DCR corrected, very point-like sources (red dashed-line).

Since the objects in Stripe 16 experience very small DCR effects, this stripe allows us to isolate the effects of using very point-like objects from the effects of DCR. In Stripe 16 the orange and red solid lines overlap and the orange and red dotted lines overlap because the effects of refraction are weak. Stripe 16 shows little change across the red and orange curves, both solid and dashed, in Figure 5 for the brightest objects. For fainter objects, there is a noticeable change between the general and very point-like objects (solid versus dotted lines). More point-like objects provide a greater advantage in astrometric accuracy for the fainter objects, both because fainter objects are more likely to be blended with similar brightness neighbors and also because the lower signal-to-noise ratio for fainter objects can make it more difficult to confidently identify point-like objects for the reference sample.

For Stripes 2 and 30, the DCR corrections are most effective for brighter objects. The largest improvements are for the bright end of the plots for Stripes 2 and 30 where the residuals are reduced by more than 25%. The DCR correction is less dramatic for fainter objects due to their larger random astrometric errors from noise. Random errors are not reduced by either the median shift correction or the DCR correction, so the removal of those systematic errors has a smaller apparent effect on the overall astrometric residuals for noisy, fainter sources. There may also be a contribution from changing color distributions with magnitude if the blue objects, which experience stronger DCR effects, are generally brighter than the red objects.

Figure 6 plots the normalized distribution functions of the distance between Gaia and PS1 cross matched objects for the cases of Gaia DR2, Gaia EDR3, and Gaia EDR3 with DCR corrections for all stripes. The normalization is such that the areas under the curves are the same and equal to unity. The Gaia DR2 case is the same as in Paper 1. As described by equation 3 of Pa-

Figure 5. Plot of the PS1/Gaia EDR3 residuals of reference objects as a function of PS1 $i$-band magnitude for uncorrected (blue), iteration 0 (orange), and iteration 8 (red) cases, in Stripes 2, 16, and 30. (The orange line is hidden behind the red line for Stripe 16.) The solid lines are for all reference objects in the stripe, while the dotted lines are for the very point-like reference objects having a point-source score greater than 0.99 (Tachibana & Miller 2018).
per 1, these functions are approximately of the form of the Rayleigh distribution. As in Paper 1, the main tail of the plotted distributions from 20 mas to 40 mas are well fit to an exponential, while far into the tail (40 to 100 mas) the distributions follow a power law with index $\sim -2.8$. We see that there is a small difference between the results for Gaia DR2 and Gaia EDR3 without DCR corrections. Gaia EDR3 contained improvements to the accuracy of the astrometry, particularly in the accuracy of proper motions. However, the epoch difference between PS1 and Gaia is typically only about three years and PS1 is limited by its ground-based resolution. Consequently, these improvements produced a small reduction on residuals whose median values changed from 9.0 to 8.7 mas. The unnormalized number distribution (not shown) reveals an additional improvement in the peak of the distribution in using Gaia EDR3 over using Gaia DR2 because about 4% more PS1 objects cross matched to Gaia EDR3.

The DCR corrections reduced the overall median residual of reference objects to 8.3 mas, a reduction of about 8% relative to Gaia DR2. However, as we see in Figure 3 the DCR improvements can be much larger for blue objects observed away from the zenith. For example, the median residuals in Stripe 30 for $0 < g - i < 1$ decrease by 27%, as seen in Figure 7.

4. RESIDUAL ERRORS IN THE POSITIONS

The algorithm we have adopted makes some simplifying assumptions. One major assumption is that the DCR correction is a function solely of the object’s color and its decl. That is reasonable as long as fields are usually observed as they transit the meridian. In this section we explore the accuracy of that assumption using information on the actual distribution of PS1 observations, which is available in the PS1 database. We also measure the residual bias in the DCR-corrected catalog by averaging the positional errors (compared with Gaia EDR3) over small sky regions. We conclude that despite the absence of any DCR correction in R.A., the residual bias in the catalog positions is less than 1 mas in both R.A. and decl., even for objects with very red or blue colors.

We have already seen in Figure 5 that Stripe 16 that contains the zenith involves small (less than 1 mas) DCR corrections in declination, since the orange and red curves overlap. In addition, we see in Figure 4 that the R.A. and decl. residual distributions are nearly identical. This suggests there are not significant errors in R.A. due to DCR.

4.1. Hour-angle distribution

Figure 8 shows the distribution of hour angles for all the PS1 observations. The distributions are shown separately for each of the five PS1 filters (grizy) as well as for all filters combined. The z-axis is the distance to the meridian, $H \cos \delta$, where $H$ is the hour angle of the observation in degrees (which is zero as the target crosses the meridian) and $\delta$ is the decl. The color plot shows the density of observations as a function of decl. (the y-axis), with individual pointings in sparse regions shown as black points. The hole in the middle is the position of the zenith at the observatory and is a zone of avoidance due to the telescope’s Alt-Az mount. The histogram shows the distribution integrated over decl., with separate lines for the declination band within 20° of the zenith (orange) and points outside that region (blue).
Figure 8. Distribution of hour angles for PS1 observations. The distributions are shown for each of the five PS1 filters (grizy) as well as the combined distribution for all filters. The observations are sufficiently close to the meridian to produce DCR effects that are strongly concentrated along decl. except near the zenith (where the airmass of the observations are always moderate, leading to small DCR effects). The observations that are off the meridian are approximately symmetrical about the y-axis, leading to small biases (< 1 mas) due to DCR in the R.A. direction. See the discussion for additional description of the figure.
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Figure 9. Distribution of predicted R.A. and decl. components of DCR for PS1 observations of extremely blue stars. The combined hour-angle distribution (lower right panel of Fig. 8) was used, along with the largest amplitude correction that was measured for any color stars in our sample. The DCR effects in R.A. are typically small even in this worst-case example; the effects on the mean positions are significantly smaller because most PS1 objects use many measurements to determine the means, reducing the DCR bias by a factor \( \sqrt{N} \) for \( N \) observations (typically \( N = 10 \) to \( 60 \)).

Large deviations from hour angles near zero would lead to significant DCR effects in the R.A. direction. Strong asymmetries (e.g., observing targets systematically as they are rising or setting) could also create systematic errors from DCR in R.A. These plots show that the hour angle distribution is relatively tight except near the zenith, with a half-width at half maximum of 11.5°. The distribution is particularly tight in the far north and far south, where the DCR effects are the largest, which also helps reduce the amplitudes of significant errors in the DCR correction.

How large are the errors that could be introduced by the observed amount of hour-angle scatter? As a partial answer to that question, we have used the hour-angle data to construct a simple model of the expected errors in R.A. The hour angle and decl. of all the observations from Figure 8 have been used to compute the direction of the DCR vector, which always points at the zenith. The DCR is assumed to scale with zenith distance \( \zeta \) as

\[
 f_{\text{DCR}}(\zeta) = B_{\text{max}} \tan \zeta / \tan (90° - l_{\text{obs}}) ,
\]

where \( l_{\text{obs}} = 20.7082° \) is the latitude of the observatory, \( 90° - l_{\text{obs}} \) is the largest zenith distance, and \( B_{\text{max}} = 30 \text{ mas} \) is the largest DCR correction that we compute for the most extreme (blue) stars. Figure 9 shows the resulting distribution of R.A. and decl. DCR components; the histogram again shows the distribution integrated over decl., with separate lines for the declination band within 20° of the zenith (orange) and points outside that region (blue).

Despite the choice of a worst-case blue color for the DCR scaling, the half-width at half maximum of the R.A. DCR distribution is only 2.7 mas. The remaining DCR errors for the mean positions in the catalog will be even smaller. If there are \( N \) observations with hour angles sampled randomly from this distribution, the error in the mean will be smaller by a factor \( \sqrt{N} \). PS1 objects can have \( N \) ranging from 3 (the lowest \( N \) considered for this paper) to more than 60, with typical objects having 10 or more measurements. We can therefore expect biases in R.A. from residual uncorrected DCR of around 1 mas or less.

4.2. Measured bias in positions

Finally, we directly measure the bias in our positions by comparing the final corrected positions to Gaia EDR3. Recall that we explicitly avoid using the Gaia measurement of the object itself in calculating the correction (Paper 1), leaving our PS1 positions for the PS1-Gaia reference sample uncontaminated and independent of the Gaia measurement. The average positional error of a group of PS1-Gaia stars is, if there are enough stars, a measure of the bias in the PS1 coordinate system.

We computed the mean offsets in R.A. and decl. between the PS1 and Gaia positions in small sky regions covering approximately \( 4.5° \times 4.5° \). The regions were chosen to be large enough to have a sufficient red and blue stars for an accurate mean calculation (usually with \( > 1000 \) objects per spatial bin), while remaining compact enough to reveal any sky regions where the mean error is unusually large. Our calculation is similar to using PS1 as an astrometric reference catalog for aligning an astronomical image.

The results are shown in Figure 10, which shows the average positional bias as a function of sky positions for
Figure 10. Mean positional bias in PS1 catalog positions compared with Gaia as a function of sky position for blue stars (left column) and red stars (right column). The top row shows the decl. offset before the DCR correction (iteration 0), and the middle row shows the decl. offset after the DCR correction (iteration 8). The bottom row shows the offset in R.A., which is not changed by the DCR correction. The same scale is used for all panels. The faintly seen difference between higher and lower declination regions in the R.A. plot is due to uncorrected DCR effects. However, the very small amplitude (< 1 mas), combined with the complex nature of an algorithm to correct it, led us not to attempt a DCR correction for the R.A.

blue stars (0 < g - i < 1, left column) and red stars (2.5 < g - i < 4, right column). The decl. offset before the DCR correction (top row) is clearly dominated by the large DCR effects, with the sign of the offsets changing around the declination of the zenith, and with the red and blue stars having offsets in opposite directions. After the DCR correction (middle row), the decl. errors are well behaved and small except for some local errors in the Galactic plane.

The structures in the Galactic plane, which are particularly visible before the DCR correction, are the result of changes in the average colors of reference stars near the plane (Fig. 1). In the center of the plane, dust absorption makes typical reference stars as red as our “red” sample, meaning that there are no DCR-induced offsets between them. As a result, the decl. error before DCR correction is close to zero for red objects (top right panel). Conversely, the (rare) blue stars in the plane have enormous color differences compared with the red stars, leading to very large DCR errors (top left panel). After correction the errors for blue stars are greatly reduced in the plane, though they still remain at a low level. That is at least partly attributable to severe crowding that limits the quality of both astrometry and photometry in the plane. There are in any case few blue stars in the plane that are affected by the remaining errors.

Errors in the R.A., which is not changed by our DCR correction algorithm, are generally small and are comparable to the corrected decl. errors (as expected from Fig. 4). There is no evidence for any seasonal variation in the R.A. errors, which could have resulted if there were changes in the observing strategy due to different weather patterns at different times of the year.

A slight difference between higher and lower declination regions is visible in the R.A. plot. That difference changes sign for red and blue objects, indicating that it is almost certainly an uncorrected DCR effect. However, its amplitude is very small. Since the R.A. bias is primarily a function of decl., Figure 11 shows the mean error for the post-DCR-correction errors as a function of decl. While both the red and blue stars show the characteristic sign change around the decl. of the zenith that is expected from DCR, the amplitude of the remaining bias in both R.A. and decl. is less than 1 mas, even for these stars having extreme colors. For stars with more typical colors, the biases are much smaller. That makes our improved PS1 positions useful as an as-
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5. SUMMARY

We extended the astrometric correction algorithm of Paper 1 to use Gaia EDR3 and include corrections for differential chromatic refraction (DCR). Gaia EDR3 provides an improvement of \( \sim 3\% \) in PS1 astrometric accuracy of all reference objects compared with Gaia DR2. DCR corrections provide an additional improvement of \( \sim 5\% \) (Fig. 6). However, the DCR corrections improve the astrometric accuracy as much as \( \sim 30\% \) for brighter objects \((i < 17)\) or bluer objects that are well off the zenith (Figs. 5 and 7). The amplitude of systematic astrometric errors from these effects is substantially reduced to less than 1 mas for objects with PS1 colors in the range \( 0 < g - i < 4.5 \) (Fig. 11), which makes this a useful astrometric reference catalog in fields where there are few Gaia stars available. As a result of the DCR corrections, the R.A. and decl. residual distributions are quite similar (Fig. 4). We are making these improvements to astrometry available soon in the SQL query interface called CasJobs at https://mastweb.stsci.edu/ps1casjobs and through the Barbara A. Mikulski Archive for Space Telescopes (MAST) catalogs interface at https://catalogs.mast.stsci.edu.

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