# VVV Survey - ESO Phase 3 <br> VVV Infrared Astrometric Catalogue (VIRAC) v1 release 

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| Data <br> Collection | VVV |
| :--- | :--- |
| Release <br> Number | 4.1 |
| Data Provider <br> Date | Leigh Smith, Philip Lucas et al. |


#### Abstract

We describe the VIRAC proper motion catalogue (Smith et al.2018) based on the VVV survey data, in the form that is provided in the ESO archive. The VVV survey (ESO programme 179.B-2002) spanned a 5 year period (2010-2015) observing a $560 \mathrm{deg}^{2}$ area of the Galactic bulge and the adjacent southern mid-plane. There were tyically ~80 epochs of observation in Ks in the bulge fields and $\sim 55$ epochs in the Galactic disc fields. There were also observations in the ZYJH passbands: the VIRAC product provides ZYJHKs bandmerged magnitudes for each star, wherein the Ks magnitude is a mean value. Although VVV was designed as a variable star survey rather than an astrometric survey, these data enabled relative proper motion measurements with typical precision of $0.67 \mathrm{mas} / \mathrm{yr}$ for bright stars $(11<\mathrm{Ks}<14)$. These data complement the Gaia satellite by providing kinematic information in optically obscured parts of the Galactic plane. The precision is sufficient to study the kinematics of stellar population studies across the Milky Way. Full details of the VIRAC calculation methods for proper motions and parallaxes are described in Smith et al. (2018). This release description describes the details of the proper motion product for 312 million stars. The VIRAC parallax catalogue is not included since that much smaller product was included in the journal paper.


## Overview of Observations

The VISTA Variables in the Via Lactea Survey (VVV, Minniti et al.2010) was conducted with the 4 m VISTA telescope at Carro Paranal using the VIRCAM infrared camera (Sutherland et al.2015). VIRAC version 1 was constructed from all VVV Ks data that were judged to be of sufficient quality to be used in the astrometric calculations. These data taken between January 2010 and October 2015. A single epoch of Z, Y, J and H data is also included in this release: these data were from multi-colour ZY or JHKs OBs that were typically observed in the 2010-2011. A $2^{\text {nd }}$ epoch of multi-colour OBs taken in 2015 was used to fill in some gaps caused by poor data. All the approved VVV data were processed by v1.3 of the CASU pipeline.

VIRCAM has 16 HgCdTe infrared array detectors that are spatially separated from each other. VVV observations used the usual VIRCAM tiling pattern, in which 6 telescope pointings, which we call "pawprints", are used to cover a tile with an area of $1.4 \times 1.1$ degrees. Every part of the tile area is covered by at least 2 pawprints, except for the edges.

VIRAC proper motion solutions are initially calculated using the multi-epoch pawprint catalogues produced by the v1.3 CASU pipeline, rather than the tiles, because the pawprints can be better calibrated for precise astrometry. However, these pawprint-based astrometric products were then combined with overlapping pawprints, using inverse variance weighting, to produce a more precise proper catalogue for each VVV tile. This averaging is also done across tile boundaries, so all parts of the survey footprint except the outer border benefit from averaging across pawprints.

This Phase 3 release of the proper motion data has 348 tile catalogues and a metadata file listing the 348 file names. The total volume is 59 GB . In addition the release includes the 156206 pawprint images from which the CASU catalogues were produced.

The VVV dataset is divided into different Galactic disc and bulge tiles. The tile nomenclature goes from d001 to d152 in the disc, and from b201 to b396 in the bulge. The coordinates of the tile centers are listed in Tables 1 and 2 below, for the bulge and disc, respectively. These Tables contain the tile ID and equatorial coordinates RA and DEC (J2000) in degrees. The map with the field IDs is shown in Figure 1, overlapped on the extinction map from Schlegel et al.(1997).


Figure 1. Maps showing the VVV tile numbers and Galactic coordinates for the bulge and the disc. The disc fields cover the approximate latitude range $-2<b<2^{\circ}$.

## Release Content

TABLE 1: Tile coordinates and number of epochs at end of survey

| ID | RA | Dec | Longitude | Latitude |
| :---: | :---: | :---: | :---: | :---: |
| b201 | $18: 04: 24.77$ | $-41: 44: 35.9$ | 350.753 | -9.689 |
| b202 | $18: 08: 00.58$ | $-40: 27: 11.5$ | 352.231 | -9.689 |
| b203 | $18: 11: 29.83$ | $-39: 09: 34.6$ | 353.709 | -9.688 |
| b204 | $18: 14: 53.35$ | $-37: 51: 45.4$ | 355.187 | -9.689 |
| b205 | $18: 18: 11.50$ | $-36: 33: 44.3$ | 356.665 | -9.689 |
| b206 | $18: 21: 25.06$ | $-35: 15: 56.9$ | 358.138 | -9.692 |
| b207 | $18: 24: 33.43$ | $-33: 57: 14.0$ | 359.622 | -9.688 |
| b208 | $18: 27: 38.04$ | $-32: 38: 48.1$ | 1.099 | -9.688 |
| b209 | $18: 30: 39.00$ | $-31: 20: 15.4$ | 2.577 | -9.689 |
| b210 | $18: 33: 36.43$ | $-30: 01: 37.2$ | 4.055 | -9.688 |
| b211 | $18: 36: 30.94$ | $-28: 42: 54.0$ | 5.533 | -9.689 |
| b212 | $18: 39: 22.54$ | $-27: 24: 06.1$ | 7.011 | -9.688 |
| b213 | $18: 42: 11.74$ | $-26: 05: 16.4$ | 8.489 | -9.689 |
| b214 | $18: 44: 58.75$ | $-24: 46: 40.1$ | 9.963 | -9.691 |
| b215 | $17: 59: 16.27$ | $-41: 13: 36.8$ | 350.751 | -8.596 |
| b216 | $18: 02: 56.38$ | $-39: 56: 49.9$ | 352.225 | -8.596 |
| b217 | $18: 06: 29.88$ | $-38: 39: 45.7$ | 353.698 | -8.596 |
| b218 | $18: 09: 57.17$ | $-37: 22: 27.8$ | 355.172 | -8.596 |
| b219 | $18: 13: 19.09$ | $-36: 04: 57.9$ | 356.646 | -8.596 |
| b220 | $18: 16: 36.24$ | $-34: 47: 28.3$ | 358.117 | -8.599 |
| b221 | $18: 19: 48.00$ | $-33: 29: 24.0$ | 359.593 | -8.596 |
| b222 | $18: 22: 56.21$ | $-32: 11: 46.0$ | 1.061 | -8.600 |
| b223 | $18: 25: 59.90$ | $-30: 53: 13.9$ | 2.540 | -8.596 |
| b224 | $18: 29: 00.24$ | $-29: 34: 58.8$ | 4.014 | -8.596 |
| b225 | $18: 31: 57.79$ | $-28: 16: 49.4$ | 5.485 | -8.599 |
| b226 | $18: 34: 51.98$ | $-26: 58: 32.5$ | 6.956 | -8.600 |
| b227 | $18: 37: 43.22$ | $-25: 39: 38.9$ | 8.435 | -8.596 |
| b228 | $18: 40: 32.38$ | $-24: 21: 03.2$ | 9.909 | -8.596 |
| b229 | $17: 54: 12.86$ | $-40: 41: 49.2$ | 350.749 | -7.504 |
| b230 | $17: 57: 57.26$ | $-39: 25: 49.8$ | 352.216 | -7.507 |
| b231 | $18: 01: 34.46$ | $-38: 09: 29.5$ | 353.683 | -7.508 |
| b232 | $18: 05: 05.30$ | $-36: 52: 20.3$ | 355.159 | -7.504 |
| b233 | $18: 08: 30.67$ | $-35: 35: 19.7$ | 356.629 | -7.504 |
| b234 | $18: 11: 50.81$ | $-34: 18: 06.5$ | 358.098 | -7.504 |
| b235 | $18: 15: 06.17$ | $-33: 00: 40.7$ | 359.569 | -7.504 |
| b236 | $18: 18: 17.11$ | $-31: 43: 05.5$ | 1.038 | -7.504 |
| b237 | $18: 21: 24.00$ | $-30: 25: 21.4$ | 2.508 | -7.504 |
| b238 | $18: 24: 27.02$ | $-29: 07: 27.5$ | 3.978 | -7.504 |
| b239 | $18: 27: 26.86$ | $-27: 49: 27.1$ | 5.448 | -7.504 |
| b240 | $18: 30: 23.83$ | $-26: 31: 33.6$ | 6.915 | -7.507 |
| b241 | $18: 33: 17.42$ | $-25: 13: 08.8$ | 8.388 | -7.504 |
| b242 | $18: 36: 08.74$ | $-23: 54: 51.5$ | 9.858 | -7.504 |
| b243 | $17: 49: 14.33$ | $-40: 09: 10.1$ | 350.747 | -6.412 |
| b244 | $17: 53: 02.06$ | $-38: 53: 33.7$ | 352.214 | -6.412 |
| b245 | $17: 56: 42.70$ | $-37: 37: 34.3$ | 353.681 | -6.411 |
| b246 | $18: 00: 17.47$ | $-36: 21: 21.6$ | 355.147 | -6.412 |
| b247 | $18: 03: 46.15$ | $-35: 04: 51.0$ | 356.614 | -6.412 |
| b248 | $18: 07: 09.48$ | $-33: 48: 06.8$ | 358.081 | -6.412 |
| b249 | $18: 10: 28.22$ | $-32: 31: 22.4$ | 359.545 | -6.415 |
| b250 | $18: 13: 41.62$ | $-31: 13: 58.4$ | 1.014 | -6.412 |
| b2 |  |  |  |  |
| b2 |  |  |  |  |


| b251 | 18:16:51.58 | -29:56:51.4 | 2.478 | 5 |
| :---: | :---: | :---: | :---: | :---: |
| b252 | 18:19:56.33 | -28:37:50.2 | 3.965 | -6.400 |
| b253 | 18:22:59.30 | -27:21:28.4 | 5.414 | -6.412 |
| b254 | 18:25:58.34 | -26:03:42.1 | 6.881 | -6.412 |
| b255 | 18:28:54.34 | -24:45:49.0 | 8.347 | -6.412 |
| b256 | 18:31:47.81 | -23:27:48.6 | 9.814 | -6.412 |
| b257 | 17:44:20.50 | -39:35:44.2 | 350.746 | -5.320 |
| b258 | 17:48:11.76 | -38:20:41.6 | 352.21 | -5.320 |
| b259 | 17:51:55.97 | -37:05:17.2 | 353.674 | -5.320 |
| b260 | 17:55:34.03 | -35:49:48.4 | 355.135 | -5.322 |
| b261 | 17:59:05.57 | -34:33:34.6 | 356.602 | -5.320 |
| b262 | 18:02:31.90 | -33:17:17.2 | 358.066 | -5.320 |
| b263 | 18:05:53.09 | -32:00:46.4 | 359.53 | -5.320 |
| b264 | 18:09:09.96 | -30:44:13.6 | 0.992 | -5.322 |
| b265 | 18:12:22.20 | -29:27:18.7 | 2.455 | -5.323 |
| b266 | 18:15:30.07 | -28:09:57.2 | 3.922 | -5.320 |
| b267 | 18:18:34.68 | -26:52:38.6 | 5.386 | -5.320 |
| b268 | 18:21:35.88 | -25:35:11.8 | 6.85 | -5.319 |
| b269 | 18:24:34.08 | -24:17:37.0 | 8.314 | -5.320 |
| b270 | 18:27:29.54 | -22:59:55.7 | 9.778 | -5.320 |
| b271 | 17:39:31.66 | -39:01:31.1 | 350.745 | -4.228 |
| b272 | 17:43:25.99 | -37:47:04.2 | 352.206 | -4.228 |
| b273 | 17:47:13.73 | -36:32:26.9 | 353.666 | -4.231 |
| b274 | 17:50:54.10 | -35:17:02.4 | 355.13 | - 4.228 |
| b275 | 17:54:28.85 | -34:01:31.1 | 356.592 | -4.228 |
| b276 | 17:57:57.94 | -32:45:42.8 | 358.054 | -4.228 |
| b277 | 18:01:21.89 | -31:29:38.8 | 359.516 | -4.228 |
| b278 | 18:04:40.94 | -30:13:18.5 | 0.978 | -4.227 |
| b279 | 18:07:55.66 | -28:56:44.9 | 2.440 | -4.228 |
| b280 | 18:11:06.19 | -27:39:59.0 | 3.902 | -4.227 |
| b281 | 18:14:13.06 | -26:23:02.4 | 5.364 | -4.228 |
| b282 | 18:17:16.37 | -25:05:55.0 | 6.826 | -4.227 |
| b283 | 18:20:16.56 | -23:48:39.2 | 8.287 | -4.228 |
| b284 | 18:23:13.80 | -22:31:13.8 | 9.749 | -4.227 |
| b285 | 17:34:47.71 | -38:26:47.0 | 350.741 | -3.138 |
| b286 | 17:38:44.71 | -37:12:41.4 | 352.204 | -3.135 |
| b287 | 17:42:34.97 | -35:58:24.6 | 353.664 | -3.136 |
| b288 | 17:46:18.55 | -34:43:43.7 | 355.125 | -3.135 |
| b289 | 17:49:55.99 | -33:28:41.9 | 356.585 | -3.135 |
| b290 | 17:53:27.67 | -32:13:22.4 | 358.045 | -3.135 |
| b291 | 17:56:54.07 | -30:57:43.2 | 359.505 | -3.135 |
| b292 | 18:00:15.70 | -29:41:49.2 | 0.966 | -3.136 |
| b293 | 18:03:32.93 | -28:25:51.2 | 2.424 | -3.138 |
| b294 | 18:06:45.43 | -27:09:14.8 | 3.886 | -3.135 |
| b295 | 18:09:54.41 | -25:52:38.3 | 5.347 | -3.136 |
| b296 | 18:12:59.69 | -24:35:50.6 | 6.807 | -3.135 |
| b297 | 18:16:01.78 | -23:18:52.6 | 8.268 | -3.135 |
| b298 | 18:19:00.72 | -22:01:45.5 | 9.728 | -3.135 |
| b299 | 17:30:08.04 | -37:51:07.2 | 350.74 | -2.046 |
| b300 | 17:34:07.87 | -36:37:36.5 | 352.202 | -2.043 |
| b301 | 17:38:00.94 | -35:24:04.3 | 353.659 | -2.046 |
| b302 | 17:41:46.90 | -34:09:41.4 | 355.121 | -2.043 |
| b303 | 17:45:26.88 | -32:55:09.8 | 356.58 | -2.043 |
| b304 | 17:49:01.30 | -31:40:29.6 | 358.037 | -2.046 |
| b305 | 17:52:29.86 | -30:25:03.4 | 359.499 | -2.043 |
| b306 | 17:55:53.66 | -29:09:32.8 | 0.958 | -2.043 |
| b307 | 17:59:12.86 | -27:53:46.7 | 2.417 | -2.043 |
| b308 | 18:02:27.65 | -26:37:45.1 | 3.876 | -2.043 |
| b309 | 18:05:38.57 | -25:21:28.8 | 5.336 | -2.043 |


| b310 | 18:08:45.82 | -24:05:00.6 | 6.795 | -2.043 |
| :---: | :---: | :---: | :---: | :---: |
| b311 | 18:11:49.68 | -22:48:19.8 | 8.254 | -2.043 |
| b312 | 18:14:50.18 | -21:31:34.0 | 9.712 | -2.043 |
| b313 | 17:25:32.76 | -37:14:32.6 | 350.743 | -0.951 |
| b314 | 17:29:35.30 | -36:01:46.6 | 352.202 | -0.951 |
| b315 | 17:33:30.62 | -34:48:34.6 | 353.66 | -0.951 |
| b316 | 17:37:19.27 | -33:34:56.6 | 355.119 | -0.951 |
| b317 | 17:41:01.49 | -32:20:52.4 | 356.578 | -0.951 |
| b318 | 17:44:38.18 | -31:06:50.8 | 358.031 | -0.955 |
| b319 | 17:48:09.05 | -29:51:40.3 | 359.495 | -0.951 |
| b320 | 17:51:34.97 | -28:36:34.6 | 0.954 | -0.951 |
| b321 | 17:54:56.16 | -27:21:10.4 | 2.412 | -0.951 |
| b322 | 17:58:13.01 | -26:05:30.1 | 3.871 | -0.951 |
| b323 | 18:01:25.82 | -24:49:35.0 | 5.33 | -0.951 |
| b324 | 18:04:34.78 | -23:33:24.5 | 6.789 | -0.951 |
| b325 | 18:07:40.30 | -22:17:01.3 | 8.247 | -0.951 |
| b326 | 18:10:42.89 | -21:00:51.1 | 9.701 | -0.955 |
| b327 | 17:21:02.45 | -36:37:42.6 | 350.74 | 0.139 |
| b328 | 17:25:07.06 | -35:25:19.6 | 352.201 | 0.141 |
| b329 | 17:29:04.68 | -34:12:39.2 | 353.66 | 0.141 |
| b330 | 17:32:55.51 | -32:59:30.1 | 355.119 | 0.141 |
| b331 | 17:36:39.58 | -31:46:10.6 | 356.573 | 0.140 |
| b332 | 17:40:18.53 | -30:31:55.9 | 358.036 | 0.141 |
| b333 | 17:43:51.58 | -29:17:34.4 | 359.495 | 0.141 |
| b334 | 17:47:19.25 | -28:03:06.8 | 0.950 | 0.140 |
| b335 | 17:50:42.70 | -26:47:51.4 | 2.412 | 0.141 |
| b336 | 17:54:01.39 | -25:32:31.6 | 3.871 | 0.141 |
| b337 | 17:57:15.93 | -24:16:56.2 | 5.33 | 0.141 |
| b338 | 18:00:26.54 | -23:01:04.4 | 6.789 | 0.141 |
| b339 | 18:03:33.72 | -21:44:59.6 | 8.247 | 0.141 |
| b340 | 18:06:37.80 | -20:28:54.5 | 9.703 | 0.138 |
| b341 | 17:16:36.05 | -35:59:49.6 | 350.743 | 1.233 |
| b342 | 17:20:43.01 | -34:48:12.6 | 352.202 | 1.233 |
| b343 | 17:24:42.67 | -33:36:03.2 | 353.661 | 1.233 |
| b344 | 17:28:35.52 | -32:23:24.0 | 355.12 | 1.233 |
| b345 | 17:32:22.06 | -31:10:16.3 | 356.58 | 1.233 |
| b346 | 17:36:02.66 | -29:56:44.5 | 358.039 | 1.233 |
| b347 | 17:39:37.82 | -28:43:00.5 | 359.496 | 1.231 |
| b348 | 17:43:07.42 | -27:28:28.6 | 0.958 | 1.233 |
| b349 | 17:46:32.38 | -26:13:50.5 | 2.417 | 1.233 |
| b350 | 17:49:52.70 | -24:58:52.0 | 3.876 | 1.233 |
| b351 | 17:53:09.14 | -23:43:49.1 | 5.333 | 1.231 |
| b352 | 17:56:21.43 | -22:28:16.7 | 6.792 | 1.230 |
| b353 | 17:59:29.74 | -21:12:13.7 | 8.254 | 1.233 |
| b354 | 18:02:34.99 | -19:56:09.6 | 9.714 | 1.233 |
| b355 | 17:12:14.18 | -35:21:31.3 | 350.744 | 2.326 |
| b356 | 17:16:23.06 | -34:10:28.2 | 352.204 | 2.325 |
| b357 | 17:20:24.62 | -32:58:48.7 | 353.664 | 2.326 |
| b358 | 17:24:19.42 | -31:46:38.6 | 355.124 | 2.325 |
| b359 | 17:28:07.75 | -30:33:59.4 | 356.585 | 2.326 |
| b360 | 17:31:50.21 | -29:20:53.5 | 358.045 | 2.325 |
| b361 | 17:35:26.93 | -28:07:21.7 | 359.505 | 2.325 |
| b362 | 17:38:58.51 | -26:53:25.1 | 0.966 | 2.325 |
| b363 | 17:42:25.06 | -25:39:06.5 | 2.426 | 2.326 |
| b364 | 17:45:47.14 | -24:24:29.5 | 3.887 | 2.325 |
| b365 | 17:49:04.75 | -23:09:32.4 | 5.347 | 2.325 |
| b366 | 17:52:18.50 | -21:54:17.3 | 6.807 | 2.325 |
| b367 | 17:55:28.46 | -20:38:44.9 | 8.267 | 2.325 |
| b368 | 17:58:35.09 | -19:22:55.9 | 9.728 | 2.325 |


| 9 | 17:07:56.47 | -34:42:39.6 | 350.744 | 8 |
| :---: | :---: | :---: | :---: | :---: |
| b370 | 17:12:07.25 | -33:32:07.1 | 352.206 | 3.417 |
| b371 | 17:16:10.39 | -32:20:58.6 | 353.668 | 3.418 |
| b372 | 17:20:06.86 | -31:09:18.4 | 355.129 | 3.418 |
| b373 | 17:23:57.19 | -29:57:20.5 | 356.589 | 3.415 |
| b374 | 17:27:41.02 | -28:44:24.0 | 358.054 | 3.418 |
| b375 | 17:31:19.56 | -27:31:17.8 | 359.515 | 3.417 |
| b376 | 17:34:52.54 | -26:17:43.4 | 0.977 | 3.418 |
| b377 | 17:38:20.59 | -25:03:49.7 | 2.439 | 3.418 |
| b378 | 17:41:44.26 | -23:49:28.2 | 3.901 | 3.418 |
| b379 | 17:45:03.46 | -22:34:49.4 | 5.363 | 3.418 |
| b380 | 17:48:18.48 | -21:19:51.6 | 6.825 | 3.418 |
| b381 | 17:51:29.81 | -20:04:35.0 | 8.287 | 3.418 |
| b382 | 17:54:37.66 | -18:49:01.6 | 9.749 | 3.418 |
| b383 | 17:03:42.94 | -34:03:25.2 | 350.743 | 4.507 |
| b384 | 17:07:55.03 | -32:53:12.5 | 352.209 | 4.510 |
| b385 | 17:11:59.88 | -31:42:33.1 | 353.673 | 4.510 |
| b386 | 17:15:57.96 | -30:31:19.9 | 355.137 | 4.510 |
| b387 | 17:19:49.25 | -29:19:48.0 | 356.597 | 4.509 |
| b388 | 17:23:35.30 | -28:07:18.8 | 358.065 | 4.510 |
| b389 | 17:27:15.26 | -26:54:33.5 | 359.530 | 4.510 |
| b390 | 17:30:45.46 | -25:43:04.8 | 0.961 | 4.508 |
| b391 | 17:34:15.58 | -24:29:12.8 | 2.430 | 4.510 |
| b392 | 17:37:40.80 | -23:15:26.6 | 3.891 | 4.507 |
| b393 | 17:41:01.09 | -22:00:52.5 | 5.358 | 4.510 |
| b394 | 17:44:17.50 | -20:46:11.3 | 6.822 | 4.510 |
| b395 | 17:47:30.12 | -19:31:10.9 | 8.286 | 4.510 |
| b396 | 17:50:39.17 | -18:15:53.3 | 9.750 | 4.510 |
| d001 | 11:43:27.74 | -63:31:38.3 | 295.443 | -1.648 |
| d002 | 11:56:15.41 | -63:52:19.9 | 296.902 | -1.648 |
| d003 | 12:09:20.18 | -64:08:44.5 | 298.361 | -1.648 |
| d004 | 12:22:38.06 | -64:20:44.2 | 299.820 | -1.648 |
| d005 | 12:36:05.54 | -64:28:13.4 | 301.279 | -1.648 |
| d006 | 12:49:38.06 | -64:31:10.2 | 302.738 | -1.648 |
| d007 | 13:03:11.21 | -64:29:27.6 | 304.197 | -1.648 |
| d008 | 13:16:40.42 | -64:23:10.7 | 305.656 | -1.648 |
| d009 | 13:30:01.27 | -64:12:21.6 | 307.115 | -1.648 |
| d010 | 13:43:07.58 | -63:57:24.8 | 308.569 | -1.652 |
| d011 | 13:56:02.26 | -63:37:32.7 | 310.033 | -1.648 |
| d012 | 14:08:35.52 | -63:13:49.8 | 311.492 | -1.648 |
| d013 | 14:20:47.04 | -62:46:08.5 | 312.951 | -1.648 |
| d014 | 14:32:34.58 | -62:14:40.9 | 314.410 | -1.648 |
| d015 | 14:43:42.53 | -61:40:42.2 | 315.836 | -1.652 |
| d016 | 14:54:39.50 | -61:02:24.0 | 317.295 | -1.652 |
| d017 | 15:05:10.61 | -60:20:37.0 | 318.759 | -1.648 |
| d018 | 15:15:13.66 | -59:36:15.5 | 320.218 | -1.648 |
| d019 | 15:24:50.21 | -58:49:11.6 | 321.677 | -1.648 |
| d020 | 15:34:00.86 | -57:59:37.7 | 323.136 | -1.648 |
| d021 | 15:42:46.42 | -57:07:46.9 | 324.595 | -1.648 |
| d022 | 15:51:07.87 | -56:13:46.2 | 326.054 | -1.648 |
| d023 | 15:59:06.12 | -55:17:47.8 | 327.513 | -1.648 |
| d024 | 16:06:42.36 | -54:20:02.0 | 328.972 | -1.648 |
| d025 | 16:13:57.77 | -53:20:48.1 | 330.429 | -1.651 |
| d026 | 16:20:53.06 | -52:19:59.5 | 331.885 | -1.652 |
| d027 | 16:27:30.36 | -51:17:13.9 | 333.349 | -1.648 |
| d028 | 16:33:50.04 | -50:13:47.6 | 334.805 | -1.651 |
| d029 | 16:39:53.11 | -49:08:42.0 | 336.267 | -1.648 |
| d030 | 16:45:40.30 | -48:02:59.6 | 337.722 | -1.650 |
| d031 | 16:51:14.42 | -46:55:46.9 | 339.185 | -1.648 |


| d032 | 16:56:33.77 | -45:48:07.9 | 3 | -1.649 |
| :---: | :---: | :---: | :---: | :---: |
| d033 | 17:01:41.93 | -44:39:08.6 | 342.103 | -1.648 |
| d034 | 17:06:37.75 | -43:29:37.0 | 343.562 | -1.648 |
| d035 | 17:11:22.70 | -42:19:22.8 | 345.021 | -1.649 |
| d036 | 17:15:57.60 | -41:08:39.1 | 346.478 | -1.651 |
| d037 | 17:20:22.10 | -39:57:08.3 | 347.935 | -1.650 |
| d038 | 17:24:38.88 | -38:44:46.3 | 349.398 | -1.648 |
| d039 | 11:45:55.20 | -62:28:16.3 | 295.442 | -0.556 |
| d040 | 11:58:16.78 | -62:48:13.0 | 296.901 | -0.556 |
| d041 | 12:10:50.64 | -63:04:13.4 | 298.355 | -0.560 |
| d042 | 12:23:39.43 | -63:15:48.6 | 299.813 | -0.560 |
| d043 | 12:36:36.00 | -63:23:01.7 | 301.271 | -0.560 |
| d044 | 12:49:41.07 | -63:25:37.0 | 302.736 | -0.556 |
| d045 | 13:02:43.30 | -63:23:59.6 | 304.195 | -0.556 |
| d046 | 13:15:41.95 | -63:17:57.8 | 305.653 | -0.556 |
| d047 | 13:28:33.10 | -63:07:34.3 | 307.112 | -0.556 |
| d048 | 13:41:13.61 | -62:52:53.0 | 308.571 | -0.556 |
| d049 | 13:53:39.77 | -62:34:01.2 | 310.030 | -0.556 |
| d050 | 14:05:48.53 | -62:11:10.0 | 311.488 | -0.556 |
| d051 | 14:17:37.68 | -61:44:25.4 | 312.947 | -0.556 |
| d052 | 14:29:05.40 | -61:14:00.2 | 314.405 | -0.556 |
| d053 | 14:40:10.13 | -60:40:06.2 | 315.864 | -0.556 |
| d054 | 14:50:49.58 | -60:03:15.5 | 317.318 | -0.56 |
| d055 | 15:01:07.25 | -59:22:36.8 | 318.781 | -0.556 |
| d056 | 15:10:58.73 | -58:39:26.6 | 320.240 | -0.556 |
| d057 | 15:20:25.78 | -57:53:35.2 | 321.699 | -0.556 |
| d058 | 15:29:28.82 | -57:05:14.3 | 323.157 | -0.556 |
| d059 | 15:38:08.11 | -56:14:31.9 | 324.616 | -0.556 |
| d060 | 15:46:24.77 | -55:21:42.1 | 326.075 | -0.556 |
| d061 | 15:54:19.25 | -54:26:52.1 | 327.533 | -0.556 |
| d062 | 16:01:52.94 | -53:30:13.0 | 328.992 | -0.556 |
| d063 | 16:09:06.70 | -52:31:50.9 | 330.451 | -0.556 |
| d064 | 16:16:01.46 | -51:31:56.3 | 331.909 | -0.556 |
| d065 | 16:22:38.40 | -50:30:35.6 | 333.368 | -0.556 |
| d066 | 16:28:58.06 | -49:28:17.4 | 334.821 | -0.56 |
| d067 | 16:35:02.30 | -48:24:11.9 | 336.283 | -0.559 |
| d068 | 16:40:51.17 | -47:19:19.2 | 337.739 | -0.56 |
| d069 | 16:46:26.50 | -46:13:04.8 | 339.200 | -0.559 |
| d070 | 16:51:48.14 | -45:05:46.0 | 340.661 | -0.556 |
| d071 | 16:56:57.60 | -43:58:13.1 | 342.115 | -0.56 |
| d072 | 17:01:55.61 | -42:49:02.6 | 343.579 | -0.556 |
| d073 | 17:06:42.65 | -41:39:30.6 | 345.037 | -0.556 |
| d074 | 17:11:19.82 | -40:29:29.8 | 346.493 | -0.559 |
| d075 | 17:15:47.26 | -39:18:45.0 | 347.950 | -0.56 |
| d076 | 17:20:06.07 | -38:07:05.5 | 349.411 | -0.559 |
| d077 | 11:48:12.67 | -61:24:46.4 | 295.442 | 0.536 |
| d078 | 12:00:07.22 | -61:44:12.5 | 296.896 | 0.532 |
| d079 | 12:12:21.34 | -61:59:17.2 | 298.360 | 0.536 |
| d080 | 12:24:43.03 | -62:10:26.4 | 299.819 | 0.536 |
| d081 | 12:37:12.10 | -62:17:23.3 | 301.278 | 0.536 |
| d082 | 12:49:45.38 | -62:20:06.0 | 302.737 | 0.536 |
| d083 | 13:02:16.94 | -62:18:36.0 | 304.191 | 0.535 |
| d084 | 13:14:47.59 | -62:12:47.9 | 305.650 | 0.535 |
| d085 | 13:27:11.52 | -62:02:46.3 | 307.109 | 0.535 |
| d086 | 13:39:26.02 | -61:48:36.7 | 308.568 | 0.535 |
| d087 | 13:51:29.40 | -61:30:19.1 | 310.031 | 0.536 |
| d088 | 14:03:15.41 | -61:08:11.4 | 311.490 | 0.536 |
| d089 | 14:14:43.73 | -60:42:19.1 | 312.949 | 0.536 |
| d090 | 14:25:52.27 | -60:12:52.4 | 314.407 | 0.536 |


| d091 | $14: 36: 40.32$ | $-59: 39: 59.8$ | 315.867 | 0.536 |
| :--- | :--- | :--- | :--- | :--- |
| d092 | $14: 47: 04.90$ | $-59: 04: 13.8$ | 317.320 | 0.532 |
| d093 | $14: 57: 09.62$ | $-58: 24: 42.5$ | 318.784 | 0.536 |
| d094 | $15: 06: 50.26$ | $-57: 42: 41.4$ | 320.243 | 0.536 |
| d095 | $15: 16: 06.77$ | $-56: 58: 09.8$ | 321.698 | 0.535 |
| d096 | $15: 25: 02.11$ | $-56: 10: 59.2$ | 323.157 | 0.535 |
| d097 | $15: 33: 35.40$ | $-55: 21: 27.7$ | 324.616 | 0.535 |
| d098 | $15: 41: 48.34$ | $-54: 29: 34.1$ | 326.079 | 0.536 |
| d099 | $15: 49: 39.29$ | $-53: 35: 52.4$ | 327.538 | 0.536 |
| d100 | $15: 57: 10.15$ | $-52: 40: 18.1$ | 328.996 | 0.536 |
| d101 | $16: 04: 22.06$ | $-51: 43: 01.6$ | 330.455 | 0.536 |
| d102 | $16: 11: 15.77$ | $-50: 44: 08.2$ | 331.914 | 0.536 |
| d103 | $16: 17: 52.18$ | $-49: 43: 47.3$ | 333.373 | 0.536 |
| d104 | $16: 24: 11.50$ | $-48: 42: 18.0$ | 334.828 | 0.535 |
| d105 | $16: 30: 16.87$ | $-47: 39: 04.3$ | 336.291 | 0.536 |
| d106 | $16: 36: 06.91$ | $-46: 34: 55.6$ | 337.750 | 0.536 |
| d107 | $16: 41: 43.13$ | $-45: 29: 39.8$ | 339.209 | 0.536 |
| d108 | $16: 47: 06.43$ | $-44: 23: 26.9$ | 340.667 | 0.536 |
| d109 | $16: 52: 17.66$ | $-43: 16: 15.6$ | 342.126 | 0.536 |
| d110 | $16: 57: 17.59$ | $-42: 08: 13.2$ | 343.586 | 0.536 |
| d111 | $17: 02: 06.58$ | $-40: 59: 24.7$ | 345.044 | 0.536 |
| d112 | $17: 06: 45.65$ | $-39: 49: 50.2$ | 346.503 | 0.536 |
| d113 | $17: 11: 15.31$ | $-38: 39: 35.6$ | 347.962 | 0.536 |
| d114 | $17: 15: 36.19$ | $-37: 28: 41.9$ | 349.421 | 0.536 |
| d115 | $11: 50: 21.26$ | $-60: 21: 07.9$ | 295.443 | 1.628 |
| d116 | $12: 01: 56.33$ | $-60: 39: 45.4$ | 296.902 | 1.628 |
| d117 | $12: 13: 43.66$ | $-60: 54: 30.2$ | 298.362 | 1.628 |
| d118 | $12: 25: 40.25$ | $-61: 05: 15.7$ | 299.821 | 1.628 |
| d119 | $12: 37: 43.90$ | $-61: 11: 58.2$ | 301.281 | 1.628 |
| d120 | $12: 49: 51.02$ | $-61: 14: 34.4$ | 302.741 | 1.628 |
| d120 | $12: 49: 51.02$ | $-61: 14: 34.4$ | 302.741 | 1.628 |
| d121 | $13: 01: 58.46$ | $-61: 13: 03.0$ | 304.200 | 1.628 |
| d122 | $13: 14: 00.77$ | $-61: 07: 41.2$ | 305.655 | 1.624 |
| d123 | $13: 26: 01.94$ | $-60: 57: 42.5$ | 307.119 | 1.628 |
| d144 | $16: 31: 33.74$ | $-45: 49: 29.6$ | 337.771 | 1.628 |
| d145 | $16: 37: 10.78$ | $-44: 45: 18.0$ | 339.228 | 1.626 |
| d146 | $16: 42: 35.28$ | $-43: 39: 52.2$ | 340.688 | 1.625 |
| d147 | $16: 47: 47.69$ | $-42: 33: 13.3$ | 342.150 | 1.628 |
| d125 | $13: 49: 31.91$ | $-60: 43: 59.9$ | 308.579 | 1.628 |
| d148 | $16: 52: 49.08$ | $-41: 26: 08.9$ | 343.607 | 1.625 |
| d126 | $14: 00: 53.14$ | $-60: 26: 23.3$ | 310.039 | 1.628 |
| d127 | $-60: 06.7$ | 311.494 | 1.627 |  |
| d139 | $15: 59$ | $16: 06: 43.42$ | $-49: 55: 05.2$ | 331.933 |


| d149 | $16: 57: 39.62$ | $-40: 17: 47.4$ | 345.069 | 1.628 |
| :--- | :--- | :--- | :--- | :--- |
| d150 | $17: 02: 20.45$ | $-39: 08: 52.1$ | 346.529 | 1.628 |
| d151 | $17: 06: 51.91$ | $-37: 59: 15.0$ | 347.988 | 1.628 |
| d152 | $17: 11: 14.57$ | $-36: 48: 57.2$ | 349.448 | 1.628 |

## Release Notes

## Data Reduction and Calibration

The photometric and astrometric calibrations of the VVV/VIRAC v1 product are both derived from the 2MASS Point Source Catalogue. (This will be superseded in version 2, where the Gaia DR2 absolute reference frame will be used.) Users should be aware that VIRAC v1 relative proper motions typically differ from absolute proper motions by up to $6 \mathrm{mas} / \mathrm{yr}$, depending on Galactic coordinates. If absolute motions are required, users can perform a simple approximate correction by matching to Gaia DR2 for the field in question.

The data reduction and calibration procedures for individual epochs are as described in the VVV DR4 release. Since this is an advanced product, the details are not repeated here. All of the VIRAC v1 photometry is aperture photometry with an aperture diameter of $\sqrt{ } 2$ arcsec. The CASU aperture photometry attempts to deblend the fluxes of adjacent sources with overlapping apertures but the results are not as good as profile fitting photometry (which is much more computationally intensive). VIRAC version 2 will employ profile fitting photometry.

The VVV saturation limit is near $\mathrm{Ks}=11 \mathrm{mag}$, with some variation depending on observing conditions and variation between the 16 VIRCAM detectors. However, the centroiding of the CASU v1.3 pipeline remains good for sources as bright as Ks=10 mag. Moreover, a saturation correction was done for bright stars using an aperture corresponding to an annulus with inner diameter of 2 arcsec and outer diameter of 4 arcsec.

## Data Quality

The Quality Control for the Phase 3 data from v1.3 was performed with involvement of ESO and of many scientists from the VVV Survey Science Team. Algorithmic quality control cuts to identify tile images with low zero points (after correcting for the seasonal trend), seeing that was significantly outside specification, or high average ellipticity were applied and the component pawprints were not used in VIRAC. Additional procedures identified a small number of tiles or pawprints where telescope guiding had been lost and fields with blurred or distorted image profiles. In addition we also identified some bad tiles where there was a large variation in the seeing or in the zero points between the 6 constituent pawprints, even though the values for the tile had passed the quality threshold.

For VIRAC v1, additional cuts were made to reject the following:
(i) pawprint catalogues with seeing > 1.2 arcsec in Ks;
(ii) pawprint catalogues in which one or more of the 16 arrays contained fewer than $25 \%$ of the median source counts for the pawprint set. (A pawprint set is defined in VIRAC as a sequence of spatially coincident VVV pawprints, with a tolerance of 30 arcsec);
pawprint catalogues for which the median astrometric residual to the CASU v1.3 pipeline astrometric solution across all 16 arrays is $>0.2$ arcsec.

Following Gaia DR2, comparisons of Gaia absolute proper motions and VIRAC relative proper motions were made for all fields. Gradients in the VIRAC reference frame exist on small scales but these are generally at a level slightly below the measurement uncertainty for individual stars.

## Proper motion quality flags

A "reliable" flag is included as a column in all VIRAC tables. Data with reliable $=1$ correspond to more reliable proper motion solutions based on at least 2 pawprint sets.

High proper motion stars are included in VIRAC, with sensitivity to motions in excess of 10 arcsec per year. All 432 sources with reliable $=1$ and proper motion, $\mu>200 \mathrm{mas} / \mathrm{yr}$ were visually inspected and found to be bona fide high proper motion stars, with one slightly ambiguous exception caused by blending. However, a number of false-positive high proper motion stars with $\mu<200 \mathrm{mas} / \mathrm{yr}$ were independently shown to be present in the very crowded Galactic centre region, caused by blending-related issues (Fernandes et al., 2018AAS...23123715G). Such false-positives typically, but not always, have unusually high values of "ell", the mean Ks ellipticity parameter. Bona fide high proper motion sources can have reliable $=0$, so the reliable flag should be used as a simple way of selecting a less complete but more reliable subsets of measurements from a field. Reliability can be further improved by selecting stars with ell <0.3.

For each star, an error flag value, epm flag, was computed for every proper motion solution that contributes to the final average. (Separate solutions were calculated for each pawprint set before averaging.) epm flag $=0$ indicates no issues with the solution; epm flag $=1$ indicates either a saturated star or a faint star near the detection threshold, such that the median proper motion uncertainty for the pawprint set is over $5 \mathrm{mas} / \mathrm{yr}$ for stars at the given Ks magnitude. epm flag $=2$ indicates an unusually high proper motion uncertainty for the given Ks magnitude, above a threshold defined as median uncertainty plus 3 times the spread (where the spread is defined as max( 0.3 mas/yr, median absolute deviation)). epm flag is additive, so it has a range from 0 to 3 for each proper motion solution.

The present VIRAC product provides proper motions only after averaging across all the solutions for a star (using inverse variance weighting). Therefore we provide information on the epm flag values through the parameters $n \_e p m f \_0, n_{-} e p m f \_1, n_{-} e p m f \_2$ and $n \_e p m f \_3$, which represent the number of proper motion solutions with each of the epm flag values. The number of proper motion solutions for a star is given by the dets parameter. Good (averaged) solutions therefore typically have $n \_e p m f \_0=$ dets.

To be flagged as 'reliable' a source must have a minimum of two proper motion solutions, all solutions must be from different pawprint sets, and epm flag $=0$ for all solutions. This corresponds to dets $\geq 2$, dets $=$ pawprintdets, and $n_{-}$epmf_ $0=$ dets. Here pawprintdets is the number of pawprint sets (typically 1 to 6 ) that contribute to the proper motion average. Typically, dets = pawprintdets but a pawprint set may occasionally have more than one proper motion solution for a star, corresponding to different parts of the time series. E.g. in the case
of a faint star near the detection threshold or a high proper motion star, this occurs if successful cross-matching across multiple observing seasons occurred at a late stage in the calculation.

## Known Issues

The CASU v1.3 pipeline has some imperfections with regard to photometric calibration. The Z and Y calibration is fairly good for fields located $>2^{\circ}$ off the Galactic equator but at present it remains unreliable for fields at latitudes $|\mathrm{b}|<2^{\circ}$. This issue is somewhat improved in the new v1.5 pipeline but this new pipeline has not yet been run on the VVV data. Calibration of all filters in very crowded fields in the inner bulge remains a work in progress.

## Data Format

## File Types

There is one type of catalogue file, in FITS format. E.g. "virac_v1_d001.fits" contains proper motion data for VVV tile d001. Each of the 348 catalogue files contains the provenance data for the corresponding VVV tile, i.e. the list of pawprint images that made up each of the 6 pawprint sets in the tile. Each file has 45 columns. This is slightly more than the 41 columns described in the original VIRAC release available at vvv.herts.ac.uk: 4 columns were added, corresponding to detection flags for the $\mathrm{Z}, \mathrm{Y}, \mathrm{J}$ and H passbands for each stars.

The 156206 pawprint image files from which the proper motion catalogue files were ultimately constructed are provided in compressed FITS format. Each files is nameed by observing date and file number on the night in question. E.g. "v20130325_00036_st.fits.fz". Here the "st" suffix indicates that the pawprint image is a stack of 2 images at 2 positions a few arcsec apart.

Catalogue Columns

| 1 | sourceid | unique source identifier |
| :--- | :--- | :--- |
| 2 | ra | RA from astrometric fit at epoch 2012.0 |
| 3 | de | Dec from astrometric fit at epoch 2012.0 |
| 4 | mag | Ks band magnitude (Vega system). mag and emag are inverse <br> variance weighted averages across overlapping pawprint sets. A <br> magnitude and uncertainty from each pawprint set are the me- <br> dian and median absolute deviation of Ks measurements from <br> all epochs in the pawprint set. |
| 5 | emag | Error on Ks band magnitude. See "mag" description above. |
| 6 | ell | Mean Ks band ellipticity |
| 7 | pm | Total proper motion (mas/yr). The proper motion measurements <br> and their errors are inverse variance weighted averages across <br> their measured values from all pawprint sets. |
| 8 | epm | Error on total proper motion |


| 9 | rapm | Proper motion in RAcosDec |
| :---: | :---: | :---: |
| 10 | erapm | Error on proper motion in RAcosDec |
| 11 | depm | Proper motion in Dec |
| 12 | edepm | Error on proper motion in Dec |
| 13 | epochs | Total number of epochs across all pawprint sets contributing to the measurement. |
| 14 | dets | The number of separate pawprint sets/epoch groups (see pawprintdets) in which the source was detected. For sources detected in only 1 tile, there may be up to 6 pawprint sets (more typically 2). Faint sources or high proper motion sources can occasionally have more than 1 det (i.e. multiple epoch groups) within a pawprint set if they are not matched between consecutive observing seasons until a late stage of the calculation. |
| 15 | stellardets | The number of pawprint sets in which the modal morphological classification of the source was stellar. |
| 16 | pawprintdets | the number of separate pawprint sets in which a source was detected. Technically 'dets' can be greater than this value where e.g. a high proper motion or faint source was not matched between consecutive observing seasons until a late stage of the calculation. |
| 17 | n_epmf_0 | Number of pawprint sets with proper motion error flag '0' |
| 18 | n_epmf_1 | Number of pawprint sets with proper motion error flag ' 1 ' |
| 29 | n_epmf_2 | Number of pawprint sets with proper motion error flag '2' |
| 20 | n_epmf_3 | Number of pawprint sets with proper motion error flag ' 3 ' |
| 21 | reliable | Reliability flag for proper motion: ' 1 ' is more reliable, ' 0 ' is less reliable. This is a combination of dets $>=2$, dets=pawprintdets, and no proper motion error flags in any pawprint sets ( $\mathrm{n} \_$epmf_ $0=$ dets) |
| 22 | Zmag | VVV DR4 Z band magnitude |
| 23 | eZmag | Error on VVV DR4 Z band magnitude |
| 24 | Zell | Ellipticity of Z band detection |
| 25 | Zclass | $Z$ band morphological classification. <br> $1=$ resolved (e.g. blended stars or a galaxy); <br> $0=$ noise; <br> -1 = stellar <br> -2 $=$ probably stellar <br> $-3=$ probable galaxy <br> $-7=$ bad pixel within 2" aperture <br> $-9=$ saturated (saturation correction attempted) |
| 26 | Zsep | Distance to Z band detection (arcsec) |
| 27 | Ymag | VVV DR4 Y band magnitude |
| 28 | eYmag | Error on VVV DR4 Y band magnitude |
| 29 | Yell | Ellipticity of $Y$ band detection |
| 30 | Yclass | Y band morphological classification, see column 25. |
| 31 | Ysep | Distance to Z band detection (arcsec) |
| 32 | Jmag | VVV DR4 J band magnitude |
| 33 | eJmag | Error on VVV DR4 J band magnitude |


| 34 | Jell | Ellipticity of J band detection |
| :--- | :--- | :--- |
| 35 | Jclass | J band morphological classification, see column 25. |
| 36 | Jsep | Distance to Z band detection (arcsec) |
| 37 | Hmag | VVV DR4 H band magnitude |
| 38 | eHmag | Error on VVV DR4 H band magnitude |
| 39 | Hell | Ellipticity of H band detection |
| 40 | Hclass | H band morphological classification, see column 25. |
| 41 | Hsep | Distance to H band detection (arcsec) |
| 42 | Zdetflag | Z detection flag, $1=$ not detected, $2=$ not observed |
| 43 | Ydetflag | Y detection flag, $1=$ not detected, $2=$ not observed |
| 44 | Jdetflag | J detection flag, $1=$ not detected, $2=$ not observed |
| 45 | Hdetflag | H detection flag, $1=$ not detected, $2=$ not observed |

## Acknowledgments

Please cite the VIRAC paper (Smith et al.2018, MNRAS 474, 1826) when using data from this release. Please also use the following statement in your articles: based on data products from VVV Survey observations made with the VISTA telescope at the ESO Paranal Observatory under programme ID 179.B-2002.

## Further Details

More detailed information can be found in the peer-reviewed journal paper:
L. C. Smith, P. W. Lucas, R. Kurtev, R. Smart, D. Minniti, J. Borissova, H.R.A Jones, Z.H. Zhang, F. Marocco, C. Contreras Peña, M. Gromadzki, M.A. Kuhn, J.E. Drew, D.J. Pinfield, L.R. Bedin, 2018, MNRAS, 474, 1826

- the VIRAC web page (https://vvv.herts.ac.uk)
- the CASU webpages http://casu.ast.cam.ac.uk/surveys-projects/vista/
- by contacting Leigh Smith (Ismith [at] ast.cam.ac.uk) or Philip Lucas (p.w.lucas [at] herts.ac.uk)
- the VVV Science Team papers:
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