

Milky Way Bulge PSF Photometry

Abstract

The Milky Way Bulge PSF Photometry provides a comprehensive census of the stellar populations in the inner ~ 300 deg² of the Galaxy. It is based on observations obtained with the near-IR imager VIRCAM mounted at the VISTA telescope as part of the ESO public survey VISTA Variables in the Via Lactea (VVV, ESO programme 179.B-2002).

The present data release contains nearly 600 million stars across the bulge area surveyed by the VVV, and it consists of 196 tiles catalog obtained by performing PSF-fitting photometry of multi-epoch J and K_s VVV images.

Extensive artificial star experiments conducted on all 3912 images allowed to properly assess the completeness and accuracy of the photometric measurements.

With a limiting magnitudes K_s~20 and J~21, this new photometric compilation allows to characterize the evolved and un-evolved stellar population of the Milky Way bulge over most its extension.

A detailed description of the data reduction and catalogs construction is provided in Surot et al. 2019, A&A, 2019arXiv190701972S (hereafter paper II).

In particular, the red clump stellar population is properly sampled with a photometric completeness ranging from nearly 100% to 70% throughout the VVV bulge area, with the exception of the innermost field close to the Galactic Center where the completeness drops to 50%. The photometry is accurate and deep enough to sample the old main sequence turnoff across the whole outer bulge region (i.e. $|b| \geq 3.5^\circ$) with over 50% completeness, hence enabling studies of stellar ages, and star formation history reconstruction based on synthetic CMD-fitting techniques (e.g. Surot et al. 2019, A&A, 623,168S, paper I).

Overview of Observations

We use a combination of J and K_s band VVV observations of bulge fields collected with the wide field near-IR imager VIRCAM mounted at the VISTA 4-m telescope at the ESO Paranal Observatory.

VIRCAM is equipped with a mosaic of 16 detectors with gaps between the detectors of about 90% of the chip size along the X-direction, and 42.5% along Y.

The average pixel scale of the detectors is 0.339", with percent-level variations across the whole detectors ensemble, resulting in each detector covering ~ 133 arcmin² on the sky.

A single VIRCAM frame (i.e. *pawprint*) consists of 16 single-detector images (SDIs).

The VVV observing strategy was designed to obtain a pair of pawprints jittered by $\sim 20''$ to account for detectors bad cosmetics, at 6 different positions. The combination of the paired jittered pawprints is referred to as stacked pawprint.

The offsets pattern between the 6 positions was properly defined in order to get a nearly homogeneous sky coverage of $\sim 1.5^\circ \times 1.2^\circ$, the so-called *tile*.

In summary, a single tile is composed of 16×6 SDIs (i.e. a stacked pawprint $\times 6$ positions), per epoch, per filter.

The exposure time per pawprint and epoch was only 4 sec for K_s and 2×6 sec for J. With this strategy almost every pixel within a tile gets exposed at least twice, yielding effective exposure time of 8 sec for K_s and 24 sec for J-band for the stacked pawprints.

However, the overlap areas between stacked pawprints and edges of the tiles had 2-6 times higher exposures causing the noise distribution within a tile to vary strongly with position in the sky. For this reason, we worked on the stacked pawprint images (i.e. average of the two jittered exposures at each pawprint position), rather than using the final tile images.

Figure 1 shows schematically the bulge area covered by the observations together with the official VVV tiles numbering, which has been adopted for this release as well.

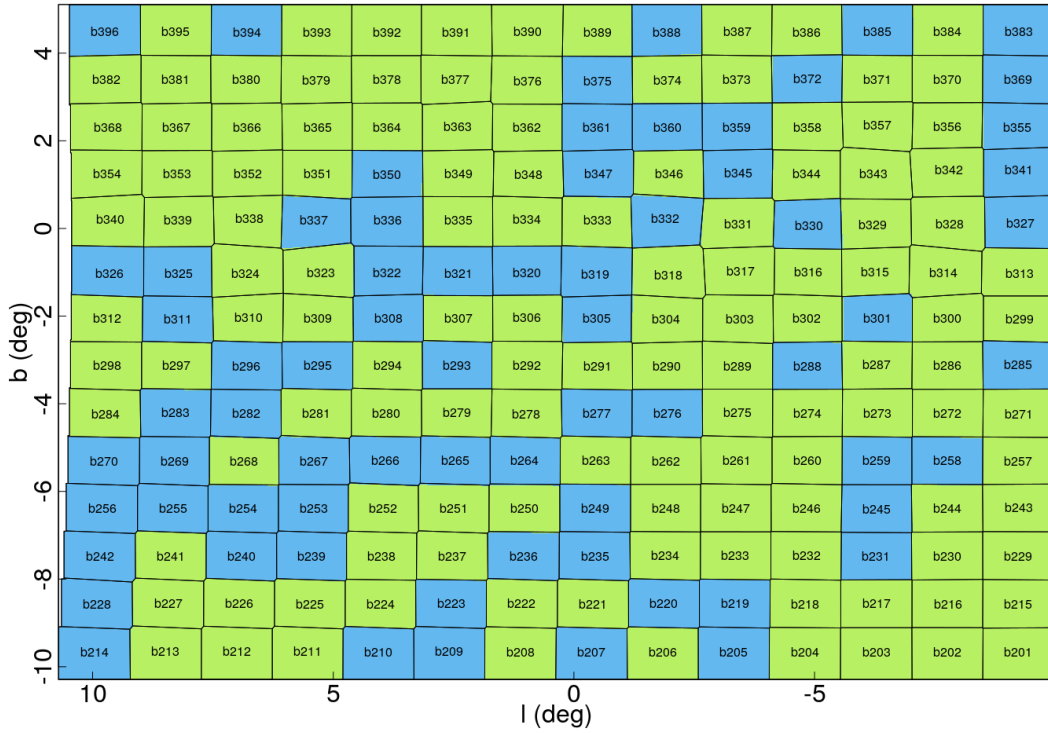


Figure 1: VVV survey bulge area (319.32 deg^2) and tile numbering. The color code refers to the number of epochs used to construct the photometric catalog of each tile (green for 2 epochs and blue for 1 epoch).

Tiles for which 2 epochs in J and K_s have been used are highlighted in green, whereas those in blue have been obtained by using 1 epoch only. The average image quality of the selected images is $0.75'' \pm 0.1$ and $0.54'' \pm 0.04^1$ for J and K_s bands, respectively.

Release Content

This release comprises J and K_s photometric catalog for 196 tiles covering a continuous total area of 319.23 deg^2 around the Galactic Center (see Fig. 1).

Each tile catalog provides a homogenous sky coverage of $1.5^\circ \times 1.2^\circ$, and it contains all stars detected within the tile area in both bands. In other words, there is no single band source detection. Tile centers given in Equatorial (RA, DEC) and Galactic (l, b) coordinates, together with the total number of detected sources are listed in Table 1.

The volume of the photometric global set amounts to $\sim 98.2 \text{ Gb}$.

Photometric catalogs are released individually per tile, and within a given tile the detected sources ID is unique. However, because the tiling strategy adopted by the VVV to survey the bulge leads to $\sim 10\%$ of overlap between adjacent tiles (see Saito et al. 2012, A&A, 537, A107 for further details), catalog of adjacent tiles contains multiple sources in common.

In other words, should multiple adjacent tiles be used together a cross-correlation between the photometric catalogs should be performed in order to account for the stars present in the tile overlapping regions.

¹ Close to the instrumental PSF size, thus the best IQ that VIRCAM can deliver.

Table 1: Summary of photometric catalogs release: tile name, Equatorial and Galactic coordinates center, number of detected sources, and volume of the data in megabytes

| Tile | RA | DEC | l° | b° | No. stars | Mb |
|------|-------------------|--------------------|-------|-------|-----------|--------|
| b201 | 271.096626515 | -41.74643904 | -9.25 | -9.69 | 1399123 | 223.88 |
| b202 | 271.9962108375 | -40.4527784325 | -7.77 | -9.69 | 1382993 | 221.30 |
| b203 | 272.8682449775 | -39.16153244 | -6.29 | -9.69 | 1574440 | 251.93 |
| b204 | 273.7170717775 | -37.8625489325 | -4.81 | -9.69 | 1635620 | 261.72 |
| b205 | 274.54207927 | -36.560972725 | -3.33 | -9.69 | 1087760 | 174.06 |
| b206 | 275.348043395 | -35.260822585 | -1.86 | -9.69 | 1643781 | 263.03 |
| b207 | 276.13420703 | -33.95391527 | -0.38 | -9.69 | 1331178 | 213.01 |
| b208 | 276.9042469875 | -32.64700201 | 1.1 | -9.69 | 1774039 | 283.87 |
| b209 | 277.65891268 | -31.341634385 | 2.57 | -9.69 | 1548021 | 247.70 |
| b210 | 278.39781895 | -30.030076665 | 4.05 | -9.69 | 1468706 | 235.01 |
| b211 | 279.124877385 | -28.7145328325 | 5.53 | -9.69 | 1843252 | 294.94 |
| b212 | 279.8406837975 | -27.4018782275 | 7.01 | -9.69 | 1739410 | 278.33 |
| b213 | 280.5457774375 | -26.087971275 | 8.49 | -9.69 | 1695746 | 271.34 |
| b214 | 281.241071 | -24.775128735 | 9.97 | -9.69 | 1334366 | 213.52 |
| b215 | 269.81238117 | -41.23021878500001 | -9.25 | -8.6 | 1585924 | 253.77 |
| b216 | 270.7296745725 | -39.949025245 | -7.78 | -8.6 | 1681644 | 269.08 |
| b217 | 271.6194471625 | -38.66364486000001 | -6.3 | -8.6 | 1919827 | 307.19 |
| b218 | 272.4823070875 | -37.3740835175 | -4.83 | -8.6 | 2024957 | 324.01 |
| b219 | 273.324831385 | -36.085544475 | -3.36 | -8.6 | 1734779 | 277.58 |
| b220 | 274.1447825 | -34.79020461499999 | -1.88 | -8.6 | 1802673 | 288.45 |
| b221 | 274.9453387675 | -33.49187199 | -0.41 | -8.6 | 2137234 | 341.98 |
| b222 | 275.7283427875 | -32.1890065575 | 1.07 | -8.6 | 2207425 | 353.21 |
| b223 | 276.49612619 | -30.891827025 | 2.54 | -8.6 | 1976133 | 316.20 |
| b224 | 277.2469655 | -29.58246751 | 4.01 | -8.6 | 2230271 | 356.86 |
| b225 | 277.98558445 | -28.2758280375 | 5.49 | -8.6 | 2248867 | 359.84 |
| b226 | 278.710901795 | -26.9688156825 | 6.96 | -8.6 | 2234908 | 357.61 |
| b227 | 279.426869435 | -25.660350265 | 8.43 | -8.6 | 2061087 | 329.80 |
| b228 | 280.1311742300001 | -24.350671485 | 9.91 | -8.6 | 1491003 | 238.58 |
| b229 | 268.54815143 | -40.6966028175 | -9.25 | -7.5 | 1733738 | 277.42 |
| b230 | 269.48129753 | -39.42623865 | -7.78 | -7.5 | 2186654 | 349.88 |
| b231 | 270.387204525 | -38.15303505 | -6.31 | -7.51 | 1931866 | 309.12 |
| b232 | 271.26689484 | -36.871352935 | -4.84 | -7.5 | 2658841 | 425.44 |
| b233 | 272.1227260625 | -35.59058018 | -3.37 | -7.51 | 2816357 | 450.64 |
| b234 | 272.9570229975 | -34.30131579 | -1.9 | -7.5 | 2885889 | 461.76 |
| b235 | 273.772109685 | -33.01075216 | -0.43 | -7.5 | 2501685 | 400.29 |
| b236 | 274.566987445 | -31.717538505 | 1.04 | -7.5 | 2222797 | 355.67 |
| b237 | 275.34594763 | -30.42279558 | 2.51 | -7.5 | 2969227 | 475.10 |
| b238 | 276.1095007475 | -29.1245937675 | 3.98 | -7.5 | 3077436 | 492.41 |
| b239 | 276.858674415 | -27.8272985 | 5.45 | -7.51 | 2612029 | 417.94 |
| b240 | 277.59517793 | -26.525395975 | 6.91 | -7.51 | 2514074 | 402.27 |
| b241 | 278.3193918825 | -25.21897972 | 8.39 | -7.5 | 2595791 | 415.35 |
| b242 | 279.03355303 | -23.917378275 | 9.85 | -7.51 | 2164610 | 346.36 |
| b243 | 267.3038051925 | -40.1527212 | -9.25 | -6.41 | 1959829 | 313.60 |
| b244 | 268.252591075 | -38.893955665 | -7.79 | -6.41 | 2625376 | 420.08 |
| b245 | 269.17298268 | -37.62950486 | -6.32 | -6.41 | 2364926 | 378.41 |

| Tile | RA | DEC | l° | b° | No. stars | Mb |
|------|----------------|--------------------|-------|-------|-----------|--------|
| b246 | 270.0673356425 | -36.356047735 | -4.85 | -6.41 | 3303155 | 528.53 |
| b247 | 270.937096225 | -35.08215819500001 | -3.39 | -6.41 | 3367866 | 538.88 |
| b248 | 271.78522077 | -33.8018483875 | -1.92 | -6.41 | 3425851 | 548.16 |
| b249 | 272.611924815 | -32.518787925 | -0.45 | -6.41 | 2728265 | 436.54 |
| b250 | 273.41960637 | -31.23322226 | 1.01 | -6.41 | 3261585 | 521.88 |
| b251 | 274.21001215 | -29.94409449 | 2.48 | -6.41 | 3572046 | 571.55 |
| b252 | 274.9834702875 | -28.65199803 | 3.95 | -6.41 | 3455322 | 552.87 |
| b253 | 275.743732895 | -27.36098376 | 5.41 | -6.41 | 3105875 | 496.96 |
| b254 | 276.490129155 | -26.064386945 | 6.88 | -6.41 | 3035178 | 485.65 |
| b255 | 277.223377315 | -24.76668694 | 8.34 | -6.41 | 2847620 | 455.64 |
| b256 | 277.946482885 | -23.46636283 | 9.81 | -6.41 | 2641608 | 422.68 |
| b257 | 266.080124875 | -39.597070815 | -9.26 | -5.32 | 2900681 | 464.13 |
| b258 | 267.04357882 | -38.345909405 | -7.79 | -5.32 | 2643730 | 423.01 |
| b259 | 267.9786165 | -37.0882039 | -6.33 | -5.32 | 2994619 | 479.16 |
| b260 | 268.8862337925 | -35.826253075 | -4.86 | -5.32 | 3726389 | 596.24 |
| b261 | 269.7684422575 | -34.55954398 | -3.4 | -5.32 | 3812760 | 610.06 |
| b262 | 270.627662265 | -33.2881590075 | -1.93 | -5.32 | 3653118 | 584.52 |
| b263 | 271.46575862 | -32.01440112 | -0.47 | -5.32 | 3550876 | 568.16 |
| b264 | 272.285943325 | -30.737700995 | 0.99 | -5.32 | 3234889 | 517.60 |
| b265 | 273.08714618 | -29.45148172 | 2.46 | -5.32 | 3584437 | 573.53 |
| b266 | 273.87198001 | -28.168717535 | 3.92 | -5.32 | 3379801 | 540.79 |
| b267 | 274.640228955 | -26.88175775 | 5.38 | -5.32 | 3597268 | 575.58 |
| b268 | 275.3960483575 | -25.58816908 | 6.85 | -5.32 | 2881015 | 460.98 |
| b269 | 276.139204335 | -24.298130335 | 8.31 | -5.32 | 2737636 | 438.04 |
| b270 | 276.87068901 | -23.00180731 | 9.78 | -5.32 | 3062617 | 490.04 |
| b271 | 264.876472155 | -39.02781872 | -9.26 | -4.23 | 2886107 | 461.80 |
| b272 | 265.8537316375 | -37.78846127 | -7.8 | -4.23 | 2894420 | 463.13 |
| b273 | 266.80102959 | -36.538860125 | -6.33 | -4.23 | 3352879 | 536.48 |
| b274 | 267.7213872625 | -35.28770173 | -4.87 | -4.23 | 3847945 | 615.69 |
| b275 | 268.61546182 | -34.027230945 | -3.41 | -4.23 | 4206454 | 673.05 |
| b276 | 269.48604225 | -32.763891665 | -1.95 | -4.23 | 3905045 | 624.83 |
| b277 | 270.337109885 | -31.49350902 | -0.48 | -4.23 | 3521544 | 563.47 |
| b278 | 271.1659834925 | -30.22151198 | 0.98 | -4.23 | 3970862 | 635.36 |
| b279 | 271.97832882 | -28.9459852275 | 2.44 | -4.23 | 4357527 | 697.23 |
| b280 | 272.7721926525 | -27.6662777875 | 3.9 | -4.23 | 4115993 | 658.58 |
| b281 | 273.55147971 | -26.383939075 | 5.36 | -4.23 | 3695493 | 591.30 |
| b282 | 274.315673205 | -25.101341915 | 6.82 | -4.23 | 3175469 | 508.09 |
| b283 | 275.066297015 | -23.81386325 | 8.28 | -4.23 | 3221126 | 515.40 |
| b284 | 275.804747055 | -22.5205694075 | 9.75 | -4.23 | 3536829 | 565.91 |
| b285 | 263.6927735 | -38.4424582 | -9.26 | -3.14 | 2758634 | 441.40 |
| b286 | 264.681687195 | -37.21124137 | -7.8 | -3.14 | 3339493 | 534.34 |
| b287 | 265.64139324 | -35.9730008825 | -6.34 | -3.14 | 3301236 | 528.22 |
| b288 | 266.57347701 | -34.730319825 | -4.88 | -3.14 | 3418025 | 546.90 |
| b289 | 267.4795219925 | -33.480040875 | -3.42 | -3.14 | 4515069 | 722.43 |
| b290 | 268.360392945 | -32.222643155 | -1.96 | -3.14 | 4162211 | 665.97 |
| b291 | 269.2216286075 | -30.963822155 | -0.5 | -3.14 | 4097944 | 655.69 |
| b292 | 270.06160619 | -29.698110935 | 0.96 | -3.14 | 4196605 | 671.48 |
| b293 | 270.88346403 | -28.428850205 | 2.42 | -3.14 | 4426400 | 708.24 |
| b294 | 271.6856843025 | -27.153632175 | 3.89 | -3.14 | 4740866 | 758.56 |
| b295 | 272.473663955 | -25.88019032 | 5.34 | -3.14 | 4399500 | 703.94 |
| b296 | 273.24692026 | -24.60057295 | 6.8 | -3.14 | 2834042 | 453.46 |
| b297 | 274.004776025 | -23.31667674 | 8.27 | -3.14 | 3065617 | 490.52 |
| b298 | 274.750871475 | -22.02868621 | 9.73 | -3.14 | 3690386 | 590.48 |
| b299 | 262.527869075 | -37.84831063750001 | -9.26 | -2.04 | 2683979 | 429.46 |

| Tile | RA | DEC | l° | b° | No. stars | Mb |
|------|-------------------|--------------------|-------|-------|-----------|--------|
| b300 | 263.5284103825 | -36.62650782 | -7.8 | -2.04 | 3298312 | 527.75 |
| b301 | 264.499482705 | -35.399688375 | -6.34 | -2.04 | 3164848 | 506.39 |
| b302 | 265.4413196475 | -34.1614021475 | -4.88 | -2.04 | 4053418 | 648.57 |
| b303 | 266.3580266775 | -32.921314225 | -3.42 | -2.04 | 3764843 | 602.39 |
| b304 | 267.25123642 | -31.672958935 | -1.96 | -2.04 | 3473787 | 555.83 |
| b305 | 268.12186703 | -30.42110389 | -0.5 | -2.05 | 3691971 | 590.73 |
| b306 | 268.9715822525 | -29.1628189775 | 0.95 | -2.05 | 4536525 | 725.87 |
| b307 | 269.800152015 | -27.898054665 | 2.42 | -2.04 | 4514594 | 722.36 |
| b308 | 270.61197033 | -26.631978315 | 3.87 | -2.05 | 4449772 | 711.98 |
| b309 | 271.4074637575 | -25.3585658775 | 5.33 | -2.04 | 4571886 | 731.52 |
| b310 | 272.187652855 | -24.0837928125 | 6.79 | -2.04 | 4103044 | 656.51 |
| b311 | 272.9541109199999 | -22.804972235 | 8.25 | -2.04 | 3050926 | 488.17 |
| b312 | 273.70805141 | -21.5256964 | 9.71 | -2.04 | 3997931 | 639.69 |
| b313 | 261.382298615 | -37.24391925499999 | -9.26 | -0.95 | 2148252 | 343.74 |
| b314 | 262.3930650225 | -36.034396255 | -7.8 | -0.95 | 2108223 | 337.34 |
| b315 | 263.37347681 | -34.81155332500001 | -6.34 | -0.95 | 3428097 | 548.52 |
| b316 | 264.32651586 | -33.586287035 | -4.88 | -0.95 | 3440969 | 550.58 |
| b317 | 265.25249064 | -32.35005511 | -3.42 | -0.95 | 3371572 | 539.47 |
| b318 | 266.154515675 | -31.1072753275 | -1.96 | -0.95 | 3010465 | 481.70 |
| b319 | 267.03430844 | -29.86172368 | -0.5 | -0.95 | 3008121 | 481.32 |
| b320 | 267.893273525 | -28.612990645 | 0.95 | -0.95 | 3849830 | 615.99 |
| b321 | 268.731571265 | -27.35611555 | 2.41 | -0.95 | 3458118 | 553.32 |
| b322 | 269.55157484 | -26.095174385 | 3.87 | -0.95 | 3367557 | 538.83 |
| b323 | 270.3549012375 | -24.8267183475 | 5.33 | -0.95 | 3167142 | 506.76 |
| b324 | 271.1423930925 | -23.556665715 | 6.79 | -0.95 | 3000696 | 480.13 |
| b325 | 271.915837815 | -22.28709229 | 8.24 | -0.95 | 2501609 | 400.28 |
| b326 | 272.67533813 | -21.007476245 | 9.71 | -0.95 | 2862260 | 457.98 |
| b327 | 260.25454224 | -36.62833575 | -9.26 | 0.14 | 1997329 | 319.59 |
| b328 | 261.2749145175 | -35.423882345 | -7.8 | 0.14 | 1902380 | 304.40 |
| b329 | 262.2647381475 | -34.2103160225 | -6.34 | 0.14 | 2640191 | 422.45 |
| b330 | 263.227004165 | -32.991466725 | -4.88 | 0.14 | 2573045 | 411.70 |
| b331 | 264.1626061925 | -31.7650081725 | -3.42 | 0.14 | 2757331 | 441.20 |
| b332 | 265.073082745 | -30.53413907 | -1.97 | 0.14 | 2609702 | 417.57 |
| b333 | 265.9605570575 | -29.294538735 | -0.51 | 0.14 | 2890370 | 462.48 |
| b334 | 266.828550745 | -28.047271825 | 0.95 | 0.14 | 2784575 | 445.55 |
| b335 | 267.6745440025 | -26.797912405 | 2.41 | 0.14 | 2881855 | 461.12 |
| b336 | 268.50325482 | -25.545350325 | 3.87 | 0.14 | 2931994 | 469.14 |
| b337 | 269.314065945 | -24.28218822 | 5.33 | 0.14 | 2542177 | 406.77 |
| b338 | 270.107978105 | -23.01952633 | 6.79 | 0.14 | 3263923 | 522.25 |
| b339 | 270.8878196125 | -21.75147929 | 8.25 | 0.14 | 2603588 | 416.60 |
| b340 | 271.653821395 | -20.48031691 | 9.7 | 0.14 | 3015528 | 482.51 |
| b341 | 259.14740949 | -36.00057174 | -9.26 | 1.23 | 2040777 | 326.54 |
| b342 | 260.1750428825 | -34.8010558425 | -7.8 | 1.23 | 2697211 | 431.58 |

| Tile | RA | DEC | l° | b° | No. stars | Mb |
|------|----------------|---------------------------|-------|------|-----------|--------|
| b343 | 261.174127945 | -33.601186135 | -6.34 | 1.23 | 2958569 | 473.39 |
| b344 | 262.1437597125 | -32.391349495 | -4.88 | 1.23 | 3242736 | 518.86 |
| b345 | 263.08815808 | -31.17300499 | -3.42 | 1.23 | 3220470 | 515.29 |
| b346 | 264.0069761475 | -29.9465938875 | -1.96 | 1.23 | 3898456 | 623.77 |
| b347 | 264.90332736 | -28.71883218 | -0.51 | 1.23 | 4006247 | 641.02 |
| b348 | 265.777677585 | -27.4747167575 | 0.96 | 1.23 | 4265745 | 682.54 |
| b349 | 266.6316796775 | -26.23078997 | 2.42 | 1.23 | 3855901 | 616.97 |
| b350 | 267.466977335 | -24.98066149 | 3.88 | 1.23 | 3548349 | 567.75 |
| b351 | 268.284517055 | -23.7265017175 | 5.33 | 1.23 | 4137241 | 661.98 |
| b352 | 269.085483515 | -22.46723831 | 6.79 | 1.23 | 3830855 | 612.96 |
| b353 | 269.87183907 | -21.207931215 | 8.25 | 1.23 | 3781682 | 605.09 |
| b354 | 270.642864385 | -19.9365160125 | 9.71 | 1.23 | 3274781 | 523.99 |
| b355 | 258.05567572 | -35.35861801999999 | -9.26 | 2.33 | 3008393 | 481.36 |
| b356 | 259.0934529625 | -34.17402126250001 | -7.8 | 2.33 | 3278285 | 524.55 |
| b357 | 260.0993768025 | -32.9805542225 | -6.34 | 2.33 | 3218617 | 515.00 |
| b358 | 261.078499425 | -31.777442075 | -4.88 | 2.33 | 3783094 | 605.32 |
| b359 | 262.02980725 | -30.56781134 | -3.42 | 2.32 | 3961437 | 633.85 |
| b360 | 262.9560354 | -29.34977837 | -1.96 | 2.32 | 4167142 | 666.76 |
| b361 | 263.860176005 | -28.126494695 | -0.5 | 2.32 | 4497397 | 719.60 |
| b362 | 264.74040386 | -26.89258289 | 0.96 | 2.32 | 4066063 | 650.59 |
| b363 | 265.601858415 | -25.65361161 | 2.42 | 2.32 | 4463307 | 714.15 |
| b364 | 266.4428432525 | -24.40843715 | 3.89 | 2.33 | 4516674 | 722.69 |
| b365 | 267.26729221 | -23.16043461 | 5.34 | 2.32 | 4411708 | 705.89 |
| b366 | 268.0744208 | -21.90678517 | 6.81 | 2.32 | 4366395 | 698.64 |
| b367 | 268.8668523425 | -20.6456545475 | 8.27 | 2.33 | 4070848 | 651.36 |
| b368 | 269.6437716975 | -19.382234245 | 9.73 | 2.33 | 3467062 | 554.75 |
| b369 | 256.98236663 | -34.71090621499999 | -9.26 | 3.42 | 2964196 | 474.29 |
| b370 | 258.025956365 | -33.535045425 | -7.79 | 3.42 | 3391629 | 542.68 |
| b371 | 259.039666625 | -32.34912314250001 | -6.33 | 3.42 | 3479262 | 556.70 |
| b372 | 260.025151025 | -31.155412245 | -4.87 | 3.42 | 3311537 | 529.87 |
| b373 | 260.984458485 | -29.9521451375 | -3.41 | 3.42 | 4666841 | 746.72 |
| b374 | 261.9181062725 | -28.7401851225 | -1.95 | 3.42 | 4488339 | 718.16 |
| b375 | 262.82938206 | -27.525370425 | -0.49 | 3.41 | 4085177 | 653.65 |
| b376 | 263.7163968725 | -26.2997133 | 0.97 | 3.42 | 3890613 | 622.52 |
| b377 | 264.5840331375 | -25.063938955 | 2.44 | 3.42 | 3863582 | 618.20 |
| b378 | 265.4311860475 | -23.8244609475 | 3.9 | 3.42 | 4495853 | 719.36 |
| b379 | 266.262136505 | -22.582700005 | 5.36 | 3.42 | 4405261 | 704.86 |
| b380 | 267.07523652 | -21.33310718 | 6.82 | 3.42 | 4211861 | 673.92 |
| b381 | 267.872175545 | -20.07627051 | 8.29 | 3.42 | 3845982 | 615.38 |
| b382 | 268.6545806175 | -18.8171186875 | 9.75 | 3.42 | 3476476 | 556.26 |
| b383 | 255.924922315 | -34.05357911 | -9.26 | 4.51 | 2215181 | 354.45 |
| b384 | 256.9757898475 | -32.8871759825 | -7.79 | 4.51 | 3398751 | 543.82 |
| b385 | 257.99686294 | -31.711335065 | -6.33 | 4.51 | 3112811 | 498.07 |
| b386 | 258.9886823525 | -30.5222607625 | -4.86 | 4.51 | 3353753 | 536.62 |
| b387 | 259.9541399725 | -29.3262589225 | -3.4 | 4.51 | 3555555 | 568.91 |
| b388 | 260.89363018 | -28.12396625 | -1.94 | 4.51 | 2488265 | 398.14 |
| b389 | 261.810652275 | -26.91180359 | -0.47 | 4.51 | 3716884 | 594.72 |
| b390 | 262.731505475 | -25.75686656 | 0.95 | 4.45 | 4219276 | 675.11 |
| b391 | 263.56360295 | -24.48569464 | 2.43 | 4.51 | 4103050 | 656.51 |
| b392 | 264.4172828175 | -23.253962135 | 3.89 | 4.51 | 3750957 | 600.17 |
| b393 | 265.252876465 | -22.0151755 | 5.36 | 4.51 | 3939193 | 630.29 |
| b394 | 266.0709345 | -20.768954745 | 6.82 | 4.51 | 3167416 | 506.81 |
| b395 | 266.8747787425 | -19.52401669 ⁴ | 8.28 | 4.51 | 3527123 | 564.36 |
| b396 | 267.662217555 | -18.26255653 | 9.75 | 4.51 | 2336196 | 373.81 |

Release Notes

The data for the present released uses VVV stacked pawprint images (i.e. 16 SDIs per pawprint image) downloaded from the CASU web page², after the corresponding raw science and calibration frames have been processed by the VISTA data flow system pipeline (v 1.3, and v 1.5 Lewis et al. 2010).

The photometric catalogs have been obtained by using PSF-fitting algorithms on each SDI independently. SDI mosaicking and catalogs photometric calibration were obtained by using the CASU catalogs.

The photometric completeness has been assessed through artificial star experiments, which also allowed to account for the combined effect of systematics and photometric uncertainties.

Data Reduction and Calibration

While the procedure to reduce and calibrate the data is described in detail in Surot et al. 2019, paper II, here we only briefly summarize the main points.

Specifically, each SDI has been processed with an ad-hoc customized pipeline based on DAOPHOT, ALLSTAR (Stetson 1987, PASP, 99, 191), and ALLFRAME (Stetson 1994, PASP, 106, 250) to extract the magnitudes of detected sources.

DAOMASTER (Stetson 1993, IAU Collq. 136, Vol. 136, 2091) was used for subsequent SDI coordinates transformations and internal cross-matching.

The final source magnitudes and positions are given in the VVV photometric and astrometric systems as obtained from the cross-correlation with the CASU catalogs.

The photometric completeness was carried out by adding artificial stars with the same observed PSF onto the SDI paying attention to avoid artificially increasing of the crowding, and then re-processing the modified SDI by using exactly the same procedure adopted on the original SDI sets. Since the catalogs have joint JK_s, that is there is no measure in one filter without the other, the final product is a completeness value that is function of both magnitudes: $p=p(JK_s)$.

In addition to the $p=p(JK_s)$ values, the completeness experiments provide for each source an estimate of the total (i.e. systematic and photometric) uncertainty of the detection. Such estimate, which in the catalogs we refer to as the combined error (i.e. JCOMBERR, KCOMBERR table columns), comes from a 4th-degree polynomial fit to the dispersion of $(m^{\text{in}} - m^{\text{rec}})$, where m^{in} and m^{rec} are the magnitude of the injected and recovered artificial stars, respectively.

By tracing the red clump population across the surveyed area, we have derived a new reddening map (Surot et al. in prep, paper III), whose definition ranges from ~ 2 arcmin (in the outer bulge region) to ~ 10 arcsec (in the most central region), and which has been used to provide for each source detection the corresponding $E(J-K_s)$ color excess (i.e. EJK table column).

In addition, extinction corrected magnitudes (i.e. JCORR, KCORR table columns) have been obtained as follows:

$$J_0 = J - 1.422 \times E(J-K_s)$$

$$K_0 = K_s - 0.422 \times E(J-K_s)$$

Data Quality

Overall, the matches with CASU, leading to the final photometric calibration, have a natural spread of about $\pm(0.02 - 0.03)$ mag for J and usually 50% higher for K_s.

Internal cross-checks on matches between different pawprint images generally lead to a well centered dispersion of magnitude difference, Δm , around 0 with nominal spread within 0.5σ , and with an intrinsic scatter of ± 0.01 mag for J and $\sim 50\%$ higher for K_s.

The completeness, in general, is different from one detector to another, with nominal ± 0.2 variations around $p=0.5$ level, regardless of actual stellar density. Figure 2 provides an overview of

² <http://casu.ast.cam.ac.uk/>

the global photometric completeness as a function of the position within the bulge, in the form of the mean observed K_s magnitudes of stars at $50 \pm 3\%$ completeness level.

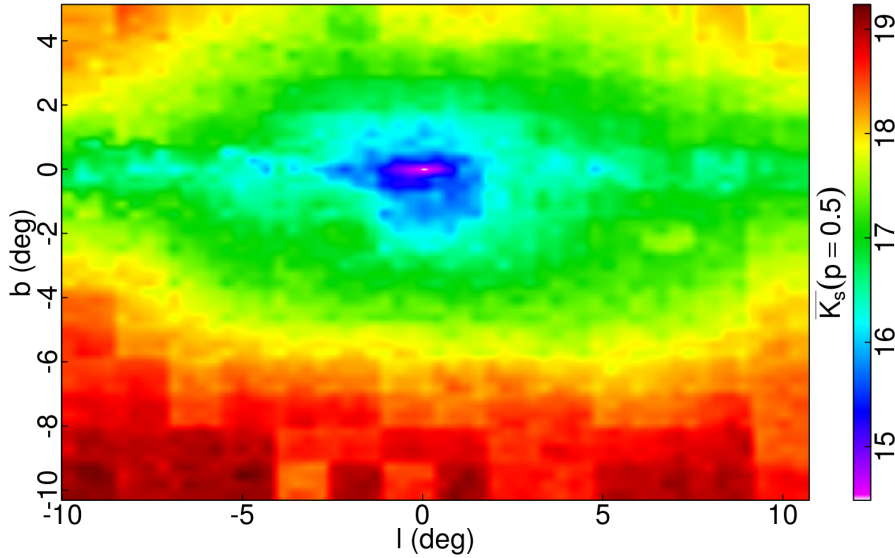


Figure 2: Observed mean K_s magnitude of stars with 50% completeness level ($p=0.50\pm0.03$) across the whole bulge area sampled by the present data release

To properly assess the photometric quality of each catalog one should not exclusively use the tabulated photometric errors (i.e. JERR, KERR table columns), but rather the combined errors. Indeed, as shown in Fig. 6 of paper II, the combined effect of systematics and photometric uncertainties produces a spread in the *recovered* versus *injected* magnitudes that is considerably larger than what one would expect from the photometric error alone.

The provided χ^2 (i.e. CHI table column) and sharpness s (i.e. SHARP table column) values can be additionally used to flag and filter out poor and/or false detections from the catalog. The χ^2 refers to the quality of the star PSF-fitting, and its value should be distributed around 1: i.e. $\chi^2=1$ is a perfect fit, and any value far from 1 is a poor fit. The sharpness provides a measurement of how round ($s = 0$) the detection looks in the image.

A number of possible *quality filters* with different properties, fine-tuned to the characteristics of a given tile can be applied to the provided photometric catalog. Such *quality filters* have all the common effect of removing poor and false detections (i.e. $|\chi^2| \gg 1$, and/or $|s| > 1.5$). The *unlikely stars* appear more evidently as a diffuse feature in the observed CMD, and generally have minimal effect on the global shape of the CMD. Extended sources, such as background distant galaxies, can still pass internal quality cut and therefore appear in the final CMD.

The first quality filter, and the most effective in nominal (i.e. not very crowded) fields, is obtained in the $[J \text{ vs } s]$ plane, where one takes bins in J and use iterative σ -clipping to get rid of the most deviant s stars per J bin. This usually results in removing a small portion of the stars in the derived CMD but targeting mostly outliers in the s distribution.

For the most crowded fields, the former filter is not effective enough because the high star density produces more frequent blending events, which skews the $s(J)$ distribution enough to prevent effective cleaning. For these fields, we recommend the use of the index $[s \times (\chi^2 - 1)]$ on the 3D histogram obtained in the $[K_s \text{ vs } (J-K_s) \text{ vs } s \times (\chi^2 - 1)]$ space, and simply removing the stars within the least populated cubic bins. Removing the lower 1-4% least populated quantiles seems to solve the problem, although with a non-zero removal of *bona fide* stars. However, the removed *true* stars are not particularly concentrated in the CMD, but rather uniformly distributed within the outer CMD contours. When applying the above-mentioned filters to the present release, the resulting limiting magnitude of the photometric compilation is $J \approx 21$ and $K_s \approx 20$.

Finally, we stress here that particular care must be paid to ensure that the adopted *quality filters* (if applied) do not alter the shape of the CMD, and do not remove too many stars in relation to the total number of stars, otherwise a non-negligible correction to the completeness function would become necessary. In fact, stronger selections that might produce thinner/better-defined sequence in the CMD might change significantly the completeness and therefore should be applied with caution when studying star counts.

Known issues

In the available technical documentation at the CASU website³ several known issues regarding the VISTA image quality are listed and described. Most of them are either unavoidable or resolved by the time of the observations, but there is a precaution we thought would be best to take, and that is to not include detectors #4 and #16 in the completeness analysis. Because of bad pixels and some bad rows detector #4 and #16 are affected by variable depth. Although in the case of detector #4 the problem is mild and not always present, we nevertheless decided to exclude it regardless. For detector #16, however, the defect is persistent and too hard to correct effectively.

Data Format

Files Types

There are 196 VVV bulge tiles, each covering a total area on sky of 1.08 deg². For each tile we provide the corresponding photometric catalog together with 4 figures describing its global properties in terms of photometric quality, completeness and extinction. The following table lists the adopted naming convention:

| Name | Type | Property |
|----------------------------|-------------------|--|
| MW-BULGE-PSFPHOT-bXXX.fits | FITS binary table | Photometric catalog |
| bXXXObservedCMD.png | png | Observed [K _s , J-K _s] CMD |
| bXXXCompletenessMap.png | png | [K _s , J-K _s] photometric completeness |
| bXXXDereddenedCMD.png | png | Dereddened [K _{s0} , (J-K _s) ₀] CMD |
| bXXXReddeningMap.png | png | E(J-K _s) extinction map |

Where XXX = 201, 202... 396.

As an example, the 4 figures describing the properties of tile b253 are shown in Fig. 3.

In addition, there are 1950 pawprints, and associated confidence maps and source lists (aperture photometry based). This additional dataset has been processed by the CASU similarly as for the VVV DR1 (see ESO Phase 3 data release description provided by D. Minniti and published on 2011-07-25).

The adopted naming convention is as follows:

Stacked pawprint images: v????????_????_st.fits.fz
Associated confidence map: v????????_????_st_conf.fits.fz
Source list per pawprint: v????????_????_st_cat.fits

Where the name is constructed as observing-date(YYYYMMDD)_number_type.fits(.fz)

³ <http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/known-issues>

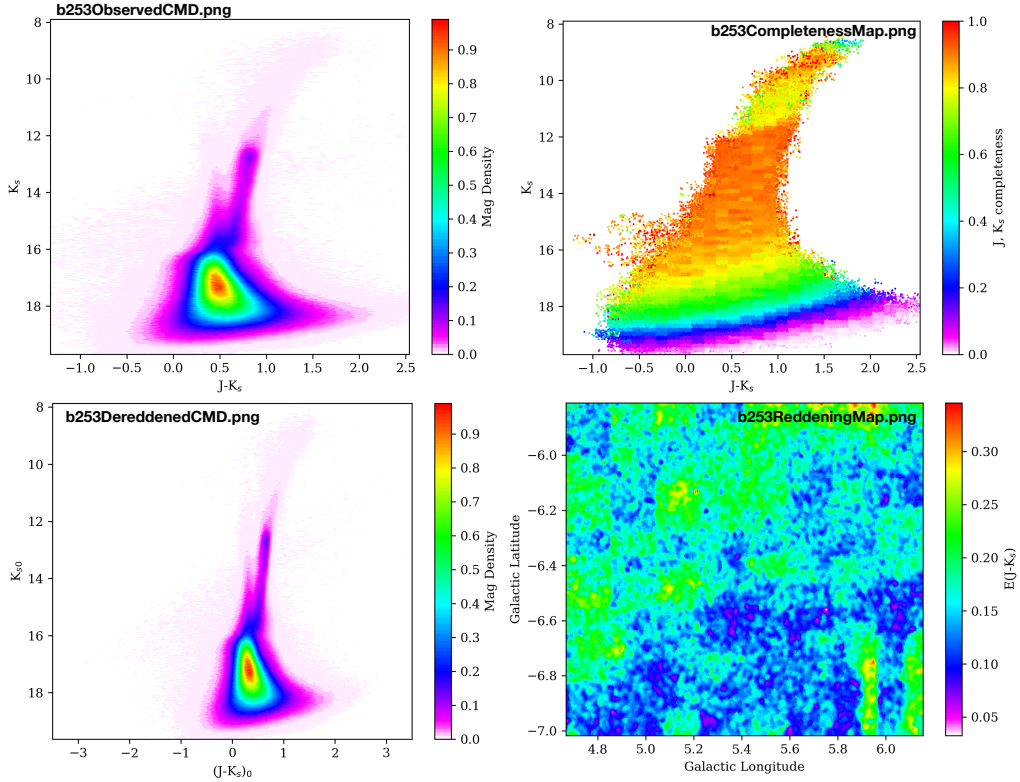


Figure 3: Observed (upper left) Hess diagram of tile b253 located at $l=+5.41^\circ$ and $b=-6.41^\circ$, with the corresponding photometric completeness map (upper right). The reddening map of the region sampled by tile b253 shown in the lower right panel has been used to correct for extinction the Hess diagram shown in the lower left panel.

Catalogue Columns

The photometric catalog of each tile contains 20 columns, whose name, format and description are listed in the table below.

| Col | Name | Description | Format |
|-----|----------|---|--------|
| 1 | SOURCEID | Unique source identifier | D |
| 2 | RA2000 | Right Ascension | D |
| 3 | DEC2000 | Declination | D |
| 4 | L | Galactic Longitude | D |
| 5 | B | Galactic Latitude | D |
| 6 | J | Observed J magnitude | D |
| 7 | JERR | J mag photometric error | D |
| 8 | JCOMBERR | J mag combined error (photometric and systematic) | D |
| 9 | K | Observed K_s magnitude | D |
| 10 | KERR | K_s mag photometric error | D |
| 11 | KCOMBERR | K_s mag combined error (photometric and systematic) | D |
| 12 | P | $p(J, K_s)$ completeness | D |
| 13 | SHARP | Source sharpness | D |
| 14 | CHI | Source Chi square χ^2 | D |
| 15 | EJK | $E(J-K_s)$ color excess | D |
| 16 | EJKERR | Error on the $E(J-K_s)$ color excess | D |
| 17 | JCOR | Dereddened J magnitude | D |
| 18 | KCOR | Dereddened K_s magnitude | D |
| 19 | REP | Number of source detections within the detectors mosaic | D |

| | | | |
|----|----|---|---|
| 20 | FL | Binary (based 2) flag tracing the source provenience within the detector mosaic | K |
|----|----|---|---|

The format refers to the FITS standard notation such as:
D – double floating points (8 bytes), and K – long integer (8 bytes).

Acknowledgements

Any publication making use of this dataset, whether obtained from the ESO archive or via third parties, must include the following acknowledgment:

- "This paper uses data from the MW-BULGE-PSFPHOT compilation (Surot et al. 2019, 2019arXiv190701972S)"
- "Based on data products created from observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme(s) 179.B-2002"

If the access to the ESO Science Archive Facility services was helpful for your research, please include the following acknowledgment:

- "This research has made use of the services of the ESO Science Archive Facility."

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⁴ <https://creativecommons.org/licenses/by/4.0/>