The DECam Local Volume Exploration Survey Data Release 2

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ABSTRACT

We present the second public data release (DR2) from the DECam Local Volume Exploration survey (DELVE). DELVE DR2 combines new DECam observations with archival DECam data from the Dark Energy Survey, the DECam Legacy Survey, and other DECam community programs. DELVE DR2 consists of $\sim 160,000$ exposures that cover $> 21,000$ deg$^2$ of the high Galactic latitude ($|b| > 10$ deg) sky in four broadband optical/near-infrared filters ($g, r, i, z$). DELVE DR2 provides point-source and automatic aperture photometry for $\sim 2.5$ billion astronomical sources with a median 5σ point-source depth of $g=24.3$, $r=23.9$, $i=23.5$, and $z=22.8$ mag. A region of $\sim 17,000$ deg$^2$ has been imaged in all four filters, providing four-band photometric measurements for $\sim 618$ million astronomical sources. DELVE DR2 covers more than four times the area of the previous DELVE data release and contains roughly five times as many astronomical objects. DELVE DR2 is publicly available via the NOIRLab Astro Data Lab science platform.

Keywords: Surveys – Catalogs

1. INTRODUCTION

Digital sky surveys at optical/near-infrared wavelengths have revolutionized astronomy. These large, untargeted observational programs provide expansive data sets that enable unprecedented statistical studies and fortuitous discoveries across a wide range of astronomical fields. The Sloan Digital Sky Survey (SDSS; York et al. 2000), the Two Micron All-Sky Survey (2MASS Skrutskie et al. 2006), the Pan-STARRS1 survey (PS1; Chambers et al. 2016), and the SkyMapper Southern Sky Survey (Wolf et al. 2018) have provided an unprecedented view of the sky. However, these surveys were carried out on relatively small ($\lesssim 2.5$-m diameter) telescopes, which limited their sensitivity, especially in the southern hemisphere.

The 570-megapixel Dark Energy Camera (DECam; Flaugher et al. 2015) on the 4-m Victor M. Blanco Telescope at Cerro Tololo in Chile is the premier optical/near-infrared survey instrument in the southern hemisphere. Since commissioning in 2012, DECam has been used by the Dark Energy Survey (DES; DES Collaboration 2005, 2016), the DECam Legacy Survey (DECaLS; Dey et al. 2019), and numerous smaller community programs. Through these programs, DECam has gradually, and somewhat unsystematically, imaged much of the southern celestial hemisphere (e.g., Nidever et al. 2021). The DECam Local Volume Exploration Survey (DELVE; Drlica-Wagner et al. 2021)$^1$ seeks to complete contiguous DECam coverage of the southern sky by selectively observing regions of the sky that lack existing observations. The primary science goals of DELVE are to discover and characterize faint satellite galaxies and other resolved stellar systems around the Milky Way, Magellanic Clouds, and isolated Magellanic analogs in the Local Volume (Drlica-Wagner et al. 2021). The DELVE science program has already resulted in the discovery and characterization of five ultra-faint Milky Way satellites (Mau et al. 2020; Martínez-Vázquez et al. 2021; Cerny et al. 2021a,b, 2022) and an extended study of the Jet stellar stream (Ferguson et al. 2022). Moreover, the unprecedented wide, deep DELVE data set has broad applicability to a wide range of Galactic and extragalactic science (see Drlica-Wagner et al. 2021 for examples).

$^1$ https://delve-survey.github.io
We present the DELVE second data release (DR2), which includes imaging from DELVE, DES, DE CamLS, and other public DECam programs covering $>21,000$ deg$^2$ of sky in $g$, $r$, $i$, and $z$ individually and $\sim 17,000$ deg$^2$ in all four bands (Figure 1). These DECam data have been consistently processed with the DES Data Management (DESDM; Morganson et al. 2018) pipeline, providing accurate point-spread function (PSF) and automatic aperture measurements for $\sim 2.5$ billion astronomical sources. In this paper, we describe the DELVE DR2 data set (Section 2) and data reduction pipeline (Section 3). We present studies characterizing the sky coverage, astrometry, photometric calibration, depth, and object classification of the DELVE DR2 catalog in Section 4. In Section 5 we describe how the DELVE DR2 data can be accessed via the NSF’s National Optical-Infrared Astronomy Research Laboratory (NOIRLab) Astro Data Lab. Finally, we conclude in Section 6.

2. DATA SET

DELVE DR2 is comprised of 161,380 DECam exposures assembled from $>270$ DECam community programs (Appendix A). The largest contributors to the DELVE DR2 data set are DES (DES Collaboration 2021). DECaLS (Dey et al. 2019), DELVE (Drlica-Wagner et al. 2021), and the DECam eROSITA Survey (DeROSITAS; PI Zenteno)$^2$. DELVE DR2 more than quadruples the sky area of DELVE DR1 by including exposures in the southern Galactic cap ($b < -10^\circ$) and exposures in the northern celestial hemisphere ($Dec. > 0^\circ$). In addition, DELVE and DeROSITAS have continued to observe regions of the sky that lack DECam imaging to increase the coverage and uniformity of the DECam data set (see Section 3 of Drlica-Wagner et al. 2021). The key properties of the DELVE DR2 data set are listed in Table 1.

Separate criteria were used to select input exposures in the northern Galactic cap, the southern Galactic cap, and the DES region. The northern Galactic cap data set is comprised of DECam exposures with $b > 10^\circ$ plus an extension into the Galactic plane ($b > 0^\circ$) in the region of $120^\circ < RA < 140^\circ$ to enable an extended analysis of the Jet stellar stream (Jethwa et al. 2018; Ferguson et al. 2022). Exposures in the southern Galactic cap were selected to have $b < -10^\circ$, excluding exposures within the DES footprint and exposures collected by the DES program. The DES exposures reside in the southern Galactic cap, but they were selected separately when defining the input to DES DR2 (DES Collaboration 2021).

For each exposure, we calculate the effective depth based on the effective exposure time scale factor, $t_{eff}$, which compares the achieved seeing, sky brightness, and extinction due to clouds relative to canonical values for the site (Neilsen et al. 2016). Exposures in the northern Galactic cap region were required to have an effective exposure time scale factor of $t_{eff} > 0.3$. The requirement on $t_{eff}$ was relaxed in the southern Galactic cap to avoid rejecting exposures taken close to the southern celestial pole. These exposures are observed at high airmass ($sec(z) \sim 2$) and have systematically worse PSF full width at half maximum (FWHM). Exposures in the southern Galactic cap were required to have $t_{eff} > 0.2$ and $t_{eff} \times T_{exp} > 12$ s. No explicit cut was placed on the PSF FWHM in the northern Galactic cap (the cut on $t_{eff}$ removes exposures with very poor seeing), while a cut of FWHM < 1″ was applied in the southern Galactic cap. The resulting distribution of PSF FWHM and effective exposure time for the full DELVE DR2 data set are shown in Figure 2.

All exposures in the northern and southern Galactic caps were required to have good astrometric solutions when matched to Gaia DR2 (Gaia Collaboration 2018) by SCAMP (Bertin 2006). These criteria required $>250$ astrometric matches, $\chi^2_{astrom} < 500$, $\Delta(RA) < 150$ mas, and $\Delta(Dec) < 150$ mas. We identified and removed exposures that were heavily contaminated by spurious scattered and reflected light from bright stars using the ray-tracing procedure developed by DES (Kent 2013). In addition, rare failures in the sky background estimation can cause a large number of spurious object detections. A handful of exposures suffering from this processing failure were identified as having a large fraction of unmatched objects, and they were removed from the final catalog production.

DELVE DR2 includes $\sim 60,000$ exposures collected by DES that were processed and calibrated as input into DES DR2 (DES Collaboration 2021).$^3$ The DES processing pipeline required $t_{eff} > 0.2$ for $g$-band exposures and $t_{eff} > 0.3$ for exposures taken in $r$, $i$, and $z$. DES applied a wavelength-dependent criterion to remove exposures with poor PSF FWHM resulting in a maximum PSF FWHM of $\{1^\prime72, 1^\prime62, 1^\prime56, 1^\prime50\}$ in $g$, $r$, $i$, $z$, respectively. Additional cuts were applied to remove exposures that were contaminated by stray or scattered light, airplanes, excessive electronic noise, and other adverse conditions.

$^2$ http://astro.userena.cl/derositas

$^3$ DELVE DR2 does not include the DES Y-band imaging.
DELVE DR2 Coverage (griz)

Figure 1. DELVE DR2 covers > 20,000 deg$^2$ in each of the $g, r, i, z$ bands (colored regions) and ~17,000 deg$^2$ in all four bands simultaneously (blue region). The ~5,000 deg$^2$ footprint of DES is outlined in black. These and other sky maps are shown in the equal-area McBryde-Thomas flat polar quartic projection.

tifacts. A full description of the DES data selection and processing criteria can be found elsewhere (Morganson et al. 2018; DES Collaboration 2018, 2021).

3. DATA PROCESSING

All exposures in DELVE DR2 were processed with the DESDM “Final Cut” pipeline (Morganson et al. 2018) as implemented for the processing of DES DR2 (DES Collaboration 2021). Data were reduced and detrended using seasonally averaged bias and flat images, and full-exposure sky background subtraction was performed (Bernstein et al. 2018). SourceExtractor (Bertin & Arnouts 1996) and PSFEx (Bertin 2011) were used to automate source detection and photometric measurement. Astrometric calibration was performed against Gaia DR2 using SCAMP (Bertin 2006). We note that DELVE DR2 does not include the production of coadded images (e.g., DES Collaboration 2018, 2021); however, we expect that coadded images will be produced as part of a future DELVE data release.

Photometric zeropoints for each DECam CCD were derived independently for the DES exposures and the other DECam exposures included in DELVE DR2. For the DES exposures, we applied zeropoints that were derived for DES DR2 using the forward global calibration module (FGCM; Burke et al. 2018). The FGCM procedure fits time-dependent atmospheric and instrumental conditions to establish an internal network of calibration stars. These calibration stars are then used to iteratively refine the photometric calibration of exposures taken during both photometric and non-photometric conditions. The FGCM has been demonstrated to achieve a relative photometric calibration uncertainty of ~2 mmag when applied to the DES exposures (DES Collaboration 2021). In contrast, the non-DES exposures included in DELVE DR2 were calibrated following the simple external calibration procedure developed for DELVE DR1 (Drlica-Wagner et al. 2021). Briefly, we performed a 1′′ match between objects in the Final Cut catalogs for each DECam CCD and the ATLAS Refcat2 catalog (Tonry et al. 2018). ATLAS Refcat2 covers the entire sky by placing measurements from PS1 DR1 (Chambers et al. 2016), SkyMapper DR1 (Wolf et al. 2018), and several other surveys onto the PS1 $g, r, i, z$-bandpass system. Transformation equations from the ATLAS Refcat2 system to the DECam system were derived by comparing calibrated stars from DES DR1 (Appendix A of Drlica-Wagner et al. 2021). Zeropoints were

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4 Associated configuration files can be found at: https://github.com/delve-survey/delve_config.
Table 1. DELVE DR2 key numbers and data quality summary.

| Survey Characteristic                                      | Band     | g  | r  | i  | z  | Reference |
|-----------------------------------------------------------|----------|----|----|----|----|-----------|
| Number of exposures                                       |          | 42034 | 41852 | 39003 | 38491 | Section 2 |
| Median PSF FWHM (arcsec)                                  |          | 1.24 | 1.10 | 1.02 | 1.00 | Section 2 |
| Sky coverage (individual bands, deg²)                     |          | 24663 | 22939 | 21283 | 22866 | Section 4.1 |
| Sky coverage (g, r, i, z intersection, deg²)              |          | 16972 |       |       |       | Section 4.1 |
| Astrometric repeatability (angular distance, mas)         |          | 28 | 27 | 28 | 32 | Section 4.2 |
| Photometric repeatability (mmag)                          |          | 4.9 | 5.0 | 4.5 | 5.4 | Section 4.3 |
| Photometric uniformity vs. Gaia (mmag)                    |          | 7.2 |       |       |       | Section 4.3 |
| Absolute photometric uncertainty (mmag)                    |          | ≤20 |       |       |       | Section 4.5 |
| Magnitude limit (PSF, S/N = 5)                            |          | 24.3 | 23.9 | 23.5 | 22.8 | Section 4.6 |
| Magnitude limit (AUTO, S/N = 5)                           |          | 23.9 | 23.5 | 23.0 | 22.4 | Section 4.6 |
| Galaxy selection (EXTENDED_COADD ≥ 2, 19 ≤ MAG_AUTO_G ≤ 22) |          |       |   |   |   | Eff. > 99%; Contam. < 2% | Section 4.7 |
| Stellar selection (EXTENDED_COADD ≤ 1, 19 ≤ MAG_AUTO_G ≤ 22) |          |       |   |   |   | Eff. > 97%; Contam. < 2% | Section 4.7 |

Figure 2. (Left) PSF FWHM distributions for DECam exposures included in DELVE DR2. (Right) Distributions of effective exposure time ($t_{eff} \times T_{exp}$) for exposures included in DELVE DR2.

derived by finding the median offset required to match the DECam observations to the matched ATLAS Refcat2 observations. Zero-points derived from the DELVE processing and photometric calibration pipeline were found to agree with those derived by DES DR2 with a scatter of $\sim$10 mmag. While the external calibration against ATLAS Refcat2 yields a significantly larger scatter than the FGCM, it can be quickly and easily applied to any DECam exposure.

We built a multi-band catalog of unique sources by combining the SourceExtractor catalogs from each individual CCD image following the procedure described in Drlica-Wagner et al. (2021). We took the set of SourceExtractor detections with $\text{FLAGS} < 4$, which allowed neighboring and deblended sources, and $(\text{IMAFLAGS}_{\text{ISO}} \& 2047) = 0$, which removed objects containing bad pixels within their isophotal radii (Morgan et al. 2018). We further required each detection to have a measured automatic aperture flux, a measured PSF flux, and a PSF magnitude error of < 0.5 mag. We sorted SourceExtractor detections into $\sim$3 deg² ($\text{nside} = 32$) HEALPix pixels (Górański et al. 2005), and within each HEALPix pixel we grouped detections into clusters by associating all detections within a 0′5 radius. This matching radius was chosen to be significantly larger than the astrometric uncertainty (Section 4.2), but smaller than the PSF FWHM (Figure 2). Furthermore, we identified and split pairs of closely separated objects that were observed in the same image (Drlica-Wagner et al. 2021).

Each cluster of detections was associated with an object in the DELVE DR2 catalog. The astrometric position of each object was calculated as the median of the individual single-epoch measurements of the object. We
track two sets of photometric quantities for each object: (1) measurements from the single exposure in each band that has the largest effective exposure time (i.e., the largest $t_{\text{eff}} \times T_{\text{exp}}$), and (2) the weighted average of the individual single-epoch measurements (these quantities are prefixed by $\text{WAVG}$). The weighted average and unbiased weighted standard deviation were calculated following the weighted sample prescriptions used by DES (Appendix A of DES Collaboration 2021).\(^5\) In addition, we track cluster-level statistics such as the number of detections in each band.

We follow the DES procedure to calculate the interstellar extinction from Milky Way foreground dust (DES Collaboration 2018). We compute the value of $E(B-V)$ at the location of each catalog source by performing a bi-linear interpolation in (RA,Dec) to the maps of Schlegel et al. (1998). The reddening correction for each source in each band, $A_b = R_b \times E(B-V)$, is calculated using the fiducial interstellar extinction coefficients from DES DR1 (DES Collaboration 2018): $R_g = 3.185$, $R_r = 2.140$, $R_i = 1.571$, and $R_z = 1.196$. Note that, following the procedure of DES DR1, the Schlafly & Finkbeiner (2011) calibration adjustment to the Schlegel et al. (1998) maps is included in our fiducial reddening coefficients ($N = 0.78$). The $A_b$ values are included for each object in DELVE DR2, but they are not applied to the magnitude columns by default. The list of the photometric and astrometric properties provided in DELVE DR2 can be found in Appendix B.

3.1. Improvements Relative to DELVE DR1

We have made several improvements to the pipeline described by Drlica-Wagner et al. (2021).

1. The seasonally averaged bias and flat images used for image detrending have been updated to include calibration products from the fifth and sixth years of DES observing. The final epoch of DES calibration products have been used to process all exposures taken after the end of DES data taking.

2. Images that were heavily affected by reflected or scattered light from bright stars were identified using the DES ray-tracing tool (Kent 2013). Objects detected on these CCDs were removed from the DELVE DR2 catalog.

3. The radius for matching sources within and across bands has been reduced from 1\(\text{''}\) to 0\(\text{''}.5\). This change was motivated by the excellent astrometric precision of the DELVE DR1 catalog (\(~30\text{mas})

The change, along with improvements in the algorithm for splitting pairs of closely separated objects, reduces the number of objects that are spuriously merged.

4. DATA RELEASE

DELVE DR2 is derived from DECam data covering $> 20,000\text{deg}^2$ in each of the $g$, $r$, $i$, $z$ bands, while $\sim 17,000\text{deg}^2$ are jointly covered in all four bands (Figure 1). DELVE DR2 consists of a catalog of $\sim 2.5$ billion unique astronomical objects, with $\sim 618$ million objects that have measurements in all four bands. This section describes the characterization of the sky coverage, astrometry, photometry, depth, and object classification of the DELVE DR2 catalog. Summary statistics of this characterization are given in Table 1.

4.1. Sky Coverage

We quantify the area covered by DELVE DR2 by pixelizing the geometry of each DECam CCD using the decasu\(^6\) package built on healsparse.\(^7\) This package maps the geometry of each CCD using higher-resolution nested HEALPix maps ($\text{nside} = 16384; \sim 166\text{arcsec}^2$) and sums the resulting covered pixels to generate lower resolution maps ($\text{nside} = 4096; \sim 0.74\text{arcmin}^2$) containing the fraction of each pixel that is covered by the survey. We quantitatively estimate the covered area as the sum of the coverage fraction maps in each band independently and the intersection of the maps in all four bands (Table 1).

4.2. Astrometry

We assess the internal astrometric repeatability by comparing the distributions of angular separations of individual detections of the same objects over multiple exposures. The median global astrometric spread is 29\(\text{mas}\) across all bands and is found to be fairly consistent within each band (Table 1). Furthermore, we estimate the external astrometric accuracy by calculating the angular separation between bright stars in DELVE DR2 ($16 < g < 19$) and sources in Gaia EDR3 (Gaia Collaboration 2021) matched within 2\(\text{''}\) (Figure 3). We find that the median separation between the positions measured by DELVE DR2 and Gaia EDR3 is 22\(\text{mas}\), which confirms that no significant astrometric offsets have been introduced by the catalog coaddition procedure. Since the DESDM astrometric calibration does not incorporate proper motions, we expect some corre-

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\(^5\) Note that we do not apply the “error floor” applied by DES.

\(^6\) https://github.com/erykoff/decasu

\(^7\) https://healsparse.readthedocs.io
4.3. Relative Photometric Calibration

We assess the photometric repeatability in each band from the root-mean-square (rms) scatter between independent PSF magnitude measurements of bright stars. For each band, we select stars with $16 < \text{WAVG_MAG_PSF} < 18$ mag and calculate the median rms scatter in $\sim 0.2\text{deg}^2$ HEALPix pixels ($\text{nside} = 128$). We estimate the median of the rms scatter over the entire footprint in each band. This quantity is found to be $\sim 5$ mmag and is listed for each band in Table 1.

We validate the photometric uniformity of DELVE DR2 by comparing to space-based photometry from Gaia EDR3 (Figure 4). We transform the $g, r, i, z$ photometry from DELVE to the Gaia $G$ band using a set of transformations derived for DES DR2 (Sevilla-Noarbe et al. 2021; DES Collaboration 2021). We compare the Gaia EDR3 $G$-band magnitude in the AB system ($G_{\text{Gaia}}$) to the predicted $G$-band magnitude of stars in DELVE ($G_{\text{DELVE}}$). We calculate the median difference, $G_{\text{DELVE}} - G_{\text{Gaia}}$, within each $\text{nside} = 128$ HEALPix pixel for stars with $16 < r < 20$ mag, $0.5 < (g-i) < 1.5$ mag, and $\text{Gaia} G < 20$ mag. We plot the spatial distribution of the median difference along with histograms for the median difference within the DES region and over the full DELVE DR2 footprint in Figure 4. While the median difference within the DES footprint is zero by construction, we find a small ($< 1$ mmag) offset between DELVE DR2 and Gaia EDR3. We estimate the photometric uniformity of DELVE DR2 as the standard deviation of the median differences across pixels, which yields a value of $7.2$ mmag (Table 1). However, because the distribution of residuals is non-Gaussian (Figure 4), we also provide the 68% containment interval, which is $9.1$ mmag. We find no significant magnitude-dependent trends in $G_{\text{DELVE}} - G_{\text{Gaia}}$ within the magnitude range that we study ($16 < r < 20$ mag).

Similar comparisons between DES DR2 and Gaia DR2 demonstrated that the nonuniformity of Gaia observations can be the dominant contributor to photometric nonuniformity estimated using this technique (Burke et al. 2018; Sevilla-Noarbe et al. 2021; DES Collaboration 2021). Within the DES footprint, we find that comparing to Gaia EDR3 reveals much less structure than was seen when comparing to Gaia DR2 (DES Collaboration 2021). Furthermore, it is clear that outside the DES footprint spatial structure in the DELVE DR2 calibration dominate the nonuniformity relative to Gaia. We observe a systematic shift of $\sim 10$ mmag relative to Gaia EDR3 at Dec $= -30$ deg where ATLAS Refcat2 switches from using PS1 to SkyMapper (Tonry et al. 2018; Drlica-Wagner et al. 2021). It should be possible to improve the relative photometric calibration of DELVE by applying the FGCM (Burke et al. 2018). Initial tests using several thousand square degrees of the DELVE data suggest that a relative photometric uniformity of $\lesssim 5$ mmag is possible.

4.4. Color Uniformity

As an additional check of the color uniformity and relative photometric calibration of DELVE DR2, we perform an analysis of the stellar sequence using the $g$, $r$, and $i$ bands (e.g., Ivezić et al. 2004; MacDonald et al. 2004; High et al. 2009; Gilbank et al. 2011; Coupon et al. 2012; Kelly et al. 2014; Drlica-Wagner et al. 2018). The stellar sequence follows a tight locus in the $(g-r)$ vs. $(r-i)$ color-color plane, especially in the region from $0.3 < (g-r) < 1.1$. This region of the stellar sequence is dominated by main sequence stars and has a small intrinsic width. This tight relation allows us to assess the calibration quality in two ways: (1) On small scales, we can probe the statistical error in color measurements by computing the width of the stellar sequence ($w_{\perp}$). (2) On larger angular scales, we can use variations in the location of this sequence as an estimate of systematic color uniformity.
Figure 4. Median difference between the DELVE DR2 photometry transformed into the Gaia $G$-band, $G_{\text{DELVE}}$, and the measured magnitude from Gaia EDR3, $G_{\text{Gaia}}$. The spatial distribution of the median difference in each pixel is shown in the left panel (color range clipped to $\pm 10$ mmag), while the right panel shows a histogram of the pixel values. A shift in the zeropoint can be seen at Dec. $\sim -30$ deg, which corresponds to the boundary between the ATLAS Refcat2 use of PS1 and SkyMapper (Section 4.3). This comparison is restricted to the area with overlapping DELVE DR2 coverage in all four bands ($g, r, i, z$).

Figure 5. Left: Spatial distribution of the measured width of the stellar locus $w_\perp$ using WAVG_MAG_PSF magnitudes for each $nside=128$ HEALPix pixel in the DELVE DR2 footprint. The DES region can be seen to have much smaller values of $w_\perp$ indicating lower statistical error in these measurements. Right: Histogram of $w_\perp$ values ($w_\perp = \sqrt{\sigma^2 + w_{\perp,0}^2}$), where $w_{\perp,0} \sim 8$ mmag. The black line shows the same data as the spatial map (WAVG_MAG_PSF magnitudes for the full footprint, a clear bimodality can be seen due to the difference in relative statistical error in measurements between the DES region calibrated with FGCM ($\sigma_{\text{FGCM,WAVG}} \sim 3$ mmag), and the rest of the DELVE footprint calibrated with ATLAS Refcat2 ($\sigma_{\text{ATLAS R2,WAVG}} \sim 7$ mmag). The gray histograms illustrate the difference in the measured width between the weighted-average (solid) and single best measurements (dotted).

We follow the methodology of Ivezić et al. (2004) to measure both the width and location of the stellar sequence. Briefly, we select high confidence stars (EXTENDED_CLASS$G=0$) that are bright with $g, r$, and $i$ extinction-corrected magnitudes brighter than 20 mag and extinction-corrected color $0.3 < (g-r) < 1.1$.

We performed a linear fit on the data and derived principal components, $P_1$ and $P_2$, where $P_2$ is perpendicular to the stellar locus line of best fit.

We define $w_\perp$ to be the $3\sigma$-clipped rms of the distribution of stars in the $P_2$ direction. The location of the stellar sequence is summarized as a residual between the $(r-i)$ color of the linear fit at $(g-r) = 0.7$. This value is computed relative to a low extinction ($E(B-V) < 0.015$) empirical stellar locus computed from the DES DR2 catalog, where $(r-i)_{\text{DES}} = 0.221$ mag at $(g-r)_{\text{DES}} = 0.7$ mag.

To estimate the magnitude of the statistical error on color we split our data set into two areas. First, we...
analyze the DES footprint, which is covered homogeneously and has zeropoints derived from FGCM. Second, we analyze the rest of the DELVE DR2 footprint where zeropoints were derived from ATLAS Refcat2 (Section 3). We calculate the width of the stellar sequence, \( w_{\perp} \), using both the best single-epoch measurement (\textsc{mag}\_\textsc{psf}) and the weighted-average catalog coadd measurements (\textsc{wavg}\_\textsc{mag}\_\textsc{psf}) for each \textsc{nside} = 128 HEALPix pixel. The spatial distribution of \( w_{\perp} \) derived from the weighted-average magnitudes can be seen in Figure 5. For the region in the DES footprint, we also compute an estimate of the relative difference in the statistical errors between each type of magnitude measurement, \( N_{\text{eff}} = \text{\textsc{magerr}\_\textsc{psf}}^2 / \text{\textsc{wavg}\_\textsc{magerr}\_\textsc{psf}}^2 \). Assuming that \( w_{\perp} \) comes from the statistical uncertainty in the photometric calibration (\( \sigma_{\text{stat}} \)) and intrinsic width of the stellar sequence (\( w_{\perp,0} \)) added in quadrature (\( w_{\perp}^2 = \sigma_{\text{stat}}^2 + w_{\perp,0}^2 \)), we can use the two measurements of \( w_{\perp} \) and effective number of observations (\( N_{\text{eff}} \)) for the \textsc{wavg} measurement to solve for \( \sigma_{\text{stat}} \) and \( w_{\perp,0} \).

Distributions for \( w_{\perp} \) in the DES region for the single measurement and \textsc{wavg} measurement cases are shown on the right of Figure 5 in gray. We find a median single measurement (\textsc{wavg} measurement) error of \( \sigma_{\text{fgcm}} \sim 8 \) mmag (\( \sigma_{\text{fgcm, wavg}} \sim 3 \) mmag) for the region with zeropoints derived from FGCM, and median intrinsic width of the stellar locus \( w_{\perp,0} \sim 8 \) mmag. To estimate \( \sigma_{\text{stat}} \) for the ATLAS Refcat2 calibrated region where the coverage is not as homogenous, we use the \( w_{\perp,0} \) estimate from the FGCM region. The median single measurement (\textsc{wavg} measurement) error of \( \sigma_{\text{ATLAS R2, wavg}} \sim 10 \) mmag (\( \sigma_{\text{ATLAS R2, wavg}} \sim 7 \) mmag) for the region with zeropoints derived from ATLAS Refcat2. This value of \( \sigma_{\text{ATLAS R2, wavg}} \) agrees with the comparison to Gaia EDR3 data in Section 4.3. Furthermore, this analysis highlights the differences in color uncertainty between the FGCM calibrated region and the ATLAS Refcat2 calibrated region. We note that variations in reddening and underlying stellar populations could cause variations in the intrinsic width of the stellar locus, and our value in the DES region of \( w_{\perp,0} = 8 \) mmag can be thought of as a lower limit over the rest of the sky. Therefore, the inferred \( \sigma_{\text{ATLAS R2}} \) is an upper limit on the statistical color uncertainty in the ATLAS Refcat2 calibrated region.

As described above, we use the position of the stellar locus in the \((g - r)\) vs. \((r - i)\) plane as a probe of color uniformity in DELVE. Similar to \( w_{\perp} \), we use the residuals of our fit calculated for each \textsc{nside} = 128 HEALPix pixel. The offsets between the calculated value and the DES Y6 value for each HEALPix pixel are shown in the top of Figure 6. Using \textsc{mag}\_\textsc{psf} (\textsc{wavg}\_\textsc{mag}\_\textsc{psf}) we find a median rms in the \((r - i)\) color of the linear fit at \((g - r) = 0.7\) of 9 mmag (8 mmag) for the entire survey footprint, with a scatter between \textsc{mag}\_\textsc{psf} and \textsc{wavg}\_\textsc{mag}\_\textsc{psf} of less than 3 mmag. If we compare the DES footprint to the rest of the DELVE using \textsc{mag}\_\textsc{psf}, we find median rms measurements of 5 mmag and 9 mmag respectively. It is likely that some of this scatter can be attributed to the effects of interstellar extinction and changes in the observed stellar populations across the footprint, which will shift the location of the stellar locus (see Section 2.3 of High et al. 2009). To estimate the effect of reddening on these values, we compute a

Figure 6. Top: Offset in the stellar locus \((r - i)\) color at \((g - r) = 0.7\) fit in each \textsc{nside} =128 HEALPix pixel relative to the DES value of \((r - i)_{\text{DES}} = 0.221\) mag. Offsets in this distribution at large spatial scales are likely due to changing stellar populations. Middle: Polynomial fit to the \((r - i)\) offset map smoothed with a \( r = 5^\circ \) Gaussian kernel. Bottom: Map of residuals after the polynomial fit has been subtracted. This residual map highlights variations in the location of the stellar locus at smaller scales and is an estimate of the color uniformity.
median rms only for regions with $E(B-V) < 0.5\,\text{mag}$ and find that our results are unchanged. This indicates that reddening systematics do not strongly contribute to the spatial structure seen in the top row of Figure 6. In order to account for shifts of the stellar locus on large spatial scales (tens of degrees) and estimate the color uniformity on scales of a few degrees, we smooth the spatial distribution of the residuals with a Gaussian kernel with a standard deviation of $\sigma = 5^\circ$ and fit a 5th order polynomial. This polynomial is then subtracted from the spatial distribution, mitigating the effect of spatially dependent changes in the location of the stellar locus and highlighting systematic scatter in the color uniformity at scales of a few degrees. Using this subtracted map, we find a median rms of 4 mmag for the DES region and 7 mmag for the rest of the DELVE DR2 footprint. This can be interpreted as a lower limit on the systematic uncertainties in the color measurements of DELVE DR2.

4.5. Absolute Photometric Calibration

The photometry of DELVE DR2 is tied to the $AB$ magnitude system (Oke & Gunn 1983) via the HST CalSpec standard star C26202. Within the DES footprint, the DES FGCM zeropoints are directly tied to C26202 as described in Section 4.2.2 of DES Collaboration (2021). Outside the DES footprint, the calibration is tied more indirectly to C26202 via the zeropoints of the ATLAS Refcat2 transformation equations, which were adjusted to match DES DR2 (see Appendix A of Drlica-Wagner et al. 2021). Due to this procedure, DELVE DR2 cannot have a better absolute calibration accuracy than DES DR2, which sets a lower limit on the statistical uncertainty of 2.2 mmag per band and a systematic uncertainty of 11 to 12 mmag per band (see Table 1 of DES Collaboration 2021). The global offset seen between the PS1 and SkyMapper regions of ATLAS Refcat2 when compared to Gaia EDR3 suggests that the absolute calibration cannot be better than 10 mmag. Combining the maximum systematic uncertainty on the absolute calibration from DES DR2 and the DELVE DR2 offset relative to Gaia EDR3, we estimate that the absolute photometric accuracy of DELVE DR2 is $\lesssim 20$ mmag.

DELVE performed dedicated observations of the CalSpec standard star SDSS151421 during twilight hours in 2020. These observations were not used to set the absolute calibration of DELVE DR2, and they can instead be used to validate our estimate of the absolute calibration uncertainty. We find that the median offsets between the DELVE PSF magnitudes and the CalSpec STIS magnitudes for SDSS151421 are $\Delta g=4.4$, $\Delta r=23.3$, $\Delta i=7.2$, and $\Delta z=1.6\,\text{mmag}$ with a scatter of $\sim 6\,\text{mmag}$. Similar analyses performed by DES found $\sim 10\,\text{mmag}$ offsets when comparing the DES photometry to several CalSpec standard stars and DA white dwarfs within the DES footprint (DES Collaboration 2021). Based on these comparisons, we maintain the stated absolute calibration accuracy of $\lesssim 20\,\text{mmag}$.

4.6. Photometric Depth

The photometric depth of DELVE DR2 can be assessed in several ways. One common metric is to determine the magnitude at which a fixed signal-to-noise ratio (S/N) is achieved (e.g., Rykoff et al. 2015). The statistical magnitude uncertainty is related to the S/N ratio via $\delta m = 2.5 \delta F / \ln 10$ (Pogson 1856),

$$\delta m = \frac{2.5}{\ln 10} \frac{\delta F}{F}. \quad (1)$$

Using this equation, we estimate the magnitude at which DELVE DR2 achieves S/N=5 ($\delta m \approx 0.2171$) and S/N=10 ($\delta m \approx 0.1085$). We calculate these magnitude limits for point-like sources using MAG_PSF and for all sources using MAG_AUTO. For each magnitude and S/N combination, we select objects and interpolate the relationship between $m$ and median($\delta m$) in $\sim 12\,\text{arcmin}^2$ HEALPix pixels (nside = 1024). The resulting median magnitude limits estimated over the DELVE DR2 footprint are shown in Table 2. We show histograms of the MAG_PSF magnitude limit for point-like sources at S/N=5 in the left panel of Figure 7. In the right panel of Figure 7 we show the DELVE DR2 area as a function of depth in each band. The magnitude limits as a function of location on the sky are shown in Appendix C. Due to the catalog-level coaddition process, the depth of DELVE DR2 is set by the single best exposure in any

| Measurement | $g$ (mag) | $r$ (mag) | $i$ (mag) | $z$ (mag) |
|-------------|----------|----------|----------|----------|
| MAG_PSF (S/N=5) | 24.3 | 23.9 | 23.5 | 22.8 |
| MAG_PSF (S/N=10) | 23.5 | 23.1 | 22.7 | 22.1 |
| MAG_AUTO (S/N=5) | 23.9 | 23.5 | 23.0 | 22.4 |
| MAG_AUTO (S/N=10) | 22.8 | 22.5 | 22.1 | 21.4 |

Note—The MAG_PSF depth is estimated from point-like sources, while the MAG_AUTO depth is estimated from all DELVE DR2 sources. Both MAG_PSF and MAG_AUTO are estimated from the best exposure of each object (see Section 4.6).
region of the sky. This means that the depth of DELVE DR2 is very similar to that of DELVE DR1 (Drlica-Wagner et al. 2021) and significantly shallower than DES DR2 even in the overlapping DES region (DES Collaboration 2021). At bright magnitudes, the DECam CCDs will saturate at $g = 15.2$, $r = 15.7$, $i = 15.8$, and $z = 15.5$ for point sources observed in a 90 s exposure with median seeing (DES Collaboration 2021). While $\sim 85\%$ of the exposures included in DELVE DR2 have exposure times of $\lesssim 90\,$s, there are some regions with longer exposure times where saturation will occur at fainter magnitudes. Therefore, objects detected by SourceExtractor with the saturation flag bit set were removed from the DELVE DR2 catalog production.

4.7. Object Classification

DELVE DR2 includes the SourceExtractor SPREAD_MODEL parameter, which can be used to separate spatially extended galaxies from point-like stars and quasars (e.g., Desai et al. 2012). Following DES (e.g., DES Collaboration 2018, 2021) and DELVE DR1 (Drlica-Wagner et al. 2021), we define EXTENDED_CLASS parameters as a sum of several Boolean conditions,

\[
\text{EXTENDED\_CLASS}\_G = \\
\left( (\text{SPREAD\_MODEL}\_G + 3 \cdot \text{SPREADERR\_MODEL}\_G) > 0.005 \right) \\
+ \left( (\text{SPREAD\_MODEL}\_G + \text{SPREADERR\_MODEL}\_G) > 0.003 \right) \\
+ \left( (\text{SPREAD\_MODEL}\_G - \text{SPREADERR\_MODEL}\_G) > 0.003 \right).
\]

When true, each Boolean condition adds one unit to the classifier such that an EXTENDED_CLASS value of 0 indicates high-confidence stars, 1 is likely stars, 2 is likely galaxies, and 3 is high-confidence galaxies. Objects that lack coverage in a specific band or where the SPREAD_MODEL fit failed are set to a sentinel value of −9. We calculate EXTENDED_CLASS values similarly for each band; however, we recommend the use of the $g$-band classifier, EXTENDED_CLASS\_G, since the $g$ band has the widest coverage and deepest limiting magnitude.

In Figure 8, we characterize the performance of EXTENDED_CLASS\_G as a function of magnitude by matching DELVE DR2 objects to data from the W04 (WIDE12H+GAMA15H) equatorial field of the wide layer of HSC-SSP PDR3 (Aihara et al. 2021). To improve uniformity, we select only overlapping regions where the S/N = 5 limiting PSF magnitude from DELVE is representative of the DELVE DR2 survey (magnitude limit of $24 < g < 24.5$; Appendix C). The superior image quality ($i$-band PSF FWHM $\sim 0.61\,$s) and depth ($i \sim 26.2\,$mag) of the wide layer of HSC-SSP PDR3 enable robust tests of star–galaxy separation in DELVE DR2. The matched data set covers $\sim 394\,$deg$^2$ and contains $\sim 9.6$ million matched objects. Following previous analyses (DES Collaboration 2018; Drlica-Wagner et al. 2021), we select point-like sources from HSC-SSP PDR3 based on the difference between the $i$-band PSF and model magnitudes of sources,

\[
\text{HSC\_STARS} = \\
\left( (I\_PSFFLUX\_\text{MAG} - I\_CMODEL\_\text{MAG}) < 0.03 \right) \\
\left( (I\_PSFFLUX\_\text{MAG} - I\_CMODEL\_\text{MAG}) < 0.1 \right) \\
& (I\_PSFFLUX\_\text{MAG} < 22).
\]

This scheme requires that the PSF and model magnitudes are very similar for fainter sources, while the agreement is relaxed for brighter sources. This selection results in $\sim 7.1$ million matched objects classified as galaxies and $\sim 2.5$ million matched objects classified as stars. We use these objects to evaluate the differential performance of DELVE DR2 EXTENDED_CLASS\_G as a function of magnitude in Figure 8. A nominal stellar sample ($0 \leq \text{EXTENDED\_CLASS}\_G \leq 1$) contains
The spatial number density of high-confidence stars ($\text{EXTENDED CLASS} = 0$) and high-confidence galaxies ($\text{EXTENDED CLASS} = 3$) are shown in Figure 9. The stellar density map clearly shows increasing stellar density toward the Galactic plane, as well as the high stellar density associated with the LMC and SMC. The galaxy density map is dominated by the large-scale clustering of galaxies at high Galactic latitudes, but stellar contamination is apparent close to the Galactic bulge, LMC, and SMC. These maps have had a magnitude cut applied at $\text{MAG}_{\text{AUTO},G} \leq 22$ mag in Table 1.

The spatial number density of high-confidence stars ($\text{EXTENDED CLASS} = 0$) and high-confidence galaxies ($\text{EXTENDED CLASS} = 3$) are shown in Figure 9. The stellar density map clearly shows increasing stellar density toward the Galactic plane, as well as the high stellar density associated with the LMC and SMC. The galaxy density map is dominated by the large-scale clustering of galaxies at high Galactic latitudes, but stellar contamination is apparent close to the Galactic bulge, LMC, and SMC. These maps have had a magnitude cut applied at $\text{MAG}_{\text{AUTO},G} \leq 22$ mag and have not been corrected for interstellar extinction, so some apparent variations in depth come from the extinction while others come from actual variations in depth over the footprint.

4. Spatial coverage maps were created at a resolution of $\text{nside} = 16384$, corresponding to linear pixel dimensions of $\sim 13''$. Thus, there are a small number of catalog objects that reside outside the coverage maps due to the slight inaccuracy at the CCD boundaries. These objects reside at the edges of the DELVE footprint and are $< 0.0001\%$ of the catalog.

5. DATA ACCESS

Access to DELVE DR2 is provided through the Astro Data Lab (Fitzpatrick et al. 2016; Nikutta et al. 2020), a part of the Community Science and Data Center (CSDC) hosted by NOIRLab. DELVE DR2 includes a main object table consisting of photometric measurements for $\sim 2.5$ billion objects. In addition, the Astro Data Lab has computed cross-match tables between the DELVE DR2 catalog and catalogs from AllWISE, Gaia EDR3, NSC DR2, SDSS DR16, and unWISE DR1 (Cutri et al. 2021; Gaia Collaboration 2021; Nidever et al. 2021; Ahumada et al. 2020; Schlafly et al. 2019). These cross-match tables and their reverse counterparts are served alongside the DELVE DR2 main object table at the Astro Data Lab (see Appendix B). The DELVE DR2 catalog data can be accessed via both a

\[\text{https://datalab.noirlab.edu}\]
Table Access Protocol (TAP)\(^9\) service and from direct PostgreSQL queries via web-based, command-line, and programmatic query interfaces. In addition, the Astro Data Lab provides an image cutout service, built on the Simple Image Access (SIA) protocol, that can be used to access versions of the DELVE DR2 imaging data processed with the DECam Community Pipeline (Valdes et al. 2014). More detailed information on accessing the DELVE DR2 data can be found on the Astro Data Lab website.\(^{10}\)

6. SUMMARY

DELVE seeks to study the physics of dark matter and galaxy formation by observing resolved dwarf galaxies and stellar substructures in the Local Volume. To do so, DELVE has set out to complete contiguous deep imaging coverage of the southern high Galactic latitude sky. DELVE DR2 combines new observations with archival DECam data to cover > 20,000 deg\(^2\) individually in \(g, r, i, z\) and \(\sim 17,000\) deg\(^2\) in all four bands simultaneously. The DELVE DR2 catalog contains PSF and automatic aperture measurements for \(\sim 2.5\) billion astronomical objects with a 5σ PSF depth of \(g = 24.3, r = 23.9, i = 23.5, z = 22.8\) mag (Table 1). The DELVE DR2 data products are accessible through the NOIRLab Astro Data Lab.

As of 2022 January, DELVE has completed \(\sim 80\%\) of its 126 nights of scheduled DECam observing. Additional DECam observations will increase the coverage, uniformity, and depth of future DELVE catalogs. Furthermore, we expect that future DELVE data releases will include products derived from image coaddition, as well as deeper targeted regions of the DELVE footprint.

We anticipate that DELVE DR2 and future DELVE data releases will be a valuable resource for the community in advance of the Vera C. Rubin Observatory Legacy Survey of Space and Time.

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\(^9\) [http://ivoa.net/documents/TAP](http://ivoa.net/documents/TAP)

\(^{10}\) [https://datalab.noirlab.edu/delve](https://datalab.noirlab.edu/delve)
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Facilities: Blanco (DECam), Astro Data Lab, Gaia, Subaru (HSC)

Software: astropy (Astropy Collaboration 2018), fitsio,11 HEALPix (Górski et al. 2005),12 healpy (Zonca et al. 2019),13 healsparse,14 matplotlib (Hunter 2007), numpy (Harris et al. 2020), PSFEx (Bertin 2011), scipy (Virtanen et al. 2020), SCAMP (Bertin 2006), skymap,15 SourceExtractor (Bertin & Arnouts 1996)

APPENDIX

11 https://github.com/esheldon/fitsio
12 http://healpix.sourceforge.net
13 https://github.com/healpy/healpy
14 https://healsparse.readthedocs.io/en/latest/
15 https://github.com/kadrlica/skymap
A. DECAM DATA

DELVE DR2 combines DECam observations acquired by 278 programs. These programs and the number of exposures they each contributed to DELVE DR2 are listed in Table 3.

| Prop.ID     | PI               | $N_{\text{exp}}$ | Prop.ID     | PI               | $N_{\text{exp}}$ | Prop.ID     | PI               | $N_{\text{exp}}$ | Prop.ID     | PI               | $N_{\text{exp}}$ |
|-------------|------------------|------------------|-------------|------------------|------------------|-------------|------------------|------------------|-------------|------------------|------------------|
| 2012B-0001  | Josh Frieman     | 63656            | 2018A-0909  | Thomas H Puzia   | 121              | 2012B-0620  | Jeremy Mould    | 23               |
| 2014B-0404  | David Schlegel   | 28823            | 2015A-0631  | Alfredo Zenteno  | 120              | 2021A-0010  | Travis Rector   | 23               |
| 2019A-0305  | Alex Drlica-Wagner| 12459            | 2019B-0080  | Bryan Miller     | 119              | 2019B-0008  | Casey Papovich  | 23               |
| 2018A-0386  | Alfredo Zenteno  | 3029             | 2013A-0737  | Scott Sheppard   | 111              | 2013A-0737  | Scott Sheppard  | 22               |
| 2013B-0440  | David Nidever    | 2753             |             |                  |                 |             |                  |                  |
| 2019A-0372  | Alfredo Zenteno  | 2452             |             |                  |                 |             |                  |                  |
| 2017A-0260  | Marcelle Soares-Santos| 2297          |             |                  |                 |             |                  |                  |
|             |                  |                  |             |                  |                 |             |                  |                  |
| Table 3    |                  |                  | Table 3    |                  |                 |             |                  |                  |

Table 3 continued
Table 3 (continued)

| Prop.ID | PI                  | N exp | Prop.ID | PI                  | N exp | Prop.ID | PI                  | N exp |
|---------|---------------------|-------|---------|---------------------|-------|---------|---------------------|-------|
| 2014A-0412 | Armin Rest         | 303   | 2019B-0910 | Yue Shen          | 55    | 2013A-0455 | Scott Sheppard    | 7     |
| 2013A-0719 | Abhijit Saha       | 291   | 2017B-0163 | Prashin Jethwa    | 54    | 2012B-0416 | David Nidever    | 7     |
| 2019A-0205 | Daniel Goldstein   | 290   | 2013A-0612 | Yun-Kyeong Sheen  | 53    | 2017B-0199 | Anton Koekemoer  | 7     |
| 2018A-0215 | Jeffrey Carlin     | 289   | 2017A-0913 | Luisbda Santan da Silva | 51    | 2013A-0609 | Douglas P Geisler | 7     |
| 2014A-0620 | Andrew Carey       | 287   | 2014A-0610 | Matthew Taylor    | 50    | 2020B-0021 | Haojing Yan     | 7     |
| 2015A-0306 | Eduardo Ballinot   | 280   | 2015A-0371 | Armin Rest        | 50    | 2017A-0366 | Sangeeta Malhotra | 7     |
| 2014B-0244 | Anja von der Linden| 280   | 2016B-0173 | Anton Koekemoer   | 49    | 2017B-0253 | Jeffrey Carlin   | 6     |
| 2019B-0371 | Marcelle Soares-Santos | 280  | 2017A-0909 | Jeffrey Cooke     | 49    | 2014A-0399 | Christopher Johnson | 6     |
| 2016B-0905 | Helmut Jerjen      | 276   | 2015A-0615 | Brenda McMenigal  | 49    | 2015B-0314 | Brad Tucker      | 5     |
| 2017A-0914 | Grant Tremblay     | 274   | 2017A-0389 | Annalisa Calamida | 48    | 2020A-0415 | Armin Rest       | 5     |
| 2016A-0630 | Thomas H Puzia     | 218   | 2020A-0142 | Tom Shanks        | 42    | 2015A-0614 | Jeffrey Cooke    | 5     |
| 2016A-0327 | Douglas P Finkbeiner | 216  | 2014B-0608 | Yara Jaffe        | 44    | 2019B-1012 | Jeffrey Cooke    | 5     |
| 2018B-0122 | Armin Rest         | 213   | 2017A-0911 | Ana Chies Santos  | 39    | 2020B-0288 | Alex Leauthaud   | 4     |
| 2012B-0569 | Lori Allen         | 206   | 2020A-0909 | Patricia Arevalo  | 39    | 2012B-0624 | Aaron Robotham   | 4     |
| 2019A-0915 | Jose Pena          | 191   | 2016A-0004 | Ana Bonaca        | 38    | 2012B-3002 | Josh Bloom       | 4     |
| 2015A-0619 | Thiago Goncalves   | 186   | 2014A-0157 | Andrej Favia      | 38    | 2015B-0603 | Leopoldo Infante | 4     |
| 2014A-0327 | Armin Rest         | 183   | 2012B-0363 | Josh Bloom        | 38    | 2015A-0177 | Cristian Eduard Rusu | 3     |
| 2018A-0059 | Herve Bouy         | 182   | 2016A-0068 | Thomas Deboer     | 38    | 2012B-0448 | Paul Thornman    | 3     |
| 2015A-0163 | Carl J Grillmair   | 179   | 2015B-0191 | Sarah Rice        | 37    | 2014B-0378 | Armin Rest       | 3     |
| 2018A-0911 | Francisco Forster  | 174   | 2014A-0255 | Anton Koekemoer   | 35    | 2013A-0613 | Ricardo Munoz    | 3     |
| 2017B-0110 | Edo Berger         | 174   | 2017B-0951 | Kathy Vivas       | 35    | 2013A-0400 | Josh Bloom       | 3     |
| 2016B-0910 | Thomas H Puzia     | 174   | 2016B-0904 | Igor Andreoni     | 33    | 2013A-0616 | Geraint Lewis   | 2     |
| 2015A-0130 | Denija Crnojevic   | 173   | 2019A-0060 | Herve Bouy        | 33    | 2020A-0913 | Jeremy Mould     | 2     |
| 2016B-0279 | Douglas P Finkbeiner | 170  | 2021A-0113 | Melissa L Graham  | 33    | 2016A-0610 | Leopoldo Infante | 2     |
| 2013B-0614 | Ricardo Munoz      | 167   | 2018A-0907 | Ricardo Munoz     | 32    | 2013A-0608 | Ricardo Demarco  | 2     |
| 2015A-0121 | Anja von der Linden| 160   | 2019B-1004 | Julio Chaname     | 32    | 2014A-0191 | Hendrik Hildebrandt | 2     |
| 2019A-0917 | Paulo Lopes        | 159   | 2012B-0506 | Daniel D Kelson   | 32    | 2017B-0905 | Jeremy Mould     | 2     |
| 2018A-0369 | Armin Rest         | 156   | 2015A-0632 | Cesar Briceno     | 31    | 2015B-0250 | Jonathan Hargis  | 1     |
| 2017A-0918 | Alexandra Yip      | 155   | 2013B-0531 | Eric Mamajek      | 31    | 2012B-3016 | Scott Sheppard   | 1     |
| 2013A-0611 | Dougall Mackey     | 142   | 2018B-0904 | Lee Splitter      | 30    | 2012B-0617 | Robert I Hynes  | 1     |
| 2014B-0146 | Mark Sullivan      | 141   | 2014A-0623 | Ken Freeman       | 30    | 2013A-0610 | Mario Hanuy     | 1     |
| 2014A-0256 | Kathleen Eckert    | 136   | 2013A-0723 | Eric Mamajek      | 28    | 2016A-0386 | Sangeeta Malhotra | 1     |
| 2015A-0205 | Eric Mamajek       | 135   | 2019A-0315 | Matthew Penny     | 28    | 2017A-0917 | Franz Bauer      | 1     |
| 2014A-0321 | Marla Gehr         | 133   | 2013A-2101 | Alistair Walker   | 28    | 2013B-0502 | Ian Dell’Antonio | 1     |
| 2017B-0904 | Paulo Lopes        | 133   | 2015A-0107 | Claudia Belardi   | 28    | 2013B-0613 | Roberto R Munoz | 1     |
| 2019A-0913 | Julio Carballo-Bello | 133  | 2013B-0438 | Casey Papovich    | 26    | 2015A-0059 | Sarah Sonnett    | 1     |
| 2015A-0397 | Armin Rest         | 126   | 2013A-0621 | Matias Gomez      | 25    | 2013A-0704 | Matt A Wood      | 1     |
| 2019B-1010 | Jose Pena          | 123   | 2016A-0104 | Mark Sullivan     | 24    |          |                     |       |

Note—Programs are ordered by the number of exposures contributed. The largest single contributors to the DELVE DR2 data set are DES, DECaLS and the DELVE program itself. Programs with no principal investigator (PI) listed are generally Target-of-Opportunity (ToO) or multi-PI programs.
B. DELVE DR2 TABLES

The DELVE DR2 catalog data are accessible through the `DELVE_DR2.OBJECTS` table hosted by the Astro Data Lab. This table includes the photometric properties assembled from a catalog-level co-add of the individual single-epoch measurements. The table columns are described in Table 4. In addition, cross-matches between objects in the DELVE DR2 catalog and objects within 1''5 from external catalogs are provided in individual tables:

- `DELVE_DR2.X1P5_OBJECTS_ALLWISE_SOURCE` - AllWISE (Cutri et al. 2021)
- `DELVE_DR2.X1P5_OBJECTS_GAIA_EDR3_SOURCE` - Gaia EDR3 (Gaia Collaboration 2021)
- `DELVE_DR2.X1P5_OBJECTS_NSC_DR2_OBJECT` - NSC DR2 (Nidever et al. 2021)
- `DELVE_DR2.X1P5_OBJECTS_SDSS_DR16_SPECOBJ` - SDSS DR16 (Ahumada et al. 2020)
- `DELVE_DR2.X1P5_OBJECTS_UNWISE_DR1_OBJECT` - unWISE DR1 (Schlafly et al. 2019)

A template for the columns in these tables are described in Table 5. The schema for these tables are also described in detail on the Astro Data Lab website.

C. DEPTH

This appendix includes sky maps showing variations in the S/N=5 depth of DELVE DR2 in the $g, r, i, z$ bands. The S/N=5 depth was derived from the magnitude at which the median magnitude uncertainty was $\delta m = 0.2171$ mag (Section 4.6). These values were derived in $\sim 12\text{arcmin}^2$ HEALPix pixels ($nside = 1024$) and are shown in Figure 10.
Table 4. DELVE.DR2.MAIN table description: 2,500,247,752 rows; 126 columns

| Column Name                  | Description                                                                 | Columns |
|------------------------------|-----------------------------------------------------------------------------|---------|
| QUICK_OBJECT_ID              | Unique identifier for each object                                           | 1       |
| RA                           | Right ascension derived from the median position of each detection (deg)    | 1       |
| DEC                          | Declination derived from the median position of each detection (deg)        | 1       |
| GLON                         | Galactic longitude derived from RA,DEC (deg)                               | 1       |
| GLAT                         | Galactic latitude derived from RA,DEC (deg)                               | 1       |
| ELON                         | Ecliptic longitude derived from RA,DEC (deg)                               | 1       |
| ELAT                         | Ecliptic latitude derived from RA,DEC (deg)                                | 1       |
| A_IMAGE_[G,R,I,Z]            | Semi-major axis of adaptive aperture in image coordinates (pix)            | 4       |
| B_IMAGE_[G,R,I,Z]            | Semi-minor axis of adaptive aperture in image coordinates (pix)            | 4       |
| CCDNUM_[G,R,I,Z]             | CCD number for best exposure in each band                                  | 4       |
| CLASS_STAR_[G,R,I,Z]         | Neural-network-based star–galaxy classifier                               | 4       |
| EBV                          | $E(B-V)$ value at the object location interpolated from the map of Schlegel et al. (1998) | 1       |
| EXPNUM_[G,R,I,Z]             | Exposure number for best exposure in each band                             | 4       |
| EXPTIME_[G,R,I,Z]            | Shutter-open exposure time for best exposure in each band                  | 4       |
| EXTENDED_CLASS_[G,R,I,Z]     | Spread-model-based morphology class (see Section 4.7)                     | 4       |
| EXTINCTION_[G,R,I,Z]         | Interstellar extinction calculated from Schlegel et al. (1998). Subtract these columns from the magnitude columns to correct for extinction (see Section 3). | 4       |
| FLAGS_[G,R,I,Z]              | SourceExtractor flags for the best detection in each band                  | 4       |
| HPX2048                      | HEALPix index for each object in RING format at resolution $nside = 2048$  | 4       |
| HTM9                         | HTM Level-9 index                                                          | 1       |
| MAG_AUTO_[G,R,I,Z]           | Automatic aperture magnitude derived from the best exposure in each band   | 4       |
| MAGERR_AUTO_[G,R,I,Z]        | Automatic aperture magnitude uncertainty derived from the best exposure in each band | 4       |
| MAG_PSF_[G,R,I,Z]            | PSF magnitude derived from the best exposure in each band                  | 4       |
| MAGERR_PSF_[G,R,I,Z]         | PSF magnitude uncertainty derived from the best exposure in each band      | 4       |
| MJD_OBS                      | Median Modified Julian Date of the observations that were used to determine the astrometric position | 1       |
| NEPOCHS_[G,R,I,Z]            | Number of single-epoch detections for this object                         | 4       |
| NEST4096                     | HEALPix index for each object in NEST format at resolution $nside = 4096$  | 1       |
| RANDOM_ID                    | Random ID in the range 0.0 to 100.0 for subsampling                       | 1       |
| RING256                      | HEALPix index for each object in RING format at resolution $nside = 256$  | 1       |
| SPREAD_MODEL_[G,R,I,Z]       | Likelihood-based star–galaxy classifier (Desai et al. 2012)               | 4       |
| SPREADERR_MODEL_[G,R,I,Z]    | Likelihood-based star–galaxy classifier uncertainty (Desai et al. 2012)   | 4       |
| T_EFF_[G,R,I,Z]              | Effective exposure time scale factor for best exposure in each band        | 4       |
| THETA_IMAGE_[G,R,I,Z]        | Position angle of automatic aperture in image coordinates (deg)           | 4       |
| WAVG_FLAGS_[G,R,I,Z]         | OR of SourceExtractor flags from all detections in each band              | 4       |
| WAVG_MAG_AUTO_[G,R,I,Z]      | Weighted average of automatic aperture magnitude measurements in each band | 4       |
| WAVG_MAGERR_AUTO_[G,R,I,Z]   | Sum in quadrature of the automatic aperture magnitude uncertainties in each band | 4       |
| WAVG_MAGRMS_AUTO_[G,R,I,Z]   | Unbiased weighted standard deviation of the automatic aperture magnitude in each band | 4       |
| WAVG_MAG_PSF_[G,R,I,Z]       | Weighted average of PSF magnitude measurements in each band               | 4       |
| WAVG_MAGERR_PSF_[G,R,I,Z]    | Sum in quadrature of the PSF magnitude uncertainties in each band         | 4       |
| WAVG_MAGRMS_PSF_[G,R,I,Z]    | Unbiased weighted standard deviation of the PSF magnitude in each band     | 4       |
| WAVG_SPREAD_MODEL_[G,R,I,Z]  | Weighted average spread model in each band                                | 4       |
| WAVG_SPREADERR_MODEL_[G,R,I,Z] | Sum in quadrature of the spread model uncertainties in each band         | 4       |
| WAVG_SPREADRMS_MODEL_[G,R,I,Z]| Unbiased weighted standard deviation of SPREAD_MODEL in each band       | 4       |
Table 5. Crossmatch tables between DELVE DR2 and external catalogs.

| Column Name | Description                                           | Columns |
|-------------|-------------------------------------------------------|---------|
| DEC1        | Declination from DELVE DR2 (deg)                      | 1       |
| DEC2        | Declination from external catalog (deg)               | 1       |
| DISTANCE    | Angular separation between RA1,DEC1 and RA2,DEC2 (arcsec) | 1       |
| ID1         | ID in DELVE DR2 (**QUICK_OBJECT_ID**)                 | 1       |
| ID2         | ID in external catalog (**SOURCE_ID**)                | 1       |
| RA1         | Right ascension from DELVE DR2 (deg)                  | 1       |
| RA2         | Right ascension from external catalog (deg)           | 1       |
Figure 10. Sky maps and histograms of the S/N=5 magnitude limit computed from the statistical uncertainty in MAG_PSF. Dashed vertical lines indicate the median depth quoted in Table 1. Sky maps are plotted using an equal-area McBryde–Thomas flat polar quartic projection in celestial equatorial coordinates.
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