

The CatWISE Preliminary Catalog: Motions from *WISE* and *NEOWISE* Data

PETER R. M. EISENHARDT,¹ FEDERICO MAROCCHI,^{1, 2,*} JOHN W. FOWLER,³ AARON M. MEISNER,^{4, †}
J. DAVY KIRKPATRICK,² NELSON GARCIA,² THOMAS H. JARRETT,⁵ RENATA KOONTZ,⁶
ELIJAH J. MARCHESE,⁶ S. ADAM STANFORD,⁷ DAN CASELDEN,⁸ MICHAEL C. CUSHING,⁹
ROC M. CUTRI,² JACQUELINE K. FAHERTY,¹⁰ CHRISTOPHER R. GELINO,² ANTHONY H. GONZALEZ,¹¹
AMANDA MAINZER,¹ BAHRAM MOBASHER,¹² DAVID J. SCHLEGEL,¹³ DANIEL STERN,¹
HARRY I. TEPLITZ,² AND EDWARD L. WRIGHT¹⁴

¹*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, M/S 169-327, Pasadena, CA 91109, USA*

²*IPAC, Mail Code 100-22, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA*
³*230 Pacific St., Apt. 205, Santa Monica, CA 90405, USA*

⁴*National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719, USA*

⁵*Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch, 7701, South Africa*

⁶*University of California, Riverside, 900 University Ave, Riverside, CA 92521, USA*

⁷*Department of Physics, University of California Davis, One Shields Avenue, Davis, CA 95616, USA*

⁸*Gigamon Applied Threat Research, 619 Western Avenue, Suite 200, Seattle, WA 98104, USA*

⁹*Department of Physics and Astronomy, University of Toledo, 2801 West Bancroft St., Toledo, OH 43606, USA*

¹⁰*Department of Astrophysics, American Museum of Natural History, Central Park West at 79th Street, NY 10024, USA*

¹¹*Department of Astronomy, University of Florida, 211 Bryant Space Center, Gainesville, FL 32611, USA*

¹²*University of California, Riverside, 900 University Ave, Riverside, CA 92521*

¹³*Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*

¹⁴*Department of Physics and Astronomy, UCLA, 430 Portola Plaza, Box 951547, Los Angeles, CA 90095-1547, USA*

(Revised August 23, 2019)

Corresponding author: Peter R. M. Eisenhardt.

Peter.R.Eisenhardt@jpl.nasa.gov

Submitted to Astrophysical Journal Supplement

ABSTRACT

CatWISE is a program to catalog sources selected from combined *WISE* and *NEOWISE* all-sky survey data at 3.4 and 4.6 μm (W1 and W2). The CatWISE Preliminary catalog consists of 900,849,014 sources measured in data collected from 2010 to 2016. This dataset represents four times as many exposures and spans over ten times as large a time baseline as that used for the AllWISE catalog. CatWISE adapts AllWISE software to measure the sources in coadded images created from six-month subsets of these data, each representing one coverage of the inertial sky, or epoch. The catalog includes the measured motion of sources in 8 epochs over the 6.5 year span of the data. From comparison to *Spitzer*, the SNR=5 limits in magnitudes in the Vega system are W1=17.67 and W2=16.47, compared to W1=16.90 and W2=15.95 for AllWISE. From comparison to *Gaia*, CatWISE positions have typical accuracies of 50 mas for stars at W1=10 mag and 275 mas for stars at W1=15.5 mag. Proper motions have typical accuracies of 10 mas yr $^{-1}$ and 30 mas yr $^{-1}$ for stars with these brightnesses, an order of magnitude better than from AllWISE. The catalog is available in the WISE/NEOWISE Enhanced & Contributed Products area of the NASA Infrared Science Archive.

Keywords: catalogs, infrared:stars, proper motions, brown dwarfs

1. INTRODUCTION

NASA's *Wide-field Infrared Survey Explorer* mission (*WISE*; Wright et al. 2010) revealed iconic objects, including the first Earth Trojan asteroid (Connors et al. 2011), the closest and coolest brown dwarfs (Luhman 2013, 2014), and the most luminous galaxy yet found in the Universe (Tsai et al. 2015). These discoveries were made using two or more infrared coverages of the sky (or epochs)

* NASA Postdoctoral Program Fellow

† Hubble Fellow

obtained from January 2010 to February 2011. Each epoch typically consists of a dozen exposures per band taken within two days at a given position. The satellite was reactivated as *NEOWISE* and resumed searching for near-Earth objects in December 2013 (Mainzer et al. 2014), and has continued to cover the sky every six months since then.

In November 2013, the AllWISE release (Cutri et al. 2013) made available to the community an atlas from coadding the two dozen exposures per position from the initial year of WISE surveying, and a catalog of source fluxes and positions measured from those exposures. With at least two epochs per inertial position, AllWISE also provided motion estimates, and became the definitive catalog in the WISE bandpasses. Each year, *NEOWISE* releases the individual exposures from the reactivated survey (Cutri et al. 2015), corresponding to two additional epochs. With the 2019 April 10 *NEOWISE* release, exposures from 12 epochs are now available. Meisner et al. (2018a) used unWISE processing (Lang 2014) to produce an image atlas which combines the 2010 and 2011 data used for AllWISE with the 2013 through 2016 *NEOWISE* data. An obvious next step is to catalog the sources revealed in these combined exposures.

The unWISE Catalog (Schlafly et al. 2019) uses a crowded-field point-source photometry code called “crowdsource” to do this, measuring source fluxes and positions in the coadded image, with the measurements at $3.4\text{ }\mu\text{m}$ (W1) and $4.6\text{ }\mu\text{m}$ (W2) carried out independently. In contrast, CatWISE has adapted AllWISE software to produce a full-sky catalog of sources selected simultaneously in both W1 and W2, and also provides motion estimates. For the CatWISE Preliminary catalog described in this paper, sources were selected from the ensemble of 8 epochs of *WISE* and *NEOWISE* data from Meisner et al. (2018a, the “full coadd”), and the least-squares best-fit solution for point source flux, position and motion were determined from measurements on the individual “epoch coadd” images (Meisner et al. 2018d) rather than individual exposures, to reduce computational cost. Because the total time spanned by CatWISE epochs at a given inertial position is over 6 years, compared to a typical value of 6 months for AllWISE, the CatWISE motion estimates are far more accurate. This in addition to the greater depth of the CatWISE catalog relative to AllWISE are being used to extend the census of the coldest brown dwarfs in the solar neighborhood and enable definitive measurement

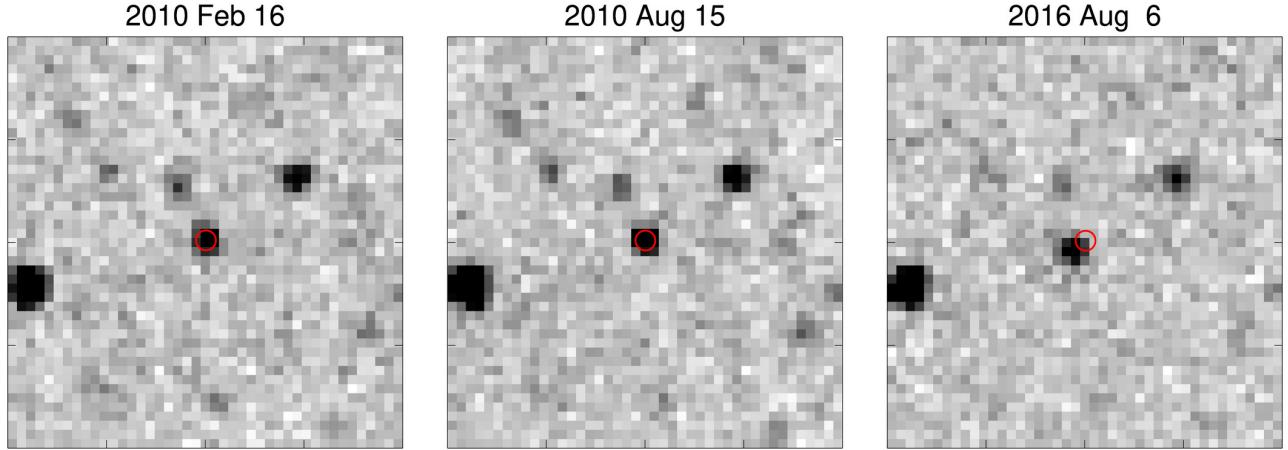


Figure 1. The *Spitzer*-determined $\mu_\alpha = 554.4 \pm 1.2 \text{ mas yr}^{-1}$, $\mu_\delta = -476.7 \pm 1.2 \text{ mas yr}^{-1}$ proper motion of WISEA J161441.47+173935.4, a T9 brown dwarf at 10 pc (Kirkpatrick et al. 2019), is not well measured with the 6 month baseline of AllWISE (left and center), but becomes obvious to CatWISE with the inclusion of NEOWISE data from 2016 (right). In AllWISE, WISEA J161441.47+173935.4 has $\mu_\alpha = 352 \pm 412 \text{ mas yr}^{-1}$, $\mu_\delta = -69 \pm 452 \text{ mas yr}^{-1}$, while in the CatWISE Preliminary catalog, CWISEP J161441.63+173933.7 has $\mu_\alpha = 583.6 \pm 23.5 \text{ mas yr}^{-1}$, $\mu_\delta = -442.0 \pm 25.0 \text{ mas yr}^{-1}$. The panels show $2' \times 2'$ cutouts in W2 centered on the *WISE* position of the source at the first epoch, marked with a red circle.

of the form of the low-mass end of the star formation process (Kirkpatrick et al. 2019). Figure 1 illustrates an example of the potential of CatWISE to progress in this area.

In §2 of this paper we summarize relevant aspects of the *WISE* and *NEOWISE* mission phases. §3 describes the CatWISE processing steps. §4 assesses the astrometric and photometric performance of CatWISE using comparisons to *Gaia* and *Spitzer* data. §5 provides some initial examples of science results enabled by CatWISE, and §6 provides information on accessing CatWISE data products. Appendices provide additional information on CatWISE column entries, cautions on known issues in the CatWISE Preliminary catalog, and details on how positions were combined from alternating survey scan directions (§2). The CatWISE website is <https://catwise.github.io>.

2. OBSERVATIONS

WISE was launched on 2009 December 14, with its 40-cm telescope cooled to 12 K by an outer cryostat tank, and the W1 and W2 detectors operated at 32 K. The 12 and 22 μm (W3 and W4)

detectors were cooled to 7.8 K by an inner cryostat tank. Both tanks were filled with frozen hydrogen. The cryostat cover was ejected and the first images obtained on 2009 December 31, and science survey data began being taken on 2010 January 7.

WISE uses dichroics to image the same 47×47 arcmin region of sky simultaneously in all bands using 1024×1024 pixel arrays with $2.^{\prime\prime}75$ pixels, and obtaining exposures every 11 seconds. The duration of each W1 and W2 exposure is 7.7 seconds due to readout time and scan mirror settling, and discarding the initial readout.

The Sun-synchronous polar *WISE* orbit was designed to precess so that the satellite stays over the Earth's terminator. The basic *WISE* survey strategy is to point near the zenith, scanning at the orbital rate along lines of ecliptic longitude, with the image motion compensated by a scan mirror that flies back for the start of each exposure. The precession rate sweeps across the imaging field of view in approximately 12 orbits (less than one day) near the ecliptic, although the detailed survey strategy extends this time to more than a day. Because images are obtained on both sides of the orbit, the same region of inertial sky is covered every six months, with the direction of the survey scans alternating between ascending and descending in ecliptic latitude. CatWISE processes ascending and descending scans separately for source measurement.

The fully cryogenic survey covered the sky 1.2 times, continuing until the hydrogen in the outer tank evaporated on 2010 August 6 (Figure 2). *WISE* then surveyed an additional 30% of the sky during its 3-Band (W1, W2, and W3) cryogenic phase, with the W3 detector operating at reduced sensitivity. After the cryogen in both tanks was exhausted on 2010 September 29, the post-cryogenic *NEOWISE* survey (Mainzer et al. 2011) in W1 and W2 began, as the telescope and detectors warmed to ~ 73 K. Surveying continued until 2011 February 1, completing a second pass over the sky in W1 and W2, after which the satellite was placed into hibernation. In September 2013, the spacecraft was brought out of hibernation, where it had equilibrated at ~ 200 K due to thermal radiation from the Earth, and renamed *NEOWISE*. On 2013 December 13, with the telescope and detectors passively cooled below 76 K, *NEOWISE* resumed surveying the sky every 6 months in W1 and W2 (Mainzer et al. 2014).

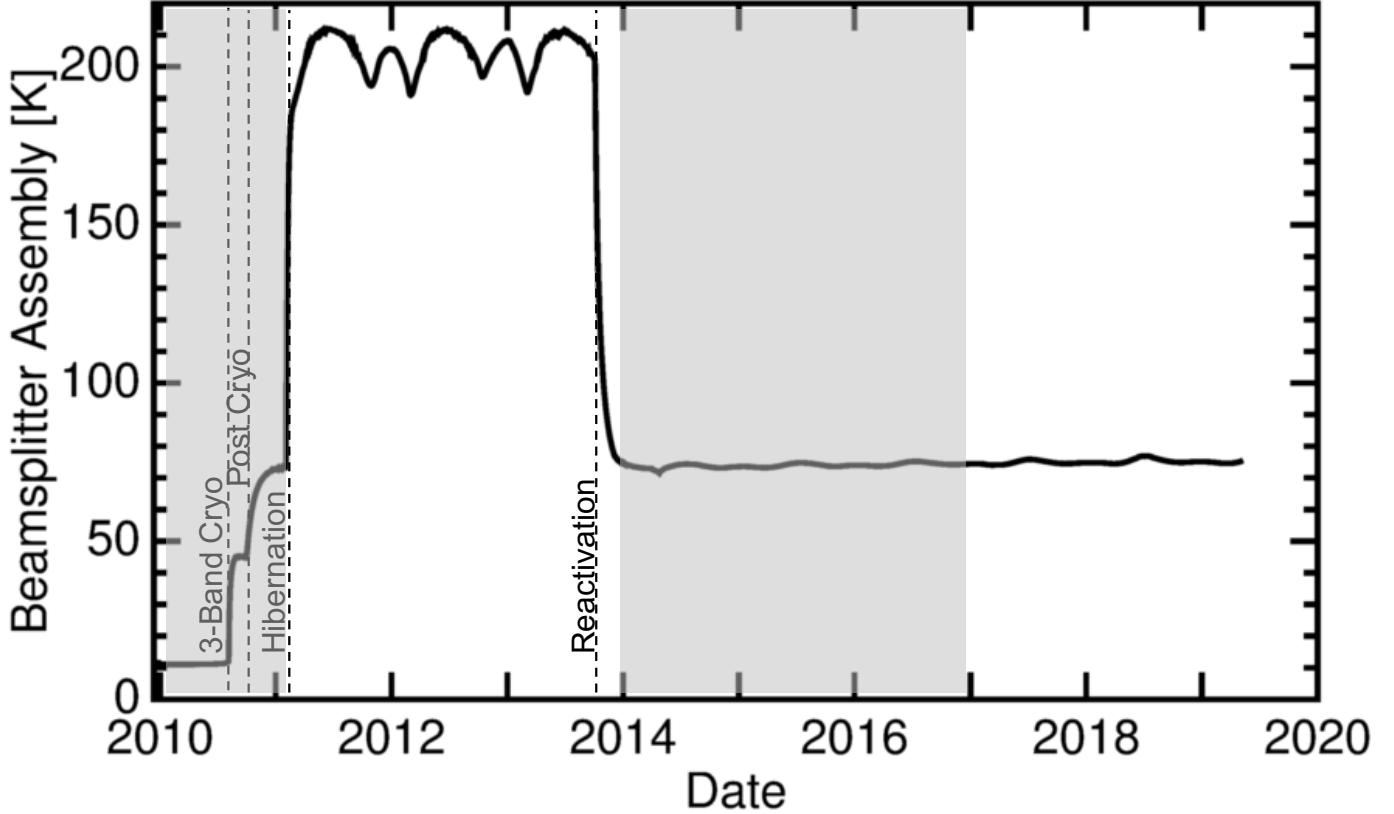


Figure 2. Temperature of the *WISE* beamsplitter assembly vs. date. This temperature is close to that of the telescope and W1 and W2 detectors. Dashed lines indicate the transitions from full cryogenic to 3-band cryogenic phases, to the post-cryogenic phase, and to the start of hibernation and reactivation. Grey shading indicates the date ranges of data used for the CatWISE Preliminary catalog. AllWISE included only the left portion of the shaded range.

The CatWISE Preliminary catalog is based on the combination of W1 and W2 exposures in the two sky coverages used for the AllWISE data release (Cutri et al. 2013) and in the six additional sky coverages from the 2017 *NEOWISE* data release. We use MJD 55480 (2010 Oct. 11) as the dividing point between cryogenic and post-cryogenic data. The average observation date is closer to MJD 56700 (2014 Feb. 12), which we adopt as the epoch for reporting positions when solving for source motion in the Preliminary catalog. Source positions, whether incorporating source motion or not, are given in the equinox J2000 coordinate frame. Magnitudes in the catalog and throughout this paper are on the Vega system.

3. CATWISE PROCESSING

CatWISE adapts the AllWISE pipeline to detect and measure source fluxes in the combined WISE and *NEOWISE* images provided by unWISE (Lang 2014). A full description of the AllWISE pipeline is provided in Cutri et al. (2013).

CatWISE processing works in the atlas tile footprint established by the WISE All-Sky Release, dividing the inertial sky into 18,240 overlapping square images (tiles), each approximately 1.56° on a side, aligned with the local right ascension and declination. Except for the “primary flagging” step (§3.6), processing steps were carried out independently on each tile. For the Preliminary catalog, CatWISE uses the full depth unWISE coaddition of 8 epochs (Meisner et al. 2018a), and the 8 individual unWISE epoch coadds (Meisner et al. 2018d, after astrometric modifications described in §3.1). Source detection (§3.3) was done on the full depth coadds, and source properties determined from measurements on the epoch coadds, treating ascending and descending epochs (§2) separately for most tiles and then merging the results (§3.4). Potential artifacts affecting the sources were identified (§3.5), and sources with multiple measurements because they were in the tile overlap region were flagged to indicate which set of measurements should be used (§3.6). Finally, sources were selected for inclusion in the catalog or reject files (§3.7). We describe these steps in more detail below.

3.1. *unWISE Coadds*

The coadded images in the atlas released with the AllWISE (and All-Sky) catalogs were primarily intended to facilitate source detection, and for this reason they are convolved with the WISE PSF. The unWISE coadds retain the resolution of individual WISE exposures. To reduce differences from the AllWISE processing approach, for source detection (§3.3) in the CatWISE Preliminary catalog, we convolved the full-depth unWISE coadds (Meisner et al. 2018a) with the PSF (§3.2). For source measurement (§3.4) we used unWISE epoch coadds (Meisner et al. 2018d) without convolution.

An adjustment was made to the world coordinate system (WCS) for the pre-hibernation unWISE epoch coadds. Although all of the released individual exposures are tied to 2MASS (Skrutskie et al. 2006), the individual pre-hibernation exposures released for AllWISE are not on the same astrometric system as the individual post-hibernation exposures released for *NEOWISE*. The *NEOWISE* images include corrections for the motions of the 2MASS reference stars, as does the AllWISE catalog (see

§V.2.b of the AllWISE Explanatory Supplement; Cutri et al. (2013)), but the released pre-hibernation images do not include those corrections. A table of corrections for these images exists, however¹, and these corrections were applied to the unWISE input, making the astrometric system of the pre-hibernation epoch coadds consistent with those from the post-hibernation epoch coadds.

3.2. Point Spread Function (PSF)

The *WISE* and *NEOWISE* PSFs have been well characterized at the individual exposure level, but CatWISE works with coadded images rather than individual exposures, so PSFs appropriate for these coadded images are needed. The W1 and W2 PSFs vary with position in the focal plane, and changed somewhat between the cryogenic and post-cryogenic phases of the mission, particularly for W1. The PSFs are also asymmetric, with an orientation that is fixed with respect to the focal plane, but the focal plane orientation with respect to equatorial coordinates varies between exposures. The focal plane orientation also flips every six months because at a given inertial location the survey scan direction alternates between ascending and descending in ecliptic latitude (§2). CatWISE addressed these issues as follows.

A 9×9 grid over the focal plane of cryogenic phase model PSFs, 8 \times oversampled relative to *WISE* pixels, is provided in §IV.4.c.iii.1 of the *WISE* All-Sky Explanatory Supplement (Cutri et al. 2012). The post-cryogenic PSFs used for *NEOWISE* are given in §IV.2.b.i of the NEOWISE Explanatory Supplement (Cutri et al. 2015). Since many focal plane positions contribute to each source in the coadded images, CatWISE averaged these model PSFs, weighted only by their partition sizes in the 9×9 array. Figure 3 (left) shows the resulting focal plane average post-cryogenic PSF model for W1. An analogous focal plane average cryogenic PSF was created for W1, as well as average cryogenic and post-cryogenic PSFs for W2. These are referred to below as the “basic” PSFs.

The basic PSFs contain fine structure in the core that is far from being rotationally symmetric. Figure 4 shows the difference between ascending and descending orientations of the W1 post-cryogenic PSF. The bright and dark stripes in and around the core correspond to variations of more than 25%

¹ http://wise2.ipac.caltech.edu/docs/doc_tree/sis/rex19

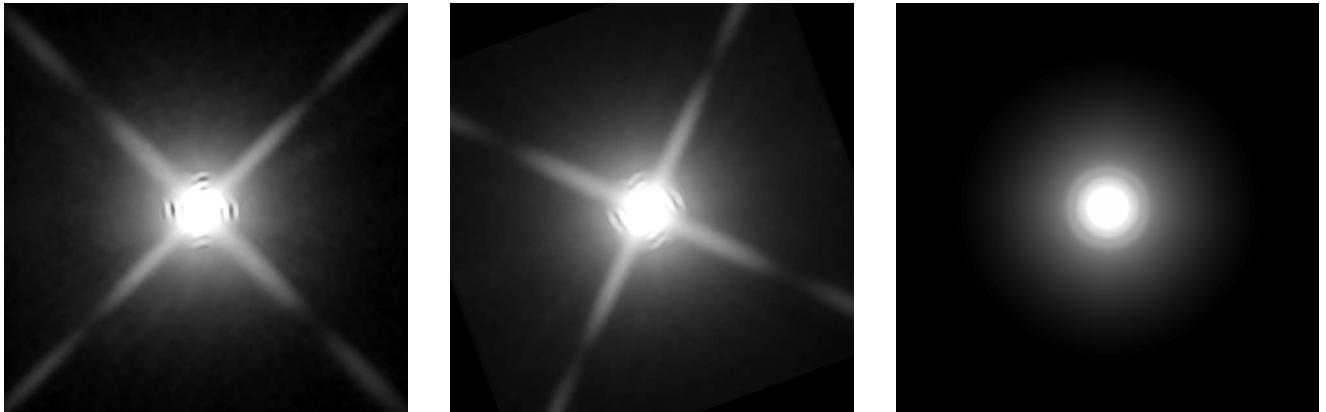


Figure 3. *Left:* The “basic” (averaged over focal plane position) post-cryogenic PSF model for W1. The grey scale uses a log stretch from 1% to 99% of the peak value. The model extends to $\pm 110''$. *Center:* The ascending scan W1 PSF for tile 1497p015 after averaging over cryogenic and post-cryogenic epochs, and a PA range from 199.93° to 200.56° . This is illustrative of the type of PSF used by CatWISE for source measurement, with the exception of 50 tiles near the ecliptic poles. *Right:* The W1 PSF averaged over all scans for tile 0890m667, which includes the south ecliptic pole and all PAs. This is illustrative of the type of PSF used by CatWISE for source measurement for 50 tiles near the ecliptic poles.

of the peak of the PSF. The center of the PSF is the most crucial region for position estimation, so inaccuracies in this part of the PSF have serious consequences for astrometry, as well as photometry.

The structure revealed here has no impact on the measurements carried out by the *WISE* and *NEOWISE* projects, because those measurements were made (and continue to be made) on individual exposures. The PSF structure is captured in the models, and the PSF orientation is always the same in the focal plane. This is not the case for CatWISE, which uses coadds in place of individual *WISE* exposures. The coadded image tile orientation is aligned with the local equatorial coordinates. Therefore CatWISE rotated the basic PSFs by an appropriate set of position angles (PAs) between focal plane and equatorial coordinates for each image tile.

The coadded images were assembled from individual exposures with a range of PA values, so histograms of exposure PA values were constructed for each tile, using a bin width of 0.1 degrees. Separate histograms were constructed for ascending vs. descending and cryogenic vs. post-cryogenic exposures. The basic PSF was rotated by each PA bin center value and these rotated PSFs averaged

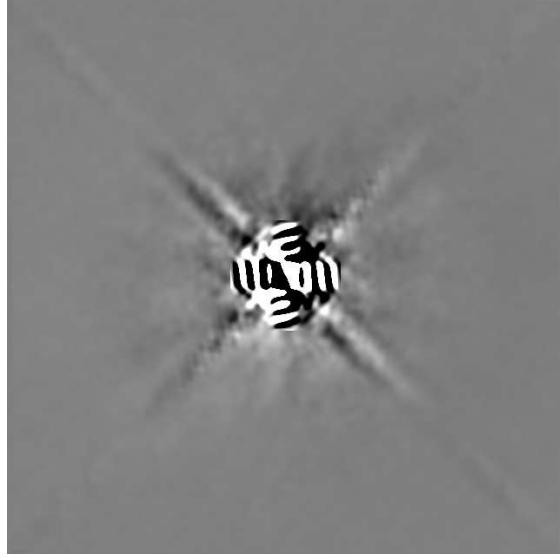


Figure 4. Difference image of W1 post-cryogenic PSFs in ascending vs. descending scans. The image extends to $\pm 110''$.

together with weights equal to the histogram bin count. Those averages were then combined for each tile with weights given by the number of corresponding cryogenic and post-cryogenic exposures to make ascending and descending PSFs for each tile.

Tiles in the vicinity of the ecliptic poles have large PA ranges, and so the tile PSF becomes very smeared (see Figure 3, right). For the 50 tiles near the ecliptic poles listed in Table 1, the ascending and descending PSFs were averaged together, weighted by the number of ascending and descending exposures. For all tiles, a down-sampled central cutout of the average of the ascending and descending PSFs for each tile was used for the detection step.

3.3. Detection

Source detection for the CatWISE Preliminary catalog was done simultaneously in W1 and W2 with the Multiband Detection (MDET) software used in the WISE pipeline (Marsh & Jarrett 2012). The Image Co-addition with Optional Resolution Enhancement (ICORE) software (Masci 2013) was used to resample the 2048×2048 $2''.75$ pixel unWISE coadds to the 4095×4095 $1''.375$ pixel detection image format employed by MDET for WISE, using a PSF appropriate for each tile and band (§3.2)

as the interpolation kernel. The PSF interpolation kernel smooths the images, providing a matched filter for optimal detection of isolated point sources.

Additional observations should reduce the incidence of spurious faint source detections due to artifacts. AllWISE, with two sky coverages, selected a minimum SNR threshold of 2.4, compared to 3.5 used for the single coverage WISE All-Sky Release. For CatWISE we carried out an initial estimate of the SNR corresponding to a source reliability of 50% based on comparison to deeper *Spitzer* data from the SERVS ([Mauduit et al. 2012](#)) and S-COSMOS ([Sanders et al. 2007](#)) programs. This SNR varied from 1.7 in the COSMOS field to 2.6 in the Lockman Hole, and a threshold of 1.8 was selected for the Preliminary catalog.

At the high source densities typical for CatWISE in coadds of ~ 100 or more individual WISE exposures, this matched filter detection methodology yields an asymptotic number of $\sim 60,000$ detected sources per tile for the Preliminary catalog (or $\sim 25,000 \text{ deg}^{-2}$, Figure 5) and hence becomes incomplete, particularly in W1. The detected source density declines slightly in the Galactic plane, for reasons not well understood at present, although overlapping saturated regions from bright stars may be responsible. [Schlafly et al. \(2019\)](#) present an alternative approach (“crowdsouce”) which results in higher detected source densities, but does not provide motion estimates. The completeness and reliability of the CatWISE Preliminary catalog are discussed further in §4.1.

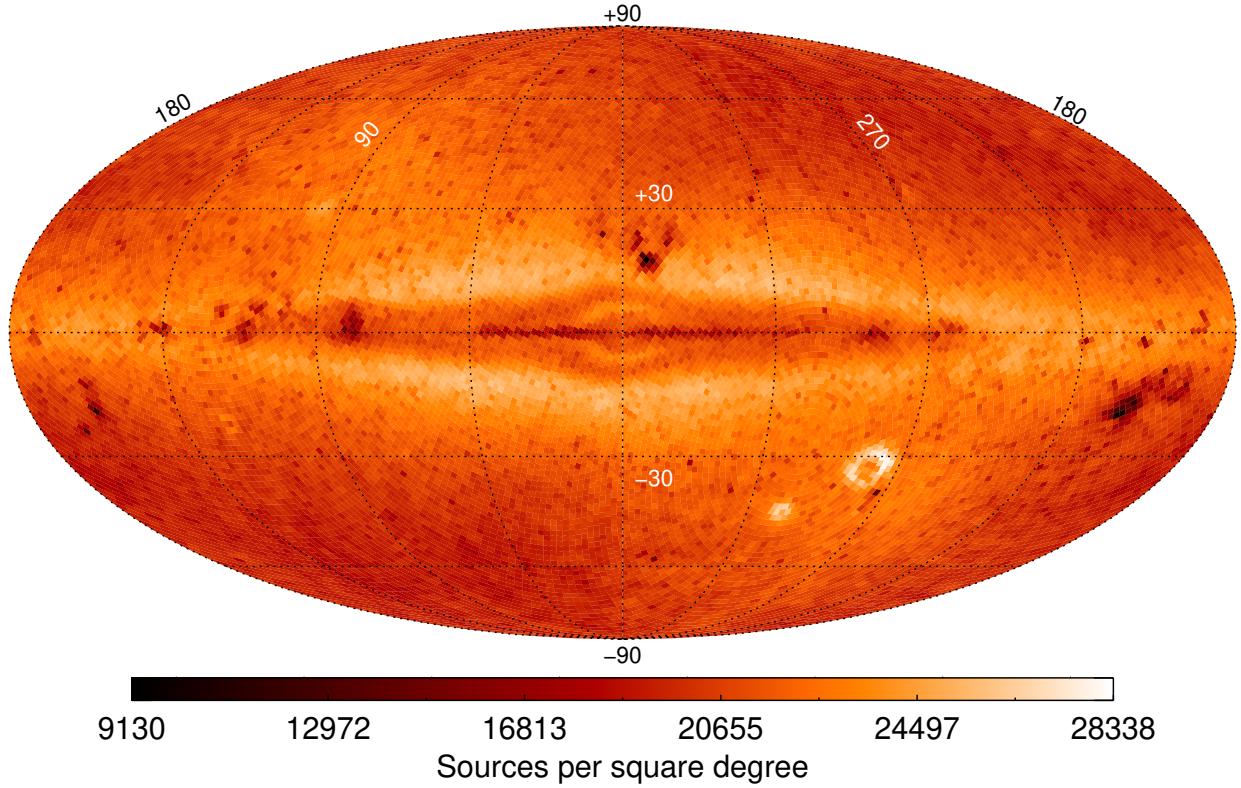


Figure 5. Map of CatWISE Preliminary catalog source density in Galactic coordinates.

3.4. Source Measurement

Source photometry, astrometry, and motion estimation for CatWISE use an adapted version of the WPHOT software developed for the AllWISE pipeline. WPHOT carries out point-source extraction, solving for both photometry and astrometry simultaneously. Source positions detected in each coadded tile image were propagated to individual exposures, and the flux and χ^2 evaluated from fitting the PSF. The source position and flux were refined by searching for a local minimum in χ^2 . For AllWISE, a linear motion was also solved for, based on the observation time of the images.

CatWISE did not have the computational resources to perform the source fitting on all of the many hundreds of individual exposures that contribute to a coadded tile image. Because the 12 exposures for a given inertial position in each sky coverage are obtained within less than two days, the motions

of sources beyond the solar system can be assumed to be fixed for each sky coverage (or epoch). Therefore CatWISE ran WPHOT treating unWISE epoch coadd images as the individual images.

The other significant modification to the AllWISE WPHOT process implemented by CatWISE addressed the alternating scan direction of each epoch and hence varying PSF orientation. WPHOT was not designed to use a time-dependent PSF, but with 8 or more epoch coadd images per position, CatWISE elected to measure source properties with WPHOT separately for the groups of four or more epoch coadds in each of the two scan directions, and then merge the two results. This methodology was used for all but 50 tiles near the ecliptic poles. For those 50 tiles, listed in Table 1, a tile-specific average PSF over all epochs was used for both scan directions, and all epochs were processed together with WPHOT.

WPHOT performs PSF-fit photometry and astrometry assuming sources are inertially fixed (the “stationary fit”), and also searches for a solution assuming a linear motion with time (the “motion fit”). The χ^2 minimization fit can be performed at any location in the flux image. The goal of astrometry is to find the location at which χ^2 has a local minimum.

Table 1. Tiles Processed Using a Single PSF per Band

RA range in decimal degrees of tiles in column				
79.1:87.9	89.0:95.7	96.2:264.2	265.0:272.1	272.6:280.8
0791m682	0890m667	0962m697	2650p681	2726p651
0803m652	0891m637	0964m667	2656p651	2729p681
0830m682	0908m652	0978m652	2672p666	2741p636
0837m697	0909m682	0988m682	2675p636	2746p666
0838m652	0920m697	1002m667	2679p696	2761p651
0853m667	0924m637	2610p681	2690p681	2762p696
0858m637	0927m667	2621p651	2691p651	2769p681
0870m682	0943m652	2635p666	2708p636	2783p666

Table 1 continued on next page

Table 1 (*continued*)

RA range in decimal degrees of tiles in column				
79.1:87.9	89.0:95.7	96.2:264.2	265.0:272.1	272.6:280.8
0873m652	0949m682	2637p696	2709p666	2796p651
0879m697	0957m637	2642p636	2721p696	2808p681

The stationary fit minimizes the total χ^2 (i.e., the combined W1 and W2 χ^2) in the two-dimensional space of right ascension (α) and declination (δ). As one moves around in the space, χ^2 decreases and increases as the local flux distribution appears more or less like a point source. In the vicinity of a real point source, χ^2 tends to be concave, although with some noise fluctuations. At any point, both χ^2 and its gradient can be calculated. The astrometry solution is found using the gradient descent method, by searching along the opposite direction of the gradient vector until the gradient flattens out and the local minimum has been found. The (α, δ) where χ^2 is estimated to be minimal is the position assigned to the source, and the scale factor on the PSF that minimizes χ^2 there is the flux estimate. The value of χ^2 is recorded, as are the individual χ^2 for the W1 and W2 flux fits. Standard Gaussian error analysis provides uncertainties for (α, δ) and flux. The error model includes both PSF error and image flux error, and is discussed further in §3.4.1. More details on WPHOT are given in §IV.4.c.iii of the *WISE* All-Sky Explanatory Supplement (Cutri et al. 2012).

The model used for the motion solution replaces the single location of the stationary solution with locations along a linear function of time. The slopes of this line in the (α, δ) directions are the angular motion rates (μ_α, μ_δ) in (α, δ) . The motion fit minimizes the total χ^2 over the four-dimensional space of $(\alpha, \delta, \mu_\alpha, \mu_\delta)$. When the motion fit is based on both ascending and descending epochs, the motions will include parallax effects (see Kirkpatrick et al. 2014), and so they are not true proper motions. However, except for the 50 tiles near the ecliptic poles, CatWISE processed ascending and descending scans separately, so that the measured motions are close to true proper motions.

3.4.1. Uncertainties

For uncertainties, the “std” unWISE images were used, which are the sample standard deviation at each pixel of the individual WISE exposures divided by $\sqrt{N - 1}$, where N is the number of exposures. Reduced χ^2 values from the CatWISE PSF fitting showed that the uncertainties needed adjustment.

The adjustments were made to the PSF and image uncertainties, with the goal of making the PSF-fit reduced χ^2 values come close to 1.0 for non-saturating sources. The PSF uncertainties were scaled down by 0.9 in W1 and 0.64 in W2 based on bright star reduced χ^2 values. Cryogenic PSF uncertainties for W1 were scaled down by an additional factor of 0.58. Based on faint star reduced χ^2 values, the image uncertainties were scaled up by 1.4 in W1 and 1.15 in W2, and those for pre-hibernation epochs were scaled up by additional factors of 1.1 in W1 and 1.05 in W2. In addition, a minimum value of 1 DN in W1 and 10 DN in W2 was imposed on the image uncertainties.

The uncertainties for the 50 tiles near the ecliptic poles, which used averages of ascending and descending PSFs (§3.2) had somewhat different adjustments. For these tiles the PSF uncertainties were scaled up by 1.3 in W1, with no further adjustment for cryogenic values, and were left unchanged for W2. The image uncertainties were scaled up by 1.75 in W1 and 1.25 in W2, and those for pre-hibernation epochs were scaled up further by 1.1 in W1 and 1.05 in W2. A minimum value of 1 DN in W1 and 5 DN in W2 was imposed on the image uncertainties.

3.4.2. *Merging Measurements from Ascending and Descending Scans*

As noted earlier, for nearly all tiles two independent measurements were made, one extracted from epoch coadds constructed from ascending scans and one from descending-scan epochs. These were merged into a single source list as follows.

Each source has an identifier (*mdetID*) corresponding to an entry in the detected source list (§3.3), and this was used to match ascending and descending measurements of the same source. The ascending and descending sources were almost in perfect one-to-one correspondence, but a small number of mismatches occurred because of active deblending in WPHOT. Active deblending inserts a new source (not from the detection program) into the fitting region if the χ^2 value exceeds a threshold and is reduced by the insertion by a minimum required amount. Full details may be found in §IV.4.c of the *WISE All-Sky Explanatory Supplement* (Cutri et al. 2012). Active deblending may proceed

differently in the ascending and descending data. Actively deblended sources have the same $mde-tID$, so when that is not unique, a nearest-match criterion is applied. If the number of ascending sources does not equal the number of descending sources, the left over sources are discarded, leaving a one-to-one association list.

Corresponding parameters for each matched ascending-descending source pair were combined when the ascending and descending apparitions have non-null values, otherwise the single non-null values (if any) were retained. Aperture magnitudes for the ascending and descending scans were measured from the same full-depth coadd, differing only slightly in the position of the aperture centers. The fluxes and flux uncertainties corresponding to these magnitudes and their uncertainties were simply averaged without weighting. Positions were averaged using inverse-covariance weighting, with the averaging done in a local Cartesian projection consistent with the uncertainty representation. Additional details are provided in Appendix C. PSF-fit photometry was combined by averaging the flux values using inverse-variance weighting. This yields refined flux values and reduced uncertainties that are used to recompute the magnitudes, magnitude uncertainties, and signal-to-noise ratios.

3.5. *Artifact Flagging*

Bright stars create a variety of scattered light effects and electronic-charge issues that require special handling by the software. These effects include scattered light halos, diffraction spikes, glints from off-frame bright stars, optical ghosting from internal reflections within the optical system, and charge persistence on the arrays. These can create false detections, hereafter called artifacts, or can contaminate detections of real, astrophysical sources. The goal of artifact flagging is to label spurious or affected sources so that the user can easily create source lists for which most of these problems are eliminated.

The CatWISE Preliminary catalog employs two types of artifact flagging. One is the cc_flags values copied directly from AllWISE processing. If a source was found in either the AllWISE Catalog or Reject Table within $2.^{\circ}75$ of a CatWISE source, its cc_flag was included in the entry for the CatWISE source; if no AllWISE source was found within this radius, then cc_flags contains a null value. For a CatWISE source having multiple AllWISE sources within the $2.^{\circ}75$ radius, the most pessimistic

value per band is retained, as described in §3.5.1. These *cc_flags* values indicate whether a source is likely to be spurious because it is dominated by an artifact (encoded as an upper-case letter) or is a real source contaminated by an artifact (encoded as a lower-case letter). Each band is flagged separately, and since AllWISE processing included data in all four WISE bands the *cc_flags* value is a four-character string. The possibilities are “0” for no artifact or contamination, “D” or “d” for a diffraction spike, “H” or “h” for a scattered light halo, “O” or “o” for an optical ghost, or “P” or “p” for charge persistence. The *cc_flags* field conveys only the main features of the full artifact flag information contained in the AllWISE *w1cc_map*, *w1cc_map_str*, *w2cc_map*, and *w2cc_map_str* fields,² which are also provided in the CatWISE source entry. A more detailed description can be found in §IV.4.g of the *WISE* All-Sky Explanatory Supplement (Cutri et al. 2012).

The second type of artifact flag is called *ab_flags*, which was determined for every CatWISE source and is based on artifact flagging images provided by unWISE (unWISE bit masks). The *ab_flags* do not attempt to distinguish between an outright artifact and a real astrophysical source that suffers from some level of artifact contamination. However, we have adjusted the flagging (§3.5.3) so that only egregious artifacts more likely to be spurious detections are flagged. By analogy with *cc_flags*, the *ab_flags* thus contain only upper-case letters “D”, “H”, “O”, or “P” or the value “0”. Furthermore, because the CatWISE data deal only with W1 and W2 data, the *ab_flags* values are only two characters long. Additional details are given in §3.5.2.

These *cc_flags* and *ab_flags* values should be regarded as two different yet complementary methods for tagging sources of special concern to the user. As described in § IV.4.g of the *WISE* All-Sky Explanatory Supplement (Cutri et al. 2012), the *cc_flags* are known to overflag; their purpose is to produce a reliable catalog of source extractions free of contamination by artifacts, but they do so at the expense of completeness. AllWISE *cc_flags* are not available for sources detected only in CatWISE, so requiring a source to have “0” in its *cc_flags* entry again emphasizes reliability over completeness. In contrast the *ab_flags*, which are available for every CatWISE source, are used to

² Note that the column descriptions for these fields in §II.1.a of the AllWISE Explanatory Supplement (Cutri et al. 2013) are incorrect. Corrected descriptions are provided in Appendix A.

tag only the more egregious artifacts, thereby emphasizing completeness, albeit at the expense of reliability. Users of the CatWISE data products can thus query against these two sets of artifact flags to best fit their needs.

3.5.1. Setting the *cc_flags* Values When There are Multiple Matches

The values of *cc_flags* were taken directly from a join of the AllWISE Point Source Catalog and Reject Table. When more than one of these AllWISE sources matches to within 2 $''$.75 of a CatWISE source, the band-by-band *cc_flags* value of the CatWISE source was determined as follows. If there is an upper-case letter for any matching source, it takes precedence over any lower-case letter. The letter ‘‘D’’ is the highest priority followed, in order, by ‘‘P’’, ‘‘H’’, and ‘‘O’’. If there are no upper-case letters for any matching source, lower-case letters have the next highest priority, in the same order (‘‘d’’, ‘‘p’’, ‘‘h’’, and ‘‘o’’). If all matching sources have a value of ‘‘0’’ in that band, then ‘‘0’’ is used.

For the binary bit encoding of AllWISE artifacts given by *w1cc_map* and *w2cc_map*, when there is more than one AllWISE match to a CatWISE source, a logical ‘‘OR’’ was performed over all the matches for each bit. The *w1cc_map_str* and *w2cc_map_str* values were then constructed using the priority rules given in the previous paragraph.

3.5.2. Translating the unWISE Bit Mask Values to *ab_flags*

The unWISE bit mask values at the (x,y) pixel location of the source were used to set the value of *ab_flags*, as shown in Table 2, where we use the prefix ‘‘b’’ to indicate specific unWISE mask bits in column 3. The checks against b21 and b22 are to ensure that the bright star is not flagged by its own diffraction spikes or scattered light halo. A full description of the unWISE mask bit meanings is available through the unWISE Catalog data release website³.

In addition to the *ab_flags* field, the CatWISE catalog includes fields with detailed artifact flag information (*w1ab_map*, *w1ab_map_str*, *w2ab_map*, and *w2ab_map_str*) for each source, analogous to the similar fields providing detailed artifact information related to *cc_flags*.

³ http://catalog.unwise.me/files/unwise_bitmask_writeup-03Dec2018.pdf, see Table 2.

Table 2. Logic Used in Converting unWISE Bitmask Values to *ab_flags* Values

Value	Band	Logic
(1)	(2)	(3)
“D”	W1	b0 or b1 or b7 or b27 or b29 but only if not b21
...	W2	b2 or b3 or b8 or b28 or b30 but only if not b22
“H”	W1	b23 but only if not b21
...	W2	b24 but only if not b22
“O”	W1	b25 or b26
...	W2	b11 or b12
“P”	W1	b13 or b14 or b17 or b18
...	W2	b15 or b16 or b19 or b20

3.5.3. Adjusting the *ab_flags* Values

For the *ab_flags*, we performed by-eye checks on selected tiles to make sure that the extent of the flagging matched expectations. These included tiles at a range of Galactic latitudes. Several iterations were performed, primarily to adjust the extent of the halo flagging, before values were finalized. Figure 6 shows examples of the resultant final artifact flagging in tiles containing 47 Tucanae (0048m727, $b = -44^\circ$), a portion of the Hyades (0657p151, $b = -24^\circ$), the COSMOS field (1497p015, $b = +41^\circ$), and Barnard’s Star (2688p045, $b = +15^\circ$). Note that the upper-case *cc_flags* slightly overflag, as designed, particularly in scattered light halos.

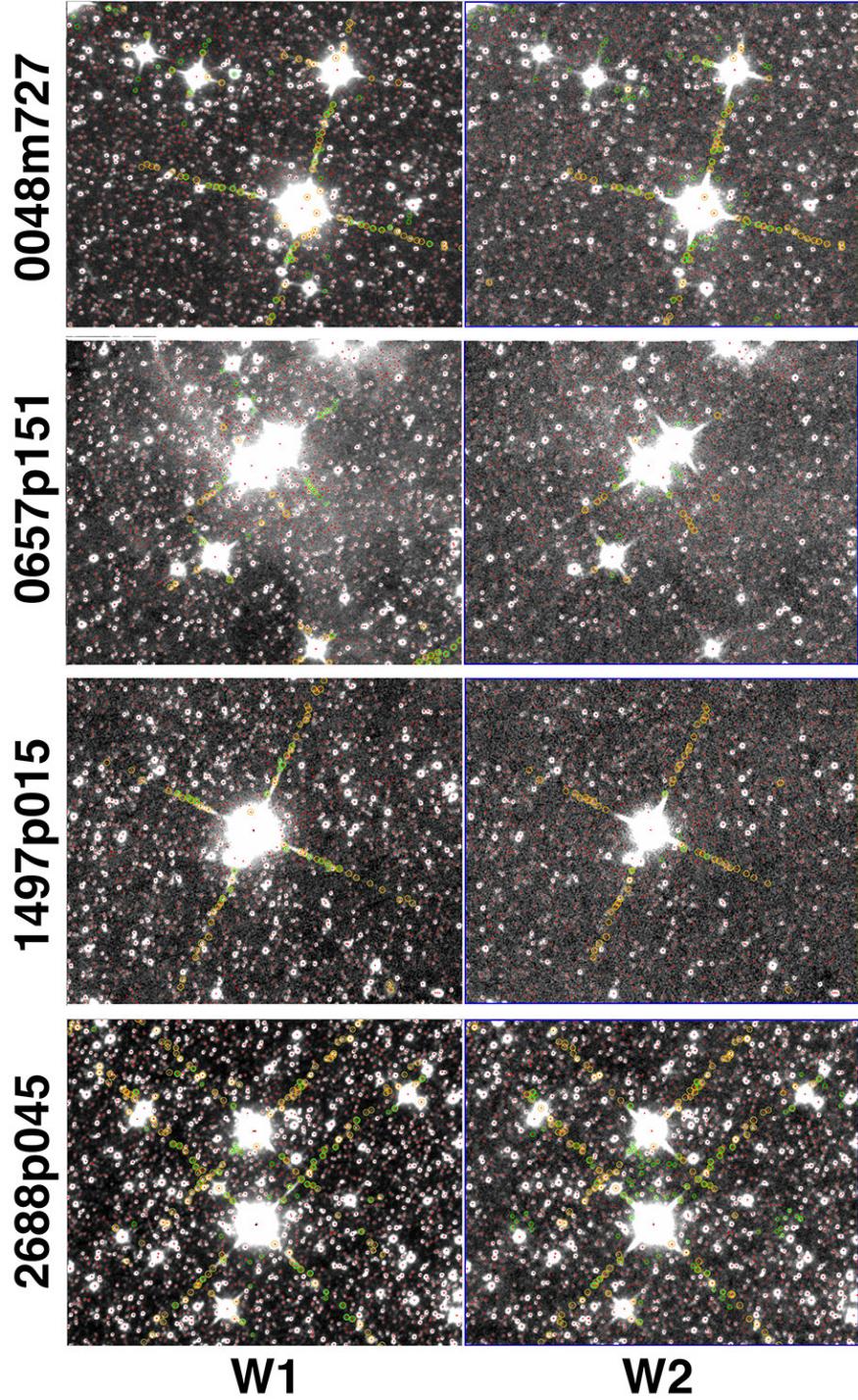


Figure 6. Example artifact flags for $16.5' \times 13.0'$ cutouts in W1 (left) and W2 (right) from the tiles listed along the far left. Detected CatWISE sources are shown by the red markers. Sources with upper-case *cc_flags* are circled in green and sources marked as artifacts by *ab_flags* are circled in orange. Zoom in for details.

3.6. Duplicate Source Measurements

WISE tiles, and, therefore, un*WISE* coadds, overlap each other by $\sim 3'$ on the equator. As a result, sources appearing near the edge of a tile will also be measured in neighboring tiles. To remove these duplicate measurements we adopted the approach used by [Schlafly et al. \(2019\)](#). For each source in a tile, its coordinates were used to calculate the minimum distance to the edge of the tile. The same coordinates were used to calculate the minimum distance to the edge for all neighboring tiles, and the source was flagged as “primary” if these other minimum distances were all smaller.

3.7. The CatWISE Preliminary Catalog

With the necessary flagging in place, catalog generation could proceed. CatWISE Preliminary catalog sources are required to:

- 1) be from the tile where that source is furthest from the tile edge (i.e. flagged as “primary,” §3.6) and
- 2a) have W1 SNR ≥ 5 with no identified artifacts (a value of 0 in the left character of *ab_flags*) or
- 2b) have W2 SNR ≥ 5 with no identified artifacts (a value of 0 in the right character of *ab_flags*).

There are 900,849,014 sources that meet these criteria. The 167,831,546 sources that fail to meet these criteria go into the reject file for their tile. Individual tile reject files typically contain 8,000 sources, although near the celestial poles they can contain over 30,000 sources due to large tile overlap. There are 186 formatted columns of information about each source in the tile catalog files. Reject files have one additional column, indicating if the source is primary in its tile. Descriptions of most of the columns are available in §II.1.a of the All*WISE* Explanatory Supplement ([Cutri et al. 2013](#)), and descriptions for columns unique to CatWISE are provided in Appendix A.

The individual Preliminary catalog and reject files for the 18,240 tiles were transferred to the NASA Infrared Science Archive (IRSA), where they were merged into the IRSA database. Four columns (with names in italics in Table 5) were removed from view by IRSA, for reasons explained in that Table. Information regarding access to the catalog is provided in §6.

CatWISE source designations should be given as CWISEP Jhhmmss.ss \pm ddmmss.s for objects in the CatWISE Preliminary catalog and CWISEPR Jhhmmss.ss \pm ddmmss.s for objects in the CatWISE Preliminary reject table⁴. The designation for each source, without the leading CWISEP or CWISEPR prefix, is given by the field *source_name* which is the first column in the files. For example, the quasar 3C 273 is CWISEP J122906.70+020308.6⁵

4. PERFORMANCE CHARACTERIZATION

The greatest potential for improvement of the CatWISE Preliminary catalog over existing *WISE* catalogs is in providing more accurate motion measurements, due to the much longer time baseline compared to AllWISE. Hence, characterization has focused on astrometric properties of the Preliminary catalog. Photometric depth is also improved due to the four times larger number of exposures than AllWISE. Characterization has emphasized comparison to external truth sets, using *Spitzer* for photometric comparisons including completeness and reliability, and *Gaia* for astrometric comparisons. We begin with the photometric assessments.

4.1. Completeness and Reliability

4.1.1. Bright Sources

CatWISE completeness and reliability for sources with W1 or W2 <8 mag were assessed using an updated version of the *WISE* Bright Star List (BSL) as a truth set. The list was generated by the *WISE* team for artifact flagging (see §4.4.g.vi in the *WISE* All-Sky Release Explanatory Supplement; Cutri et al. 2012). To avoid degradation of completeness or reliability due to missed matches for fast-moving sources, astrometric information for sources moving faster than $0.^{\circ}275 \text{ yr}^{-1}$ was added to the BSL to propagate the positions of such stars to the CatWISE epoch. Astrometric information was taken from *Gaia* DR2 (Gaia Collaboration et al. 2018; Lindegren et al. 2018) or, when not available (given *Gaia*'s known incompleteness for bright stars) from the *Hipparcos* main

⁴ These designations conform to the naming conventions outlined by the International Astronomical Union (<http://cdsweb.u-strasbg.fr/Dic/iau-spec.html>), where the decimal portions of RA and Dec are truncated rather than rounded, and the "J" indicates that the coordinates are for J2000 equinox.

⁵ The CatWISE Preliminary catalog coordinates for 3C 273 are within 11 mas of the *Gaia* DR2 coordinates.

catalogue (van Leeuwen 2007), the *Tycho-2* catalog (Høg et al. 2000), or the Gliese-Jahreiß catalog (Stauffer et al. 2010).

CatWISE completeness was determined as the percentage of sources that have astrometric matches in CatWISE as a function of BSL magnitude. Differential CatWISE reliability was determined as the percentage of sources that have astrometric matches in the BSL as a function of CatWISE magnitude. We used a relatively large matching radius of $5''.5$ (corresponding to two *WISE* pixels) to account for the poorer centroiding accuracy expected for highly saturated sources.

Figure 7 shows the results for completeness, compared to those from AllWISE. CatWISE achieves $\sim 99\%$ completeness in the BSL $W1 \sim 5.5 - 8$ mag and $W2 \sim 5 - 8$ mag ranges, slightly lower than AllWISE. For reasons that we have not investigated, CatWISE completeness drops for brighter stars, falling to $\sim 50\%$ by $W1 \sim 4.3$ mag and $W2 \sim 3.6$ mag. AllWISE completeness remains above 90% even for stars as bright as 0.25 mag, making it preferable to CatWISE for investigations of the brightest stars.

CatWISE reliability is $\sim 99\%$ for $W1 \sim 4.8 - 8$ mag and $W2 \sim 4.5 - 8$ mag, somewhat better than AllWISE, as can be seen in Figure 8. (For sources without artifacts in either CatWISE or AllWISE, the median (CatWISE - AllWISE) value over the 2.5 to 8 mag range is 0.17 mag in $W1$ and 0.02 mag in $W2$, and the median absolute deviation is 0.08 mag in $W1$ and 0.02 mag in $W2$). Even though completeness falls rapidly for brighter stars, CatWISE reliability is $\sim 90\%$ or better down to 2.5 mag. For the brightest stars, CatWISE completeness is poor, and CatWISE reliability shows large fluctuations due in part to the resulting small number statistics.

4.1.2. Faint Sources

Completeness and reliability were assessed for faint sources using the *Spitzer* South Pole Telescope Deep Field (SSDF) survey (Ashby et al. 2013) as a truth set. The SSDF covers ~ 94 deg 2 with 2 minutes of integration per position with *Spitzer*. *WISE* survey depth increases towards the ecliptic poles, and at $\beta \sim -46^\circ$, the typical number of CatWISE exposures is 125, or 16 minutes. Nevertheless the larger *Spitzer* mirror diameter (85 cm vs. 40 cm for *WISE*) and better image quality ($2''$ vs. $6''$) makes the SSDF data more sensitive than CatWISE.

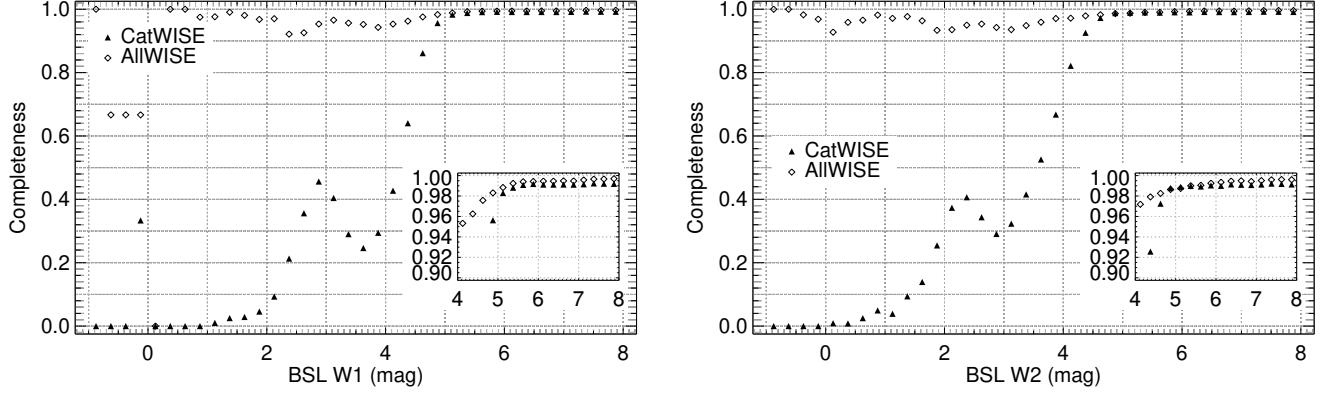


Figure 7. Differential completeness of the CatWISE Preliminary catalog as a function of the Bright Star List’s W1 (left) and W2 (right), compared to AllWISE.

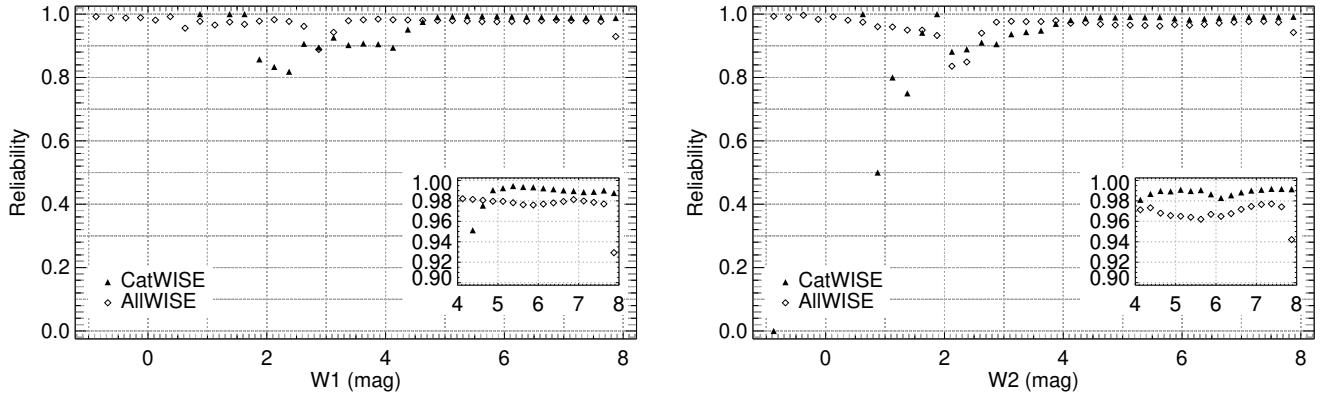


Figure 8. Differential reliability of the CatWISE Preliminary catalog as a function of W1 (left) and W2 (right), compared to AllWISE.

The radius used to match *Spitzer* SSDF sources with CatWISE sources was $2.^{\circ}5$, and otherwise the methodology to determine completeness and reliability was the same as in §4.1.1. The results are shown in Figures 9 and 10.

At this coverage depth, the CatWISE Preliminary catalog completeness is $\sim 98\%$ for sources brighter than 13th mag, consistent with the performance seen from comparisons to the Bright Star List (§4.1.1), and remains above 90% for sources brighter than $[3.6] = 16$ mag or $[4.5] = 15.5$ mag, dropping to 50% at $[3.6] = 17.8$ mag and $[4.5] = 17.4$ mag. The SSDF achieves 55% completeness at $[3.6] = 18.5$ mag and $[4.5] = 18.0$ mag (Ashby et al. 2013).

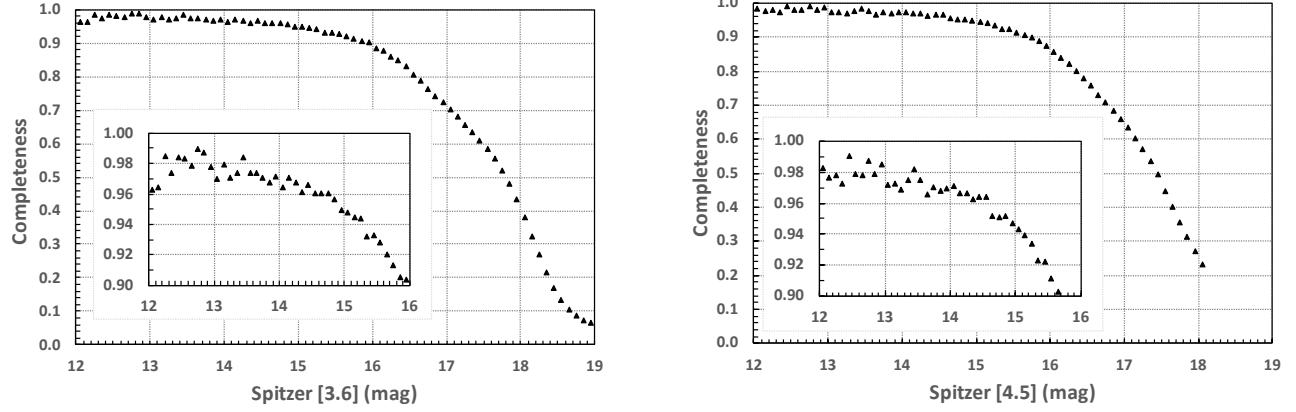


Figure 9. Completeness of the CatWISE Preliminary catalog vs. *Spitzer* $3.6\mu\text{m}$ (left) and $4.5\mu\text{m}$ (right) magnitude for sources in the SSDF.

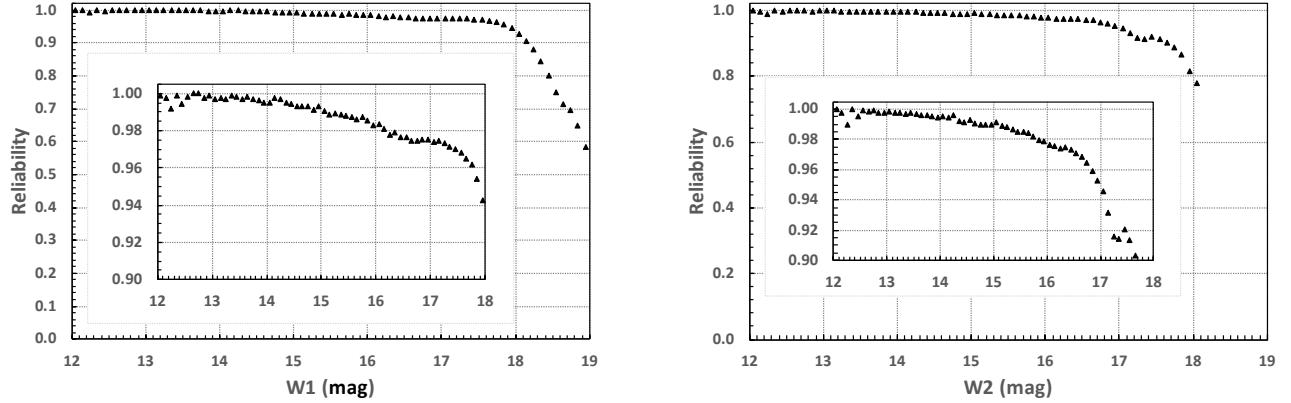


Figure 10. Reliability of the CatWISE Preliminary catalog as a function of W1 (left) and W2 (right), for sources in the SSDF.

CatWISE reliability at this coverage depth is better than 99% for sources brighter than 15th mag in both W1 and W2, again consistent with the Bright Star List results. CatWISE reliability remains above 90% to W1 = 18.2 and W2 = 17.6 for this ecliptic latitude and coverage depth. Reliability at fainter magnitudes is not well determined because the SSDF data is not deep enough.

4.2. Photometric properties

The COSMOS field is an important benchmark for assessing CatWISE performance, because it has been intensively observed, is near the ecliptic ($\beta = -11^\circ$), and is at fairly high Galactic latitude ($b = 41^\circ$). Although confusion effects are reduced by the high Galactic latitude, the ecliptic has the

highest zodiacal emission and lowest survey coverage from *WISE*, making COSMOS a representative base for performance estimates. .

Figure 11 compares CatWISE Preliminary catalog PSF-fitting photometry to 2''.9 radius aperture photometry from the *Spitzer* S-COSMOS program (Sanders et al. 2007). These observations were obtained using longer integration times (20 minutes) than for the SSDF, while the CatWISE integration is lower (12 minutes) than in the SSDF, so the S-COSMOS data are much deeper than CatWISE. The closest CatWISE source within 2''.75 was taken as the match to the S-COSMOS source. Because the CatWISE photometry is point source fitting, S-COSMOS sources were required to have $< 10\%$ flux increase between the 1''.9 and 2''.9 radius apertures. In addition, because the W1 band is significantly bluer than the [3.6] band, S-COSMOS sources at [3.6] were required to have $-0.1 \leq [3.6] - [4.5] \leq 0$ (see Figures 2 and 3 in §VI.3.a of the All-Sky Explanatory Supplement; Cutri et al. 2012). Figure 12 gives the analogous comparison to photometry from the SSDF survey.

The comparison between the CatWISE and *Spitzer* photometry is consistent for both fields, in both bands. CatWISE photometry becomes ~ 0.1 mag fainter than *Spitzer* beyond 16th mag, possibly due to the increasing incidence of extragalactic sources at faint magnitudes. The measured scatter in the SSDF reaches 0.217 mag, equivalent to an SNR of 5, at [3.6] = 17.64 mag and [4.5] = 16.49 mag. Adjusting for the mean offsets in W1-[3.6] and W2-[4.5] at these magnitudes, and subtracting 0.14 mag to adjust the SSDF 125 exposure depth to the 96 exposure depth that we take as the baseline for the CatWISE Preliminary catalog, we find that the SNR=5 limits for CatWISE are W1=17.67 mag and W2=16.47 mag.

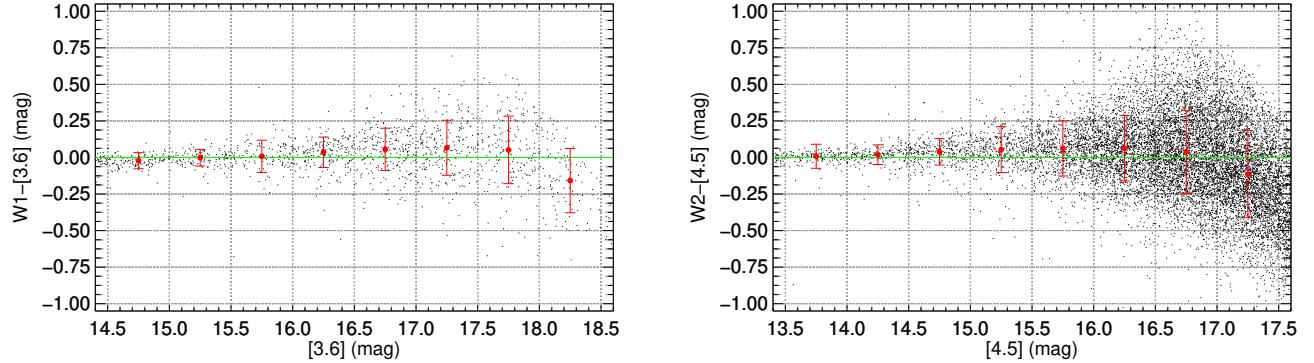


Figure 11. Comparison of CatWISE photometry to *Spitzer* photometry for COSMOS. *Left:* Difference between CatWISE W1 PSF and *Spitzer* S-COSMOS 2.9'' radius aperture photometry at [3.6], for sources with $-0.1 < [3.6] - [4.5] < 0$ and $< 10\%$ flux increase from the 1.9'' to 2.9'' aperture. Median differences and standard deviations in 0.5 mag bins are shown by the red points and error bars. *Right:* The analogous comparison for CatWISE W2 and *Spitzer* [4.5] photometry, but without the restriction on *Spitzer* source color.

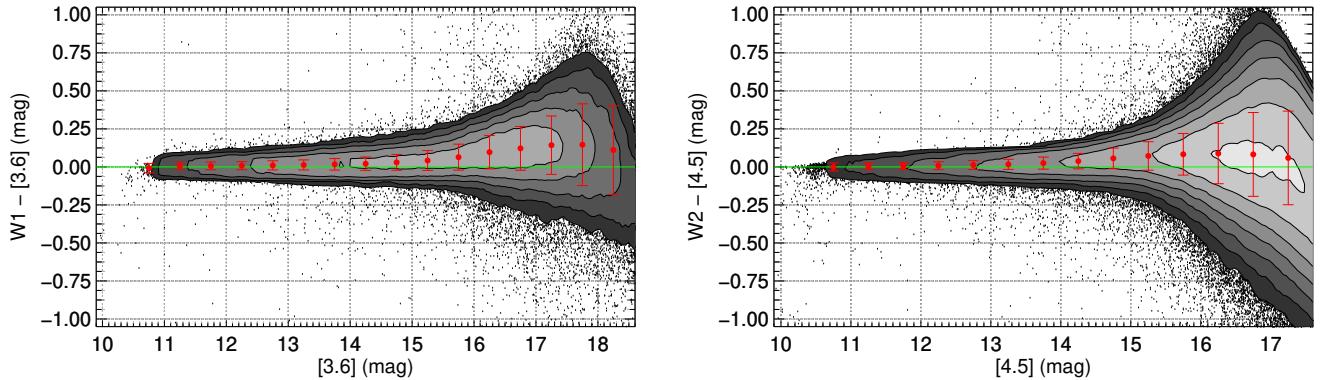


Figure 12. Comparison of CatWISE photometry to *Spitzer* photometry for the SSDF, using the same methodology as in Figure 11. The outer contour represents a source density of 10 sources per 0.05×0.05 mag bin, with each additional contour showing a factor of two increase in source density.

4.3. Astrometric properties

4.3.1. Full-sky Astrometric Assessments

The astrometric performance of CatWISE was assessed by comparing to *Gaia* DR2 ([Gaia Collaboration et al. 2018](#); [Lindegren et al. 2018](#)). Within each tile, the 10 brightest sources in bins of 0.5 mag

over the $10 < W1 < 17.5$ mag range were selected, providing a sample of 150 sources per tile, uniformly distributed on the sky. At low Galactic latitudes, CatWISE does not reach to $W1=17.5$ mag, and therefore the faintest bins are empty. The sample for astrometric comparison consists of 2,699,315 sources. These sources were cross-matched with *Gaia* DR2 using a $5.^{\circ}5$ radius (corresponding to two *WISE* pixels), requiring the *Gaia* counterpart to have measured proper motions. This returned 2,148,274 unique matches. The completeness of the match approaches 100% for sources brighter than $W1=14$ mag, and drops to $\sim 25\%$ at the faintest magnitudes. *Gaia* astrometry was used to propagate the *Gaia* counterparts to the CatWISE epoch, and the standard deviation⁶ between the CatWISE and *Gaia* position and motion was computed.

Figure 13 summarizes the results of the full sky comparison. The positional accuracy floor for bright sources approaches ~ 50 mas and remains approximately constant until $W1 \sim 12.5$ mag. At fainter magnitudes, the dispersion increases to 275 mas (1/10 of a pixel) at $W1 \sim 15.5$ mag, while in the faintest magnitude bin the dispersion is ~ 700 mas, with the dispersion in α being slightly better than in δ . This is expected since the scan direction is closer to δ and, as discussed in §3.2, the PSF is more elongated in the scan direction. At the bright end, however, the accuracy in δ is better than in α , an effect not fully understood.

The motion accuracy floor for bright stars is just under 10 mas yr^{-1} , consistent with the positional accuracy floor – given CatWISE’s 6 year baseline, and since the motion accuracy scales linearly with time, one would expect $\sigma_\mu \sim \sigma_{\text{pos}}/6$. At $W1 \sim 15.5$ mag, the motion accuracy is $\sim 30 \text{ mas yr}^{-1}$, a factor of 10 better than AllWISE (Kirkpatrick et al. 2014). At the faint end, CatWISE is sensitive to proper motion of 100 mas yr^{-1} until $W1 \sim 17$ mag.

The two panels on the right of Figure 13 show the χ^2 computed using the CatWISE catalog uncertainties, the *Gaia* catalog uncertainties, and the uncertainty introduced by the translation of the *Gaia* position to the CatWISE epoch. Since the total uncertainty is dominated by CatWISE, these χ^2 values are essentially a measurement of how accurate the CatWISE Preliminary catalog uncertainties

⁶ The IDL “robust_sigma” function was used to calculate the standard deviation.

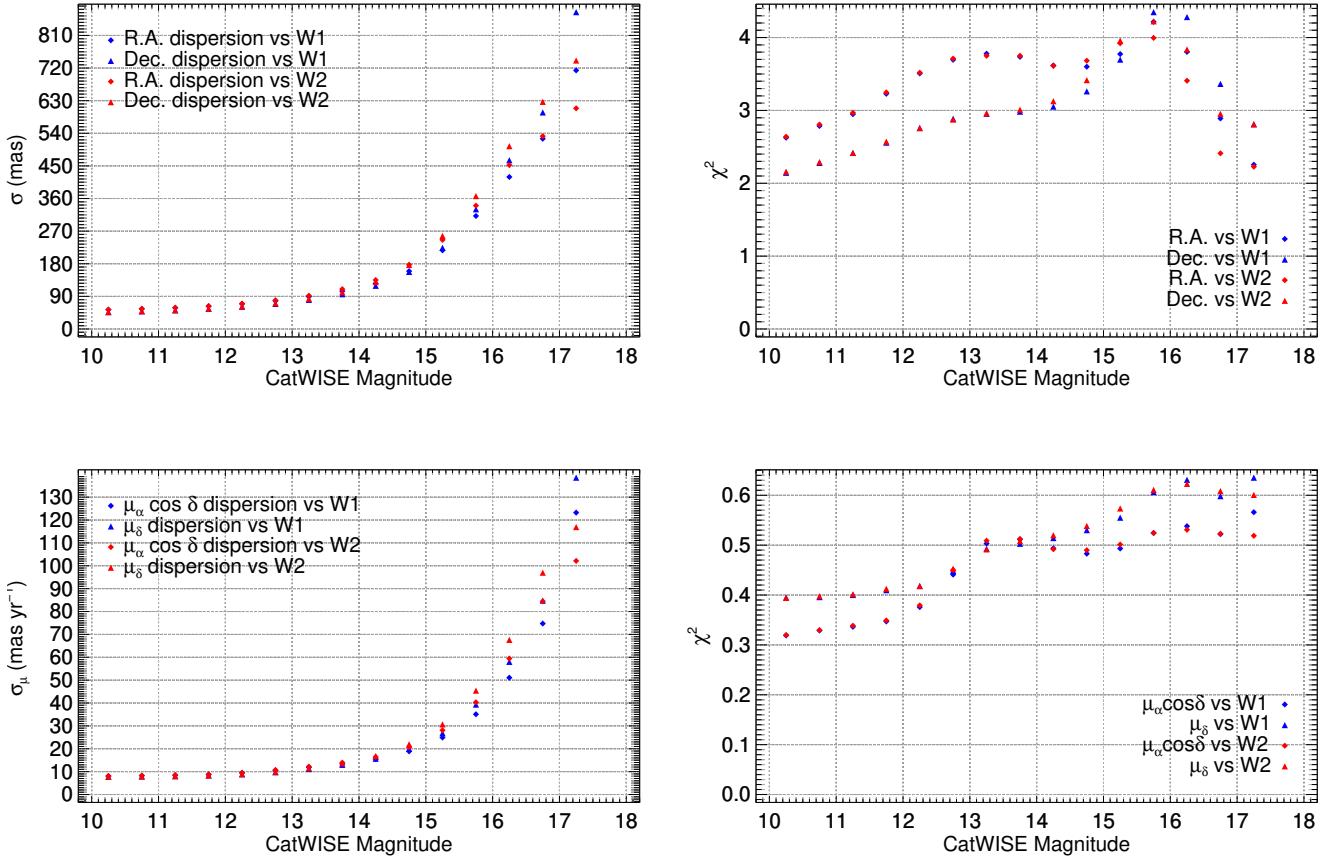


Figure 13. CatWISE astrometric performance with respect to *Gaia* DR2. *Left:* the $1-\sigma$ dispersion between CatWISE and *Gaia* R.A. and Dec. (top) and proper motion (bottom), for a subsample of ~ 2.1 million sources in the $10 < \text{W1} < 17.5$ mag range, uniformly distributed over the entire sky. *Right:* the median χ^2 computed taking into account CatWISE catalog uncertainties, *Gaia* catalog uncertainties, and the uncertainty introduced by the translation of *Gaia*'s positions to the CatWISE epoch.

are. It is apparent from the top right panel of Figure 13 that the catalog position uncertainties underestimate the actual errors by a factor of 1.6–2. In contrast, the motion uncertainties are overestimated by a factor of 1.3–1.7 (lower right panel). The latter effect is due in part to imposing a minimum value of 10 mas yr^{-1} on the motion uncertainties, a setting used by AllWISE and left unchanged for the CatWISE Preliminary catalog.

The astrometric performance is however not uniform over the sky. Figures 14–17 show the $1-\sigma$ dispersion in each tile with respect to *Gaia* positions and motion components for the full magnitude

range considered (Figures 14 and 16), and in three smaller magnitude intervals (Figures 15 and 17). The maps for the full magnitude range are smooth overall, indicating a fairly constant astrometric performance for CatWISE over the majority of the sky. The main features can be easily identified – the Galactic plane (and in particular the bulge), and the Small and Large Magellanic Clouds (SMC and LMC). In those denser regions, the astrometric accuracy for the bright stars deteriorates to ~ 500 mas for positions and ~ 30 mas yr $^{-1}$ for motions, and to $\sim 1,000$ mas and ~ 200 mas yr $^{-1}$ (or worse) for the faint stars.

The motion accuracy maps show additional features that appear to be related to the *WISE* survey strategy, and to the transition between the cryogenic and post-cryogenic phases of the mission. In particular, one can see better motion performance approaching the ecliptic poles (at $l = 96^\circ; b = 30^\circ$ and $l = 276^\circ; b = -30^\circ$, respectively) compared to regions of similar Galactic latitude. This is a result of the increased coverage of the sky by *WISE* at higher ecliptic latitude. Conversely, there are two strips of slightly poorer motion performance, which are coincident with the transition between cryogenic and post-cryogenic phases, where the PSF was changing rapidly as the telescope was warming up.

The maps for the faintest magnitude interval appear noisy. This is partly intrinsic, and partly an effect of statistical fluctuations due to the low number of sources with a *Gaia* counterpart in each tile (as discussed above, the completeness for the *Gaia* match drops to $\sim 25\%$ at the faint end). Moreover, at lower Galactic latitudes, CatWISE detects only brighter sources because of confusion noise.

4.3.2. Astrometric Assessments in Selected Tiles

We next consider the astrometric performance in more detail by focusing on four tiles:

- the North Ecliptic Pole tile (NEP, tile 2709p666), a field with maximal *WISE* coverage and average source density;
- the South Ecliptic Pole tile (SEP, tile 0890m667) a field with with maximal *WISE* coverage and high source density (the SEP tile contains part of the LMC);

- the Galactic Center tile (GC, tile 2657m288) a field with average *WISE* coverage and maximal source density; and
- the COSMOS tile (tile ID 1497p015), representative of most of the sky, i.e. a field with average *WISE* coverage and source density.

The analysis of §4.3.1 was repeated for these four tiles, but using all of the sources in each tile. The results are shown in Figure 18 and 19. We then defined ten metrics to characterize the astrometric performance of CatWISE:

- σ_{\min} and $\sigma_{\mu, \min}$ are the accuracy floor for positions and motions, respectively. These accuracy floors are determined as the median dispersion with respect to *Gaia* in the $8 < W1, W2 < 10$ mag interval, except in the GC where we restrict to $8 < W1, W2 < 9$ mag since the astrometric accuracy starts deteriorating significantly beyond $W1, W2 \sim 9$ mag (see Figure 18–19).
- $W1_{\min}$, $W2_{\min}$, $W1_{\mu, \min}$, and $W2_{\mu, \min}$ are the $W1$ and $W2$ mag at which σ_{\min} and $\sigma_{\mu, \min}$ are exceeded by no more than 20 mas and 5 mas yr^{-1} , respectively.
- $W1_{500}$ and $W2_{500}$ are the $W1$ and $W2$ mag at which the accuracy on positions reaches 500 mas.
- $W1_{\mu, 100}$ and $W2_{\mu, 100}$ are the $W1$ and $W2$ mag at which the accuracy on motion reaches 100 mas yr^{-1} .

The results for the four representative tiles are summarized in Table 4.

For brighter sources, σ_{\min} and $\sigma_{\mu, \min}$ are encouragingly small, on the order of 40 mas and 8 mas yr^{-1} , respectively. $W1_{\min}$ and $W2_{\min}$ are ~ 12 mag while $W1_{\mu, \min}$ and $W2_{\mu, \min}$ are ~ 14.5 mag. All the above metrics show little dependence on coverage and source density, except for the GC tile, where they are degraded to $\sigma_{\min} \sim 530$ mas, $\sigma_{\mu, \min} \sim 20$ mas, at a limiting depth of only ~ 8 mag and ~ 9 mag respectively. This is consistent with the uniformity of the maps in Figures 14 to 17.

For fainter sources, $W1_{500}$, $W2_{500}$, $W1_{\mu, 100}$ and $W2_{\mu, 100}$ show a clearer dependence on source density and coverage. For COSMOS (i.e. a typical CatWISE tile) these metrics are ~ 17 mag. $W1_{500}$ and $W2_{500}$ become ~ 9 mag shallower in the GC, while $W1_{\mu, 100}$ and $W2_{\mu, 100}$ measurements are upper

Table 4. CatWISE Astrometric Performance Evaluation Fields

	0890m667	1497p015	2657m288	2709p666
	SEP, LMC	COSMOS	GC	NEP
l (deg)	276.5	237.3	359.8	96.4
b (deg)	-30.2	41.4	0.6	29.5
β (deg)	-89.6	-10.2	-5.4	89.6
Exp.	7154	90	86	7839
#	71462	58961	63368	61702
σ_{\min} (mas)	52.9	27.3	526.4	37.7
W1 _{min} (mas)	11.0	12.5	8.0	12.0
W1 ₅₀₀ (mag)	15.1	17.0	8.4	18.5
W2 _{min} (mag)	11.0	12.5	8.0	12.0
W2 ₅₀₀ (mag)	15.0	16.8	8.3	19.0
$\sigma_{\mu,\min}$ (mas yr ⁻¹)	7.4	8.5	22.2	7.3
W1 _{μ,min} (mag)	14.5	13.5	9.0	15.5
W1 _{$\mu,100$} (mag)	18.2	16.8	> 11.0	> 19.0
W2 _{μ,min} (mag)	14.5	13.5	9.0	15.5
W2 _{$\mu,100$} (mag)	>20.5	16.7	>11.5	>20.0

NOTE— l , b , and β are the Galactic longitude, Galactic latitude, and ecliptic latitude for the center of the tile, in degrees. Exp. indicates the number of exposures for the tile, # the number of sources (combining catalog and reject entries). The subsequent metrics are described in detail in §4.3.

limits only. This is again a consequence of the fact that at lower Galactic latitudes CatWISE only detects brighter sources because of confusion noise, and for sources this bright the motion accuracy never degrades to the 100 mas yr⁻¹ level.

W1 _{$\mu,100$} and W2 _{$\mu,100$} become \sim 2 mag deeper (\sim 19 mag) at the ecliptic poles, thanks to the higher coverage. W1₅₀₀ and W2₅₀₀ are much deeper at the NEP than the SEP, most likely an effect of the much higher source density at the SEP, and therefore the higher confusion noise. However, this does not seem to affect the motion metrics.

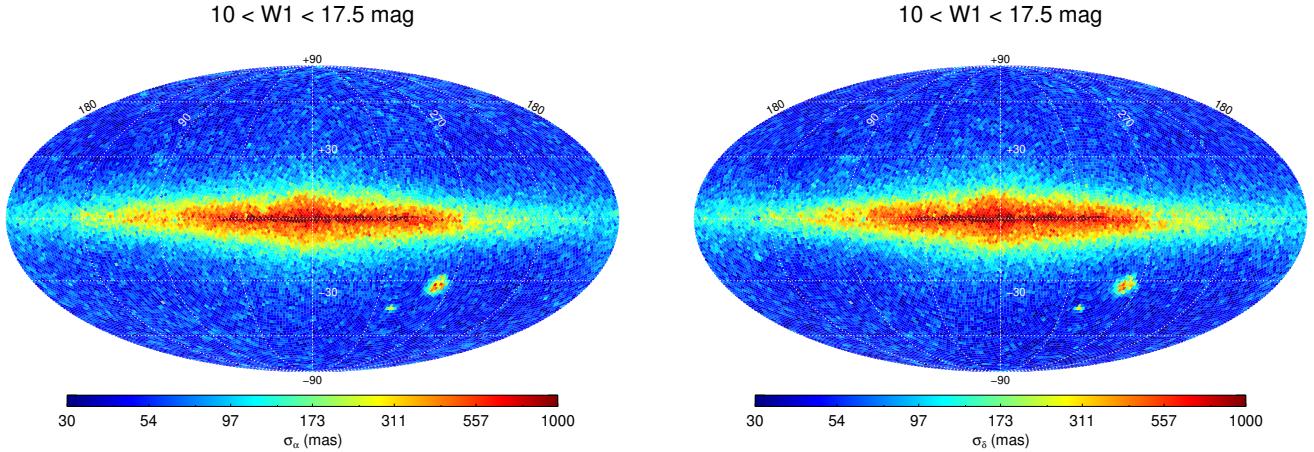


Figure 14. 1- σ dispersion of the CatWISE α (left) and δ (right) with respect to *Gaia* DR2, for sources in the $10 < W1 < 17.5$ mag range.

4.3.3. Fast Movers

We compared the astrometric performance using separate PSF's for ascending and descending scans to that using a single PSF per band for all scans (see §3.4) on a set of 19 known ultracool dwarfs, chosen from the literature. Our test set included extremely cold, very fast moving objects (e.g. WISE J085510.83–071442.5, $\mu_{\text{tot}} \sim 8$ arcsec yr $^{-1}$; Luhman 2014), as well as warmer, slower M dwarfs (e.g. WISE J072003.20–084651.2, $\mu_{\text{tot}} \sim 0.12$ arcsec yr $^{-1}$; Scholz 2014). Results using separate PSF's proved superior, delivering good motion measurements for 17 out of the 19 test objects, while the single PSF option only recovered 13 out of the 19 test objects, with a clear drop in performance for objects with $\mu_{\text{tot}} \gtrsim 2.5$ arcsec yr $^{-1}$. Only one out of the five fastest moving objects in our test sample is correctly measured using the single PSF method, while using separate ascending and descending scan PSF's measures four out of these five.

The two objects that our pipeline is unable to correctly measure – WISE J163940.83–684738.6 and WISEPC J205628.90+145953.3 – are missed at the detection stage (§3.3) because they are partly blended with brighter nearby sources. These two sources were recovered when the detection step was run without the PSF convolution (§3.1 and 3.3), yielding reasonable motions, but they are not present in the CatWISE Preliminary catalog.

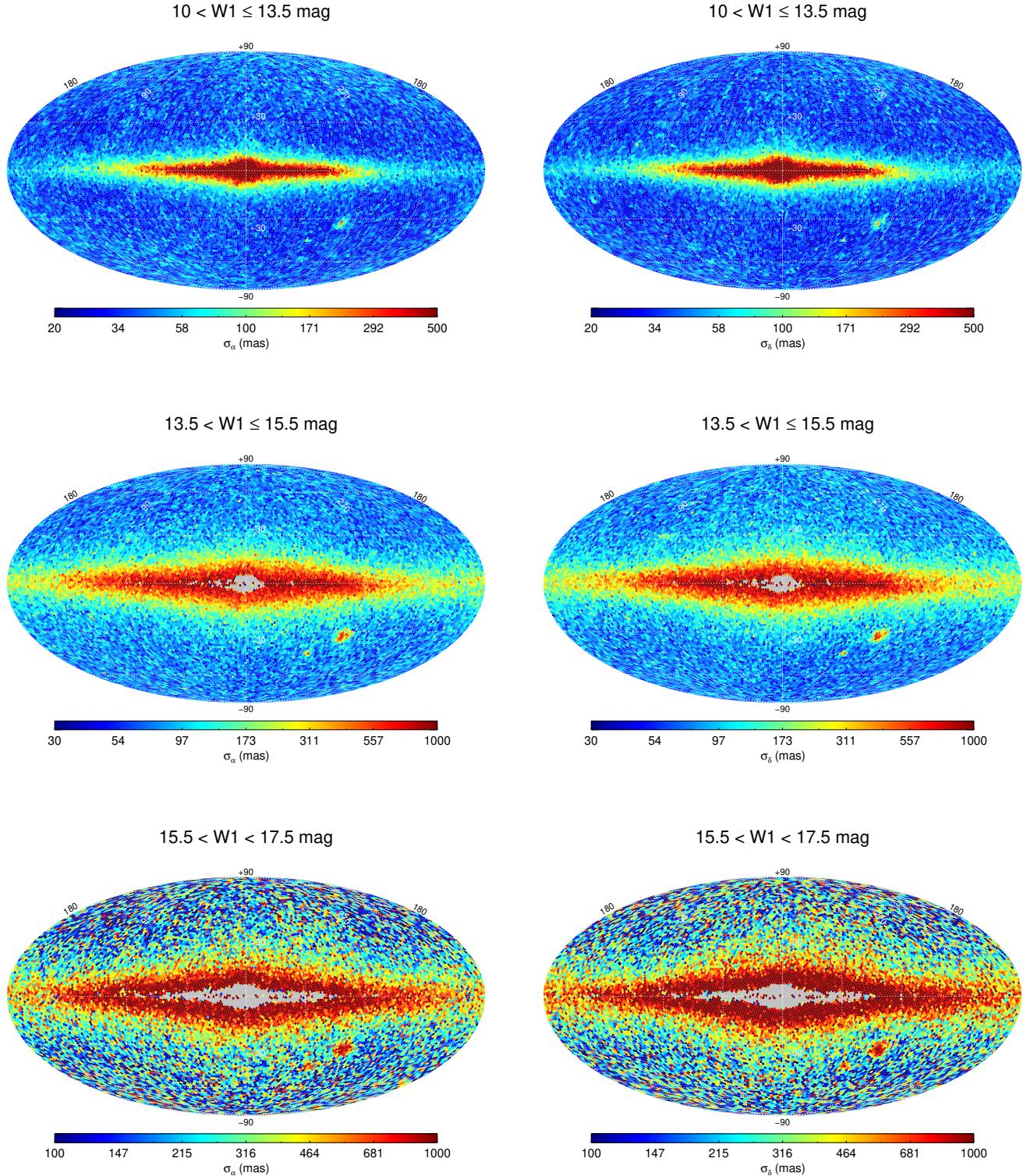


Figure 15. Same as Figure 14, but for three W1 magnitude ranges. Gray tiles are those where there were no sources in CatWISE in the given magnitude bin.

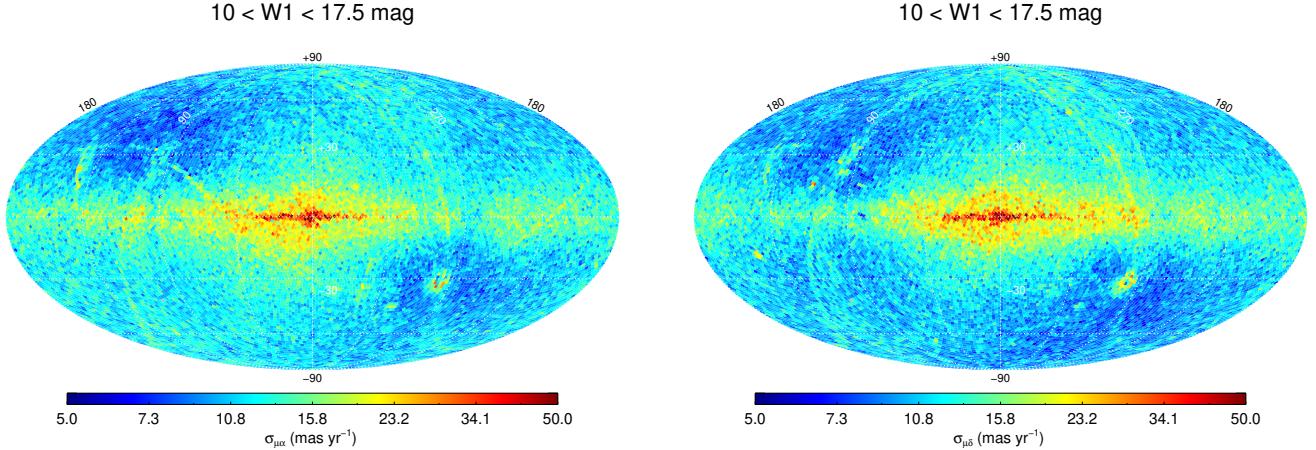


Figure 16. Same as Figure 14, but for the proper motion components.

5. EXAMPLE SCIENCE APPLICATIONS

An initial application of the CatWISE catalog was the first secure W2 detection for the Y dwarf WD0806-661 B (Meisner et al. 2018c), leading to a W2–ch2 color consistent with the population of known Y dwarfs. CatWISE represents a major hunting ground for cold brown dwarfs. The improved depth (§4.2) and motion sensitivity (§4.3) allows for a deeper, more complete search for the coldest constituents of the solar neighborhood, a crucial population if we wish to constrain the low-mass end of the mass function (see e.g. Kirkpatrick et al. 2019).

Towards this goal we are mining CatWISE using both a “classical” and a “machine learning based” approach. Here “classical” means a search based on color and motion cuts applied to the catalog data to select cold brown dwarf candidates, while machine learning uses the previously known population of cold brown dwarfs as a training set to develop a classifier that is then applied to the CatWISE catalog.

Early results include the discovery of CWISEP J193518.59–154620.3 (Marocco et al. 2019), one of the coldest brown dwarfs identified to date, with infrared colors comparable with those of the coldest brown dwarf known, WISE J085510.83–071442.5 (Luhman 2014). *Spitzer* follow-up of additional cold brown dwarf candidates is in progress (Meisner et al., in prep.).

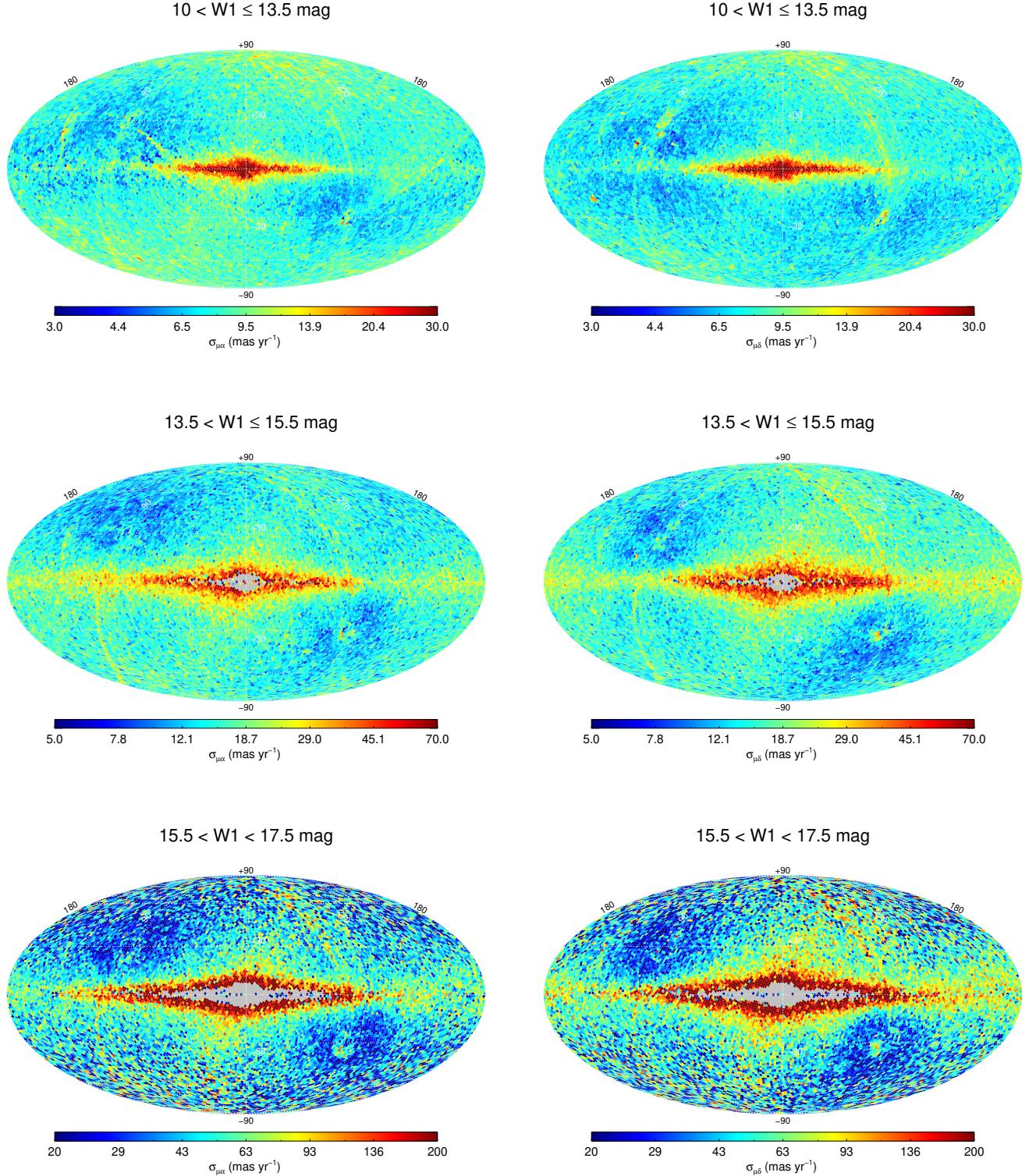


Figure 17. Same as Figure 16, but for three W1 magnitude ranges. Gray tiles are those where there were no sources in CatWISE in the given magnitude bin.

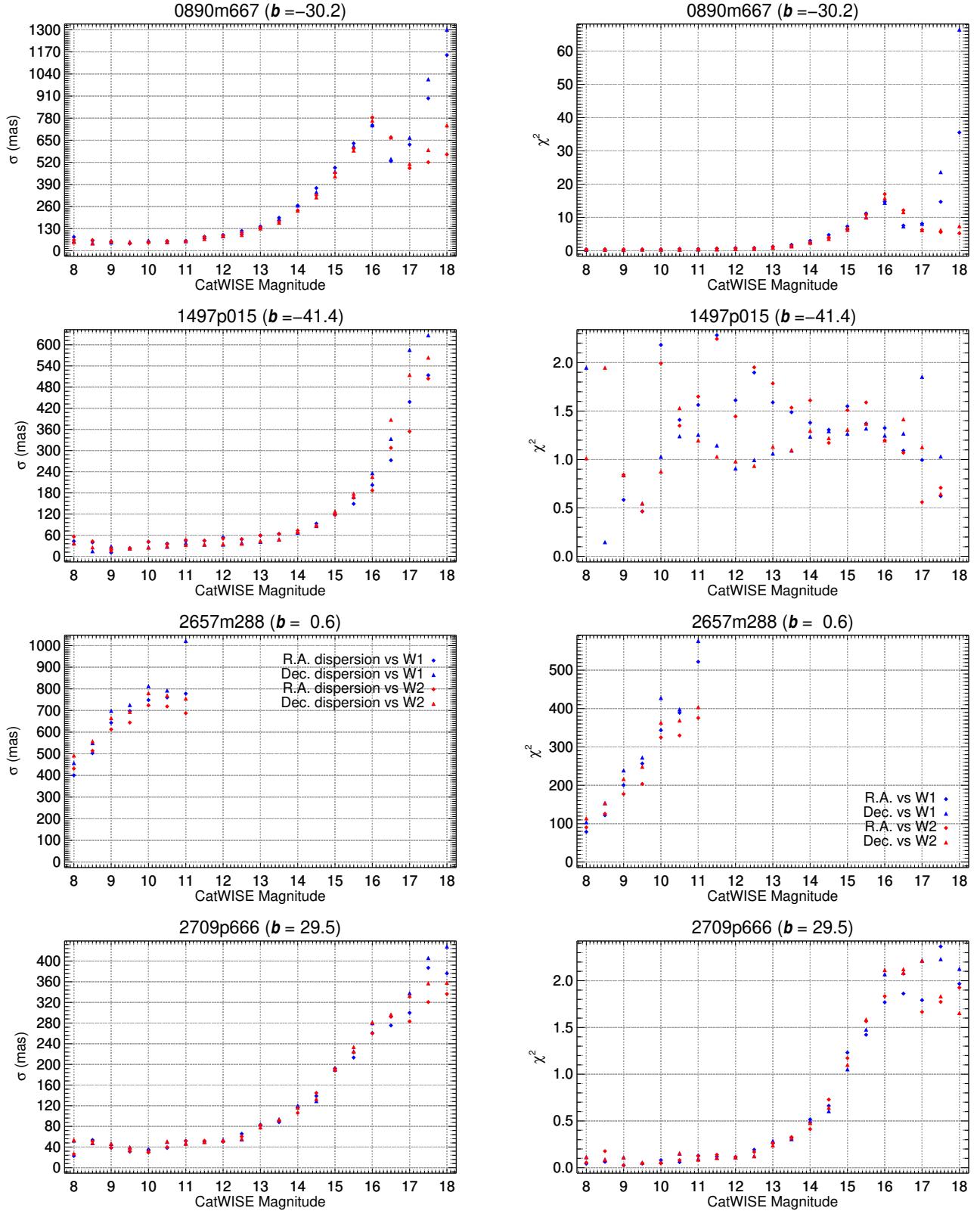


Figure 18. Same as Figure 13, but for four tiles: the SEP (0890m667), COSMOS (1497p015), the GC (2657m288), and the NEP (2709p666). The standard deviation between CatWISE position measurements and *Gaia* DR2 position measurements, and the corresponding χ^2 in 0.5 mag bins, is shown in red (R.A.) and blue (Dec.).

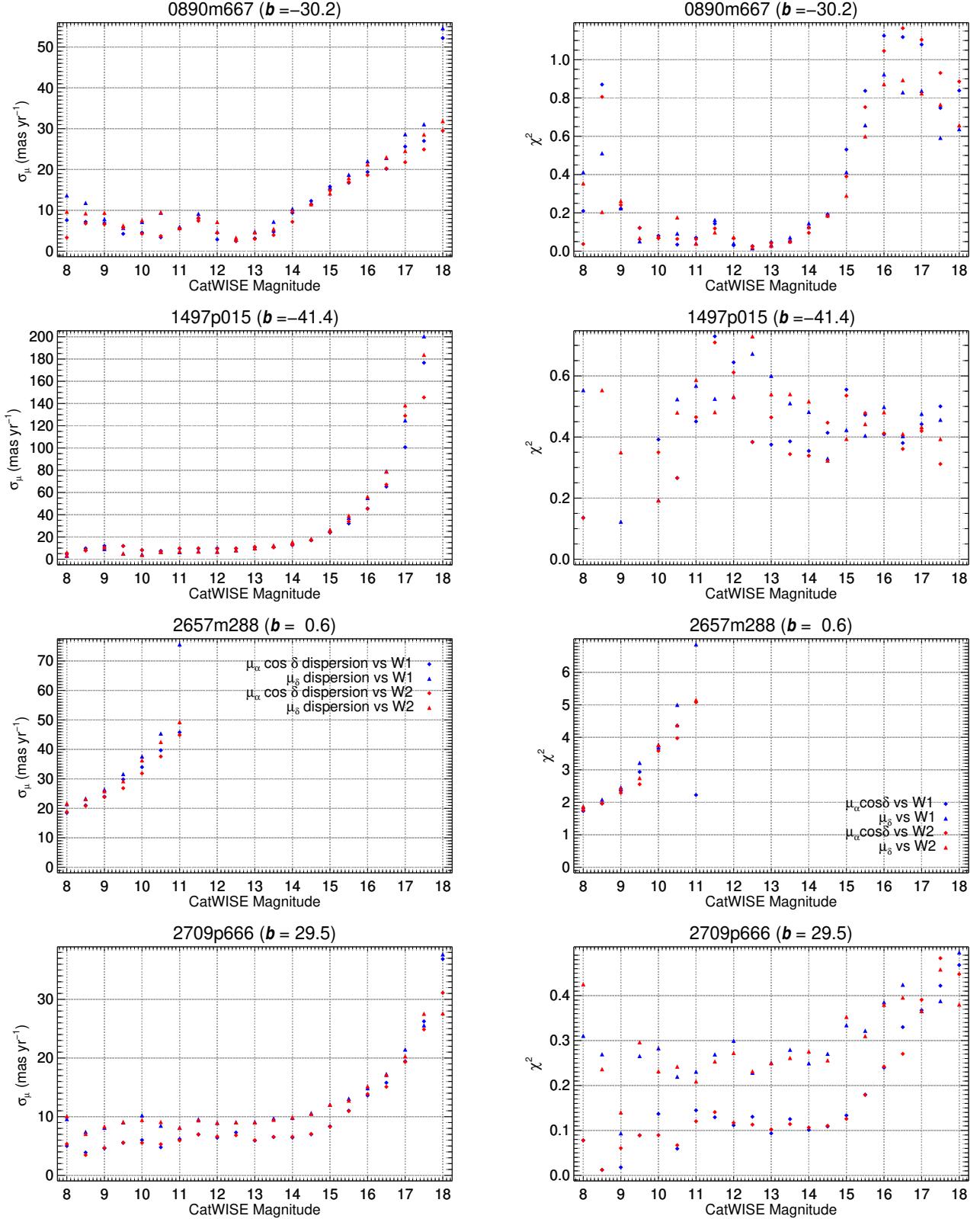


Figure 19. Same as Figure 18, but for motion measurements.

Prospects are also good for discovering distant galaxy clusters using CatWISE. [Gonzalez et al. \(2019\)](#) used the AllWISE catalog together with Pan-STARRS to carry out the Massive and Distant Clusters of WISE Survey (MaDCoWS), identifying over 2000 galaxy cluster candidates with photometric redshifts in the $0.7 - 1.5$ range. The additional depth of CatWISE compared to AllWISE increases the W1 detection limit for L* galaxies from $z \sim 0.8$ to $z \sim 2$. Figure 20 illustrates the increase in the number of distant galaxies with substantial photometric redshifts in the COSMOS field ([Laigle et al. 2016](#)) detected by CatWISE compared to AllWISE. Between $z = 1$ and 1.5 clusters transition from being mainly quiescent in terms of star formation to being more actively star-forming than the field (e.g., [Brodwin et al. 2013](#)), so CatWISE offers the potential of reaching the era where major formation and assembly of clusters is underway.

Finally, the AllWISE catalog played an important role in the discovery of ULAS J1342+0928, at $z = 7.54$ the most distant quasar known ([Bañados et al. 2018](#)). The additional depth of CatWISE may enable extending this to redshifts as large as 9, when the seeds of reionization were emerging in the overwhelmingly neutral Universe. With over 3000 refereed papers making use of the existing *WISE* catalogs, many other uses for CatWISE can be anticipated.

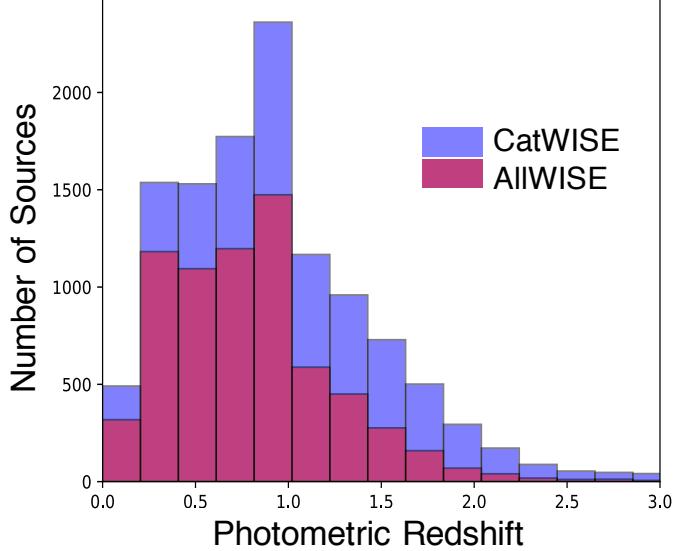


Figure 20. CatWISE detects sources ~ 0.5 mag fainter than AllWISE, providing many times more sources at $z > 1.5$. The vertical axis is the number of COSMOS sources that were detected by CatWISE and AllWISE in the 1497p015 tile and had matches within $2''.5$ of sources with the indicated photometric redshifts from Laigle et al. (2016).

6. DATA ACCESS

Current information about CatWISE data products is provided at <https://catwise.github.io>.

The merged Preliminary catalog and reject table files are available from IRSA (<https://irsa.ipac.caltech.edu>) as a contributed data set. IRSA’s catalog search tools allow for complex search queries. IRSA also hosts the AllWISE Explanatory Supplement (Cutri et al. 2013), which provides full details on the AllWISE processing algorithms, and includes descriptions of the AllWISE catalog columns, many of which are applicable to CatWISE. Columns unique to CatWISE are described in Appendix A.

The individual tile files have also been transferred to a data repository at the National Energy Research Scientific Computing Center (NERSC), and are available at <https://portal.nersc.gov/project/cosmo/data/CatWISE/prelim> in 18,240 pairs of gzipped ASCII files (one catalog and one reject file per tile) in IPAC table format, organized into 359 directories, one for each decimal degree of right ascension from 0° to 358° (there are no tiles beginning with 359). Text files providing the format

and a brief description of the columns in the catalog and reject files are also provided there. The catalog and reject files for the 50 tiles near the ecliptic poles (Table 1), where a single PSF per band was used for processing, include the string “opt0” in their names. Files for tiles where different PSFs were used for ascending and descending scans (§3.2) include the string “opt1” in their names.

CatWISE uses data products from *WISE*, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory (JPL)/California Institute of Technology (Caltech), funded by the National Aeronautics and Space Administration (NASA), and from *NEOWISE*, which is a JPL/Caltech project funded by NASA. Characterization of CatWISE performance uses data from *Gaia* and from *Spitzer*. CatWISE is led by JPL/Caltech, with funding from NASA’s Astrophysics Data Analysis Program (ADAP), and is also supported in part by ADAP grant NNH17AE75I at Lawrence Berkeley Laboratory. CatWISE is also supported by the Fellowships and Internships in Extremely Large Data Sets (FIELDS) program funded by NASA at UC Riverside. FM is supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, administered by Universities Space Research Association under a contract with NASA.

APPENDIX

A. CATWISE PRELIMINARY CATALOG NEW COLUMN DESCRIPTIONS

We adopt MJD 56700 (2014 Feb. 12) as the epoch for reporting positions when solving for source motion in the Preliminary catalog. Source positions, whether incorporating source motion or not, are given in the equinox J2000 coordinate frame. The convention for designating sources from the CatWISE Preliminary catalog and reject table is specified in §3.7.

The are 186 formatted columns of information about each source in the CatWISE Preliminary catalog. The CatWISE Preliminary reject table adds a column to indicate whether the source is “primary” (see §3.6). Four columns ($w1fitr$, $w2fitr$, $glon$, $glat$) in the NERSC release are hidden in the IRSA release, and their names are shown in parentheses in Table 5. Most of the columns have the same names as in the AllWISE catalog, and are described in §II.1.a of the AllWISE Explanatory

Supplement (Cutri et al. 2013). Table 5 provides information about columns that are new in the CatWISE Preliminary catalog, or where the information relevant for CatWISE supersedes that in the AllWISE Explanatory Supplement.

Table 5. CatWISE Preliminary Catalog New or Updated Column Descriptions

Name (1)	Units (2)	Type (3)	Format (4)	Description (5)
source_id	...	char	a25	Unique source ID, formed from a combination of the tile name, a CatWISE processing version code (always “a1” for the Preliminary catalog and reject table), and the sequential number of the source extraction in the tile (i.e. “src” in AllWISE).
(w1fitr)	arcsec	R*4	f7.2	Fitting radius for W1. In the CatWISE Preliminary catalog, w1fitr is always -99.99, 7.5, or 13.2. Hidden in IRSA release, because w1fitr does not appear to follow the prescription given in http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4c.html#wpro where rfit=1.25 FWHM ($7''.5$ for W1) or $2r_{sat}$ (saturation radius), whichever is larger.
(w2fitr)	arcsec	R*4	f7.2	Fitting radius for W2. In the CatWISE Preliminary catalog, w2fitr is always -99.99, 7.5, or 13.2. Hidden in IRSA release, because w2fitr does not appear to follow the prescription given in http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4c.html#wpro where rfit=1.25 FWHM ($7''.5$ for W2) or $2r_{sat}$ (saturation radius), whichever is larger.
nIters	...	int	i7	Number of chi-square-minimization iterations.
nSteps	...	int	i7	Number of steps in all iterations.
mdetID	...	int	i7	Source ID in MDET detection list.
p1	arcsec	R*4	f10.5	Distance in ra by which MDET position was adjusted. Detected positions from MDET are at pixel centers.

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
p2	arcsec	R*4	f10.5	Distance in dec by which MDET position was adjusted. Detected positions from MDET are at pixel centers.
MeanObsMJD	days	R*8	f13.6	Mean observation epoch
ra_pm	deg	R*8	f12.7	Right ascension (J2000) at epoch MJD=56700
dec_pm	deg	R*8	f12.7	Declination (J2000) at epoch MJD=56700
PMRA	arcsec yr ⁻¹	R*4	f10.5	Motion in ra. Because CatWISE motion values are computed from epochs at similar solar elongations (except for the 50 tiles listed in Table 1), they are essentially unaffected by parallax and therefore close to proper motions, unlike the AllWISE case.
PMDec	arcsec yr ⁻¹	R*4	f10.5	Motion in dec. Because CatWISE motion values are computed from epochs at similar solar elongations (except for the 50 tiles listed in Table 1), they are essentially unaffected by parallax and therefore close to proper motions, unlike the AllWISE case.
nIters_pm	...	int	i10	Number of chi-square-minimization iterations.
nSteps_pm	...	int	i10	Number of steps in all iterations.
dist_ad	arcsec	R*4	f9.3	Radial distance between ascending and descending apparitions. The field name in the IRSA release is dist_ad, but in the NERSC release, this field is called dist.
dw1mag	mag	R*4	f7.3	Difference between ascending and descending w1mpro values
rch2w1	...	R*4	f7.3	χ^2 for dw1mag (1 DF)
dw2mag	mag	R*4	f7.3	Difference between ascending and descending w2mpro values
rch2w2	...	R*4	f7.3	χ^2 for dw2mag (1 DF)
elon_avg	deg	R*8	f11.6	Averaged ecliptic longitude between ascending and descending apparitions

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
elonSig	arcsec	R*4	f11.3	1σ uncertainty in elon_avg
elat_avg	deg	R*8	f11.6	Averaged ecliptic latitude between ascending and descending apparitions
elatSig	arcsec	R*4	f10.3	1σ uncertainty in elat_avg
Delon	arcsec	R*4	f11.3	Descending - ascending ecliptic longitude. Will be null unless $ka = 3$. This order should have the proper sign for parallax ($\sim Delon/2$).
DelonSig	arcsec	R*4	f11.3	1σ uncertainty in Delon
Delat	arcsec	R*4	f11.3	Descending - ascending ecliptic latitude
DelatSig	arcsec	R*4	f10.3	1σ uncertainty in Delat
DelonSNR	...	R*4	f11.3	$ Delon /DelonSig$
DelatSNR	...	R*4	f11.3	$ Delat /DelatSig$
chi2pmra	...	R*4	1pE10.3	χ^2 for difference between PMRA for ascending and descing apparitions (1 degree of freedom)
chi2pmdec	...	R*4	1pE10.3	χ^2 for difference between PMRA for ascending and descing apparitions (1 degree of freedom)
ka	...	int	i3	Astrometry usage code. 0: neither ascending or descending apparitions provided a solution. 1: Only the ascending apparition provided a solution. 2: Only the descending apparition provided a solution. 3: Both ascending and descending apparitions provided a solution.
k1	...	int	i3	W1 photometry usage code. 0: neither ascending or descending apparitions provided a solution. 1: Only the ascending apparition provided a solution. 2: Only the descending apparition provided a solution. 3: Both ascending and descending apparitions provided a solution.

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
k2	...	int	i3	W2 photometry usage code. 0: neither ascending or descending apparitions provided a solution. 1: Only the ascending apparition provided a solution. 2: Only the descending apparition provided a solution. 3: Both ascending and descending apparitions provided a solution.
km	...	int	i3	Proper motion usage code. 0: neither ascending or descending apparitions provided a solution. 1: Only the ascending apparition provided a solution. 2: Only the descending apparition provided a solution. 3: Both ascending and descending apparitions provided a solution.
par_pm	arcsec	R*4	f11.3	Parallax estimate from motion solution. Computed by using PMRA and PMDec to propagate the ascending and descending motion solution positions to the MJD 56700 epoch, then dividing the ecliptic longitude difference by 2. Will be null unless km = 3.
par_pmSig	arcsec	R*4	f11.3	1σ uncertainty in par_pm
par_stat	arcsec	R*4	f11.3	Parallax estimate from stationary solution. Computed by using PMRA and PMDec to propagate the ascending stationary-solution position from the ascending observation epoch to the descending observation epoch, then dividing the ecliptic longitude difference by 2. Will be null unless ka = 3, km > 0, and all w?mjdmin/max/mean values are non-null in both ascending and descending WPHOT output.
par_sigma	arcsec	R*4	f11.3	1σ uncertainty in par_stat
dist_cc	arcsec	R*4	f13.3	Maximum distance between CatWISE and AllWISE sources providing cc_flags. See §3.5.1. The field name in the IRSA release is dist_cc, but in the NERSC release, this field is called dist_x.

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
cc_flags	...	char	a16	Worst case character cc_flag from AllWISE. See §3.5.1.
w1cc_map	...	int	i13	Worst case w1cc_map from AllWISE. The description in the AllWISE Explanatory Supplement appears to be incorrect, so an updated description is provided here. Contamination and confusion map in W1 for matching AllWISE source. This column contains the integer equivalent of the 12-bit binary number that specifies if the W1 measurement in AllWISE is believed to be contaminated by or a spurious detection of an image artifact. The elements of the binary array (with the bit number indicated below each code) are given in Table 6. Bits 0, 1, 3 and 4 indicate whether the band-detection is contaminated by an artifact. If the brightness of the detection is less than expected for that type of artifact, the source is regarded as spurious and bits 7, 8, 10, and 11 are also set accordingly. The letters denote contamination by different types of artifacts (see §3.5). For example, a measurement that is believed to be a spurious detection of a scattered light halo and contaminated by a diffraction spike has a binary bit map value of “010000001001” and w1cc_map=1033. When there is more than one AllWISE match to a CatWISE source, a logical ‘OR’ is performed over all the matches for each bit.

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
w1cc_map_str	...	char	a20	<p>Worst case w1cc_map_str from AllWISE. See §3.5.1. The w1cc_map_str description in the AllWISE Explanatory Supplement appears to be incorrect, so an updated description is provided here.</p> <p>Contamination and confusion string in W1 for matching AllWISE source. This column is a character string that denotes all artifacts that may contaminate the AllWISE W1 measurement of this source, in the priority order D,d,P,p,H,h,O,o.</p> <p>For example, a real detection that is contaminated by a diffraction spike and a latent (persistent) image has a w1cc_map_str=“dp”. A spurious detection of a diffraction spike that is also contaminated by a latent image has w1cc_map_str=“Dp”. This string is “null” if there are no artifacts that affect the measurement in this band. The value that appears in first element of the cc_flags string is the left-most character in w1cc_map_str. If w1cc_map_str is “null”, then the corresponding cc_flags entry is “0”.</p>

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
w2cc_map	...	int	i13	<p>Worst case w2cc_map from AllWISE. The description in the AllWISE Explanatory Supplement appears to be incorrect, so an updated description is provided here.</p> <p>Contamination and confusion map in W2 for matching AllWISE source. This column contains the integer equivalent of the 12-bit binary number that specifies if the W2 measurement in AllWISE is believed to be contaminated by or a spurious detection of an image artifact. The elements of the binary array (with the bit number indicated below each code) are given in Table 6. Bits 0, 1, 3 and 4 indicate whether the band-detection is contaminated by an artifact. If the brightness of the detection is less than expected for that type of artifact, the source is regarded as spurious and bits 7, 8, 10, and 11 are also set accordingly. The letters denote contamination by different types of artifacts (see §3.5).</p> <p>For example, a measurement that is believed to be a spurious detection of a scattered light halo and contaminated by a diffraction spike has a binary bit map value of “01000001001” and w2cc_map=1033. When there is more than one AllWISE match to a CatWISE source, a logical ‘OR’ is performed over all the matches for each bit.</p>

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
w2cc_map_str	...	char	a20	<p>Worst case w2cc_map_str from AllWISE. See §3.5. The w2cc_map_str description in the AllWISE Explanatory Supplement appears to be incorrect, so an updated description is provided here.</p> <p>Contamination and confusion string in W2 for matching AllWISE source. This column is a character string that denotes all artifacts that may contaminate the AllWISE W2 measurement of this source, in the priority order D,d,P,p,H,h,O,o.</p> <p>For example, a real detection that is contaminated by a diffraction spike and a latent (persistent) image has a w2cc_map_str=“dp”. A spurious detection of a diffraction spike that is also contaminated by a latent image has w2cc_map_str=“Dp”. This string is “null” if there are no artifacts that affect the measurement in this band. The value that appears in first element of the cc_flags string is the left-most character in w2cc_map_str. If w2cc_map_str is “null”, then the corresponding cc_flags entry is “0”.</p>
n_aw	...	int	i5	Number of AllWISE matches within 2''.75. See §3.5.1.
ab_flags	...	char	a9	Two character (W1 W2) artifact flag. See §3.5.2.
w1ab_map	...	int	i9	W1 artifact code value. See §3.5.2.
w1ab_map_str	...	char	a13	W1 artifact string. See §3.5.2.
w2ab_map	...	int	i9	W2 artifact code value. See §3.5.2.
w2ab_map_str	...	char	a13	W2 artifact string. See §3.5.2.
(glon)	deg	R*8	f12.6	Galactic longitude, calculated using a pole of $\alpha = 192.85^\circ$ $\delta = 27.13^\circ$, and a zero of longitude of $\alpha = 266.4^\circ$ $\delta = -28.94^\circ$ (both in J2000). Hidden in IRSA. See Appendix B for details.

Table 5 continued on next page

Table 5 (*continued*)

Name	Units	Type	Format	Description
(1)	(2)	(3)	(4)	(5)
(glat)	deg	R*8	f12.6	Galactic latitude, calculated using a pole of $\alpha = 192.85^\circ \delta = 27.13^\circ$, and a zero of longitude of $\alpha = 266.4^\circ \delta = -28.94^\circ$ (both in J2000). Hidden in IRSAs. See Appendix B for details.
p	...	int	i6	Flag to indicate if source is “primary” in tile. See §3.6.

Table 6. CC_MAP Bit Definitions

O	H	0	P	D	0	0	o	h	0	p	d
11	10	9	8	7	6	5	4	3	2	1	0

B. CAVEATS

The CatWISE Preliminary Catalog contains a number of features that users should be aware of. Among these are:

- The number of sources per square degree has relatively small variation over the sky (Figure 5).
- Catalog performance is less good in high source density regions (the Galactic plane and the ecliptic poles). Figures 14 through 19 and Table 4 illustrate this.

These issues appears to arise in the detection step. Relatively few deblended sources are added in the measurement step. We intend to investigate alternative approaches for the detection step, including using the unWISE Catalog (which contains many more sources in high density regions; Schlafly et al. 2019) as a detection list for an updated version of the CatWISE catalog that is expected to be available in 2020.

- The completeness and reliability for bright sources is low (Figure 7).

As an example, the brightest two catalog sources in W2 (CWISEP J005153.01–235140.3 and CWISEP J223327.80+060246.2) are spurious, and it is likely that other spurious bright sources are present in the catalog. Users should visually inspect interesting sources selected from the catalog using AllWISE or unWISE images before devoting significant resources to follow up observations.

Additional features present in the CatWISE Preliminary catalog include:

- Tabulated position uncertainties are significantly smaller than measured position scatter with respect to *Gaia*, as illustrated in Figure 13 (upper right) and Figure 18 (right).
- A floor of 10 mas yr^{-1} was imposed on the tabulated motion uncertainties, making them significantly larger than the measured scatter with respect to *Gaia* motion, as illustrated in Figure 13 (lower right) and Figure 19 (right).
- The Galactic coordinates in the CatWISE Preliminary catalog were calculated using a pole of $\alpha = 192.85^\circ \delta = 27.13^\circ$, and a zero of longitude of $\alpha = 266.4^\circ \delta = -28.94^\circ$ (both in J2000). These directions are not perpendicular by $22''.663$, and consequently yielded “nan” entries for the Galactic coordinates of the 31 catalog sources and 6 reject sources within $88''.3$ of the north Galactic pole, and the 39 catalog sources and 5 reject sources within $87''.8$ of the south Galactic pole. The discrepancy in the glon and glat Galactic coordinates of sources compared to coordinates calculated using the IAU-defined system (Blaauw et al. 1960) increases with absolute Galactic latitude from $< 1''$ in the Galactic plane to $88''$ near the Galactic poles. These glon and glat values (including the 81 with glat = “nan”) appear in the NERSC release of the CatWISE Preliminary catalog and reject table files. In the IRSA release, these columns are hidden, and in addition the 81 glat “nan” values have been replaced with $+90^\circ$ or -90° as appropriate.

C. COMBINING ASCENDING AND DESCENDING SCAN POSITIONS

Here we provide additional details on how ascending and descending scan positions are combined for the CatWISE Preliminary catalog. Positions are averaged using inverse-covariance weighting. The averaging is done in a local Cartesian projection consistent with the uncertainty representation.

A transformation matrix \mathbf{T} is defined as follows: starting with a Cartesian (x, y, z) system whose \mathbf{z} axis points to the celestial north pole and whose \mathbf{x} axis points to the vernal equinox, we perform two Euler rotations that place the \mathbf{z}' axis of the rotated system on the ascending celestial (α, δ) position with the \mathbf{y}' axis aligned with the local north-south direction, and the \mathbf{x}' axis aligned with the local east-west direction. First, rotate about the \mathbf{z} axis by $\phi_1 = \alpha - 90^\circ$, then rotate about the \mathbf{x}' axis by $\phi_2 = \delta - 90^\circ$. Then \mathbf{T} is given by:

$$\mathbf{T} \equiv \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \quad (\text{C1})$$

with elements:

$$\begin{aligned} T_{11} &= \cos \phi_1 \\ T_{12} &= \sin \phi_1 \\ T_{13} &= 0 \\ T_{21} &= -\cos \phi_2 \sin \phi_1 \\ T_{22} &= \cos \phi_2 \cos \phi_1 \\ T_{23} &= \sin \phi_2 \\ T_{31} &= \sin \phi_2 \sin \phi_1 \\ T_{32} &= -\sin \phi_2 \cos \phi_1 \\ T_{33} &= \cos \phi_2 \end{aligned} \quad (\text{C2})$$

This corresponds to a \mathbf{z}' axis that looks outward from the origin, so any nearby α', δ' position will have an (x', y', z') vector in the rotated system whose z' component will be positive and close to 1. By “nearby” we mean within a few arcseconds of the origin, since it is very rare for an extracted source’s position to vary between the ascending and descending solutions by more than that. This justifies our Cartesian approximation.

The coordinate system is computed for the ascending position, so that the ascending position of the source has coordinates $(0, 0, 1)$. The descending position (α', δ') is mapped into that system as follows. We construct the vector \mathbf{v} to the descending position in the original celestial coordinate system:

$$\begin{aligned} v_1 &= \cos \alpha' \cos \delta' \\ v_2 &= \sin \alpha' \cos \delta' \\ v_3 &= \sin \delta' \end{aligned} \tag{C3}$$

and transform it into the new system,

$$(x', y', z') \equiv \mathbf{T}\mathbf{v} \tag{C4}$$

wherein its x' and y' coordinates are the offsets of the descending position from the ascending position.

The (x', y') coordinates are averaged with $(0, 0)$ using inverse covariance weighting. We construct 2×2 error covariance matrices Ω_a and Ω_d for the ascending and descending vectors using the corresponding σ_α , σ_δ , and $\sigma_{\alpha\delta}$:

$$\begin{aligned} \Omega_a &= \begin{bmatrix} \sigma_\alpha^2 & \sigma_{\alpha\delta} |\sigma_{\alpha\delta}| \\ \sigma_{\alpha\delta} |\sigma_{\alpha\delta}| & \sigma_\delta^2 \end{bmatrix}_a \\ \Omega_d &= \begin{bmatrix} \sigma_\alpha^2 & \sigma_{\alpha\delta} |\sigma_{\alpha\delta}| \\ \sigma_{\alpha\delta} |\sigma_{\alpha\delta}| & \sigma_\delta^2 \end{bmatrix}_d \end{aligned} \tag{C5}$$

A minimum value of 10^{-8} is enforced for any zeroes on the diagonal. The merged (i.e., inverse-covariance-weighted average) vector (x_m, y_m, z_m) and associated covariance matrix are computed as follows:

$$\mathbf{W}_a = \Omega_a^{-1}, \quad \mathbf{W}_d = \Omega_d^{-1} \tag{C6}$$

$$\Omega = (\mathbf{W}_a + \mathbf{W}_d)^{-1} \equiv \begin{bmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{bmatrix} \tag{C7}$$

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \boldsymbol{\Omega} \left(\mathbf{W_a} \begin{bmatrix} 0 \\ 0 \end{bmatrix} + \mathbf{W_d} \begin{bmatrix} x' \\ y' \end{bmatrix} \right) = \boldsymbol{\Omega} \mathbf{W_d} \begin{bmatrix} x' \\ y' \end{bmatrix}$$

$$z_m = \sqrt{1 - x_m^2 - y_m^2}$$
(C8)

$$\sigma_\alpha = \sqrt{\Omega_{11}}, \quad \sigma_\delta = \sqrt{\Omega_{22}}, \quad \sigma_{\alpha\delta} = \text{sign}(\Omega_{12}) \sqrt{|\Omega_{12}|}$$
(C9)

The celestial coordinates corresponding to the (x_m, y_m, z_m) vector are obtained using the inverse of the transformation matrix \mathbf{T} described above, which is the transpose because \mathbf{T} is orthonormal:

$$\begin{bmatrix} v'_1 \\ v'_2 \\ v'_3 \end{bmatrix} \equiv \begin{bmatrix} T_{11} & T_{21} & T_{31} \\ T_{12} & T_{22} & T_{32} \\ T_{13} & T_{23} & T_{33} \end{bmatrix} \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix}$$
(C10)

$$\alpha_m = \tan^{-1} \left(\frac{v'_2}{v'_1} \right), \quad \delta_m = \sin^{-1} v'_3$$
(C11)

The image pixel coordinates are then computed for the merged position using the coadd WCS information.

REFERENCES

- Ashby, M. L. N., Stanford, S. A., Brodwin, M., et al. 2013, ApJS, 209, 22.
- Bañados, E., Venemans, B. P., Mazzucchelli, C., et al. Nature, 553, 473B.
- Blaauw, A., Gum, C. S., Pawsey, J. L., et al. 1960, MNRAS, 121, 123.
- Brodwin, M., Stanford, S. A., Gonzalez, A. H., et al. 2013, ApJ, 779, 138.
- Caselden, D., Westin, P., Meisner, A., et al. 2018, ASCL:1806.004.
- Connors, M., Wiegert, P., & Veillet, C. 2011, Nature, 475, 481
- Cutri, R. M., Wright, E. L., Conrow, T., et al. 2012, Explanatory Supplement to the WISE All-Sky Data Release Products, <http://wise2.ipac.caltech.edu/docs/release/allsky/expsup>

- Cutri, R. M., Wright, E. L., Conrow, T., et al. 2013, Explanatory Supplement to the AllWISE Data Release Products, <http://wise2.ipac.caltech.edu/docs/release/allwise/expsup>
- Cutri, R. M., Mainzer, A., Conrow, T., et al. 2015, Explanatory Supplement to the NEOWISE Data Release Products, <http://wise2.ipac.caltech.edu/docs/release/neowise/expsup>
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, *A&A*, 616, A1
- Gonzalez, A. H., Gettings, D. P., Brodwin, M., et al. 2019, *ApJS*, 240, 33.
- Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, *A&A*, 355, L27
- Jarrett, T. H., Cohen, M., Masci, F., et al. 2011, *ApJ*, 735, 112
- Kirkpatrick, J. D., Cushing, M. C., Gelino, C. R., et al. 2011, *ApJS*, 197, 19
- Kirkpatrick, J. D., Schneider, A., Fajardo-Acosta, S., et al. 2014, *ApJ*, 783, 122
- Kirkpatrick, J. D., Martin, E. C., Smart, R. L., et al. 2019, *ApJS*, 240, 19
- Laigle, C., McCracken, H. J., Ilbert,), et al. 2019, *ApJS*, 224, 24.
- Lang, D. 2014, *AJ*, 147, 108
- Lindgren, L., Hernández, J., Bombrun, A., et al. 2018, *A&A*, 616, A2
- Luhman, K. L. 2013, *ApJL*, 767, L1
- Luhman, K. L. 2014, *ApJL*, 786, L18
- Marsh, K. A., & Jarrett, T. H. 2012, *PASA*, 29, 269
- Masci, F. 2013, arXiv:1301.2718
- Mainzer, A., Bauer, J., Grav, T., et al. 2011, *ApJ*, 731, 53
- Mainzer, A., Bauer, J., Cutri, R. M., et al. 2014, *ApJ*, 792, 30
- Marocco, F., Caselden, D., Meisner, A. M., et al. 2019, *ApJ*, 881, 17
- Mauduit, J.-C. Lacy, M. Farrah, D., et al. 2012, *PASP*, 124, 714
- Meisner, A. M., Lang, D., & Schlegel, D. J. 2018a, *AJ*, 156, 69
- Meisner, A. M., Cushing, M. C., Cutri, R., et al. 2018b, *RNAAS*, 2, 1
- Meisner, A. M., Cushing, M. C., Cutri, R., et al. 2018c, *RNAAS*, 2, 140
- Meisner, A. M., Lang, D., & Schlegel, D. J. 2018d, *RNAAS*, 2, 202
- Sanders, D. B., Salvato, M., Aussel, H., et al. 2007, *ApJS*, 172, 86
- Schlafly, E. F., Meisner, A. M., & Green, G. M. 2019, *ApJS*, 240, 30
- Scholz, R.-D. 2014, *A&A*, 561, A113
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
- Stauffer, J., Tanner, A. M., Bryden, G., et al. 2010, *PASP*, 122, 885
- Tsai, C.-W., Eisenhardt, P. R. M., Wu, J., et al. 2015, *ApJ*, 805, 90
- van Leeuwen, F. 2007, *A&A*, 474, 653

Wright, E. L., Eisenhardt, P. R. M., Mainzer,

A. K., et al. 2010, AJ, 140, 1868