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# COMPLETENESS OF USNO-B FOR HIGH PROPER MOTION STARS

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## ABSTRACT

I test the completeness of USNO-B detections of high proper motion ($\mu > 180$ mas yr$^{-1}$) stars and the accuracy of its measurements by comparing them to the revised New Luyten Two-Tenths catalog of Salim & Gould. For $14.5 < V < 18.5$, only 6% of such stars are missing from USNO-B, while another 3% have large errors, mostly too large to be useful. Including both classes, incompleteness is 9%. These fractions rise toward both brighter and fainter magnitudes. Incompleteness rises with proper motion to ~30% at $\mu = 1''$ yr$^{-1}$. It also rises to ~35% at the Galactic plane, although this is only determined for relatively bright stars $V \lesssim 14$. For binaries, incompleteness rises from 9% at separations of 30″ to 47% at 10″. The proper-motion errors reported internally by USNO-B are generally correct. However, there is floor of $\sigma_\mu \sim 4$ mas yr$^{-1}$ below which the reported errors should not be taken at face value. The small number of stars with relatively large reported errors ($\sigma_\mu \gtrsim 20$ mas yr$^{-1}$) may actually have still larger errors than tabulated.

*Key words:* astrometry — methods: statistical

*On-line material:* machine-readable table

## 1. INTRODUCTION

Until recently, the New Luyten Two-Tenths (NLTT) catalog (Luyten 1979a, 1980) was the only all-sky catalog of high proper motion stars extending to faint magnitudes. Since its completion more than two decades ago, after a lifetime of work by Luyten, the NLTT has served as an invaluable source of candidate subdwarfs, white dwarfs, and nearby stars, as well as the basis for statistical studies of Galactic populations.

However, the NLTT does suffer from several significant shortcomings. First, while most NLTT positions are accurate to the nominal catalog precision of $1^s \times 6''$, there is a tail of errors extending out to several arcminutes and beyond (Gould & Salim 2003; Salim & Gould 2003). This means that a significant fraction of NLTT stars cannot easily be located. Second, the photographic magnitudes (and especially colors) given by NLTT are not precise enough to reliably classify stars using a reduced proper motion (RPM) diagram (Salim & Gould 2002). Third, NLTT is seriously incomplete at faint magnitudes both close to the Galactic plane and in the areas south of the first Palomar Observatory Sky Survey ($\delta < -33°$), especially $\delta < -45°$. Moreover, its completeness over the rest of the sky is not definitively known.

Since these shortcomings significantly limit NLTT's application to various problems, substantial efforts have been made to rectify them. For example, Reid & Cruz (2002) cross-identified NLTT stars with the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) entries, while Bakos, Sahu, & Németh (2002) directly identified stars from the Luyten Half-Second (LHS) catalog (Luyten 1979b) on the Digitized Sky Survey (DSS). LHS is a subset of NLTT containing essentially all NLTT stars with proper motions $\mu > 500$ mas yr $^{-1}$, as well as some slightly slower than this limit. The nominal threshold for NLTT is $\mu \geq 180$ mas yr$^{-1}$. Gould & Salim (2003) cross-identified NLTT bright stars with three modern position and proper motion (PPM) catalogs, *Hipparcos* (ESA 1997), Tycho-2 (Høg et al. 2000), and STARNET (Röser 1996), while Salim & Gould (2003) cross-identified NLTT faint stars with counterparts from USNO-A (Monet 1996, 1998) and 2MASS. Together these make up the revised NLTT catalog (rNLTT). To the extent that one can find 2MASS counterparts of NLTT stars, they can be placed on an optical/infrared color-magnitude diagram, which allows much more secure RPM classification (Salim & Gould 2002).

Finally, several groups have worked to estimate the completeness of NLTT or, in some cases, improve it. Reid (1990) made an independent search for stars exceeding NLTT's proper-motion threshold over a single high-latitude Schmidt plate. Monet et al. (2000) searched for high proper motion ($\mu > 400$ mas yr$^{-1}$) stars to faint magnitudes toward 1378 deg$^2$. Gould & Salim (2003) directly measured the completeness of bright ($V \lesssim 11$) stars by cross-identifying Tycho-2 and *Hipparcos* stars. Flynn et al. (2001) estimated NLTT completeness based on its internal properties, while I made a parameterized measurement of NLTT completeness as a function of magnitude as a by-product of my measurement of the properties of halo stars (Gould 2003). In the appendix to that paper, I argued that all the available evidence is consistent with the following picture: NLTT is virtually 100% complete for $V \lesssim 11$ except near the plane, where it falls to 75%. At fainter magnitudes (and away from the plane), completeness falls gradually to ~50% at $V \sim 18$. Even at these faint magnitudes, completeness is much higher for the small subset of high proper motion stars, $\mu > 500$ mas yr$^{-1}$. To rectify the relatively high incompleteness levels toward the plane, Lépine, Shara, & Rich (2002) have undertaken a new intensive proper-motion search in this region.

With the publication of the long-awaited USNO-B1.0 (Monet et al. 2003), the prospects for improving, or perhaps superseding the NLTT have taken a sharp turn for the better. USNO-B1.0 is an all-sky PPM catalog based on deep photographic plates taken over about four decades in the north ($\delta > -33°$) and two decades in the south. It contains $10^9$ entries, which not only specify the adopted PPM (and errors), but also the astrometric and photometric measurements at all the epochs that were combined to make these determinations. The J2000.0 position listed for each object in USNO-B1.0 is for epoch 2000.0, derived from the measured positions and calculated proper motion for each set of measurements. Hence, multiple sets of measurements for a particular star will have different USNO-B1.0 positions.

However, although USNO-B1.0 is a monumental undertaking, it cannot be used immediately to assemble a catalog of high proper motion stars. By deliberate construction, USNO-B1.0 contains entries for *all* sets of detections within 30″ that can reasonably be matched to a straight-line motion over time (and which have not previously been matched at higher confidence to other such linear ensembles of detections). These identifications were effected without making use of any additional information, such as photometry. This means that USNO-B1.0 inevitably contains a large number of false high proper motion entries. At high latitude, it contains about 200 times more entries with $\mu > 180$ mas yr$^{-1}$ than NLTT, meaning that $\gtrsim 99\%$ of these entries are spurious, formed of incorrect matching of unassociated stars or even of plate artifacts. As Monet et al. (2003) emphasize, this contamination is deliberate. The catalog's compilers sought to allow its users to sift through all possible associations to find the most possible genuine high proper motion stars. I will discuss several ideas for how to go about doing this in § 6. However, before any of these are actually implemented (or even precisely defined), it is essential to understand the properties of the catalog itself, most importantly its completeness.

In this paper, I study the completeness of USNO-B by comparing it with the rNLTT as compiled by Gould & Salim (2003) and Salim & Gould (2003). I perform two complementary comparisons, one to rNLTT binaries and one to single stars. Binaries in rNLTT are extremely well understood because the supplementary notes to NLTT give information on the separation and the position angle of the components. These permit an extra check on the reality of the rNLTT identifications. Binaries also constitute a subset of NLTT that is of interest in its own right. Hence, if NLTT is eventually extended using USNO-B, it will be important to understand USNO-B's completeness as a function of binary separation. I will show that this completeness is indeed a strong function of separation. Given this fact, binaries may seem a poor proxy for the single stars that constitute the vast majority of NLTT entries. I handle this problem in two ways. First, I examine the binaries themselves at very wide separation where USNO-B is unlikely to be affected by confusion caused by companions. Second, I examine single stars from rNLTT directly. Because they are much more numerous, single stars also permit study of completeness as functions of apparent magnitude, proper motion, and Galactic latitude. Single stars do have the drawback that their identifications in rNLTT are not quite as secure as are those of binaries, and this fact ultimately circumscribes the conclusions that can be drawn from studying them. Nevertheless, the implications of the two comparisons are broadly consistent, and thus each lends credence to the other.

In § 2, I briefly review the properties of the rNLTT. In §§ 3 and 4, I analyze the completeness of USNO-B relative to, respectively, binary and single-star samples from rNLTT. In § 5, I determine the accuracies of the USNO-B proper-motion measurements and compare these to its internal error estimates. Finally, in § 6, I discuss the prospects for combining USNO-B with other catalogs to obtain a clean, relatively complete sample of high proper motion stars.

## 2. REVIEW OF THE rNLTT

The construction of the rNLTT was a huge undertaking, which is laboriously documented in Gould & Salim (2003) and Salim & Gould (2003). Here I review the basic features of this catalog as they affect the current paper.

As mentioned in § 1, bright ($V \lesssim 11$) NLTT stars are matched to bright PPM catalogs and faint NLTT stars are (mostly) matched to pairs of stars from USNO-A and the 2MASS Second Incremental Data Release. Bright stars will not be a major concern here because USNO-B does not independently locate bright stars. Rather, it simply incorporates Tycho-2 entries directly into the catalog. Hence, rNLTT and USNO-B typically have the same bright-star entries, since they both come from the same source. Bright stars are of interest only when they are components of common proper motion (CPM) binaries. In this case, the bright star is used solely to help establish the reality of the identification of its faint companion.

While the great majority of faint stars are identified as USNO-A/2MASS pairs, some are found through several other channels. First, if no plausible pair is found within 2′ of the position given by NLTT, but a 2MASS star is found within 12″ of the position predicted by NLTT, then it is accepted as a match (provided it does not have a USNO-A counterpart at the same position, which would indicate that it is not a high proper motion star). The theory is that the NLTT star is missing from USNO-A, which can happen due to crowding, faintness, nondetection on blue plates, or other reasons that are not discernible. Second, if there is a unique USNO-A star within a 16″ × 8″ rectangle of the NLTT position but no corresponding 2MASS star, then it also is accepted. In this case, it is assumed that the star is missing from 2MASS. Third, if a star is located either in a PPM catalog or as a USNO-A/2MASS pair, but its binary companion is not, then the 2MASS catalog is searched at the relative offset predicted by the NLTT notes on binaries. Companions within a few arcseconds of the predicted position are accepted, provided they do not have USNO-A counterparts (which again would indicate that they are not high proper motion stars). Finally, a small number of stars are identified by other means, for example, by confirming identifications of Bakos et al. (2002) using 2MASS.

At this point, rNLTT does not cover the whole sky. For faint stars, it is restricted to the 44% of the sky covered by intersection of the first Palomar Observatory Sky Survey (POSS I), roughly $\delta > -33°$, and the 2MASS Second Incremental Release. From the standpoint of doing statistical studies, this is not a significant limitation (e.g., Gould 2003), but it does need to be kept in mind.

The rNLTT is about 97% complete relative to NLTT up to $R_{\rm NLTT} \sim 17$ (roughly $V \sim 18$) and is 95% complete 1 mag fainter. However, in this last magnitude, the completeness is heavily dependent on single-catalog detections, which are less secure, while at brighter magnitudes the overwhelming majority of entries are detected in both USNO-A and 2MASS (see Fig. 13 of Salim & Gould 2003). This is important because, while the overall false identification rate in rNLTT is only 1%, these errors are probably concentrated in the single-catalog identifications.

The proper-motion errors in rNLTT are about 5.5 mas yr$^{-1}$, but this excludes the 3 $\sigma$ outliers (about 5%). However, in the present context, it is important to note that very few of these outliers lie beyond 30 mas yr$^{-1}$ (see Fig. 10 of Salim & Gould 2003). While these errors are based on relatively bright ($V \lesssim 12$) USNO-A/2MASS detections, a separate test on CPM binaries (but not reported by Salim & Gould 2003) shows that the errors do not evolve strongly with magnitude.

The epoch 2000 positions (and hence the position errors) come basically from 2MASS. These uncertainties in position are typically 130 mas, but do deteriorate for the faintest stars $V \sim 19$ to about 300 mas or so. This will be important when trying to evaluate the completeness of USNO-B in this faintest bin.

Finally, I review the characteristics of rNLTT binaries. The characteristic amplitude of the two-dimensional proper-motion differences induced by errors in the measurements of their *relative* positions is only 6 mas yr$^{-1}$. The vector separations given by the NLTT notes are generally accurate to less than 1″ (see Fig. 8 of Salim & Gould 2003). This permits an additional check on all stars that are members of binaries. When the two components are found separately, they must have the offset predicted by the NLTT notes. There are few enough candidate identifications that do not that satisfy this condition that these can be individually checked to insure that they are correct. For companions that are not identified independently, the precise prediction for each one's position allows identification with good confidence (and additional checks for the handful of suspicious cases). Thus, the 2MASS-only binary detections can be accepted with much higher confidence than is the case for single stars.

## 3. USNO-B COMPLETENESS FROM BINARIES

To determine USNO-B completeness, I consider a restricted set of rNLTT binaries. First, I examine only binaries for which both components are detected and for which these components are separated by at least $\Delta\theta \geq 10''$. Closer binaries can be blended in USNO-A, which leads to unreliable proper-motion measurements. Second, I exclude components of wider binaries that are themselves members of closer binaries. This includes both triple systems recognized by NLTT, as well as NLTT " single stars " that are resolved by the Tycho Double Star Catalog (TDSC, Fabricius et al. 2002). Third, I exclude all binaries for which both components have PPM identifications. As mentioned above, USNO-B generally takes over the Tycho-2 proper motion for these stars, so they contain no information on USNO-B completeness. Next, I exclude all binaries for which one component has a USNO-A–only identification because the additional checks discussed at the end of § 2 are not available for these stars. This leaves 548 pairs, of which 85 have at least one component that is detected in 2MASS only. I put these latter aside for the moment and return to them later. Hence, 463 pairs remain.

To match these stars, I first search within 1″ of their predicted position in USNO-B. There are only 12 multiple matches, and these are easily resolved by hand. For the nonmatches, I increase the search radius to 3″, which leads to 13 additional matches, all but one within 2″. Of the 463 pairs, 377 have USNO-B identifications for both components, 67 have USNO-B identifications for one component, and 19 have neither component identified in USNO-B.

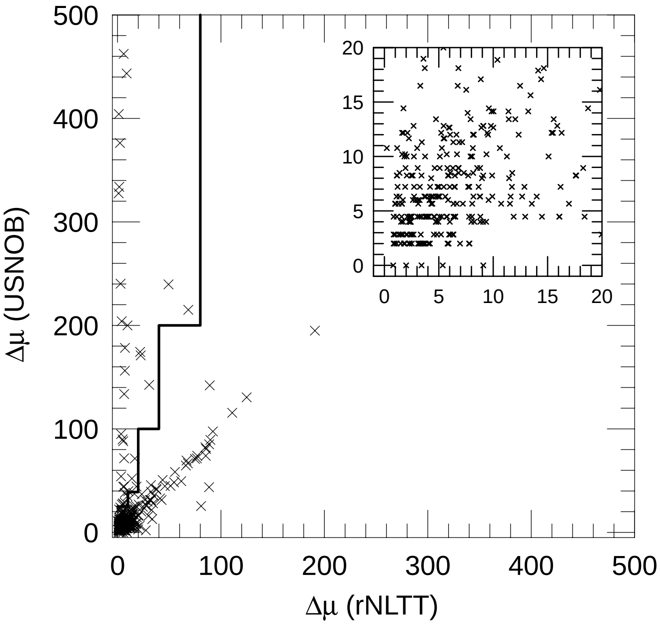

FIG. 1.—Magnitudes of the difference in the vector proper motions of NLTT " binaries " as measured by rNLTT (Gould & Salim 2003; Salim & Gould 2003) and USNO-B. The dense knot at the bottom left contains CPM binaries as determined by both USNO-B and rNLTT. The diagonal plume is non-CPM pairs as determined by both surveys. The vertical plume is CPM or near-CPM binaries for which USNO-B shows significantly discrepant proper motions. These pairs (defined by the bold boundary) are taken to have at least one erroneous USNO-B measurement.

Figure 1 shows the difference in the proper motion of the two components of the 377 binaries as measured by USNO-B and rNLTT. Of course to make this figure, I have included only binaries with independent detections of both components in each catalog. Figure 1 has three notable features: a diagonal plume, a vertical plume, and a dense knot close to the origin. The diagonal plume consists of pairs that are not physical pairs and were misidentified as such by Luyten. Both rNLTT and USNO-B agree on this verdict. The vertical plume consists of pairs that Luyten correctly identified as physical (or at any rate correctly identified as having very similar proper motions), as confirmed by rNLTT. The fact that USNO-B finds large proper motion differences between the components indicates that one or both measurements are erroneous. Note that there is no similar horizontal plume, which would consist of real CPM binaries that were confirmed as such by USNO-B but mismeasured by rNLTT. Finally, the dense knot consists of binaries that are confirmed by USNO-B and rNLTT to be physical. The inset shows that, while some of this relative motion may be real orbital motion, most of the scatter is uncorrelated between USNO-B and rNLTT and so is probably due to measurement error. The bold curve shows the contour to the left of which I conclude that one of the USNO-B measurements is in error. After inspection of these, I find that in one case, both are in error. There are three points that do not lie within this contour, nor in the dense knot, nor in the diagonal plume. In the following, I will assume that these are accurate measurements.

Figure 2 shows the individual components of the 463 binaries analyzed above (i.e., all pairs for which both

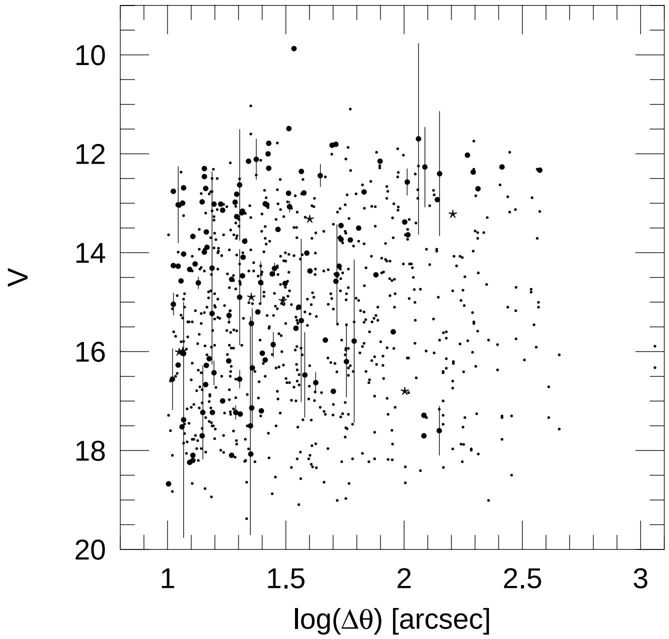

FIG. 2.—Recovery of NLTT binary members in USNO-B as functions of apparent $V$ magnitude and angular separation $\Delta\theta > 10''$. Small dots represent recovered stars whose proper motion agrees well with rNLTT (as defined by the bold boundary in Fig. 1). Filled circles are components that are either not found or whose proper motions do not agree well with rNLTT. In the latter case, the error bar indicates the size of the discrepancy in units of 200 mas yr$^{-1}$. Star symbols indicate stars recovered by USNO-B whose companions were not recovered and whose proper motions are discrepant with rNLTT. Binaries are included in this plot only if each component has a proper-motion measurement in rNLTT. Individual components whose measurement came from PPM catalogs rather than USNO-A/2MASS are excluded, since USNO-B did not measure them either.

components have independent rNLTT proper-motion measurements but excluding pairs for which both components were detected in PPM catalogs). These 463 pairs contain a total of 157 PPM stars, so the figure shows $2 \times 463 - 157 = 769$ stars. Of these, 32 (shown by filled circles with error bars) are erroneously measured components from the pairs lying inside the contour in Figure 1. The error bars indicate the proper-motion difference (i.e., the ordinate from Fig. 1) in units of 200 mas yr$^{-1}$ from USNO-B measurements. The filled circles without error bars represent the 96 stars that were not detected in USNO-B. When a star was detected in USNO-B but its companion was one of the 96 that were not, I checked its proper motion against rNLTT. The seven cases for which the difference exceeded 25 mas yr$^{-1}$ are shown by a star. The remaining 634 stars, which are deemed good proper-motion measurements, are shown by small dots. The $V$ magnitudes and $\Delta\theta$ separations are taken from rNLTT.

Figure 2 has two striking features. First, the "problem stars" (poor measurements and nonmatches) are concentrated at separations $\Delta\theta < 60''$. Second, in the region $\Delta\theta > 60''$, they are concentrated at bright magnitudes $V < 13.5$. Hence, one may already conjecture that these two problems are due to three effects, crowding (at very close separations), confusion (at moderate separations), and saturation at bright magnitudes. Plots (not shown) of problem stars versus position in celestial and Galactic coordinates reveal no obvious patterns.

To obtain a more complete picture, it is necessary to include the 2MASS-only detections from rNLTT. There are 85 such binaries, of which 39 have one component identified from PPM catalogs. Hence, there are an additional $2 \times 85 - 39 = 131$ stars for which USNO-B completeness and accuracy can in principle be tested. Of these, 59 are missing from USNO-B. When the remaining matches agree between USNO-B and rNLTT, I conclude that the USNO-B measurement is correct. There is a serious disagreement in only one case. By comparing the separations as listed in the NLTT notes and rNLTT, I find that the USNO-B proper motion is incorrect. In all the cases for which components are missing from USNO-B, comparison of the NLTT and rNLTT separations confirms that the proper motions of the two stars is similar enough that the 2MASS-only companion should have been recovered in USNO-B (if it had been there).

Figure 3 shows the components of these rNLTT binaries that were (*points*) and were not (*filled circles*) detected by USNO-B. The one USNO-B detection with a bad proper motion is indicated with an error bar. Both the underlying rNLTT sample and the USNO-B nondetections are heavily concentrated at small separations and faint magnitudes. This is reasonable. Most stars that are missing from USNO-A are either too crowded or too faint to be reliably detected. Proximity to a companion is one possible cause of crowding. These same features would make them difficult to detect in USNO-B (which is working off of the same and similar plate material). However, occasionally stars are missing from USNO-A for no discernible reason. If these stars were also preferentially missing from USNO-B, then one would expect a high relative density of solid circles among the relatively faint ($13.5 < V < 19$), well-separated ($\Delta\theta > 60''$) stars, which appear so reliably detected in

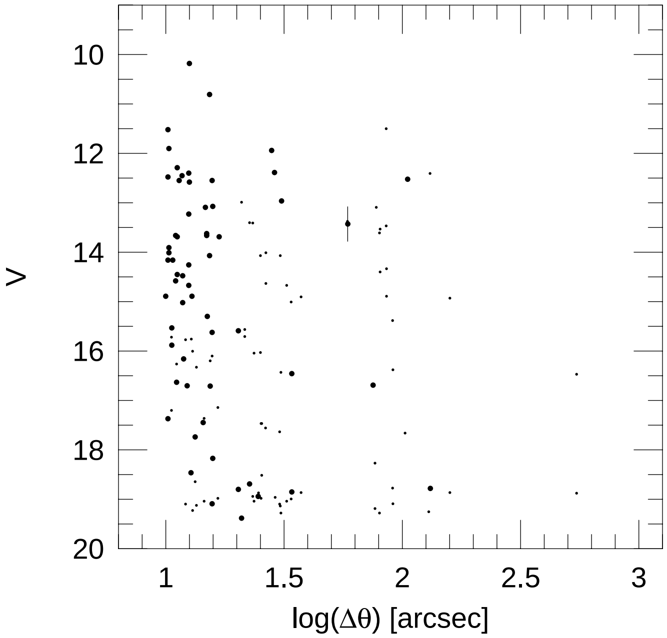

FIG. 3.—Similar to Fig. 2, except for binaries that have at least one component detected by rNLTT in 2MASS only. For these, proper-motion information can be obtained by comparing 2MASS-epoch separations with those given in the NLTT notes. Close separations and faint magnitudes are overrepresented here relative to Fig. 2 because these stars are preferentially missing from USNO-A.

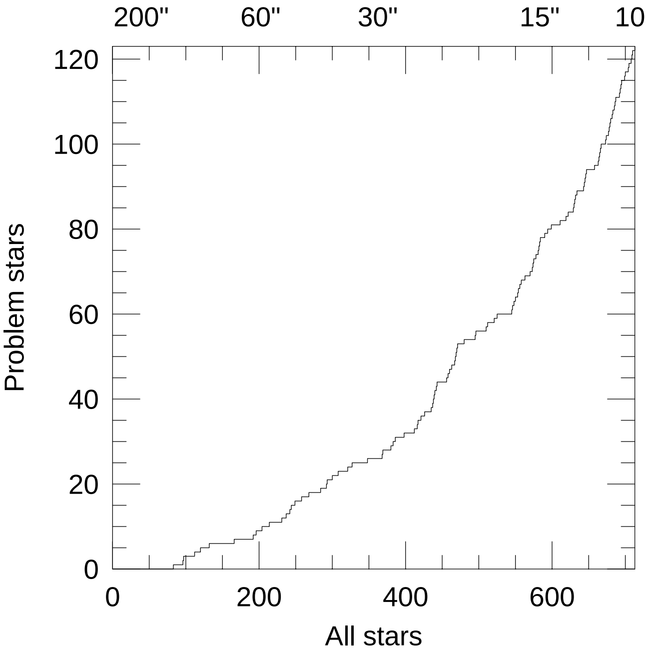

FIG. 4.—Cumulative distribution of problem stars (those missing from USNO-B or with discrepant proper motions) ranked by binary separation. There is a clear break at 30″ due to the onset of confusion caused by the presence of a companion within this radius. Apparent breaks in the curve at wider separations are consistent with statistical fluctuations.

Figure 2. That this is not the case will be important in the interpretation of the single-star results reported in § 4.

Figure 4 shows the cumulative distribution of "problem stars" (relative to all stars) as a function of binary separation. Problem stars are defined as those that were not detected in USNO-B, or whose proper motions are significantly in error (Figs. 2 and 3, *filled circles and stars*). This cumulative distribution is restricted to stars $V > 13.5$. For $\Delta\theta \geq 60''$, the problem rate is $9/203 = 4.5\%$, while for $30'' \leq \Delta\theta < 60''$, the rate is $17/164 = 10\%$, and for $10'' \leq \Delta\theta < 30''$, it is $97/346 = 28\%$. Apparently, the detection problems increase substantially for $\Delta\theta < 60''$ and do so much more dramatically for $\Delta\theta < 30''$.

These results are somewhat puzzling. While problems at $\Delta\theta = 30''$ are easy to understand, it is much more difficult to account for problems at $\Delta\theta = 60''$. USNO-B attempts to associate unmatched stars at displacements up to 30″ of their counterpart's position at a previous epoch. Hence, a binary companion at 30″ (which would of course be initially unmatched by the preliminary algorithm that matches nonmoving stars) could easily cause confusion. Stars at somewhat greater separation could still create problems if their proper motions moved them within 30″. However, the problem stars have rather typical proper motions for NLTT, with almost all having $\mu < 500$ mas yr$^{-1}$. Such proper motions would carry them only 15″ (and generally much less) over typical 30 yr epoch differences. One is therefore led to suspect some sort of selection effect in the procedure I have adopted. However, I am unable to think of any that could produce this effect.

Thus, on physical grounds, the problem rate should be roughly independent of separation for $\Delta\theta > 30''$. The mean rate at these separations is $26/367 = 7\%$. The number expected outside $\Delta\theta > 60''$ is then about 15. Hence, the nine actually counted is low by only 1.5 $\sigma$. The analysis of binaries therefore indicates that for separations too large to be affected by confusion and fainter than $V > 13.5$, the problem rate is about $7.1 \pm 1.4\%$. Inspection of Figures 2 and 3 shows that about two-thirds of these problem stars are missing from USNO-B, and most of the remainder have very significant errors, of order 100 mas yr$^{-1}$ or larger.

Data for the stars shown in Figures 2, 3 and 4 are given in Table 1. All binaries are listed in pairs of rows. Column (1) is the NLTT number. Column (2) gives my assessment of the USNO-B proper motion: −1 means excluded from sample (generally because it is a PPM star), 0 means missing from USNO-B, 1 (2) mean found in USNO-B but with an incorrect proper motion and with (without) a USNO-B companion (*points with error bars and stars*), and 3 means found in USNO-B with a good proper motion. Columns (3) and (4) give the rNLTT position. Columns (5) and (6) give the rNLTT proper motion. Columns (7) and (8) give the USNO-B proper motion. Columns (9) and (10) give the rNLTT $V$ and $V$–$J$. Column (11) gives the rNLTT three-digit source code. In particular, 555 means identified in USNO-A and 2MASS, 576 means identified in 2MASS as an NLTT CPM companion to another rNLTT star, and 566 means identified in 2MASS only based on the predicted NLTT position. The final two columns give the separation (in arcseconds) and position angle (in degrees) of the second component relative to the first. In the first row, these values are as given in the NLTT notes and, in the second, as given by the rNLTT positions.

## 4. USNO-B COMPLETENESS FROM SINGLE STARS

To find the incompleteness rate among single stars, I search for USNO-B matches to rNLTT stars whose proper motions are determined by finding counterparts in USNO-A and 2MASS. That is, all PPM detections, all USNO-A–only, and all 2MASS-only detections are eliminated. I also eliminate all binaries and all stars that are regarded as single by NLTT but are resolved in TDSC. These cuts define an rNLTT sample of 20,798 stars. As summarized in § 2, the proper motions for these stars are accurate to 5.5 mas yr$^{-1}$, with very few outliers beyond 30 mas yr$^{-1}$. The overall misidentification rate of the non-PPM stars in rNLTT is about 1%, but may differ for this subset because the subset excludes stars that were identified in only one catalog. The errors in the 2000 epoch positions are dominated by 2MASS astrometry errors and are therefore typically less than $0\overset{''}{.}2$.

I again begin by searching within a 1″ radius of rNLTT stars, which yields 18,420 unique matches and 446 double matches and one triple match. For the multiple matches, I choose the better match by hand. I then search among the 1931 nonmatches for USNO-B entries lying within a 3″ circle. For this larger radius, I accept only those stars with proper motions within 200 mas yr$^{-1}$ of rNLTT or (in 11 cases) for which USNO-B has a flag indicating a probable match with NLTT. This procedure recovers a total of 130 matches, all unique. That is, there are net totals of 18,997 matches and 1801 nonmatches.

### 4.1. *Characterization of Matches*

Figure 5 shows the magnitudes of the vector differences of three different proper-motion measurements: the abscissa is the difference between rNLTT and NLTT, while the ordinate

## TABLE 1
### BINARY SAMPLE

| NLTT No. (1) | USNO-B Validity (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | $\mu_\alpha$ (rNLTT) (arcsec yr$^{-1}$) (5) | $\mu_\delta$ (rNLTT) (arcsec yr$^{-1}$) (6) | $\mu_\alpha$ (USNO-B) (arcsec yr$^{-1}$) (7) | $\mu_\delta$ (USNO-B) (arcsec yr$^{-1}$) (8) | $V$ (mag) (9) | $V-J$ (mag) (10) | NLTT Source (11) | $\Delta\theta$ (arcsec) (12) | $\phi$(NLTT) (deg) (13) | $\Delta\theta$ (arcsec) (14) | $\phi$(rNLTT) (deg) (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2...................... | 3 | 0.63623 | −8.43833 | −0.0797 | −0.1109 | −0.082 | −0.112 | 12.41 | 2.10 | 555 | 88.0 | 39.0 | . . . | . . . |
| 3...................... | 3 | 0.65651 | −8.41476 | −0.0672 | −0.1847 | −0.070 | −0.182 | 15.37 | 3.32 | 555 | . . . | . . . | 111.4 | 40.4 |
| 84.................... | 1 | 1.04642 | −10.13772 | 0.1437 | 0.0814 | −0.284 | −0.026 | 17.50 | 3.49 | 555 | 23.0 | 123.0 | . . . | . . . |
| 86.................... | −1 | 1.05174 | −10.14110 | 0.1499 | 0.0752 | 0.148 | 0.074 | 9.83 | 1.23 | 121 | . . . | . . . | 22.4 | 122.8 |
| 175.................. | 3 | 1.40156 | −1.66081 | 0.3251 | 0.1279 | 0.322 | 0.134 | 17.16 | 4.28 | 555 | 19.0 | 166.0 | . . . | . . . |
| 176.................. | 3 | 1.40364 | −1.66565 | 0.3235 | 0.1260 | 0.320 | 0.130 | 15.93 | 4.08 | 555 | . . . | . . . | 19.0 | 156.8 |
| 401.................. | 3 | 2.30079 | −30.56101 | 0.1361 | −0.0860 | 0.116 | −0.088 | 17.59 | 4.34 | 555 | 88.0 | 147.0 | . . . | . . . |
| 410.................. | 3 | 2.31543 | −30.58221 | 0.0722 | −0.1490 | 0.048 | −0.146 | 14.56 | 1.17 | 555 | . . . | . . . | 88.8 | 149.3 |
| 405.................. | 3 | 2.32910 | 48.33399 | 0.2048 | −0.0050 | 0.204 | 0.002 | 16.41 | 3.37 | 555 | 52.0 | 116.0 | . . . | . . . |
| 412.................. | 1 | 2.34866 | 48.32773 | 0.2013 | −0.0031 | 0.000 | 0.000 | 14.44 | 2.50 | 555 | . . . | . . . | 52.0 | 115.7 |

NOTES.—Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. USNO-B validity is as follows: (−1) not used; (0) not in USNO-B; (1) bad USNO-B proper motion (with USNO-B companion); (2) bad USNO-B proper motion (without USNO-B companion); (3) good USNO-B proper motion.

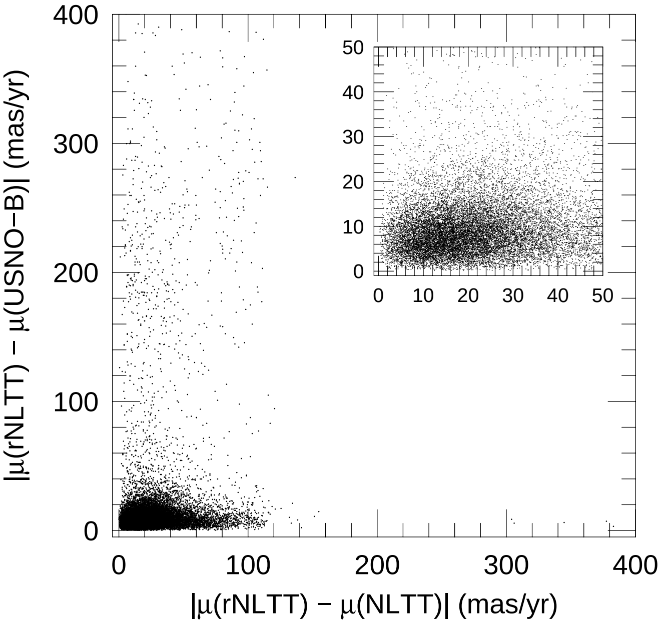

FIG. 5.—Magnitude of the vector difference of proper motions as given in three catalogs: rNLTT, NLTT, and USNO-B. The abscissa is the difference between rNLTT and NLTT, while the ordinate is the difference of rNLTT and USNO-B. Inset shows an expanded version of the knot at bottom left. Theoretical arguments predict that the vertical plume to the left (at ~30 mas yr$^{-1}$) is due to errors in USNO-B, while the one at ~90 mas yr$^{-1}$ is due to misidentifications in rNLTT.

is the difference between rNLTT and USNO-B. The figure has three prominent features: a dense horizontal plume along the $x$-axis extending out to ~115 mas yr$^{-1}$, a much less dense vertical plume centered at ~30 mas yr$^{-1}$, and a still less dense vertical plume centered at ~90 mas yr$^{-1}$. The first vertical plume extends down to the horizontal plume, but the second appears to cut off below ~150 mas yr$^{-1}$.

The horizontal plume occurs because there is a tail of NLTT proper-motion errors extending out to 100 mas yr$^{-1}$ and beyond. USNO-B confirms that the rNLTT measurements are correct, which is what gives this plume its horizontal character. Salim & Gould (2003) generally searched for 2MASS counterparts to USNO-A candidates only in a 5″ radius around the position predicted using the NLTT proper motion. Since the typical epoch difference between these surveys is ~43 yr, the maximum proper-motion difference is 5″/43 yr ~ 115 mas yr$^{-1}$, which accounts for the cutoff.

The two vertical plumes (separated somewhat arbitrarily at $\Delta\mu = 60$ mas yr$^{-1}$) contain, respectively, 647 and 168 stars above 50 mas yr$^{-1}$. The first vertical plume is due to large USNO-B errors. The fact that the plume is centered at ~30 mas yr$^{-1}$, which is the size of the (two-dimensional) NLTT proper-motion errors (Salim & Gould 2003), means that NLTT confirms the rNLTT measurements. About 37% of this plume is made up of bright ($V < 14.5$) stars, although these make up only 22% of the whole sample. Thus, large errors are overrepresented at bright magnitudes but extend to faint stars as well.

The second plume is due to false identifications in rNLTT, i.e., pairs of unrelated USNO-A and 2MASS stars that happened to have approximately the vector separation predicted by the NLTT proper motion. These tend to be found near the edge of the 5″ search circle (which contains the most area). About half of these points have $V > 18.5$ despite the fact that these faint stars comprise only 6% of the sample. Such false identifications are most likely when the NLTT star is absent from USNO-A, and this occurs most frequently for faint stars. The plume appears to begin at 150 mas yr$^{-1}$ because the 2MASS star does not have a high proper motion. Hence, the ordinate is roughly equal to the rNLTT proper motion whose scale is set by the proper-motion limit of NLTT, 180 mas yr$^{-1}$.

### 4.2. *Cleaning rNLTT of Misidentifications*

Since on the order of 15% of rNLTT entries are either missing from USNO-B or have USNO-B counterparts with very discrepant proper motions, while only 1% of rNLTT entries are the result of misidentifications, one could ignore these misidentifications without a major impact on the estimate of the *overall* USNO-B error rate. However, as analyzed in § 4.1, rNLTT misidentifications are concentrated at faint magnitudes. Hence, for purposes of understanding the USNO-B error rate as a function of magnitude, it will be important to remove the rNLTT misidentifications to the extent possible. The comparison with USNO-B offers a unique opportunity to do this: one may assume that when USNO-B and rNLTT agree on the vector proper motion of a star (located to within ~1″), both catalogs are correct. Thus, one need focus only on the nonmatches and the discrepant proper motions.

I begin by investigating the stars with vector proper-motion differences ≥100 mas yr$^{-1}$, i.e., the two vertical plumes in Figure 5. For each such star, I examine the two epochs of the DSS[1] (DSS 1 and DSS 2) to see if the rNLTT star actually moved and if so, whether it moved in approximately the direction given by rNLTT. If it did, I assume that the motion was properly measured by rNLTT because, as discussed in § 2, rNLTT proper-motion errors are small with very few outliers. If it did not move, I assume that the rNLTT identification was incorrect. I restrict this investigation to northern stars $\delta > 5°$. For southern stars, the first epoch can be quite late, so that there is only a very short interval between DSS 1 and DSS 2. This can make it extremely difficult, or in some cases impossible, to determine if the star moved. While POSS I is in principle available in digitized form from the USNO Web site, the turnaround time for requests is about 20 minutes, making large-scale investigations of this sort impractical. I return to the problem of the southern sky, $-33° < \delta < 5°$, below ($\delta = 5°$ is a convenient dividing line because it is approximately at the center of a band that is virtually completely missing from the 2MASS Second Incremental Release, and so from rNLTT).

Of the 400 such stars, I examined the first 265 in order of right ascension. This was sufficient to determine the pattern: the great majority of rNLTT misidentifications are stars for which rNLTT and NLTT disagree on position by $\Delta\theta > 50''$. The handful of misidentifications with $\Delta\theta < 50''$ mostly had vector proper motions that differed by $\Delta\mu > 70$ mas yr$^{-1}$ between rNLTT and NLTT. I therefore continued the DSS inspections only for stars with *either* $\Delta\theta > 25''$ *or* $\Delta\mu > 50$

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[1] See http://archive.eso.org/dss/dss.

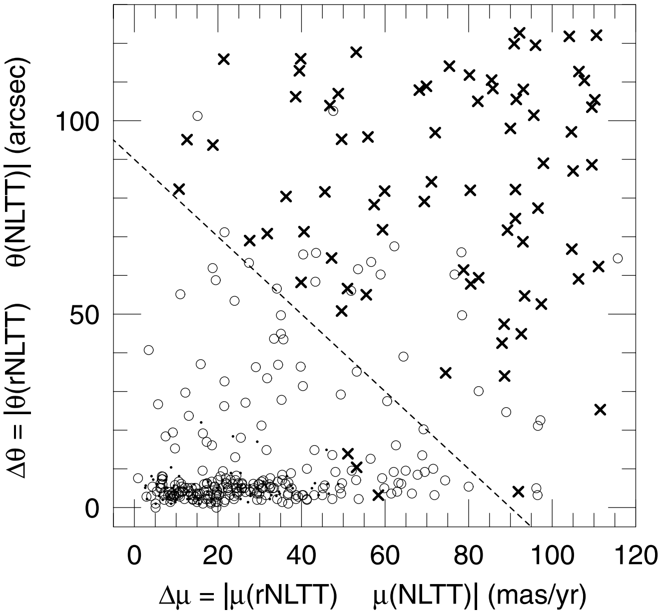

FIG. 6.—Differences of vector proper motions ($\Delta\mu$) between rNLTT and NLTT versus differences in vector positions ($\Delta\theta$) plotted for stars with major proper-motion discrepancies (greater than 100 mas $\mathrm{yr}^{-1}$) between USNO-B and rNLTT. That is, for the vertical "plumes" in Fig. 5. However, this diagram is restricted to stars with $\delta > 5°$, whereas Fig. 5 contains stars $\delta > -33°$. The crosses and circles represent rNLTT misidentifications and confirmed identifications, respectively. The dots are stars that have not been specifically checked, but their position on this diagram argues that they represent correct rNLTT identifications (and so are actually USNO-B errors.) The great majority of misidentifications lie to the top right of the dashed line given by equation (1).

mas $\mathrm{yr}^{-1}$. Figure 6 shows the results of this study. The dashed line

$$\frac{\Delta\theta}{1''} + \frac{\Delta\mu}{1\ \mathrm{mas\ yr^{-1}}} = 90 \qquad (1)$$

roughly specifies the boundary between the rNLTT and USNO-B errors: the great majority of the stars to the top right of this boundary are rNLTT misidentifications, while the great majority to the bottom left are USNO-B errors.

Figure 7 is a blowup of the two vertical plumes identified in Figure 5. This confirms that the right plume is primarily due to rNLTT misidentifications, while the left plume is primarily due to USNO-B errors. Note that there are very few rNLTT misidentifications with rNLTT/USNO-B vector differences below 150 mas $\mathrm{yr}^{-1}$. This is because for almost all such misidentifications, the 2MASS star is not moving significantly. USNO-B then properly measures this star as not moving, so the proper-motion difference is equal to the rNLTT proper motion. Since NLTT selects stars by $\mu \geq 180$ mas $\mathrm{yr}^{-1}$, the rNLTT proper motions are rarely far below this cutoff. Hence, it is not necessary to inspect DSS for the stars with proper-motion differences below 100 mas $\mathrm{yr}^{-1}$.

For the 921 nonmatches, I proceed similarly. I examine each of the first 50 stars, plus all the other stars with *either* $\Delta\theta > 25''$ *or* $\Delta\mu > 70$ mas $\mathrm{yr}^{-1}$. Since this search reveals only three stars with $\Delta\theta < 50''$ and only one with $\Delta\theta < 35''$, I assume that the great majority of the remaining stars (most of which are tightly clustered at $\Delta\theta < 10''$) are valid rNLTT identifications (see Fig. 8).

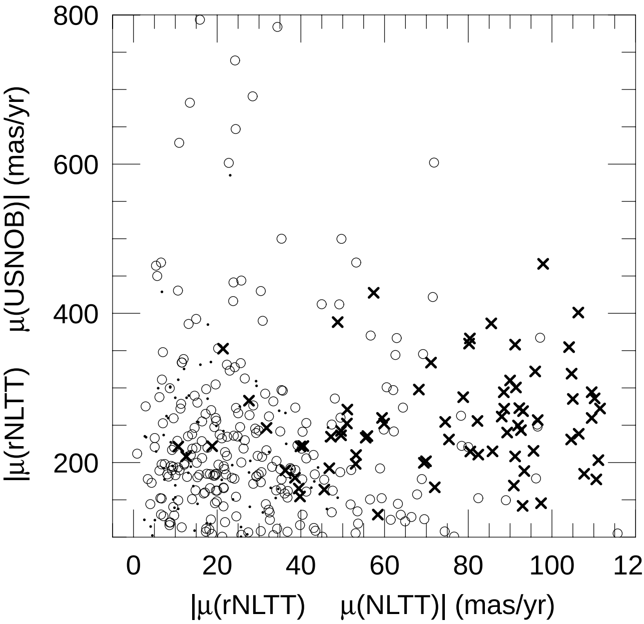

FIG. 7.—Blowup of the two vertical plumes from Fig. 5 with the same stars displayed (and with the same symbols) as Fig. 6. This diagram confirms the argument given in § 4.1 that the left plume is composed primarily of USNO-B errors and the right plume primarily of rNLTT misidentifications.

This search locates a total of 76 rNLTT misidentifications from among the 400 matches (having rNLTT/USNO-B vector proper-motion differences greater than 100 mas $\mathrm{yr}^{-1}$) and 21 from among the 921 nonmatches. I estimate that there are perhaps a dozen additional misidentifications among the $75 + 716 = 791$ stars that I did not examine individually.

To estimate the number of misidentifications in the south, $-33° < \delta < 5°$, I use equation (1). I find that 78 out of the 201 matches with rNLTT/USNO-B vector proper-motion

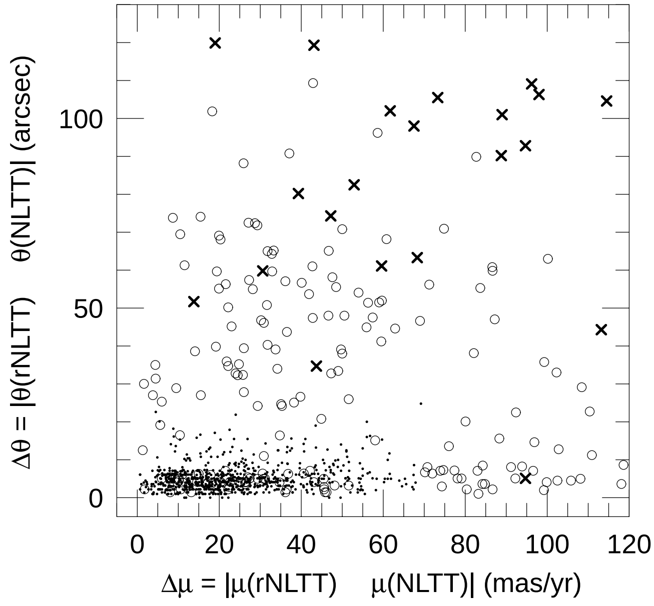

FIG. 8.—Similar to Fig. 6 except for rNLTT stars that are missing from USNO-B.

differences greater than 100 mas $\mathrm{yr}^{-1}$ lie beyond this boundary. Of course, some of these are not misidentifications, while other misidentifications lie within the boundary or appear as nonmatches. However, since the total number of such stars is expected to be small, perhaps a few dozen, they do not significantly influence the *statistical* inferences derived in the following sections.

Finally, I comment on potential rNLTT misidentifications among the binaries. There are not expected to be many because the overall rNLTT misidentification rate is 1% (as found by Salim & Gould 2003 and confirmed just above), and the vast majority of these have position differences $\Delta\theta > 50''$ from their NLTT-predicted positions. In the case of binaries, their offset from their CPM companion is given by the NLTT notes. Hence, the chance of a misidentification when the rNLTT offset agrees with the NLTT notes is extremely small. The main possibility for a misidentification is simply that Salim & Gould (2003) failed to properly check the small percentage of cases for which the offset is large, in order to confirm that these resulted from a transcription error. I therefore began by rechecking the four cases for which USNO-B failed to confirm the rNLTT proper motion (to within 30 mas $\mathrm{yr}^{-1}$) or failed to detect the rNLTT star, and for which rNLTT and NLTT disagreed on the offset by more than $5''$. One of these four (out of a total sample of 714 rNLTT binary members) was found to be a misidentification, i.e., a rate of ~0.1%. To be certain, I then individually inspected the 26 "problem stars" on which I based the primary conclusions of § 3 (i.e., those with binary separations greater than $30''$) on DSS. As expected, no additional misidentifications were found. The one rNLTT misidentification found by these procedures was removed prior to making the analysis reported in § 3.

### 4.3. *Comparison by Magnitude*

Figure 9 shows the fraction of problem stars as a function of $V$ apparent magnitude. The fraction that are "bad" or missing is denoted by a filled circle whose error bar is estimated from Poisson (actually binomial) statistics. The fraction that are simply missing from USNO-B is denoted by a cross. Here "bad" means that the amplitude of the vector difference of the USNO-B and rNLTT proper motion exceeds 30 mas $\mathrm{yr}^{-1}$ and also exceeds twice the USNO-B proper-motion errors. Recall that very few rNLTT stars have errors as large as 30 mas $\mathrm{yr}^{-1}$ (Salim & Gould 2003). Among those designated "bad," three-quarters have proper-motion differences exceeding 40 mas $\mathrm{yr}^{-1}$ and one-half exceeding 100 mas $\mathrm{yr}^{-1}$.

The results presented in Figure 9 are broadly consistent with those discussed in § 3 but contain more detail. The fraction of USNO-B stars that are either unmatched or have bad proper motions is consistently ~9% over the magnitude range $14.5 \leq V \leq 18.5$. This is consistent, within statistical uncertainties, with the estimate 7.1% ± 1.3% from wide binaries. Also in agreement with the binary analysis is the fact that about two-thirds of these problem stars are unmatched, and the remaining one-third have large proper motion errors. However, the much better statistics allow one to discern that the problems with bright stars actually extend beyond the $V = 13.5$ boundary inferred from Figure 2 to the $V = 14$ bin. Finally, there is a clear worsening in the final bin, $V = 19$, both for missing and large-error stars. One might be concerned that the rNLTT errors themselves grow worse at these faint magnitudes which, if true, would artificially inflate the number of USNO-B stars with apparently large errors. However, this potential problem would not affect the unmatched stars, which show the most severe worsening for this bin.

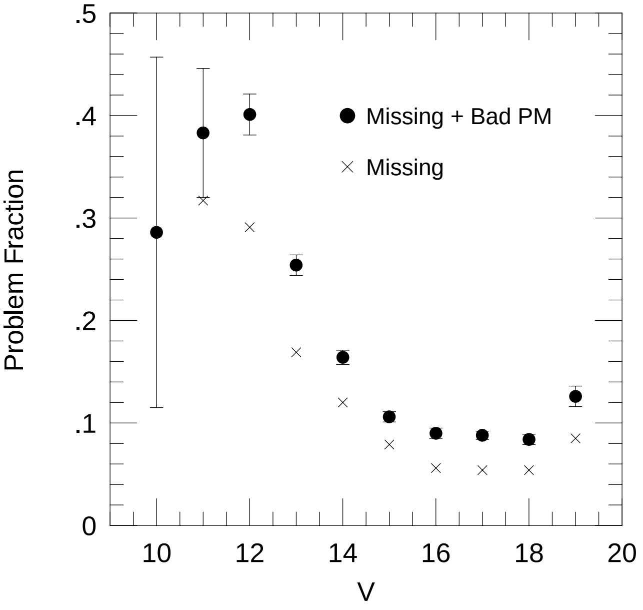

FIG. 9.—Incompleteness of USNO-B as a function of $V$ mag for a sample drawn from rNLTT nonbinary stars with identifications in both USNO-A and 2MASS. The crosses indicate the fraction that is strictly missing from USNO-B. The solid circles add in the stars whose discrepancy with rNLTT exceeds 30 mas $\mathrm{yr}^{-1}$. For the majority of these, the discrepancy exceeds 100 mas $\mathrm{yr}^{-1}$. Error bars are based on counting statistics.

One may be concerned that the results shown in Figure 9 are biased because the rNLTT sample does not include NLTT stars that lacked counterparts in USNO-A. If such nonidentifications are correlated between USNO-A and USNO-B, then the resulting incompleteness estimates would be too low. In fact, this is a potential concern only for the last two bins, $V = 18$ and $V = 19$. For $13 \leq V \leq 17$, the 2MASS-only entries make up less than 1% of rNLTT stars, so the correction is much less than this value. For the final two bins, the 2MASS-only entries make up 3% and 33%, respectively. I find that in each case, about 22% of these 2MASS-only stars are missing from USNO-B, while about 50% are either missing or have discrepant proper motions. Even if these designations were taken at face value, the fraction of problem stars in the $V = 18$ bin would only rise from 9% to 10%, which is barely significant. By contrast the fraction of problem $V = 19$ stars would rise from 13% to 25%. However, the characterization of the 2MASS-only stars must be interpreted very cautiously. In contrast to the binary case, we have no independent confirmation that the 2MASS-only identifications are real. In addition, if they are, we have no assurance that the adopted NLTT proper motions are correct. While Salim & Gould (2003) showed that the total fraction of false identifications in rNLTT is ~1%, these are very likely concentrated in the 2MASS-only detections. Since less than 3% of the rNLTT sample has 2MASS-only identifications, no strong conclusion can be drawn from the higher rate of USNO-B "incompleteness" of these stars. In addition, for the case of binaries (for which we do have independent checks on the reality of the

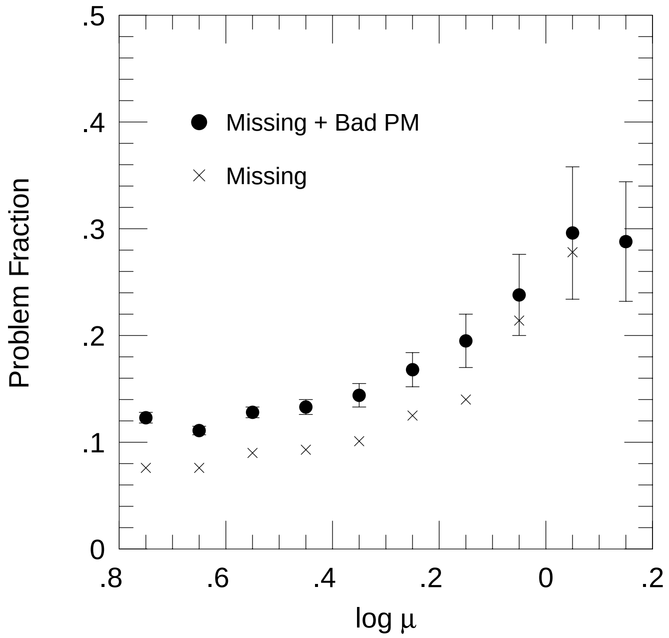

FIG. 10.—Incompleteness of USNO-B as a function of proper motion $\mu$. Symbols are the same as in Fig. 9. The last bin actually includes all stars $\mu > 1259$ mas $\mathrm{yr}^{-1}$.

identifications), there is no evidence for an especially high incompleteness rate for 2MASS-only rNLTT identifications at $V \sim 19$. In brief, the incompleteness estimates shown in Figure 9 are probably not seriously affected by the exclusion of 2MASS-only stars from the sample.

### 4.4. *Comparison by Proper Motion*

Figure 10 shows that USNO-B incompleteness gradually rises toward higher proper motion. This is to be expected from the intrinsic difficulty of identifying high proper motion stars on plates separated by one to several decades. It is somewhat exacerbated by the fact that USNO-B does not attempt to find counterparts whose plate positions differ by more than $30''$ at different epochs. Hence, very high proper motion stars can be lost simply because they have moved too far between epochs to be recovered. Note that the fraction of bad proper motions actually shrinks toward high proper motions. That is, if the star is recovered at all, its proper-motion measurement is rarely seriously in error.

### 4.5. *Comparison by Galactic Latitude*

Figure 11 shows USNO-B incompleteness relative to rNLTT as a function of (the sine of) Galactic latitude. The sample is restricted to the magnitude range $13.5 < V < 18.5$ for which overall completeness is a maximum (see Fig. 9). As would be expected, incompleteness peaks sharply at the Galactic plane.

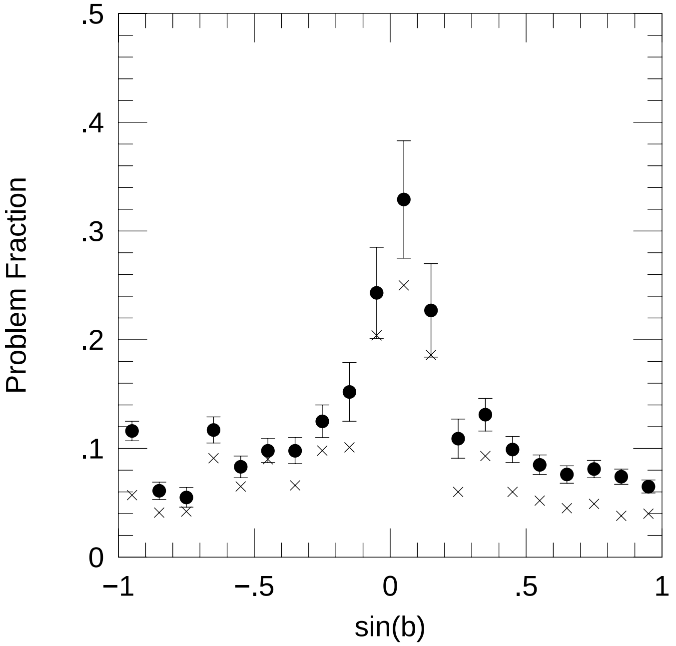

FIG. 11.—Incompleteness of USNO-B as a function of Galactic latitude $b$. Symbols are the same as in Fig. 9. Because NLTT (and so rNLTT) is very incomplete in the plane for $V \gtrsim 14$, this completeness test applies essentially to brighter stars.

However, Figure 11 should be interpreted cautiously. NLTT (and so rNLTT) is seriously incomplete near the plane at these faint magnitudes, increasing to ~90% for $15 < V < 19$ within $|b| < 5^{\circ}.7$ of the plane.[2] Since it is not known precisely what distinguishes the very few stars found by Luyten from the vast majority that he missed, one also does not know whether these are more or less likely to have been found by USNO-B. For example, Luyten's completeness was higher for LHS than NLTT. See, for example, the comparison of the studies by Monet et al. (2000) and Reid (1990) given in the appendix to Gould (2003). Since USNO-B is more incomplete for these higher proper motion stars (see Fig. 10), this effect would tend to cause USNO-B incompleteness to be overestimated. On the other hand, Luyten may have preferentially recovered stars that were intrinsically easier to find, such as brighter stars. If USNO-B also had an easier time recovering such stars, this would cause USNO-B incompleteness to be underestimated.

We can get some handle on the latter problem by considering the sample of 141 non-NLTT stars satisfying $|b| < 25^{\circ}$, $500\ \mathrm{mas\ yr}^{-1} < \mu < 2000\ \mathrm{mas\ yr}^{-1}$, $\delta > -2.8$, and $9 < R < 20$ found by Lépine et al. (2002). In order to compare as directly as possible with the central two bins of Figure 11, I further restrict this sample to the 40 (nonbinary) stars satisfying $|b| < 5^{\circ}.7$ and $14 < R < 18$. Of these, 20 have good USNO-B matches, and another four have matches with proper-motion discrepancies larger than 30 mas $\mathrm{yr}^{-1}$. That is, 40% are missing, and 50% ± 8% are either missing or bad. These numbers are somewhat higher than the two central bins of Figure 11. However, given that USNO-B incompleteness is already known to increase at these higher proper motions (see Fig. 10), the results are roughly consistent.

Lépine et al. (2002) suggest that their survey may be 99% complete for $9 < R < 19$ based on its efficiency recovering NLTT and LHS stars. If this were true, then the above analysis would imply that USNO-B is about 60% complete even very close to the plane. However, Lépine et al. (2002) also allow that NLTT has preferentially found the easiest

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[2] Figure 14 of Salim & Gould (2003) is improperly labeled. In fact, the solid (thin) histograms in the top and middle panels refer, respectively, to main-sequence and subdwarf stars in the magnitude range $V > 15$.

stars, so that no strong conclusion can be derived from the fact that their survey also recovered these. Indeed, this is very likely the case, as one may verify by comparing Figure 13 of Salim & Gould (2003) with Figure 3 of Lépine et al. (2002). The former shows that the NLTT "luminosity function" for the whole sky begins falling only for $R > 17.5$, while the latter shows that the luminosity function of Lépine et al. (2002) stars begins falling for $R > 14$. As argued by Salim & Gould (2003), the NLTT turnover is a product of the turnover in the M dwarf luminosity function combined with the effective distance cutoff imposed by the proper-motion selection (rather than a steep decline in NLTT completeness). Since the proper-motion limit of Lépine et al. (2002) is about 2.8 times greater than NLTT, one would expect this turnover to move 2.2 mag brighter. The fact that it is actually 3.5 mag brighter therefore probably indicates incompleteness of Lépine et al. (2002) at faint magnitudes. Thus, at the present time, it is simply not possible to draw strong conclusions about the completeness of USNO-B for faint stars close to the Galactic plane.

### 4.6. *Restricting the rNLTT/USNO-B Comparison to $\delta > 5°$*

Recall from § 4.2 that only the northern ($\delta > 5°$) two-thirds of the rNLTT were properly cleaned of misidentifications. The procedure to remove misidentifications from the south was cruder. Thus, one might wonder how Figures 9–11 would be affected if they were restricted to northern data. I find that overall they look extremely similar, with error bars that are about 20% larger and a correspondingly larger scatter. The one major exception is the central bin of Figure 11, which is reduced from ~33% to ~25%. However, as noted in § 4.5, the interpretation of this bin is somewhat muddled in any case. In addition, of course, the southernmost bin is completely devoid of data if the south is eliminated and the neighboring bin becomes highly uncertain as well. Since the two sets of plots do not significantly differ, I show the one representing all the available data.

## 5. PROPER-MOTION ERRORS

I determine the USNO-B errors as a function of $V$ magnitude by calculating the rms difference between the rNLTT and USNO-B measured proper motions and subtracting (in quadrature) the rNLTT errors, $\sigma_\mu(\mathrm{rNLTT}) = 5.5$ mas yr$^{-1}$. The resulting external estimates per component of the USNO-B errors are shown as open circles in Figure 12. These estimates are derived by excluding 3 $\sigma$ outliers, which constitute roughly 5% of the sample for $13 \le V \le 18$ and 12% for the remaining three bins. These external errors may be compared with the rms internal errors shown as crosses, which are computed from the errors tabulated for the same stars in USNO-B. The two sets of estimates are in good overall agreement, showing that both USNO-B and rNLTT errors are well estimated on average.

How good are the individual USNO-B error bars? Figure 13 shows external error estimates based on comparison with rNLTT as a function of internally reported USNO-B errors. Again 3 $\sigma$ outliers have been excluded and the 5.5 mas yr$^{-1}$ errors of rNLTT have been subtracted in quadrature. The internal error estimates are accurate over the range 4–20 mas yr$^{-1}$. There appears to be a threshold of $\sigma_\mu = 4$ mas yr$^{-1}$. USNO-B stars with listed error estimates below this level should be reset at the threshold. In addition, stars with reported errors larger than 20 mas yr$^{-1}$ may have even larger errors.

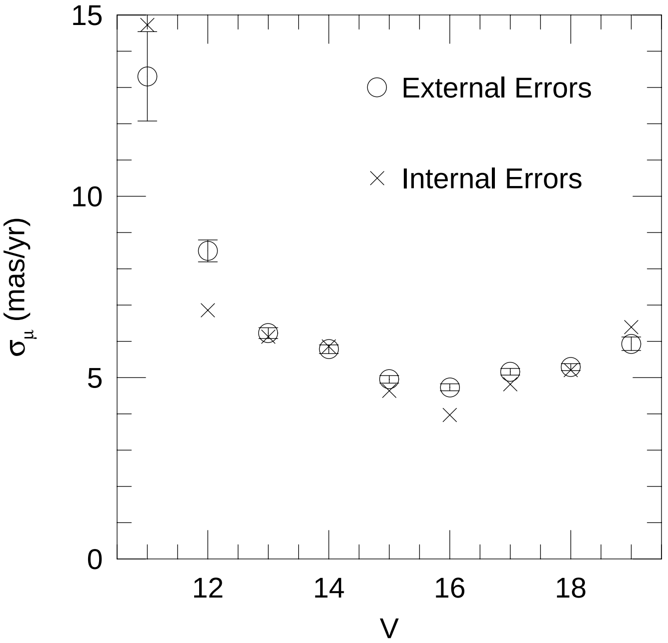

FIG. 12.—Proper-motion errors of USNO-B stars as a function of $V$ mag. Open circles show the estimate based on a star-by-star comparison with rNLTT with 3 $\sigma$ outliers removed and with the rNLTT error (5.5 mas yr$^{-1}$) subtracted in quadrature. Crosses show the rms errors of the same stars as reported by USNO-B. The error bars are based on counting statistics. Generally, the agreement is quite good indicating that, on average, both catalogs have estimated their errors correctly.

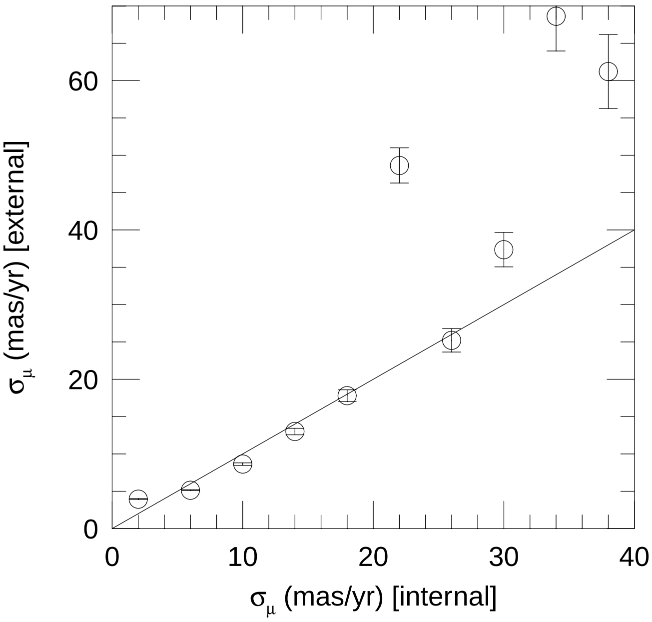

FIG. 13.—Proper-motion errors of USNO-B as a function of internally reported error estimates. Line indicates equality. Agreement is excellent for 4 mas yr$^{-1}$ $< \sigma_\mu <$ 20 mas yr$^{-1}$. The leftmost point probably indicates an error floor of $\sigma_\mu \sim 4$ mas yr$^{-1}$, even when the internally reported errors are below this value. The relatively few stars with very large reported proper-motion errors ($\sigma_\mu > 20$ mas yr$^{-1}$) may in fact have even larger errors.

## 6. DISCUSSION

As discussed in § 1, USNO-B cannot be consulted directly as a high proper motion catalog because of the large number of spurious entries. Here I briefly outline several approaches to using USNO-B to construct such a catalog.

First, USNO-B can be used to check the identifications of NLTT stars by rNLTT. I have already done this for a large fraction of stars by first isolating the rNLTT stars that are not confirmed by USNO-B, and then investigating the subset of these that arouse the greatest suspicion based on disagreements between rNLTT and NLTT. This procedure could be extended to the 2MASS-only and USNO-A–only indentifications in rNLTT.

Second, USNO-B can be used to extend rNLTT to the rest of the sky. For faint stars ($V \gtrsim 12$), rNLTT currently covers only the 44% of the sky defined by the intersection of the 2MASS Second Incremental Release and POSS I. After the full 2MASS release, it will be possible to apply the approach of Salim & Gould (2003) to the rest of the POSS I sky ($\delta > -33$), but this process would be extremely laborious. It may be far simpler to simply match USNO-B to 2MASS. This would eliminate the great majority of spurious USNO-B entries. The USNO-B/2MASS matches could then be paired to NLTT stars using the strategy described in § 3 of Gould & Salim (2003). Moreover, this approach could equally well be applied to stars south of POSS I where the method of Salim & Gould (2003) fails because USNO-A is missing most high proper motion stars in this region.

The problem of using USNO-B to overcome NLTT's incompleteness is more difficult. Once USNO-B is matched to 2MASS, as described above, one will be able to determine the rate of spurious entries by comparing with NLTT. It may then also be possible to recognize such spurious entries based on the internal characteristics of the matched entries. For example, discrepancies in the photographic magnitudes at various USNO-B epochs, or inconsistencies between the optical and infrared colors could turn out to be efficient indicators of spurious entries. Astrometric inconsistencies between USNO-B and 2MASS may also be useful indicators. Analogs of both these approaches were used by Salim & Gould (2003) when matching 2MASS and USNO-A.

More difficult will be the problem of finding high proper motion stars that are too faint and/or blue to be present in 2MASS. For those stars in NLTT, the above-mentioned approach of Gould & Salim (2003) may work even without 2MASS counterparts. High proper motion stars that were missed by NLTT and are absent from 2MASS as well will be most difficult. Perhaps the most promising prospect is the semiautomatic procedure of Lépine et al. (2002).

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