High-precision astrometry with VVV. I. An independent reduction pipeline for VIRCAM@VISTA

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ABSTRACT
We present a new reduction pipeline for the VIRCAM@VISTA detector and describe the method developed to obtain high-precision astrometry with the VISTA Variables in the Vía Láctea (VVV) data set. We derive an accurate geometric-distortion correction using as calibration field the globular cluster NGC 5139, and showed that we are able to reach a relative astrometric precision of about 8 mas per coordinate per exposure for well-measured stars over a field of view of more than 1 square degree. This geometric-distortion correction is made available to the community. As a test bed, we chose a field centered around the globular cluster NGC 6656 from the VVV archive and computed proper motions for the stars within. With 45 epochs spread over four years, we show that we are able to achieve a precision of 1.4 mas yr\(^{-1}\) and to isolate each population observed in the field (cluster, Bulge and Disk) using proper motions. We used proper-motion-selected field stars to measure the motion difference between Galactic disk and bulge stars. Our proper-motion measurements are consistent with UCAC4 and PPMXL, though our errors are much smaller. Models have still difficulties in reproducing the observations in this highly-reddened Galactic regions.

Key words: Instrumentation: Infrared Detectors / Astrometry / Techniques: Image processing / Galaxy: bulge, disk / Globular clusters: NGC 5139, NGC 6656 / Proper motions

1 INTRODUCTION
The VISTA Variables in the Vía Láctea (VVV) variability campaign started in 2010. Thanks to the VISTA InfraRed Camera (VIRCAM, Dalton et al. 2006; Emerson, McPherson, & Sutherland 2006), mounted at the 4.1 m telescope VISTA (Visible and Infrared Survey Telescope for Astronomy), this ongoing survey is mapping the Galactic bulge and disk to create a 3-D map of the Milky Way (Minniti et al. 2010; Saito et al. 2012). As for many long-term variability surveys, the observing strategy is mainly focused on covering a portion of the sky as large as possible in a single night, scanning the full field of view many times every few days. To this aim, the exposure time of each image has to be short enough in order to achieve the survey specifications. In the VVV survey, the typical exposure time for \(K_s\)-filter images is about 4 s, e.g., a factor 7 smaller than the 30-s threshold set by Platais et al. (2002) and Platais, Wyse, & Zacharias (2006) as the minimum exposure time required to average out the large-scale semi-periodic and correlated atmospheric noise that harms ground-based astrometry. In spite of this, we chose to exploit the astrometric capabilities of this survey that will release to the community a data set with more than one hundred epochs over six years.

In this paper, we present our reduction pipeline for the VIRCAM detectors and the geometric-distortion correction. As an example, we also show a few applications made possible by the astrometric accuracy reached by the VVV data set so far.
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Table 1. List of the VIRCAM@VISTA data used for the astrometric calibration. Each observing block is made by \( N_{\text{step}} \) images, where \( "\text{step}" \) is the dither spacing in arcmin between two consecutive exposures in an observing block. The single-image exposure time is given by the integration time (DIT) multiplied by the total number of individual integrations (NDIT).

| Filter | \( N_{\text{step}} \) | Exposure Time (NDIT\times DIT) | Seeing (arcsec) | Airmass (sec z) |
|--------|----------------|-------------------------------|-----------------|----------------|
| \( J \) | 251.2 | (6\times 10 s) | 0.97-1.42 | 1.026-1.107 |
| \( J \) | 258.5 | (6\times 10 s) | 0.74-1.08 | 1.134-1.198 |

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2 INSTRUMENT AND OBSERVATIONS

VIRCAM is a mosaic of 4\times 4 detectors mounted at the focus of the VISTA 4.1 m telescope. Each detector is a Raytheon VIRGO 2048\times 2048-pixel array and covers \( \sim 694\times 694 \) arcsec\(^2\) on the sky. The average pixel scale is 0.339 pixel\(^{-1}\) (Sutherland et al. 2014). The gaps between the detectors are quite large and correspond to 42.5\% and 90\% of the detector size along the X and Y direction, respectively.

Dithered observations are recommended to self-calibrate the geometric distortion of a detector (e.g., Anderson et al. 2006, Bellini & Bedin 2010, Libralato et al. 2014). However, the standard dither pattern adopted by VVV is not adequate for this purpose. For this reason, a calibration program (Program ID: 488.L-0500(A), PI: Bellini) was approved in 2012. The calibration field is centered on globular cluster NGC 5139 (\( \omega \) Cen). This field was chosen due to its relatively-high star density over more than one square degree.

The field was observed in the \( J \) filter in two runs of 25 images each (Table 1), both organized in an array of 5\times 5 pointings, but with a different dither spacing (Fig. 1). Large dithers were taken to cover the gap between the 16 chips and to allow us to construct a single reference system for all observations. The small dither pattern was obtained to allow independent modeling of the high-frequency residuals of the geometric distortion for each chip.

3 DATA REDUCTION

We developed a reduction package that makes use of the same tools described in Libralato et al. (2014) for the HAWK-I detector. Here, we briefly describe the software, and focus on the few differences between the two works.

One peculiarity of VIRCAM is the striped pattern that affects all the images, both calibration and scientific. These stripes are generated by the IRACE electronics (Sutherland et al. 2014) and change from one exposure to the next. To correct them, we made a FORTRAN routine based on the Cambridge Astronomy Survey Unit (CASU) pipeline correction, that resembles the correction applied by Maybhate et al. (2008) for the WFPC2@HST background streaks. We computed in each image the clipped-median value of the counts in each row, then we took the median of these values and subtracted it from the clipped-median value of each row. These differences represent the corrections to be applied to each row. We did not include bad/warm/hot pixels while computing the median values.

Using archival flat-field images we were not able to completely correct for the pixel-to-pixel sensitivity variation of the detectors, in particular for chip [16] where the very high quantum-efficiency variation on short timescales sometimes makes it impossible to properly apply the flat-field correction. So, we constructed master flat-field frames using the scientific images themselves, masking all bad/warm/hot pixels and those in close proximity of any significant source (stars and galaxies) and considered these purged images as on-sky flat-field images.

First, we applied dark and flat-field corrections to all images. Then, for each chip we computed the median sky value in a 5\times 5 grid and subtracted it according to the table. Then we made a 5\times 5 grid of fully-empirical PSF models for each detector of each exposure, following the prescription given in Anderson et al. (2006). Unlike the procedure given in the original img2psfWFI and img2psf_HAWK-I programs, the finding criteria (minimum flux and minimum separation from brighter stars) to choose the stars that would be used to model the PSF are applied locally and are different in each cell of the grid. This way, we are able to find the most suitable combination of these criteria in each of the 5\times 5 regions of the chip (e.g., if the cluster center is located in a corner of a chip, the minimum separation from the brighter stars in that corner is usually lower than in the opposite corner where the crowding is lower). With an array of PSF models, we are able to measure positions and fluxes for all sources on an image. The final catalogs

\[ \text{http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/known-issues} \]
(one for each chip) contain positions, instrumental magnitudes, and another quantity called quality-of-PSF-fit (QFIT) which represents the absolute fractional error in the PSF-model fit to the star (Anderson et al. 2008). The lower the QFIT, the better is the PSF fit. The QFIT parameter is a useful quantity to discriminate among well-measured and poorly-measured stars. Typically, in ω Cen catalogs we considered bright, unsaturated stars with a well-measured and poorly-measured stars. Typically, in ω Cen catalogs we considered bright, unsaturated stars with a well-measured and poorly-measured stars. These selections allow us to always have at disposal over 100 stars per chip, with an average value of 350 well-measured stars for a corner chip and 1000 stars for a centermost chip.

4 GEOMETRIC-DISTORTION CORRECTION

In the large field of view (FoV) of VIRCAM, the tangential-plane projection effects are not negligible (at one degree from the tangent point this corresponds to more than 0.18 arcsec. ~0.5 VIRCAM pixel). This means the farther from the center, the larger is the difference between the true position and the projected position of a star.

We chose to perform an auto-calibration. By using as a reference system 2MASS Skrutskie et al. (2006) or UCAC4 Zacharias et al. (2013), which are among the most accurate absolute systems, we would have unavoidably ended up limited by their accuracy (of the order of 0.2-0.3 arcsec for 2MASS). Not to mention the non-negligible contribution from the stellar motion between the reference system and our exposures. Furthermore, as stated in Bellini & Bedini (2014), it is difficult to find a distortion-free reference frame with an homogeneous stellar density and luminosity. Therefore we adopted the auto-calibration solution. The basis of the auto-calibration is to observe the same star in as many different locations on the detector as possible and to compute its average position once it is transformed onto a common reference frame. Thanks to the large number and varied spacing of our dither pattern, a given star will be observed in several different locations in the FoV and, as such, the systematic errors in its mean position should average out. This way, the average positions of the stars should provide a reasonable approximation of their true positions in a distortion-free frame (the master frame). We built the master frame by cross-identifying the stars in each single-detector catalog of each exposure. We used conformal transformations (four-parameter linear transformations: rigid shifts in the two coordinates, one rotation, and one change of scale) to bring the stellar positions measured in each image into the reference system of the master frame. In the left panels of Fig. 2 we show the effects of the projection on the master frame. The positional residuals along the X and Y axes show several bumps where two different chips overlap.

When we first examined plots like these, it was clear that the bumps at the boundaries of the chips could be due either to internal distortions within each chip or to errors in placing the chips properly with respect to each other. To ensure that the distortion within each chip was properly accounted for, we independently solve for the geometric distortion of each chip, as done in Libralato et al. (2014). For this specific purpose, we only used the small-dither images where the gaps between the chips are not covered (no detector overlaps with any other detector). The accuracy of the single-chip distortion solution was at the 0.02-pixel level (~7 mas). As an example, in the middle-left panels of Fig. 2 we show the residuals after we applied the single-chip correction to the catalogs and constructed a small-dither-based master frame using only chip #10. As shown in Fig. 2 the small dithers do not allow us to put all the 16 chips in the same reference system since the gaps are so large that the chips do not overlap each other. For this reason we selected one random chip (chip #10) to show that our single-chip distortion solution was good as we wrote above. Then, we applied our single-chip correction to all catalogs and used four-parameter linear transformations to create a new master frame based on large-dither images. Again, the positional-residual bumps were still visible (middle-right panels of Fig. 2). Therefore, these trends in the positional residuals are ascribable to projection effects, which have to be taken into account while cross-identifying the catalogs.

We chose to define a meta reference system in which to properly project all single-chip catalogs and, at the same time, solve for most of the geometric distortion that affects this detector. We proceeded as follows. We used the 2MASS catalog as our initial reference frame. We projected the 2MASS catalog onto a tangent plane centered on ω Cen and followed the prescriptions given in van de Ven et al. (2006) to convert R.A. and Dec. positions into pixel-based coordinates. This is an important step because we imposed the master-frame scale to be exactly equal to 0.339 arcsec per pixel1 for all chips. This value is the average pixel scale declared by Sutherland et al. (2014).

Initially, we cross-identified all stars of each single-chip raw frames with the 2MASS catalog by using six-parameter linear transformations (which also include the deviation from orthogonality and the change of relative scale between the two axes). Then, we located the center of each chip (x,y)=(1024,1024) on the 2MASS-based reference system. Without properly taking into account for the projection effects, the chip-center positions on the 2MASS reference frame depend on their distances from the tangent point (ω Cen center) and on the geometric distortion. To get rid of the first dependency and find the best position of the chip centers, we iteratively de-projected the 2MASS catalog onto the celestial sphere, and then projected it again using as the tangent point the current chip-center position on the 2MASS reference system, in order to compute new, improved transformations. For each chip of each exposure/image we iterated the whole process five times (after the fifth iteration the adjustments were negligible).

Once the chip centers in the 2MASS reference frame converged to fixed positions, in order to build the meta-reference system, we had to impose additional constraints. First, the meta center was defined as the average position of the four centermost chips. The second constraint we imposed is that the Y and X axes of our meta-frame system had to be oriented up and to the right, respectively. For each of the four centermost chips, we computed the angle between the expected meta-frame X axis and the segment that connects the center of the meta frame to the chip center. Then we rotated all chips by the average of the four angles.

For each image we de-projected the 2MASS frame onto the celestial sphere and projected it back on a tangent plane, but this time using as tangent point the meta center computed as described above. Then, we rotated and shifted these 2MASS-based positions according to the other constraint. The final products of this effort are 2MASS-based positions projected on the meta-frame center of each image, rotated and shifted to have the meta center in (x,y)=(0,0). These positions represent the best approximation of the expected distortion-free meta positions.

For each star in common between our catalogs and the
2MASS-based catalog, we have a pair of positional residuals that correspond to the difference between the raw-chip positions and the expected meta-frame positions (given by the stellar positions on the modified 2MASS reference frame). We used both saturated and unsaturated stars with magnitude $J<-12$ and QFIT<0.2. Since 2MASS is a shallow survey, we had to use saturated ($J<-13.4$) stars in order to have an adequate sample size. We divided each chip into a 3×3-grid elements and, in each such element, we defined the grid-point value as the average value of the residuals within. The cells have different sizes, with those close to the edges (for example $512\times512$ pixels on the corners) smaller than the central one ($1024\times1024$ pixels), in order to better model the distortion.
close to the edges. As described in Libralato et al. (2014), for those cells adjoining the detector edges we shifted the grid points to the edge. We built a look-up table of correction for any location of the chip, using a bi-quadratic interpolation among the surrounding four grid points. To avoid extrapolation, our grid points extended to the corners, but this meant that we needed several iterations (each time applying 90% of the suggested correction to the raw positions and computing new residuals) before convergence could be achieved.

After this first part of the correction, we have star positions transformed into a meta reference frame and corrected for geometric distortion. All the stellar positions collected in one meta catalog are those of the stars imaged in one exposure. Therefore, according to the Table 1, we have 50 meta catalogs at our disposal (25 of which are based on large-dither exposures, while the other 25 are based on the small-dither exposures). The astrometric accuracy achieved is about 0.2–0.3 pixel, similar to that of 2MASS. The astrometric quality of our measurements should be ten times better than this, so to further improve our result, we applied an additional table-of-residuals correction to each chip by comparing the positions of the stars as measured in different meta catalogs, thus enabling a precision of ~0.03 pixel per comparison, as follows. For each pair of meta catalogs (hereafter catalogs #1 and #2), we cross-identified all stars in common by using six-parameter linear transformations. We found the meta center of catalog #1 into the reference system of catalog #2 and projected the stellar positions measured in catalog #2 into the tangent plane centered at the center of catalog #1. Then we computed the positional residuals as the difference between the stellar positions in the meta #1 reference system and the positions in the meta #2 reference system, once projected and transformed into the meta #1 reference system. For those meta catalogs obtained from the large-dither images, we compared each of them to the other 49 catalogs, while small-dither catalogs were only compared to the large-dither ones. When we computed the distortion correction for each chip individually, we used only small-dither images. We then applied this correction to large-dither images and looked at the residuals computed by comparing our stellar positions with those of 2MASS. We noticed that the non-linear terms of the distortion over a very large scale were not completely accounted for. Therefore, we chose to compute the positional residuals by comparing only images far enough on the sky from each other. For each chip, we collected all these residuals together and divided them into an array of 11×11 square elements. We assigned to each array element the median value of the residuals within. For any location on the chip, the correction is computed as the bi-linear interpolation between the surroundings four grid points. We iterated five times, computing new residuals and adding the new correction to the previous one.

In summary, the distortion solution of each chip consists of two parts: a 3×3 look-up table of residuals (that is used to compute the correction at any inter-chip location via a bi-quadratic interpolation between the surrounding four grid points), and an additional fine-tuning 11×11 look-up table of residuals (this time using a bi-linear interpolation to compute the correction). The final stellar positions are distortion corrected and projected with respect to the center of the meta catalog. Therefore, each meta catalog is projected into a different tangent plane. It is important to transform all the catalogs into the same tangent plane during the construction of the master frame. In the rightmost panels of Fig. 2 we show the result of our efforts. We applied our distortion correction to the stars in each meta catalog. We used six-parameter linear transformations to bring these corrected positions on the master-frame reference system using the same tangent plane for each catalog. This way, the σ(Radial residuals) improves from ~1.025 pixels (347.3 mas) to 0.023 pixel (7.9 mas).

In Appendix A we show the distortion maps and the positional residuals along the X and Y axes, before and after the correction, for each of the 16 chips of VIRCAM.

With this paper, we release a FORTRAN routine to correct the geometric distortion. It requires the single-chip raw coordinates (\(x_{\text{raw}}, y_{\text{raw}}\)) and the chip number. In output, the code computes (\(x_{\text{corr}}, y_{\text{corr}}\)) coordinates in the meta-frame reference system. The code is available at our group’s web page.

5 APPLICATION: NGC 6656

To test our geometric-distortion correction we computed relative proper motions (PMs) of stars in the field of the globular cluster NGC 6656, \((\alpha, \delta)_{\text{2000.0}} = (18^h36^m23^s9, -23^\circ54'17\arc''1)\) Harris (1996, 2010 edition), using VVV data. We chose this object for its closeness and relatively-high PM with respect to the field objects. We used images taken between 2010 and 2014. We have 12 images in each of the 45 epochs used (except for one epoch for which we have 14 images) in the K_s filter (from 2010 to 2014), while for the J filter there are only 12 images taken in 2010.

We obtained astro-photometric catalogs for each image of each epoch as described in Sect. 3 distortion corrected as described in Sect. 4. The VIRCAM photometry is calibrated by using stars in common with the 2MASS catalog. We applied linear relations between the VVV instrumental magnitudes and the 2MASS magnitudes based on well-measured, unsaturated stars. We replaced the photometry of VVV saturated stars with that of 2MASS.

The adopted reference frame is based on images taken on August 16th 2012 (which have the best available seeing, are the closest to the zenith, and are taken halfway between 2010 and 2014). The covered FoV is about 11×15. We limited our PM analysis to the innermost region of the field, within a radius of 20 arcmin from the cluster center, where there is a significant number of cluster members. We then computed the coefficients of the local transformations to transform the stars’ positions of each image into the reference frame Anderson et al. (2006). Local transformations reduce most of the uncorrected distortion residuals and other systematic effects that could harm our measurements. Indeed, the astrometric accuracy reached in our reference master frame is ~0.08 pixel (27 mas), more than three times larger than that described in Sect. 3 The main reason for this larger uncertainty is that the VVV observations are not taken with an astrometric strategy in mind (see discussion in Sect. 3 and 4). Furthermore, our geometric-distortion correction is an average solution, suited for J-filter images and at a specific epoch. The fact that the positional residuals are three times

\[ \sigma(\text{Radial residual}) = \sqrt{\left(x_{\text{corr}} - x_{\text{master}}\right)^2 + \left(y_{\text{corr}} - y_{\text{master}}\right)^2} / 2, \]

where \((x_j, y_j)\) is the position of the \(i\)-th star of the \(j\)-th image, distortion corrected and transformed into the master-frame reference system, \(x_{\text{corr}}, y_{\text{corr}}\) is the transformation of the \(j\)-th image into the master frame, and \(x_{\text{master}}, y_{\text{master}}\) is the distortion-free (master-frame) position of the \(i\)-th star.

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1. The σ(Radial residuals) is defined as:

\[ \sigma(\text{Radial residual}) = \sqrt{\left(x_{\text{corr}} - x_{\text{master}}\right)^2 + \left(y_{\text{corr}} - y_{\text{master}}\right)^2} / 2, \]

where \((x_j, y_j)\) is the position of the \(i\)-th star of the \(j\)-th image, distortion corrected and transformed into the master-frame reference system. \(x_{\text{corr}}, y_{\text{corr}}\) is the transformation of the \(j\)-th image into the master frame, and \(x_{\text{master}}, y_{\text{master}}\) is the distortion-free (master-frame) position of the \(i\)-th star.

2. http://groups.dfa.unipd.it/ESPG/
Figure 3. Multi-epoch fit of PMs for a field-like ("BULGE") and a cluster-like ("M 22 HB") star. (Top): in panels (a) and (c), the empty circles represent star’s positions at different epochs transformed into the reference master frame, color-coded (as defined in the bottom panels) depending on the time interval relative to the reference epoch (J2012.62423). The master-frame position is represented by the solid black square (surrounded by an ellipse with semi-axes equal to the positional r.m.s. along the X and Y direction); the solid black circle is the expected position of the star at the reference epoch based on the PM fit. In the panel (a), the black arrow shows the ~4-yr displacement of the star. In panel (b) we show the position of the selected stars on the CMD. (Bottom): Motion in Y [panels (d) and (f)] and in X [panels (e) and (g)] as a function of the time from the reference epoch. The black line is the least-squares fit of the PM.

larger also implies that the distortion correction is not stable over time scales of 6 months. The local-transformation approach compensates for these issues.

In our local-transformation approach, we transformed the stellar positions as measured in each image into the reference-frame system using a subset of close-by, likely-cluster member (reference stars) to a given star to compute its linear-transformation coefficients. As such, our PMs are computed relative to the cluster mean motion, and cluster members will end up around the (0,0) location on the vector-point diagram (VPD). At the first iteration we selected the reference stars for the local transformation based on their position on the color-magnitude diagram (CMD). Once PMs were also estimated, we improved our reference-star list by removing all those stars which motion is not consistent with the cluster mean motion.

We computed the stellar displacements as the difference between the transformed single-exposure positions and the master-frame positions. In Fig. 3 we illustrate the multi-epoch PM fit for a Bulge star (left panels) and for a cluster member (right panels). In the top panels of the figure we show the stellar positions transformed into the reference frame, color-coded according to their epoch. In the bottom panels we show the displacements as a function of time (relative to the reference epoch). The black lines are the weighted least-squares fit to the data, where the weight is defined as the square root of stars’ QFIT (with poorly-measured stars’ having less weight). The proper motion along the two directions ($\mu_x$, $\mu_y$) is the slope of the straight lines. The relative PM errors are the formal errors of the least-squares fit. The constant terms $x_0$ and $y_0$

Figure 4. (Left): $K_S$ vs. ($J-K_S$) CMD of the NGC 6656 field. We show only well-measured-PM stars. We split the CMD in nine intervals of one mag each. The gray dashed line sets the average saturation threshold. The saturation level slightly varies within each VIRCAM chip. The variation becomes substantial across the total FoV, and of course from one exposure to the next (because of generally different seeing conditions). (Middle-left): VPDs for each of the corresponding magnitude interval. The mean motion of cluster members is centered at (0,0) in the VPDs. We plotted with red dots the cluster-like stars. The radius for the cluster-member selection (green circle) ranges from ~4.4 mas for stars with 16.5<$K_S$<17.5 to ~4.1 mas for those stars with 8.5<$K_S$<9.5. (Middle-right): Histograms for the $\mu_x \cos \delta$ proper motion distribution. The bin size changes depending on the total number of stars in each magnitude bin. Dual-Gaussian fit in black; individual Gaussians in red and azure are used for cluster and field $\mu_x \cos \delta$ distributions respectively. The field distribution is wider than that of the cluster and contaminates the cluster-member sample in all magnitude bins. (Right): CMD with only cluster-like-motion stars. It is clear that the fainter the magnitude bin, the higher is the field contamination in our sample. The PMs have been corrected for differential-chromatic refraction as described in the text. The PM errors as a function of the $K_S$ magnitude and drew by hand a fiducial line to remove obvious outliers. The cut is more important for faint stars, where PMs are less accurate. We used the same purging method for the stellar QFIT. Furthermore, we kept only those stars measured in at least 50 exposures.
displacement (defined as the 68.27th percentile of the distribution around the median) of bright, unsaturated (13 ≤ K_S ≤ 14) cluster stars in the VPD is of about 1.5 mas yr⁻¹. By subtracting in quadrature the external dispersion of 0.5 mas yr⁻¹, we end up with an external estimate of our PM precision, which is of about 1.4 mas yr⁻¹.

To further test our astrometric accuracy we measured the relative difference between the Bulge and the Disk bulk motion within the same selected VVV field of NGC 6656 (Fig. 6). To this aim, we selected two samples of stars, one from the Disk main sequence and one from the Bulge red giant branch. We considered only Disk (Bulge) stars that in the K_S vs. (J−K_S) CMD are bluer (redder) than the respective fiducial line of the sequence. Furthermore, we considered only those stars with PMs larger than 5 mas yr⁻¹ with respect to the bulk motion of the cluster. We fit a single Gaussian to the histograms of the μ_α cos δ for the Bulge and Disk stars previously selected. We fitted each histogram with a single Gaussian. (Top-right): as on Bottom-left but for the μ_δ.

To test this result, we measured the relative displacement between the Bulge and the Disk components using the motion of the same test stars as measured in the UCAC4 and the PPMXL catalogs. We found a relative displacement of 3.79 ± 0.98 mas yr⁻¹ using UCAC4 and 2.93 ± 1.3 mas yr⁻¹ using PPMXL, which are in agreement with our estimate within the error bars, though our estimate has a smaller uncertainty. We also compared our measured difference between
Bulge and Disk motion with that predicted by the Besançon models (Robin et al. 2003). We simulated both populations in the same field covered by our application. We adopted an exponential trend for photometric and PM errors as function of the magnitude to create a model as close as possible to our data. The major challenge was to take into account for the correct absorption toward the Galactic plane. We used the Bulge Extinction And Metallicity (BEAM, see Gonzalez et al. 2012, 2013) calculator to compute the average extinction in our field. This value, divided by NGC 6656 distance, gives us the dih.\[0.12 \text{ mas yr}^{-1}\]. The difference between Bulge and Disk motion obtained this way is \(1.38 \pm 0.12 \text{ mas yr}^{-1}\). This value is not consistent with our measurements. We performed different simulations varying the absorption coefficients to understand if the absorption law could somehow change the simulated kinematics, but we found the results were about the same. We attribute this significant difference to the difficulty of the Besançon model in simulating the reddening. Galaxy stellar densities and kinematics toward the Galactic Plane where the extinction is high.

5.1 Future perspectives

The VISTA Variables in the Vía Láctea will be completed in 2016 (Hemmel et al. 2014), and the time baseline provided by the uniform VVV data will be about six years. As an example, we combined the VVV images of NGC 6656 and the HAWK-I data previously used by Libralato et al. (2014). Since the HAWK-I images were taken in 2007, we used only the VVV archival images between 2010 and 2013 in order to have approximately the 6 years of time baseline. We computed the PMs as described in the previous section and in Fig. 7 we show the resulting CMDs and VPDs. As expected, with a larger time baseline we are able to completely separate cluster and field stars. This example shows again the great astrometric potential of the full-baseline VVV data. Older epochs (both optical and near-infrared data) are available in the archives, and the proper motions will be an invaluable resource to distinguish the different stellar populations in the Galaxy.

6 CONCLUSIONS

In this paper we present our reduction pipeline for the VIRCAM detector and the geometric-distortion solution based on the J filter. Thanks to our distortion correction and to the adopted dithered observing strategy, we are able to reach a positional residual of \(\sim 8\) mas in each coordinate in each exposure across the entire FoV of VIRCAM. Note that we are talking about relative astrometry. Our absolute astrometry is not as good as the relative one because the linear terms are constrained only with 2MASS.

We release a FORTRAN routine to correct the geometric distortion. For a given position in a single-chip raw frame \((x_{\text{raw}}, y_{\text{raw}})\) and the chip number, the code produces \((x_{\text{corr}}, y_{\text{corr}})\) coordinates in the meta-frame reference system. The code is available at our group’s web page\(^6\). The use of this distortion solution is encouraged regardless of the specific method adopted to measure stellar positions. Each meta catalog is projected into a plane tangential to its center. This offers the best single-catalog, distortion-free positions. Please note that, in order to construct a common reference frame, all meta catalogs should be instead projected into the same tangent plane (see Sect. 5).

As a test bed of the astrometric accuracy reached by our geometric-distortion correction, we applied our reduction pipeline to a set of VVV archival images. We chose a field centered on the globular cluster NGC 6656 and we computed the relative proper motion of the NGC 6656 and Galactic bulge and disk stars, as well as the individual motion of each star in the field. We noticed that our astrometric accuracy is worse (\(\sim 0.08\) pixel) using VVV data. Our geometric-distortion correction is an average solution and the distortion is not entirely stable. However, by starting with a good average solution, local transformations (used to compute the proper motions) can be used to efficiently achieve optimal precision even with this type of data. We demonstrate that we are able to separate cluster and background/foreground field stars with a time baseline of only four years. The cluster stars, in the cleaned CMD, can be used for the study of the stellar populations of NGC 6656. We also showed that the field stars, in the direction of NGC 6656, are of great use, e.g., to separate (and study) the proper motions of the Galactic disk and bulge components. We demonstrated that our results are consistent with what can be obtained using UCAC4 and PPMXL catalogs, though our measurements have a much smaller error. Galactic models fail to reproduce the observations, likely be-

\(^6\) http://groups.dfa.unipd.it/ESPG/
cause of the difficulties to reproduce the reddening and kinematics towards the Galactic bulge.

With the images analyzed in this paper and a time baseline of about four years, we obtained a typical astrometric precision of $1.4\,\text{mas yr}^{-1}$ for bright, unsaturated well-measured stars. This value corresponds to $\sim 21\,\text{km s}^{-1}$ at the distance of NGC 6656 (3.2 kpc from Harris 1996, 2010 edition), or $\sim 53\,\text{km s}^{-1}$ at 8 kpc (a reference distance for the Bulge). At the end of the VVV survey, the total time baseline will be of about six years, thus further increasing the final achievable PM accuracy. The use of older, archive, optical and near-infrared data will further enhance the proper-motion capability of the VVV survey. The astrometric capability of this survey is complementary to GAIA, in particular in the most crowded and heavily-absorbed regions not reachable by GAIA, and to study objects below its magnitude limit ($G \sim 20$).

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APPENDIX A: GEOMETRIC DISTORTION MAPS

In this appendix we show the distortion maps (Fig. A1) and the positional residuals (Fig. A2 and Fig. A3) for the 16 chips of VIRCAM before and after we applied the distortion solution described in Sect. 4.
Figure A1. (Left): Residual trends for the 16 chips when we use uncorrected stellar positions. The labels on the top-right corner of each box represent the chip number. The size of the residual vectors is magnified by a factor of 250. Some degree of distortion is clearly visible in the outermost chips. (Right): Residuals after our distortion correction is applied. The size of the residual vectors is now magnified by a factor 5000.

Figure A2. From the Bottom-left panels, clockwise: $\delta x$ vs. $X$, $\delta y$ vs. $Y$, $\delta x$ vs. $Y$ and $\delta y$ vs. $X$ for each of the 16 VIRCAM chips before we applied the distortion correction.
Figure A3. As in Fig. A2 but after the distortion correction is applied.