Parallaxes of Cool Objects with WISE: Filling in for Gaia

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Abstract

This paper uses the multi-epoch astrometry from the Wide-field Infrared Survey Explorer (WISE) to demonstrate a method to measure proper motions and trigonometric parallaxes with precisions of ~4 mas yr\(^{-1}\) and ~7 mas, respectively, for low-mass stars and brown dwarfs. This method relies on WISE single exposures (Level 1b frames) and a Markov Chain Monte Carlo method. The limitations of Gaia in observing very low-mass stars and brown dwarfs are discussed, and it is shown that WISE will be able to measure astrometry past the 95\% completeness limit and magnitude limit of Gaia (L, T, and Y dwarfs fainter than G \approx 19 and G = 21, respectively). This method is applied to WISE data of 20 nearby (\(<17\) pc) dwarfs with spectral types between M6–Y2 and previously measured trigonometric parallaxes. Also provided are WISE astrometric measurements for 23 additional low-mass dwarfs with spectral types between M6–T7 and estimated photometric distances <17 pc. Only nine of these objects contain parallaxes within Gaia Data Release 2.

Key words: astrometry – brown dwarfs – parallaxes – proper motions – stars: low-mass – techniques: miscellaneous

Supporting material: figure sets

1. Introduction

With the recent release of proper motions and trigonometric parallax measurements for over a billion sources from the Gaia satellite (Arenou et al. 2018; Gaia Collaboration et al. 2018; Lindegren et al. 2018; Luri et al. 2018), it is important to understand what objects are not included in the recent catalog, and what objects will be missing from the final catalog. Theissen et al. (2017) investigated the Gaia shortfall and found that Gaia will be limited in its ability to observe ultracool dwarfs (spectral types later than mid-L) at distances \(>10\) pc due to its relatively blue bandpass.

A number of projects aim to measure the trigonometric parallaxes of these ultracool dwarfs (e.g., Dupuy & Liu 2012; Faherty et al. 2012; Beichman et al. 2013; Kirkpatrick et al. 2014; Dupuy et al. 2016; Skinner et al. 2016; Weinberger et al. 2016; Smart et al. 2017a). These projects typically rely on either: (1) numerous epochs of ground-based and space-based observations, using facilities such as the Spitzer Space Telescope (Werner et al. 2004); or (2) survey data spanning multiple epochs, such as the Digitized Sky Survey (DSS), the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), or the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006). In this paper, I present a method to measure the proper motions and trigonometric parallaxes of nearby \((<17\) pc), ultracool objects using publicly available WISE data.

In Section 3, the properties and limitations of Gaia and WISE are discussed. The method for measuring proper motions and parallaxes is described in Section 4. Comparisons between this method and previous literature measurements for 20 nearby, low-mass dwarfs are provided in Section 5. In Section 6, I also provide new measurements for 23 nearby, low-mass dwarfs, 9 of which are contained within Gaia Data Release 2. Lastly, I discuss the utility of this method for the immediate future in Section 7.

2. WISE Multi-epoch Data

The all-sky observations made by WISE are ideal for astrometric studies because they span multiple epochs, most separated by \(~6\) months, with the survey strategy of observing fields close to 90° Solar elongation; this places observed objects close to their maximum parallax factors (Kirkpatrick et al. 2014). The original WISE mission surveyed the entire sky in four bands: 3.4, 4.6, 12, and 22 \(\mu\)m (hereafter W1, W2, W3, and W4). The original mission lasted from 2009 December to 2010 August, after which the cryogen was depleted, and WISE observed in W1, W2, and W3 until September (3-band survey; \(~30\%\) of the sky\(^1\)).

WISE continued to observe in W1 and W2 as part of the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE; Mainzer et al. 2011) mission until 2011 February, when it was put into hibernation upon completion of its mission. In 2013 December, WISE was reactivated to “continue rapidly surveying and obtaining measurements of minor planet physical properties” (Mainzer et al. 2014). This mission, dubbed the NEOWISE-Reactivation (NEOWISE-R; Mainzer et al. 2014) mission, continued surveying the entire sky in W1 and W2. The NEOWISE-R mission is currently ongoing. The combined WISE data set contains \(\geq 10\) epochs for every source, with a cadence of \(~6\) months and a time baseline of \(~7\) years, with approximately 2.5 years of deactivation in-between. Each single epoch has 12–13 7.7 s exposures in both W1 and W2,\(^2\) and possibly additional exposures dependent on the depth of coverage for a given line of sight.

Figure 1 shows the total WISE positional uncertainty for a single frame (i.e., \(\sqrt{\sigma_{\alpha}^2 + \sigma_{\delta}^2}\)) as a function of W2 magnitude

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1 http://wise2.ipac.caltech.edu/docs/release/3band/
2 http://wise2.ipac.caltech.edu/docs/release/allsky/
The Gaia shortfall was reevaluated here using the LaTE-MoVeRS sample, by comparing the fraction of LaTE-MoVeRS sources with a counterpart found within 6′ in Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2018; Luri et al. 2018). Figure 2 shows the fraction of matched sources with significant parallaxes (\(\pi/\sigma_\pi \geq 3\)) as a function of W2 magnitude and Sloan Digital Sky Survey (SDSS; York et al. 2000) \(i-z\) color. To put this in a Gaia context, the matched sample between Gaia DR2 and LaTE-MoVeRS was used to compute first-order linear transformations between W2 and G magnitudes as a function of \(i-z\) color, shown in Figure 2 (blue lines), and given by the equation

\[
G = 19; \quad W2 = 16.00 - 1.72(i-z) .
\]

The fraction of matched sources between LaTE-MoVeRS and Gaia DR2 typically drops below 50% for objects with \(i - z > 2\) and \(G \geq 19\) (W2 \(\geq 11-12.5\)), which corresponds to the Gaia DR2 95% completeness limit for sources with 5-parameter astrometric solutions (see Arenou et al. 2018 Figure A.1). The Gaia limiting magnitude for sources with computed 5-parameter astrometric solutions (\(G = 21\)) is also shown in Figure 2. The linear fit to \(G = 21\) is a good approximation for the observed dropout of fainter sources without Gaia parallaxes. Approximate distances for late-type dwarfs as a function of W2 and \(i-z\) are also shown in Figure 2 (magenta lines) using the photometric distance relationships from S. J. Schmidt et al. (2018, in preparation). Future Gaia data releases may have measurements for ultracool dwarfs within 10 pc and with \(G < 21\), but much of the Gaia incompleteness region will be lacking sources due to the Gaia 95% completeness limit and magnitude limit.

4. Parallaxes Using WISE Multi-epoch Data

4.1. Single Epoch Position Measurements

An illustration of the parallax method described here is shown in Figure 3 for 2MASS J02550357−4700509, a nearby (~5 pc) L8 dwarf (Martín et al. 1999; Patten et al. 2006; Kirkpatrick et al. 2008; Faherty et al. 2012). First, all Level 1b (L1b) source catalogs (i.e., All-Sky, 3-band, NEOWISE Post-Cryo, and NEOWISE-R) are queried for objects within 30″ of the expected position of 2MASS J02550357−4700509. The L1b source catalogs contain sources extracted from each single exposure.\(^3\) Sources were grouped by epoch, demarcated by 6-month periods starting 91 days after the mean modified Julian date (MJD) of the first epoch (shown as dotted lines in the top and middle panels of Figure 3). The WISE pipeline already accounts for registering dithers by obtaining a global astrometric solution to each frame using 2MASS positions.\(^4\)

A registration method similar to that used by Dupuy & Liu (2012) was investigated for residual frame-to-frame offsets that were not removed during the dither registration method already implemented within the WISE pipeline. First, a list of potential reference objects was created from the AllWISE catalog (Cutri et al. 2013), selecting all sources within a 10′ radius of the target object (WISE field-of-view = 47′ × 47′; Wright et al. 2010). Reference objects were then selected by requiring the following:

\(^3\) http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_1.html

\(^4\) http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/sec4_3d.html
1. each object has no saturated pixels in W1 and W2 (W1SAT = 0 & W2SAT = 0);
2. each object is free from contamination and confusion flags (CC_FLAG = 0000);
3. each object does not have an extended object flag (EXT_FLAG = 0);
4. each object is within the magnitude limit (W1 > 19; W2 > 12).

These criteria ensured unsaturated sources with pristine astrometry within WISE. A minimum of 40 reference sources within each frame was required, and the search radius was incrementally increased by 1 arcsec until enough reference sources were detected.

Using the final list of reference objects, sources were then extracted from each L1b frame, and positional offsets (Δα and Δδ) were computed for each object between the first frame and each subsequent frame within the given epoch. The residual α and δ between the first frame and each subsequent frame (Δα and Δδ) were then binned in a two-dimensional histogram, starting with an arbitrarily large bin size and iteratively decreasing the bin size until ≈70% of the sources were contained within a single bin (typical bin size: ≈100 mas × 100 mas). The median Δα and Δδ offsets were then taken from the peak bin, which should contain the actual offsets between two frames. These shifts were typically very small (≈10 mas), and did not have a significant effect on the final computed position and uncertainty. Therefore, this correction was not applied for the remainder of this study.

To obtain the true relative position within the WISE frame of reference, the uncertainty-weighted average position for each epoch was computed using the WISE reported position values (α, δ, σα, and σδ), using a 3σ clip to remove outliers. This method gives a statistical measure of the true position within the relative WISE frame of reference, and is based on the fact that each frame is independently calibrated using the exact same method (i.e., the WISE processing pipeline). Each epoch typically spans a period of ≈1–10 days. The true observational epoch time is selected to be the average MJD for each epoch.

Uncertainties (σα and σδ) were computed using the weighted positional uncertainty per epoch, as illustrated in the inset figure of the bottom panel of Figure 3 and given by

$$\langle \sigma_{\alpha,\delta} \rangle = \frac{1}{\sqrt{\sum_i^N 1/\sigma_i^2}},$$

where N is the number of frames within the given epoch. This method reduces the relative astrometric uncertainty by a factor of $\sim\sqrt{N}$, where N is the number of frames a source was observed in during a given epoch.

4.2. Registering Astrometry between Epochs

To obtain a relative astrometric solution, each epoch must be registered using sources common to all epochs that exhibit little or no proper motion. In principle, this step is already done through the WISE processing pipeline, similar to registration within a given epoch (i.e., dither registration). However, there is an observed dipole residual in the astrometry between forward and backward pointing frames taken with WISE (Meisner et al. 2017a). This astrometric shift between 6-month periods can be as large as 600 mas along a given line of sight, inducing a potential parallax signature in objects with no measurable parallax (Meisner et al. 2017a). Meisner et al. (2017a) posit that this astrometric shift is due to an asymmetry in the WISE point-spread function (PSF) models with respect to scan direction. This astrometric shift can be accounted for by registering epochs using a common set of reference objects across all epochs for a given line of sight.
To correct for this systematic effect, again, a procedure similar to the one outlined in Dupuy & Liu (2012) was used. This method follows the same procedure discussed in Section 4.1. First, a list of potential reference objects was created from the AllWISE catalog using the same selection criteria as Section 4.1. Using the final list of reference objects, sources were then extracted from each L1b frame, similar to the target object, and uncertainty-weighted positions were computed for each object within each epoch. Only sources found within >50% of the epochs were kept. Then, the positional shifts between the first epoch and each subsequent epoch were computed. Sources with large proper motions (≥30 mas yr⁻¹) were masked where proper motion information was available or where a proper motion was measured.

The residual α and δ between two epochs (Δα and Δδ) were then binned in a two-dimensional histogram, starting with an arbitrarily large bin size and iteratively decreasing the bin size until ≤70% of the sources were contained within a single bin (typical bin size ≈100 mas × 100 mas). The median Δα and Δδ offsets were then taken from the peak bin, which should contain the true offsets between epochs. Offsets from the first epoch were then applied to each subsequent epoch of the target object’s uncertainty-weighted position.

### 4.2.1. Testing the Efficacy of the Epoch Registration

To test the efficacy of the above registration procedure in reducing positional scatter, the above registration procedure was applied to the SDSS Data Release 14 Spectroscopic Quasar Catalog. This catalog contains 526,356 quasars confirmed based on their optical spectroscopy. These sources should exhibit no proper motion, and offer an unbiased sample—distributed approximately uniformly across one-third of the sky—on which to test the registration procedure from Section 4.2.

Only QSOs with W2 ≤ 14 (50,834 QSOs; 36 with W2 < 10) were selected to coincide with the magnitude range of objects in this study. A thousand QSOs were randomly sampled within the aforementioned magnitude range, with QSOs selected in roughly equal numbers between the limits of W2 ≤ 11, 11 < W2 ≤ 12, 12 < W2 ≤ 13, and 13 < W2 ≤ 14. The uncertainty-weighted position for each epoch was computed, epochs were then registered, and then shifts between the first epoch and each subsequent epoch were computed. The top panel of Figure 4 shows the distribution of shifts for both registered and unregistered epochs in both α and δ, weighted by the number of epochs available. The scatter relative to the position of the first epoch is reduced using the registration method from Section 4.2. The bottom panel of Figure 4 shows registered sources separated into W2 magnitude bins, showing increasing positional uncertainty with decreasing source brightness. A similar trend was not observed with α or δ position, suggesting astrometric precision is primarily a function of source magnitude rather than on-sky position. The typical precision using this registration method is ~12 mas, or 1/200 of a WISE L1b pixel. These values will be revisited in terms of positional precision in Section 5.

### 4.3. Astrometric Solutions

Using the registered positions and uncertainties, the astrometric solution was computed using the following equations:

\[(\alpha_i - \alpha_0)\cos \delta_0 = \Delta \alpha + \mu_\alpha (t_i - t_0) + \pi(P_{\alpha,i} - P_{\alpha,0}),\]

\[(\delta_i - \delta_0) = \Delta \delta + \mu_\delta (t_i - t_0) + \pi(P_{\delta,i} - P_{\delta,0}),\]

where the subscript 0 denotes the first epoch, and the subscript i denotes each subsequent epoch. \(\Delta \alpha\) and \(\Delta \delta\) represent the mean

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5 http://www.sdss.org/dr14/data_access/value-added-catalogs/?vac_id=the-sloan-digital-sky-survey-quasar-catalog-fourteenth-data-release
positions in $\alpha$ and $\delta$, respectively. $P_{\alpha}, P_{\delta}$ represents the parallax factors (van de Kamp 1967) given by (Green 1985),

$$\begin{align*}
P_{\alpha} &= X \sin \alpha - Y \cos \alpha, \quad (5) \\
P_{\delta} &= X \cos \alpha \sin \delta + Y \sin \alpha \sin \delta - Z \cos \delta, \quad (6)
\end{align*}$$

where $X$, $Y$, and $Z$ are the components of the barycentric position vector of the Earth obtained from the JPL DE430 solar system ephemeris. These equations were solved using a Markov Chain Monte Carlo (MCMC) routine built on the emcee code (Foreman-Mackey et al. 2013), assuming normally distributed parameters and uniform priors. The parameter space was sampled using 200 walkers, with each walker taking 200 steps. Convergence typically occurred after 50–75 steps, and the first 50% of chains were discarded as burn in. The posterior distributions were observed to be normally distributed, and reported values throughout this study represent the median values of the posterior distributions and the largest deviation between the median values and the 16th and 84th percentile values (corresponding to the 68%—or 1$\sigma$—values).

The above steps provide astrometric solutions relative to the WISE reference frame. To convert parallax values from relative to absolute, the finite motions of the calibration sources must be known to shift to an absolute reference frame. The absolute astrometric shifts of the calibration sources were estimated using the Besançon model (Robin et al. 2003; Czekaj et al. 2014), using the Spitzer Infrared Array Camera (IRAC; Fazio et al. 2004) $3.4 \mu$m band as a proxy for W1. Applying the magnitude cuts and search radii from Section 4.2 to select calibration stars, the average parallax of the calibration sources was found to be $\lesssim1$ mas, with $\gtrsim90\%$ of calibration sources having parallaxes $<1$ mas. These shifts are typically much smaller than the average parallax error, and are therefore negligible.

5. Comparison to Literature Astrometric Measurements

The MCMC routine described in the previous section was applied to 20 known, nearby, low-mass objects with generally well-determined parallaxes (<15% uncertainty). Sources were chosen to cover a range of spectral types, distances, and $W_2$ magnitudes. Table 1 reports the values from the MCMC posterior distributions. The computed positional uncertainty listed in Table 1 is typically larger than the relative positional scatter of QSOs with similar magnitudes (see Figure 4). Adding the positional QSO scatter (from Figure 4) in quadrature with the computed positional uncertainties does not change results significantly, indicating that further corrections or larger positional uncertainties are not warranted.

For all of the comparisons in Table 1, the computed WISE parallax values from this study are within the 2$\sigma$ combined uncertainty of the highest precision literature value (18 of 20 within 1$\sigma$), excluding the Gaia DR2 measurements. The full

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5. Gaia DR2 was released while this manuscript was under review.
Table 1
WISE Astrometry Measurements Compared to Literature Astrometry

| Parallax Source | \( \alpha_0 \) (deg) | \( \delta_0 \) (deg) | \( \langle \pi, \delta \rangle \) (mas) | \( \mu_\alpha \cos \delta \) (mas yr\(^{-1}\)) | \( \mu_\delta \) (mas yr\(^{-1}\)) | \( \pi \) (mas) | Baseline (years) |
|-----------------|-------------------|-------------------|-----------------|-----------------|-----------------|----------------|----------------|
| WISE J104915.57−531906.1 (Luhman 16AB); L7.5−T0.5 (Burgasser et al. 2013); W2 = 7.284 ± 0.019 |
| WISE 162.31553 | −53.31851 | ~0.8 | −2761 ± 3 | 358 ± 3 | 500 ± 6 | ~7 |
| Luhman (2013) | | 60−400 | −2759 ± 6 | 354 ± 6 | 496 ± 37 | ~33 |
| Bedin et al. (2017) | | ~0.3 | −2762.2 ± 2.3 | 354.5 ± 2.8 | 501.118 ± 0.093 | ~3 |
| WISE J10481463−3956062 (DENIS J10480−3956); M9 (Faherty et al. 2009); W2 = 7.798 ± 0.020 |
| WISE 162.05621 | −39.93808 | ~0.8 | −1179 ± 3 | −986 ± 3 | 241 ± 7 | ~7 |
| Lurie et al. (2014) | | 2.1−3.5 | −1165 ± 1 | −995 ± 1 | 248.08 ± 0.61 | ~12 |
| Weinberger et al. (2016) | | ~0.43 | −1159.36 ± 0.24 | −986.08 ± 0.31 | 246.36 ± 0.60 | ~7.9 |
| Gaia DR2 | | ~0.01 | −1179.18 ± 0.15 | −988.10 ± 0.18 | 247.22 ± 0.90 | ~1.75 |
| 2MASS J00113182+5908400; M6.5 (Lépine et al. 2009); W2 = 8.651 ± 0.019 |
| WISE 2.87761 | 59.14114 | ~0.8 | −905 ± 3 | −1166 ± 3 | 115 ± 7 | ~7 |
| Lépine et al. (2009) | | ~6 | −901* | −1167* | 108.3 ± 1.4 | ~3 |
| Dittmann et al. (2014) | | ~5 | −908.4* | −1162.0* | 113.6 ± 3.7 | ~4 |
| Gaia DR2 | | ~0.01 | −905.70 ± 0.09 | −1161.81 ± 0.08 | 107.42 ± 0.56 | ~1.75 |
| 2MASS J02461477−0459182 (LHS 0017); M6 (Reid et al. 1995); W2 = 9.699 ± 0.020 |
| WISE 41.56683 | −4.99427 | ~10 | 1687 ± 3 | −1875 ± 3 | 54 ± 7 | ~7 |
| Weinberger et al. (2016) | | ~0.43 | 1676.06 ± 0.27 | −1856.16 ± 0.16 | 60.10 ± 0.91 | ~6.2 |
| Gaia DR2 | | ~0.01 | 1691.12 ± 0.15 | −1881.06 ± 0.14 | 59.68 ± 0.48 | ~1.75 |
| 2MASS J23062928−0502285 (TRAPPIST-1); M8 (Cruz et al. 2003); W2 = 9.807 ± 0.020 |
| WISE 346.62505 | −5.04274 | ~10 | 924 ± 4 | −467 ± 3 | 81 ± 8 | ~7 |
| Costa et al. (2006) | | 3−5 | 922.1 ± 1.8 | −471.6 ± 1.8 | 82.58 ± 2.58 | ~3.3 |
| Gaia DR2 | | ~0.01 | 930.88 ± 0.25 | −479.40 ± 0.17 | 80.45 ± 0.73 | ~1.75 |
| 2MASS J02550357−4700509; L8 (Kirkpatrick et al. 2008); W2 = 10.207 ± 0.021 |
| WISE 43.76972 | −47.01582 | ~9 | 997 ± 3 | −539 ± 3 | 206 ± 7 | ~7 |
| Costa et al. (2006) | | ~13 | 999.6 ± 2.7 | −565.6 ± 3.7 | 201.37 ± 3.89 | ~2.4 |
| Weinberger et al. (2016) | | ~0.43 | 999.09 ± 0.45 | −547.61 ± 0.13 | 205.83 ± 0.53 | ~5.1 |
| Gaia DR2 | | ~0.01 | 1011.24 ± 0.39 | −554.77 ± 0.47 | 205.32 ± 0.54 | ~1.75 |
| 2MASS J08354193−0819227; L5 (Faherty et al. 2009); W2 = 10.407 ± 0.022 |
| WISE 128.92562 | −8.32227 | ~10 | −527 ± 4 | 306 ± 3 | 150 ± 8 | ~7 |
| Andrei et al. (2011) | | ~6 | −519.8 ± 7.7 | 285.4 ± 10.5 | 117.3 ± 11.2 | ~1.96 |
| Weinberger et al. (2016) | | ~0.43 | −527.88 ± 0.11 | 298.20 ± 0.14 | 137.49 ± 0.39 | ~6.2 |
| Gaia DR2 | | ~0.01 | −535.66 ± 0.44 | 302.74 ± 0.41 | 138.60 ± 1.23 | ~1.75 |
| 2MASS J08173001−6155158; T6 (Artigau et al. 2010); W2 = 11.265 ± 0.020 |
| WISE 124.37394 | −61.9781 | ~11 | −159 ± 3 | 1107 ± 4 | 208 ± 7 | ~7 |
| Artigau et al. (2010) | | ~20−300 | −158 ± 54 | 1095 ± 41 | 203 ± 13 | ~14 |
| Gaia DR2 | | ~0.01 | −156.44 ± 1.26 | 1099.60 ± 1.21 | 191.53 ± 3.81 | ~1.75 |
| WISE J150649.97+702736.0; T6 (Mace et al. 2013); W2 = 11.276 ± 0.019 |
| WISE 226.70825 | 70.46003 | ~12 | −1187 ± 3 | 1044 ± 4 | 191 ± 8 | ~7 |
| Marsh et al. (2013) | | ~60−300 | −1241 ± 85 | 1046 ± 64 | 310 ± 42 | ~2.5 |
| Gaia DR2 | | ~0.01 | −1194.09 ± 1.65 | 1044.30 ± 1.52 | 193.54 ± 4.68 | ~1.75 |
| 2MASS J04455387−3048204; L2 (Cruz et al. 2003); W2 = 11.340 ± 0.022 |
| WISE 71.47506 | −30.80693 | ~12 | 166 ± 4 | −421 ± 4 | 70 ± 9 | ~7 |
| Faherty et al. (2012) | | ~3 | 164.0 ± 2.8 | −415.0 ± 2.7 | 78.5 ± 4.9 | ~3 |
| Gaia DR2 | | ~0.01 | 161.48 ± 0.23 | −419.68 ± 0.39 | 61.97 ± 0.85 | ~1.75 |
| 2MASS J09393548−2448279; T8 (Burgasser et al. 2006); W2 = 11.640 ± 0.022 |
| WISE 144.89964 | −24.81069 | ~29 | 552 ± 8 | −1026 ± 9 | 195 ± 19 | ~7 |
| Faherty et al. (2012) | | ~3 | 558.1 ± 5.8 | −1030.5 ± 5.6 | 196.0 ± 10.4 | ~2.5 |
### Table 1 (Continued)

| Parallax Source | $\alpha_0$ (deg) | $\delta_0$ (deg) | <$\delta_0$> | $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $\pi$ (mas) | Baseline (years) |
|-----------------|-----------------|-----------------|------------|--------------------------------------|------------------------------|-------------|-----------------|
| 2MASS J03590101–2353083; L6.5 (Cruz et al. 2003); W2 = 11.687 ± 0.022 | | | | | | | |
| WISE | 69.75378 | −23.88610 | ~14 | −120 ± 4 | −157 ± 4 | 97 ± 10 | ~7 |
| Faherty et al. (2012) | ... | ... | ~3 | −116.3 ± 3.8 | −162.0 ± 3.8 | 110.4 ± 4.0 | ~3 |
| *Gaia* DR2 | ... | ... | ~0.01 | −113.61 ± 0.69 | −153.10 ± 0.81 | 80.79 ± 2.34 | ~1.75 |
| 2MASS J23224684–3133231; L0/3 (Reid et al. 2008; Faherty et al. 2012); W2 = 11.723 ± 0.022 | | | | | | | |
| WISE | 350.69440 | −31.55802 | ~15 | −184 ± 5 | −560 ± 4 | 73 ± 11 | ~7 |
| Faherty et al. (2012) | ... | ... | ~3 | −194.8 ± 7.4 | −527.3 ± 7.5 | 58.6 ± 5.6 | ~1.5 |
| *Gaia* DR2 | ... | ... | ~0.01 | −203.20 ± 0.53 | −540.48 ± 0.55 | 50.32 ± 1.37 | ~1.75 |
| UGPS J072227.51–054031.2; T9 (Cushing et al. 2011); W2 = 12.200 ± 0.023 | | | | | | | |
| WISE | 110.61366 | −5.67499 | ~40 | −916 ± 12 | 353 ± 13 | 251 ± 26 | ~7 |
| Leggett et al. (2012) | ... | ... | ~6.2 | −904.14 ± 1.71 | 352.025 ± 1.21 | 242.8 ± 2.4 | ~5 |
| WISE | 43.53936 | 2.39960 | ~66 | 2584 ± 16 | 214 ± 18 | 139 ± 40 | ~7 |
| Dupuy & Kraus (2013) | ... | ... | ~30 | 2588 ± 27 | 273 ± 27 | 135 ± 15 | ~2 |
| 2MASS J07290002–3954043; T8 (Looper et al. 2007); W2 = 12.972 ± 0.024 | | | | | | | |
| WISE | 112.24790 | −39.89604 | ~48 | −601 ± 11 | 1670 ± 11 | 105 ± 24 | ~7 |
| Faherty et al. (2012) | ... | ... | ~3 | −566.6 ± 5.3 | 1643.4 ± 5.5 | 126.3 ± 8.3 | ~3.7 |
| 2MASS J22282889–4310262; T6 (Burgasser et al. 2006); W2 = 13.326 ± 0.030 | | | | | | | |
| WISE | 337.12086 | −43.14786 | ~73 | 107 ± 21 | −304 ± 22 | 109 ± 46 | ~7 |
| Faherty et al. (2012) | ... | ... | ~3 | 102.3 ± 5.8 | −324.4 ± 5.1 | 94.0 ± 7.0 | ~1.5 |
| WISE* | 133.78619 | −7.24432 | ~140 | −8055 ± 56 | 677 ± 58 | 520 ± 67 | ~3.5 |
| Wright et al. (2014) | ... | ... | ~40–500 | −8051 ± 47 | 657 ± 50 | 448 ± 33 | ~4 |
| WISEP J041022.71+150248.5; Y0 (Mace et al. 2013); W2 = 14.113 ± 0.047 | | | | | | | |
| WISE | 62.59465 | 15.04681 | ~196 | 968 ± 55 | −2239 ± 59 | 209 ± 113 | ~7 |
| Marsh et al. (2013) | ... | ... | ~50–200 | 974 ± 79 | −2144 ± 72 | 233 ± 56* | ~2.5 |
| WISEPA J182831.08+265037.8; ≥Y2 (Kirkpatrick et al. 2012); W2 = 14.353 ± 0.045 | | | | | | | |
| WISE | 277.12949 | 26.84381 | ~159 | 1058 ± 47 | 111 ± 47 | 131 ± 88 | ~7 |
| Beacham et al. (2013) | ... | ... | ~50 | 1069 ± 11 | 153 ± 13 | 90 ± 10 | ~2.5 |

Notes.

* No uncertainties reported.

* Kirkpatrick et al. (2012) quoted a value of $\pi = 193 ± 26$ mas and cite the measurement to a pre-published version of Marsh et al. (2013).

* Measurements made using only NEOWISE(-R) data.

* Kirkpatrick et al. (2012) quote a value of $\pi = 164 ± 24$ mas and cite the measurement to a pre-published version of Marsh et al. (2013).

Astrometric solutions are shown in Figure Set 5. Figure 6 shows the residuals between the parallax value derived using WISE and the highest precision literature parallax, as a function of W2 magnitude. The astrometric precision severely deteriorates for sources fainter than W2 ≈ 14, setting the approximate limit for where this method is valid.

With the recent release of Gaia DR2, it is essential to compare results obtained here with results from DR2. Of the 20 objects in Table 1, 11 have cross-matches within Gaia DR2, and measurements are listed in Table 1. Many of these sources have poor Gaia goodness-of-fit statistics, and large excess astrometric noise parameters (Lindegren et al. 2012, 2018). To account for possibly underestimated uncertainties on the measured parallax values, the Gaia uncertainties reported in this study are the quadratic sum of the quoted DR2 parallax uncertainty and the excess astrometric noise parameter. Figure 7 shows the comparison between values in this study and Gaia DR2. All computed values are within the 3σ combined uncertainty (85% within 2σ).

To evaluate the uncertainties of the measurements in this study to those from Gaia DR2, the quantity ($\pi_{\text{WISE}} - \pi_{\text{Gaia}}$) / $\sqrt{\sigma^2_{\text{WISE}} + \sigma^2_{\text{Gaia}}}$ was computed. If the uncertainties are not over/underestimated, and the measurements are unbiased, this quantity should follow a normal distribution with $\mu = 0$ and $\sigma = 1$. The inset plot of Figure 7 shows the distribution of the above quantity, which has $\mu = 0.65$ mas and $\sigma = 0.90$ mas. Further comparisons are needed, as the sample size in Figure 7 is
small, and statistical comparison using tests such as the Anderson–Darling test (Anderson & Darling 1952) provide limited information. It appears that WISE parallax measurements are slightly overestimated compared to Gaia DR2; however, this is not the case for comparison to other literature values. Further investigation is warranted using a larger comparison sample and future Gaia data releases that may account for possible systematics not yet discovered in the data.

In principle, this method can be applied to any source bright enough to be extracted within a single WISE L1b frame. Saturated photometry may cause an issue with centroiding. Crowded fields also pose a challenge due to multiple nearby objects causing source confusion and poor centroiding. It is unlikely that robust parallaxes (<15% uncertainty) can be measured farther than ~20 pc using WISE data alone, assuming an average parallax precision of 8 mas. However, this distance limit is highly dependent on W2 magnitude. The first 11 objects listed in Table 1 (excluding the binary Luhman 16AB and T8 dwarf 2MASS J09393548−2448279) are contained within Gaia DR2, which is roughly consistent with the \( G < 19 \) (W2 < 12) limit discussed in Section 3.

6. New and Improved Astrometric Measurements

There are many known low-mass objects estimated to be within 20 pc based on spectrophotometric parallax relationships, that have either no trigonometric parallax measurement, or measurements with large uncertainties (>20%). Here, 23 such cases are investigated, sourced from the literature to cover a range of spectral types, distances, and W2 magnitudes, 9 of which have parallax measurements within Gaia DR2 (Table 2). The newly computed astrometric solutions are shown in Figure Set 8.
The majority of parallaxes can be found within the Database of Ultracool Parallaxes maintained by Trent Dupuy: http://www.as.utexas.edu/~tdupuy/plx/Database_of_Ultracool_Parallaxes.html (Dupuy & Liu 2012; Dupuy & Kraus 2013; Liu et al. 2016).

Using the sources from Tables 1 and 2, a second-order polynomial fit to the parallax uncertainties divided by 0.15 was computed, representing the approximate parallax limit where \(<15\%\) uncertainties can be achieved, as a function of W2 magnitude. The polynomial is shown in Figure 6, converted from parallax to distance (blue dashed line corresponding to the blue y-axis on the right side of Figure 6). Bright sources (W2 \(\lesssim 8\)) can potentially have their parallaxes measured out to distances of \(~23\) pc, with sources at the Gaia 95\% completeness limit (G \(\approx 19\); W2 \(\approx 11\)) requiring distances within \(~17\) pc. These limits will be validated in the future with a larger control sample and future Gaia data releases.

### 7. Discussion

The technique presented here has the potential to find new, nearby, ultracool objects, and measure relatively accurate parallaxes without the need for follow-up observations. This is particularly important as Spitzer is expected to be retired in 2018. Its replacement, the James Webb Space Telescope (JWST; Gardner et al. 2006), while sensitive to these faint dwarfs, is an unlikely facility for a dedicated parallax program.

There are approximately 300 objects with spectral types between L0 and T8 that currently have published parallaxes.7 As discussed here and in previous studies (Smart et al. 2017b; Theissen et al. 2017), Gaia will not provide parallaxes for many of the nearby, lowest-mass, ultracool objects, leaving only ground-based programs. The method described here is a useful alternative for the nearest (\(\lesssim 17\) pc) ultracool objects.

Figure 9 shows the absolute W2 magnitude as a function of spectral type for ultracool dwarfs. The vast majority of sources measured in this study follow the expected empirical relationships from Kirkpatrick et al. (red dashed line; 2014) and Faherty et al. (solid black line with gray uncertainty region; 2016), with a few known exceptions (e.g., the overluminous Luhman 16AB). Additionally, the spectral binary candidate 2MASS J13243553+6358281 (L8+T3.5; Burgasser et al. 2010), hereafter 2MASS J1324+6358 appears underluminous for the spectral type of the primary component. Recent results suggest that 2MASS J1324+6358 is a single T2 dwarf and member of the young (\(~150\) Myr) AB Doradus moving group (Gagné et al. 2018), consistent with the parallax measurement in this study.

Figure 9 demonstrates the utility of trigonometric parallaxes for identifying overluminous, unresolved binaries—similar to Luhman 16AB—and low-surface-gravity brown dwarfs, the latter of which are also useful for determining youth and a helpful diagnostic for membership in nearby young moving groups. Future work will focus on measuring parallaxes for all ultracool dwarfs within 17 pc without published trigonometric parallax measurements, and is applicable to any future discoveries of ultracool dwarfs.

Additionally, it may be possible to use unWISE (Lang 2014; Meisner et al. 2017b, 2017c) single-epoch coadds (Meisner et al. 2017a) for higher precision astrometric measurements of the faintest sources (e.g., Y dwarfs). Currently, not all epochs of NEOWISE-R data have been processed through unWISE, and future work will wait until all epochs become available.

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Table 2
New and Updated Astrometric Measurements

| Source            | SpT  | SpT Ref. | W2  | \(\mu_\alpha\cos\delta\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(\pi\) (mas) | \(\eta_\alpha\) (mas) | \(\eta_\delta\) (mas) | Gaia DR2 |
|-------------------|------|----------|-----|------------------------------------------|---------------------------------|--------------|---------------------|---------------------|----------|
| WISEA J154045.67−510139.3 | M6   | 9        | 7.465 ± 0.022 | 1961 ± 3 | −331 ± 3 | 189 ± 7 | 165 ± 49 | 9 | 188.04 ± 0.37 |
| SDSS J122150.17+463244.4  | M6\(^b\) | ...     | 9.797 ± 0.020 | 78 ± 3 | −24 ± 3 | 34 ± 7 | (69 ± 7) | 19 | Y\(^c\) |
| 2MASS J12351726+1318054  | M6   | 14       | 9.893 ± 0.021 | 93 ± 3 | 172 ± 3 | 41 ± 6 | (67 ± 7) | 19 | Y\(^c\) |
| 2MASS J03140344+1603056  | L0   | 15       | 10.649 ± 0.021 | −233 ± 4 | −66 ± 4 | 74 ± 9 | (69 ± 4) | 15 | 73.42 ± 1.06 |
| 2MASS J15065441+1321060  | L3   | 8        | 10.872 ± 0.021 | −1082 ± 4 | −32 ± 4 | 88 ± 9 | (83 ± 14) | 8 | 85.58 ± 1.00 |
| SDSS J141624.08+134826.7  | L6   | 17       | 11.026 ± 0.020 | 72 ± 4 | 106 ± 4 | 110 ± 9 | 127 ± 27 | 18 | 107.55 ± 1.67 |
| 2MASS J15150083+4847416  | L6   | 16       | 11.332 ± 0.021 | −945 ± 4 | 1459 ± 4 | 118 ± 8 | (145 ± 27) | 17 | Y\(^c\) |
| 2MASS J01443536−0716142  | L5   | 11       | 11.371 ± 0.021 | 363 ± 6 | −217 ± 6 | 82 ± 14 | (75 ± 8) | 5 | 79.03 ± 2.38 |
| 2MASS J08575849+5708514  | L8\(^d\) | 7        | 11.439 ± 0.021 | −406 ± 4 | −407 ± 4 | 81 ± 11 | 98.0 ± 2.6\(^c\) | 21 | 71.23 ± 4.65 |
| SDSS J090837.91−503207.5  | L8   | 17       | 11.651 ± 0.023 | −414 ± 5 | −466 ± 5 | 118 ± 12 | (122 ± 24) | 17 | 95.82 ± 2.63 |
| WISE J003110.04+745436.3  | L9   | 1        | 11.843 ± 0.021 | 525 ± 4 | −18 ± 4 | 84 ± 10 | (91 ± 8) | 20 | N |
| WISE J203042.79+074343.7  | T1.5 | 13       | 12.129 ± 0.024 | 668 ± 7 | −99 ± 7 | 107 ± 14 | (92 ± 8) | 1 | 103.97 ± 3.61 |
| SDSS J075840.33+324723.4  | T2   | 10       | 12.170 ± 0.024 | −233 ± 7 | −353 ± 8 | 108 ± 16 | (91 ± 8) | 6 | Y\(^d\) |
| WISE J185101.83+593508.6  | L7+T2 | 20       | 12.178 ± 0.022 | 42 ± 3 | 64 ± 7 | (91 ± 8) | 20 | 48.85 ± 2.45 |
| 2MASS J13243553+6358281  | L8+T3.5 (T2) | 4 (12) | 12.294 ± 0.022 | −383 ± 5 | −70 ± 4 | 111 ± 11 | (77 ± 6) | 6 | N |
| 2MASS J11061197+275225   | T0+T4.5 | 4 | 12.361 ± 0.024 | −295 ± 6 | −468 ± 7 | 61 ± 15 | (91 ± 8) | 6 | Y\(^d\) |
| PSO J140.2380+45.6487    | L9   | 13       | 12.439 ± 0.023 | −74 ± 6 | −872 ± 6 | 83 ± 14 | (70 ± 7) | 2 | Y\(^d\) |
| WISE J223617.59+510551.9  | T5.5 | 13       | 12.499 ± 0.025 | 724 ± 8 | 318 ± 8 | 119 ± 17 | (106 ± 9) | 1 | Y\(^d\) |
| 2MASS J03480772−6022270  | T7   | 3        | 12.559 ± 0.022 | −277 ± 8 | −761 ± 7 | 119 ± 16 | (111 ± 12) | 6 | N |
| WISE J180952.53−044812.5 | T1   | 2        | 12.745 ± 0.028 | −30 ± 9 | −408 ± 10 | 73 ± 20 | (67 ± 7) | 2 | Y\(^d\) |
| 2MASS J12314753+0847331  | T5.5 | 3        | 13.083 ± 0.031 | −1158 ± 16 | −1057 ± 17 | 53 ± 33 | (83 ± 7) | 6 | N |
| 2MASSI J2254188+312349    | T4   | 3        | 13.288 ± 0.030 | 57 ± 16 | 188 ± 16 | 108 ± 33 | (71 ± 10) | 6 | Y\(^d\) |
| 2MASS J21543318+5942187  | T6   | 12       | 13.579 ± 0.029 | −195 ± 17 | −539 ± 16 | 89 ± 35 | (100 ± 10) | 6 | N |

Notes.

\(^a\) Values in parentheses indicate spectrophotometric distance estimates.
\(^b\) Spectral type estimated from photometric colors.
\(^c\) No parallax measurement included in Gaia DR2, however, the source has \(G < 21\). Typically high ASTROMETRIC_SGMA5D_MAX parameters and/or high goodness-of-fit statistics (>100).
\(^d\) Potential low-gravity object discussed in Gagné et al. (2015).
\(^e\) This parallax measurement was published while this manuscript was under review.

References. (1) Best et al. (2013), (2) Best et al. (2015), (3) Burgasser et al. (2006), (4) Burgasser et al. (2010), (5) Cruz et al. (2003), (6) Faherty et al. (2009), (7) Geballe et al. (2002), (8) Gizis et al. (2000), (9) Kirkpatrick et al. (2014), (10) Knapp et al. (2004), (11) Liebert et al. (2003), (12)Looper et al. (2007), (13)Mace et al. (2013), (14) Reid et al. (2007), (15) Reid et al. (2008), (16)Schmidt et al. (2007), (17)Schmidt et al. (2010), (18)Scholz (2010), (19)Theissen et al. (2017), (20)Thompson et al. (2013), (21)Wang et al. (2018).
Figure 8. Astrometric solution for WISEA J154045.67−510139.3, similar to Figure 5. (The complete figure set (23 images) is available.)

Figure 9. Absolute $W_2$ magnitude as a function of spectral type for late-type dwarfs. The relationships from Kirkpatrick et al. (2014) and Faherty et al. (2016) are shown with the dotted red line and solid black line, respectively. Unresolved binaries in the sample are indicated with red circles. Spectral type uncertainties are typically ±1 spectral type. Also plotted are 275 objects from the Database of Ultracool Parallaxes (excluding binaries) with spectral types $\geq$L0 and measured $W_2$ magnitudes (cyan points). The blue arrow and corresponding blue marker and error bar show the best single-fit object (T2 dwarf) for the potential spectral binary 2MASS J1324+6358.

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