Milky Way Bulge PSF Photometry

Abstract

The Milky Way Bulge PSF Photometry provides a comprehensive census of the stellar populations in the inner ~ 300 deg^2 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. $|b|\geq3.5^o$) 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 $arcmin^2$ 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 ~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 ~$1.5^o \times 1.2^o$, the so-called *tile*.
In summary, a single tile is composed of 16 × 6 SDIs (i.e. a stacked pawprint × 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.

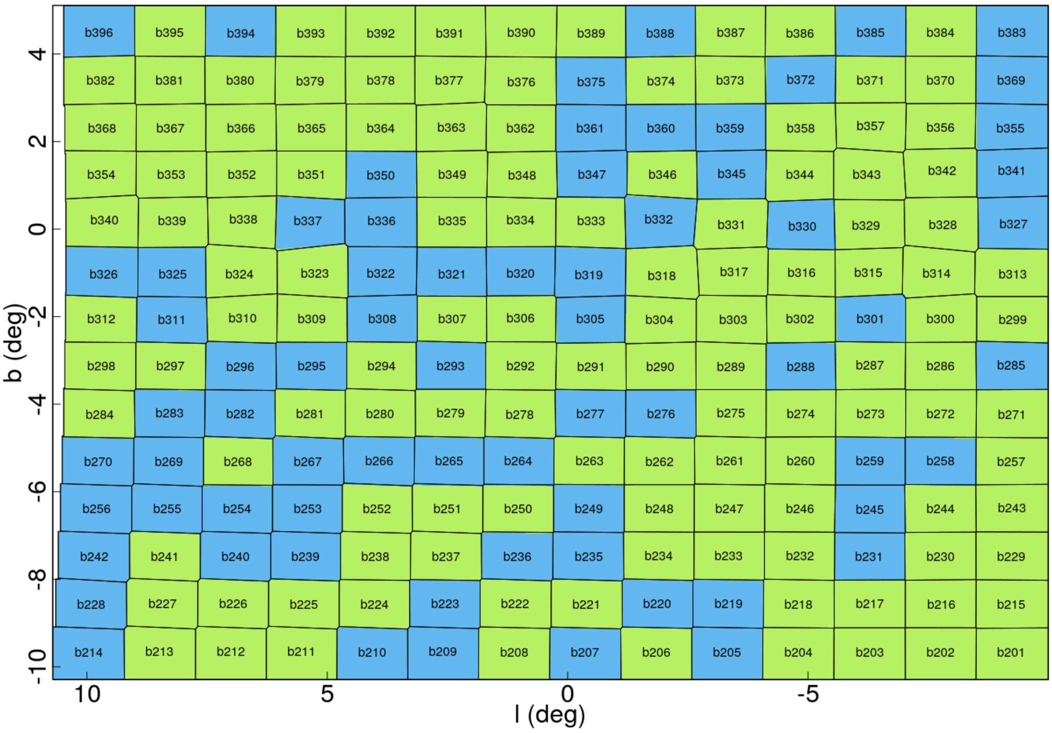

Figure 1: VVV survey bulge area (319.32 deg^2) and tile numbering. The color code refers to the number of epochs used to construct the photometric catalog of each tile (green for 2 epochs and blue for 1 epoch).

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''±0.1 and 0.54''±0.04[1] for J and K_s bands, respectively.

Release Content

This release comprises J and Ks 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 $1.5^o \times 1.2^o$, 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 ~98.2 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 ~ 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	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 page[2], 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 processes 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 reprocessing 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 ($m^{in} - m^{rec}$), 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 be 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 ±(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 ~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 ± 3% completeness level.

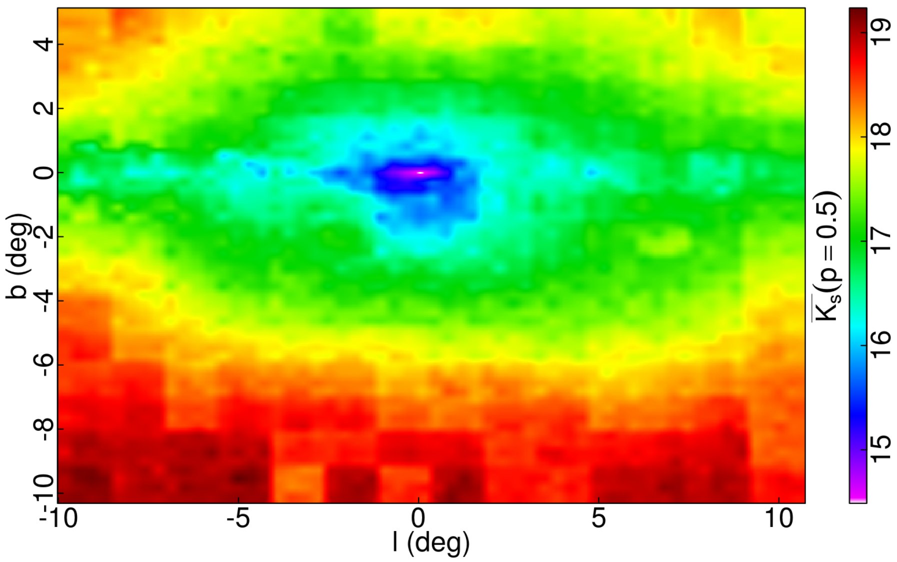

Figure 2: Observed mean Ks magnitude of stars with 50% completeness level (p=0.50±0.03) across the whole bulge area sampled by the present data release

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. $|\chi^2| >> 1$, 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 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 $[K_s$ vs $(J-K_s)$ 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 website[3] 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 deg^2.
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-b*XXX*.fits	FITS binary table	Photometric catalog
b*XXX*ObservedCMD.png	png	Observed [K_s, J-K_s] CMD
b*XXX*CompletenessMap.png	png	[K_s, J-K_s] photometric completeness
b*XXX*DereddenedCMD.png	png	Dereddened [K_{s0}, $(J-K_s)_0$] CMD
b*XXX*ReddeningMap.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

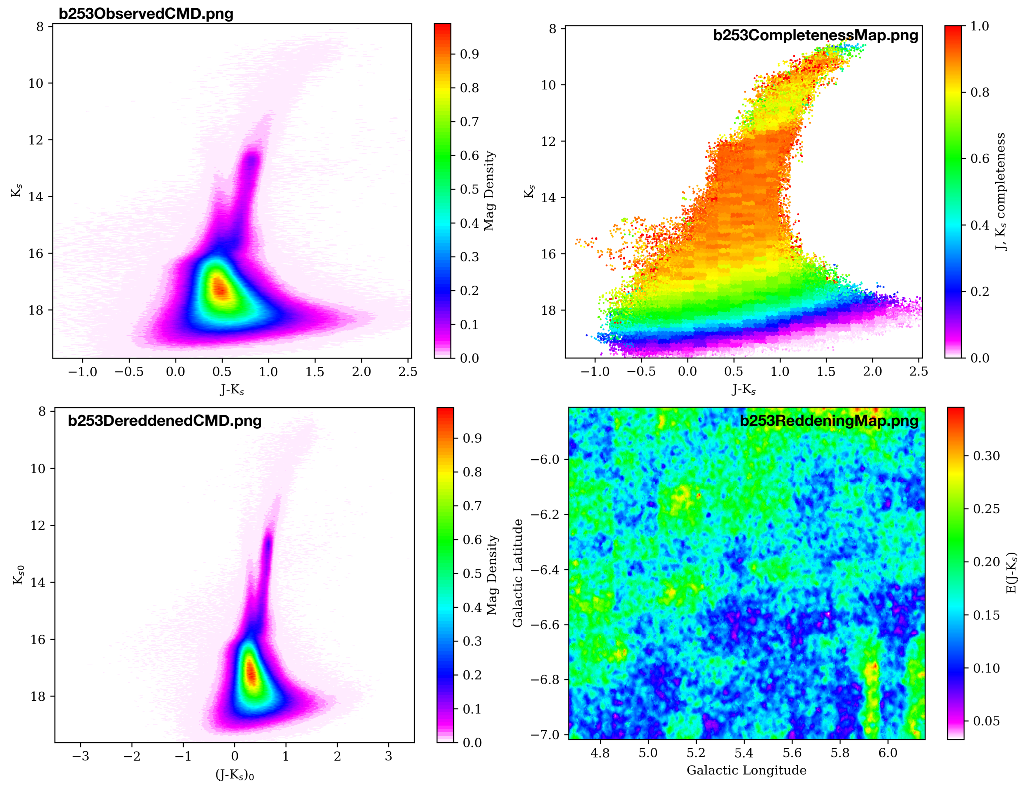

Figure 3: Observed (upper left) Hess diagram of tile b253 located at l=+5.41° and b=-6.41°, with the corresponding photometric completeness map (upper right). The reddening map of the region sampled by tile b253 shown in the lower right panel has been used to correct for extinction the Hess diagram shown 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-Ks) color excess	D
16	EJKERR	Error on the E(J-Ks) 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 you research, please include the following acknowledgment:

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

[4] https://creativecommons.org/licenses/by/4.0/