Photometry and astrometry with \textit{JWST} – II. NIRCam geometric distortion correction

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ABSTRACT

In preparation to make the most of our own planned \textit{James Webb Space Telescope} investigations, we take advantage of publicly available calibration and early-science observations to independently derive and test a geometric-distortion solution for NIRCam detectors. Our solution is able to correct the distortion to better than $\sim 0.2$ mas. Current data indicate that the solution is stable and constant over the investigated filters, temporal coverage, and even over the available filter combinations. We successfully tested our geometric-distortion solution matching the \textit{JWST} and archive HST catalogues. We considered three different applications: (i) cluster-field separation for the stars in the globular cluster M92; (ii) measuring the internal proper motions for M92’s stars; (iii) measuring the internal proper motions for the stars in the Large Magellanic Cloud system. While we were not able to detect significant variations of the geometric distortion solution over 22 days, it is clear that more data are still necessary to have a better understanding of the instrument and to characterise the solution to a higher level of accuracy. To our knowledge, the here-derived geometric-distortion solution for NIRCam is the best available and we publicly release it, as many other investigations could potentially benefit from it. Along with our geometric-distortion solution, we also release a Python tool to convert the raw-pixels coordinates of each detector into distortion-free positions, and also to put all the ten detectors of NIRCam into a common reference system.

Keywords: techniques: image processing – astrometry – proper motions – galaxies: individual: Large Magellanic Cloud – globular clusters: individual: NGC 6341 (M92)

1. INTRODUCTION, OBSERVATIONS, DATA-REDUCTION

The characterisation of the geometric distortion (GD) of an imager is of paramount importance to assess its use for high-precision astrometry. This is particularly important in the case of cameras of an out-of-atmosphere, brand-new instrument, such as the \textit{James Webb Space Telescope (JWST)}, arguably the world-wide most-important astronomical facility.

In this work, we made use of part of \textit{JWST} public data collected with the \textit{Near Infrared Camera} (NIRCam) under the Cycle1 Calibration Program 1476 (PI: M. Boyer) to derive its GD correction. While standard pipeline products for GD corrections of \textit{JWST}’s cameras are expected to be released in the future by instrument teams, our goal is to derive our own independent GD correction for NIRCam with accuracy beyond those.

This paper is part of a series to build-up our capabilities to obtain \textit{state-of-the-art} imaging astrometry and photometry with \textit{JWST}. This is a necessary task for us to properly prepare and maximise the scientific returns of our planned (March 2023) proprietary \textit{JWST} observations (GO-1979, PI: Bedin).

In our first paper Nardiello et al. (2022) (hereafter Paper I), we describe the procedure to derive high-accuracy point-spread functions (PSFs) for NIRCam in some filters, an essential step to derive high-precision photome-
Figure 1: (Left:) depth-of-coverage of the 9 pointings for each considered filter in the SW channel. The studied region in the LMC cover about 6′ × 3′, and shows large overlaps between the SW’s detectors. (Right:) a three-colour view of the region, where F090W, F150W and F444W were used for blue, green and red colour, respectively.

Figure 2: To give an idea of the richness of isolated well-measurable sources in the field we show a zoom-in of a portion of ∼ 150″ × 44″, around the brightest and reddest source (Gaia DR3 4657988450340570624, 2MASS 05212923-6927554, WISE J052129.23-692755.4) visible in right panel of Figure 1 (a red super-giant belonging to LMC classified as an extreme AGB star, Boyer et al. 2011).

We employed the set of images collected with the Short Wavelength (SW) channel in F090W, F150W, and F150W2 filters, and with the Long Wavelength (LW) channel in F277W and F444W. We also, test the derived geometric distortion solution in the available filter combos: F150W2+F162N, F150W2+F164N, F444W+F405N, F444W+F466N and F444W+F470N.

For each filter, JWST observed the field with 9 different pointings in such a way a given star is placed in 9 different positions of a detector (Fig. 1). Each pointing is an exposure obtained with a single integration. In the case of SW channel, each integration is obtained using different readout pattern as follows: (i) integrations in F090W, F150W, and F150W2 (with no other filter on the pupil) were obtained with the readout pattern RAPID, i.e. they are obtained by using $N_{\text{groups}}=2$ groups of $N_{\text{samples}}=1$ sample (with pixel integration time of 10.7 s), and $N_{\text{skip}}=0$ skipped frames (effective exposure time of a single image: 21.474 s); (ii) nine integrations in F150W2 filter + F162M (pupil

2 https://web.oapd.inaf.it/bedin/files/PAPERs_eMATERIALs/JWST/Paper_01/
Figure 3: The quality-of-fit (QFIT) distribution before (top panel) and after (bottom panel) the ePSF perturbation. The median QFIT value decreases from 0.056 to 0.030, with an improvement of $\sim 50\%$ in the PSF fitting. The figure refers to an image in F090W filter, namely jw01476001003_02101_00001, module B, detector 2. wheel) were obtained in BRIGHT2 readout pattern mode, in which each integration is obtained with $N_{\text{groups}}=4$, each one corresponding to the average of $N_{\text{samples}}=2$ samples and $N_{\text{skip}}=0$ skipped frames (effective exposure time of a single image: 85.894 s); (iii) 18 integrations in F150W2 filter + F164N (pupil wheel) filter were executed in BRIGHT1 readout pattern mode, in which each integration is formed by $N_{\text{groups}}=6$, and each group is obtained by combining $N_{\text{samples}}=1$ samples and $N_{\text{skip}}=1$ skipped frames (effective exposure time of a single image: 118.104 s). In the case of LW channel, images in F277W and F444W (with no filter on the pupil) were obtained with readout pattern RAPID, $N_{\text{groups}}=2$, $N_{\text{samples}}=1$, $N_{\text{skip}}=0$ (effective exposure time 21.474 s), images in F444W+F405N with readout pattern BRIGHT1, $N_{\text{groups}}=6$, $N_{\text{samples}}=2$, $N_{\text{skip}}=1$ (effective exposure time 118.1 s), while the observations in F444W+F466N and F444W+F470N were obtained with readout pattern SHALLOW4, $N_{\text{groups}}=5$, $N_{\text{samples}}=5$, $N_{\text{skip}}=1$ (effective exposure time 257.7 s).

We extracted catalogues of positions and fluxes for point sources from the NIRCam calibrated images by adopting the procedure described in Paper I.

Briefly, for each image, we used a list of bright, isolated, unsaturated stars to perturb the library ePSFs obtained in Paper I, in such a way as to take into account the time variations of the JWST ePSFs. Figure 2 shows a zoom-in of the studied region at a meaningful scale to display individual sources; it is representative of the entire field, which is rather homogeneous and rich in bright sources, relatively isolated, and well-measurable.

In Fig. 3 we show why it is important to perturb the library ePSF. In the top panel, the quality-of-fit parameter (QFIT) obtained employing the library ePSFs (from Paper I) is shown as a function of the instrumental magnitudes ($m_{\text{instr}} = -2.5 \log \Sigma(\text{counts})_{\text{used pixels}}$). The parameter QFIT essentially quantifies the difference between the adopted ePSF model and the observed stars on the images. In the bottom panel, the same PSF diagnostic is shown when the perturbed ePSFs are used. In this case, the QFIT parameter significantly decrease, getting closer to zero, so, better resembles the real stars. This translates into improved astrometry, photometry, and source separations.

We used the perturbed ePSFs to extract catalogues of unsaturated sources with a total flux $\geq 50$ counts and an isolation index of 5 pixel. We refer the reader to Paper I for a more detailed description of the data reduction.

2. GEOMETRIC DISTORTION CORRECTION

Our derivation of the GD correction for NIRCam followed the empirical approach and procedure successfully applied to derive the GD correction of many other cameras at the focus of space- and ground-based telescopes (Anderson & King 2003; Anderson et al. 2006; Bellini & Bedin 2009; Bellini et al. 2011; Libralato et al. 2014, 2015; Kerber et al. 2019).

Our GD solution is derived independently for each of the ten 2048×2048 pixels NIRCam detectors (8 for SW, and 2 LW), and it is made up of three parts. First, a backbone third-order polynomial (Section 2.1) derived through an auto-calibration procedure; second, a first-order polynomial derived by exploiting the Gaia DR3 reference system, to fix the linear terms of the geometric distortion (Section 2.2), and third, a fine-scale table that accounts for spatial high-frequency systematic residuals that the polynomial correction can not absorb (Section 2.3).

The procedure that we will describe in the next sections have been applied independently to each detector of both modules (A and B). The final distortion map is shown in Figure 4. The colour map represents the pixels' area variation across the detectors due to the geometric distortion, which is relevant to show for those investigations dealing with surface brightness. Each of

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3 https://jwst-pipeline.readthedocs.io/
Figure 4: Geometric distortion map of NIRCam short (top) and long (bottom) wavelength channel for both module A (left) and module B (right); detector number is shown in red on the bottom left corner of each vector plot. The size of the residual vectors is magnified by a factor 20. For each detector we also show the single residual trends along $x$ and $y$ axes. Units are in raw NIRCam pixels. The colour map represents the pixels’ area variation across the detectors (see text).
the $16 \times 16$ cells maps a $128 \times 128$ pixels region, and is coloured according to the ratio between the GD corrected area and the raw area. We computed the GD corrected area using the corrected positions of the corners of each cell, thus the value represents the mean area variation of the pixels in that cell.

2.1. Polynomial correction

The polynomial GD solution is represented by a third-order polynomial; we checked that higher-orders (fifth and seventh) do not provide better results. We chose the pixel $(x_0, y_0) = (1024, 1024)$ in each detector as a reference position and solved for the distortion with respect to it, using the normalised coordinates $(\tilde{x}, \tilde{y}) = \left( \frac{x-x_0}{x_0}, \frac{y-y_0}{y_0} \right)$ (cfr. Anderson & King 2003; Bellini et al. 2011).

To derive the polynomial coefficients we performed a series of iterations in which we alternate two main tasks: building the master frame, which will be the temporary reference system closer to the distortion-free solution than the previous iteration, and calculating the residuals between the positions of the sources as measured on the master frame and those measured in the raw catalogues. These residuals are then used to derive the polynomial coefficients. The polynomial correction is performed as follows:

- We selected the sources in each catalogue with instrumental magnitude in the range $-12.5 < m_{\text{instr}} < -8$ and with QFIT lower than 0.1, to avoid artefacts, saturated and poorly measured stars which would affect the distortion solution.
- We conformally transformed the positions of each star in each catalogue into the reference system of the central dither.
- We built a master frame by cross-identifying the sources in each catalogue, keeping only the sources that are found in at least three exposures.
- At this point, we computed the conformal transformations $(T)$ between stars in each exposure and the master frame.
- The inverse transformation $(T^{-1})$ is then used to compute the position of the master frame’s stars in the raw-coordinate system of each image, that is then cross-identified with the closest source, after applying the inverse GD correction derived in the previous iteration (which, of course, at the first iteration is equal to the identity). Each such cross-identification generates a pair of positional residuals $\delta x = x_{\text{raw}} - X^{T^{-1}} \circ GD^{-1}$ and $\delta y = y_{\text{raw}} - Y^{T^{-1}} \circ GD^{-1}$.

- We performed a least-square fit of the residuals to obtain the coefficients for the two third-order polynomials that are added to those derived at the previous iteration. To ensure convergence, the 75 percent of the correction is then applied to all stars’ positions.

The procedure is iterated over up to 45 iterations, until convergence is reached, starting from the corrected catalogues, each time refining the master frame and the polynomial coefficients. At the end of the procedure, we had a set of coefficients for each filter. The polynomials derived independently for each filter turned out to be in agreement within the uncertainties, therefore we computed a weighted mean to get a single final polynomial for each individual detector. While the polynomials for filter combinations were marginally in agreement with those obtained for single filters, they were not used to compute the average polynomials.

2.2. GD linear terms

So far, the first epoch of calibration program 1476 has observations collected at one single orientation of the telescope. This fact makes it very hard to solve for the linear terms of the GD. For this reason, we will make leverage of the existing astrometric flat field provided by Gaia DR3 to perform this task.

While common sources are very few, faint and poorly measured, we need only 3 stars, in principle, to fix these linear terms, as the most general linear transformation has only 6 parameters (therefore the 2D positions of three stars would be sufficient).

Nevertheless, in each detector, there are always at least 350 stars in common between Gaia and NIRCam observations of program 1476 for the SW channel, and
Figure 6: As Fig. 5 but after applying also the fine-scale table correction. These black dots are our internal errors, which are always smaller than 20 $\mu$as, and are the formal uncertainty of our GD correction; whereas the larger error bars (in red) show the positional random error for the individual “typical” source.

at least 1200 for LW channel, more than enough for our purposes.

We then proceeded in the same way as described in the previous section, but this time using Gaia (projected onto the tangent plane of each exposure) as a master frame, starting with the catalogues corrected with the third-order polynomial, and using all the filters together. We needed 10 iterations to reach convergence.

The residuals between the inter-comparison between all the dithered exposures for detector A1 are shown in Figure 5: we notice the presence of small spatial residuals, that we wanted to remove. We corrected these systematics with a lookup table as described in the next section.

2.3. Fine-structure table of residuals

The systematic trends observed in Fig. 5 could not be removed with the polynomial corrections. Additional iterations did not provide any improvements. For this reason, we decided to proceed with a fine-structure table of residuals.

We followed two different procedures for the SW channel and the LW channel; for the SW channel we employed again a self-calibration procedure. We started from the catalogues corrected with the two polynomials and followed the first five steps of the bullet list in Section 2.1. We then divided the residuals into a lookup table of $16 \times 16$ cells in $x$ and $y$. To each cell, we assigned a residual in $x$ and $y$ using the 3$\sigma$-clipped mean of the residuals in that cell. The positions of the stars are then corrected with the residual calculated with a bilinear interpolation of the residuals of the four most adjacent cells (cfr. Libralato et al. 2014). This procedure is iterated over 10 times to converge. The systematic trends were successfully corrected; after the correction, the inter-comparison of corrected frames is consistent to the sub-mas level (Figure 6, assuming a pixel scale of 31.23 mas, see Section 5).

We applied the same self-calibration procedure to the LW channel, unsuccessfully. After 10 iterations, the residuals between the inter-comparison of dithered exposures did not show any clear trend. However, the comparison of these positions with the Gaia catalogue showed a global trend in the residual distribution: we suspect that the data are insufficient for a self-calibration of the GD for the LW channel. Indeed, the dither pattern (which is the same for both channels) offers larger inter-comparison overlaps for SW than for LW.

Therefore, we exploited our just corrected SW catalogues to build a distortion-free master frame, on which we can calibrate also the LW channel. We proceeded with the same steps that we followed to derive the SW channel lookup table, but this time as a master frame we employed the one built employing the SW corrected catalogues. Adopting this procedure, also in this case, 10 iterations were sufficient to reach convergence.

This is the final step that concludes the derivation of our GD correction for the NIRCam detectors. In Sect. 6 we will give details about the Python routine, which we release as electronic material part of this publication, that will enable readers to transform the raw pixel coordinate of each of the 10 individual detectors of NIRCam into a distortion-free frame.

2.4. Gaia validation

Although our formal (internally estimated) errors provide uncertainties smaller than 20 $\mu$as, these are very likely underestimates of the true errors. However, it is not easy to compare these corrected positions with other catalogues able to reach similar accuracy for such faint stars. The only available is Gaia DR3 which, however, we used to fix the linear terms. Therefore, while we will not be able to independently test the linear terms of our solution, we will nonetheless still be able to test the accuracy of the non-linear terms of our GD correction.

Unfortunately, common sources are faint for Gaia and we end up being limited by the errors in the Gaia catalogue in both positions and motions. Gaia DR3 gives positions at the epoch 2016.0, while the new JWST observations are collected at epoch $\sim$2022.53. Given the internal proper-motion dispersion for LMC stars in this field (which also has a distribution far from being Gaussian) of about 40 km s$^{-1}$ (Anderson et al. 2021, and assuming a distance of 50 kpc, in 6.53 years (2022.53-2016.0), we expect a dispersion of 1.1 mas.

We cross-identified the sources in our SW and LW catalogue of a single image (namely
Figure 7: Left: positional residuals between the positions measured by us and those given by Gaia DR3 catalogue, for the SW channel (top) and the LW channel (bottom). Right: colour-magnitude diagram in the Gaia filters for the common sources.

Figure 8: Positional residuals in $x$ and $y$ (top and middle) and magnitude residuals (bottom) from the intercomparison of dithered images in F090W after the GD correction have been applied. Red lines indicate the median value of the residuals for well-measured sources ($-13.5 < m < -10$, QFIT< 0.2).

correction. Doing the same for the LW we obtain again $\sim$0.6 mas.

This is a rough estimate for the minimum limit in the accuracy of our GD correction and is mainly affected by the strongly non-Gaussian internal proper-motion distributions for LMC stars (see Fig. 15 of Anderson et al. 2021, and Sect. 4.3 of this work).

2.5. Internal errors

Figures 5 and 6 give positional residuals for the bulk of the measured sources in the field (red error bars), here instead, we want to show these quantities as a function of the instrumental magnitude for the individual sources. This is possible by inter-comparing the positions and magnitudes measured employing the same filter (9 dithered images), which provide an estimate of the expected r.m.s. of the quantities, as measured in a single image, for individual sources. In Fig. 8, we show for the case of detector A1 in F090W these trends, with median values of 0.013 pixels (i.e., 0.4 mas) for the 1-D positioning, and 16 milli-mag in the photometry for well-measured sources, i.e. those with $-13.5 < m < -10$ and QFIT< 0.2. Similar results are obtained for the other detectors/filters. In the following applications and considerations, it is important to distinguish the difference between these random errors for individual sources and the systematic errors of geometric distortion residuals.
3. COLOUR-MAGNITUDE DIAGRAMS

The dither pattern of the observations provides large overlaps, which in turn, allows us to compare the photometry obtained from the different detectors of a module to register the zero points of the detectors into a common photometric reference system. In the case of the SW channel, we chose as reference system the first image obtained with detectors A1 and B1, and, for each filter and module, we transformed the positions and magnitudes of the stars measured in all the images into the reference system defined by this first image. We do this for each module, separately. We averaged the transformed positions and magnitudes of each detector, to obtain a more robust catalogue of stars measured in at least three images and we iterated refining the transformations by using as reference system the new catalogue containing the mean positions and magnitudes. We report in Table 1 the photometric zero-points of each detector within each module of the SW channel compared to detectors A1 and B1 (which by definition have null shifts).

Even if the overlap between modules A and B is small, we also were able to measure the zero points δmag=mag[A]-mag[B] between the catalogues obtained with the different modules in one filter (it means the zero-point between A1 and B1 in the case of SW channel, and A and B in the case of LW channel). We found δF090W = −0.31±0.06, δF150W = −0.20±0.07, δF277W = +0.03±0.11, and δF444W = −0.06±0.07.

For each filter, we carried out selections by using quality parameters like the photometric RMS and the quality-of-fit, as done in Paper I. Figure 9 shows the F090W versus F090W−X instrumental CMDs of the stars in the LMCs observed by NIRCam in the F090W, F150W, F277W, and F444W filters and that passed the quality selections. The deepest CMD is the F090W−F150W one, which reaches two magnitudes below the MS turn-off with a SN~5; the same signal is reached by the F444W filter two magnitudes brighter, making this filter the shallowest among those used in this work to follow the MS stars of the LMC.

4. DEMONSTRATIVE APPLICATIONS

In this section, we demonstrate that applying our just-derived GD correction to positions of sources, and comparing these positions with those measured in an earlier archival HST data set, we are able to detect stellar motions at sub-mas level precision.

To this aim, we considered three applications, sorted by increasing difficulty: (1) the cluster-field separation in the case of the globular cluster M92; (2) the estimate of the internal motion of the same cluster; and finally

(3) the clear detection of the internal motions in the LMC system, a stellar system at ∼50 kpc.

4.1. Field-object decontamination in M92

To compute the displacements of the stars in a field centred in M92, we adopted as the first epoch the HST observations collected under programme GO-10775 (PI: Sarajedini, Sarajedini et al. 2007, epoch 2006.27), and as a second epoch the JWST data from the ERS-1334 (PI: Weisz, epoch 2022.47). For the first epoch, we used the catalogue obtained by Nardiello et al. (2018), while for the second epoch we used the catalogues obtained in Paper I, corrected by using the GD solution of this work. We matched the HST F814W catalogue with the JWST F090W and F150W catalogues by using 6-parameter global transformations. Sources that moved the least, and by far the large majority, are M92 member stars, therefore the zero of the motion coincides with the mean motion of the cluster. Top panel of Figure 10 shows the resulting vector-point diagram (VPD) of the displacements of the stars in δt = 16.2 yrs. We arbitrarily defined as field stars all the sources with a proper motion larger than ∼0.9 mas/yr (red points), which is about 3.5σ of the internal distribution (see next sect.). The bottom panel shows, for the same sources in the VPD, the mF090W versus mF814W − mF150W CMD, employing the same symbols and colour codes.

Unfortunately, M92 is not an ideal target for a striking demonstration of the cluster-members field-objects decontamination, mainly because of the extremely sparse density of Galactic and extra-galactic sources in the direction of M92, where we count at most 20 sources.
4.2. M92 internal dispersion

The globular cluster M92 (NGC 6341) is a relatively massive system (3.5×10⁵ M☉) located at a distance of ~8.5 kpc and with a half-mass of 4.5 pc, i.e., 110" (Vasiliev & Baumgardt 2021, hereafter VB21). In the radial range explored by the combined HST-JWST epochs, i.e., 20-100 arcsec from the centre of the cluster, according to the literature, we expect internal-velocity dispersion between 8 and 5.5 km s⁻¹ (i.e., between 0.20 and 0.12 mas yr⁻¹, VB21).

In this section, we further test our GD correction estimating the internal-proper motion dispersion for M92, and in the process we will also obtain a check on the precision of NIRCam astrometry.

We consider positions (X, Y) measured within JWST at epoch 2022.47, in the two filters F090W and F150W, separately. With those positions, we computed the displacements of sources in F090W and F150W, with respect to those measured within HST at epoch 2006.27, for each filter separately. We selected best-measured sources in all data sets, in the brightest 2 magnitudes just below the saturation and with photometric diagnostics QFIT and r.m.s. selected as described in Fig 5 of Paper I. We plot the two displacements in top panels of Fig. 11. The first epoch is identical for the two computed displacements, and the second epoch is essentially also the same. Indeed, F150W images were collected only a few minutes after F090W images, which does not change much the time baseline of ~16.2 years. The two displacements correlate with the identity (red line, not a fit) in both coordinates (X on the left, Y on the right). Assuming Gaussian distributions for both the dispersion along the red line (σ∥), and perpendicularly to it (σ⊥), we can derive crude estimates for both dispersion in the M92’s internal motions (σintr) and for the errors (σerr). Bottom panels in Fig. 11 show the histograms for displacements along the parallel (in orange) and perpendicular (in blue) to the identity line.

Any error in the HST 2006 epoch has the effect to move a source only along the red line. So, the cross dispersion, i.e., perpendicular to the red line, reflects the errors only in the two JWST epochs. Assuming the same dispersion for the two filters, σJWST, we can write σJWST = σ⊥/√2. Taking the average in X and Y we obtain σ⊥ = 0.25 mas, and therefore σJWST = 0.18 mas for the single JWST epoch (note, dispersion of displacements not of proper motions). This is essentially, just another way to put an upper limit to the errors in on our GD correction, although, internal to the method.

As four single JWST images participate in the precision of the single filter, we can multiply by a factor √(4−1) to get the precision for the typical star in the individual image, about 0.3 mas, or ~0.01 pixel; consistent with positioning precision for the best measured sources, which means that the errors in our GD corrections should be negligible with respect to it.

Now, we try to infer an estimate of the intrinsic proper-motion dispersion of M92 stars in the region covered by the two epochs. Similarly to what was done for the errors, we can assume that σobs = σ∥/√2.
Figure 10: *Top:* vector-point-diagram of proper motions for sources in the common field between images collected with *HST* under program GO-10775, and the available images from *JWST* program ERS-1334. A black circle defines our arbitrary criterion to separate members (grey) and field objects (orange). *Bottom:* CMD in filters F814W−F150W vs. F090W; colour code is the same as top panel.

Figure 11: *(Top:*) Correlation between positional displacements obtained using an *HST* epoch collected in 2006.27 with filter ACS/WFC/F814W, and two different *JWST* data sets, in filters NIRCam/SW/F090W and F150W, both collected in 2022.47. The identity is indicated by the red line. X-coordinate on the *(left)*, and Y on the *(right)*. *(Bottom:*) Histogram of the displacement distributions along and perpendicular to the identity line. Note the different scale for the two quantities, given in the opposite axes (see text).

Again, taking the average of $X$ and $Y$ we obtain a $\sigma_\parallel = 4.15 \text{ mas}$, and therefore $\sigma_{\text{obs}} = 2.93 \text{ mas}$. To know the intrinsic displacement dispersion we need to subtract in quadrature the errors. To the errors this time participate one *JWST* and one *HST* epoch. So, we sum in quadrature the errors just derived above $\sigma_{\text{JWST}} = 0.18 \text{ mas}$, and assume *HST* errors from the literature. For best stars we expect 0.32 \text{ mas} (from Bellini et al. 2011), but as four *HST* images from 2006 participate to determine the positions, we take $\sigma_{\text{HST}} = 0.32 \text{ mas}/\sqrt{(4-1)} = 0.18 \text{ mas}$. This makes the total errors, sum in quadrature of $\sigma_{\text{JWST}}$ and $\sigma_{\text{HST}}$, amount to $\sigma_{\text{err}} = 0.25 \text{ mas}$; negligible when compared to $\sigma_{\text{obs}}$ (as obvious from a glance to Fig.11). Nevertheless, the intrinsic dispersion of the observed displacement is $\sigma_{\text{intr}} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{err}}^2} = 2.92 \text{ mas}$.

Finally, taking into account the time base-line of 16.2 yr, we derive an estimate for the internal proper motion of M92 stars of 0.18 mas yr$^{-1}$; consistent with the value found by VB21 in the core (0.2 mas yr$^{-1}$).
Figure 12: Displacements positions for sources in the LMC field as measured in archival HST images in year 2006.39, and the corresponding positions as measured in JWST in filter F090W at epoch 2022.53.

the centre, and 0.1 mas yr$^{-1}$ at 100 arcsec). Indeed, our star sample is biased toward the centre, due to the spatial distribution of sources in a globular cluster.

The result is even more remarkable, taking into account that in the process of deriving displacement, we use a global transformation to transform from HST into JWST master frames, letting us completely at the mercy of residual in the geometric distortion of both JWST and ACS (which are sizable in this particular data set, cfr. Sect. 4.3 of Anderson et al. 2021, but thankfully diluted in a 16.2 yr time baseline). This means that by using a local transformations approach (as described in, e.g. Bedin et al. 2003; Anderson et al. 2006; Bellini et al. 2018) residual errors of various origins, could be suppressed. For these reasons, the results presented in this section are even more impressive.

4.3. LMC internal dispersion

To detect the internal proper motion dispersion of LMC stars, we adopted as a first epoch the HST data collected during the calibration program CAL/OTA-10753 (PI: Diaz-Miller). The data set consists of $5 \times 19 \, s + 2 \times 32 \, s + 25 \times 343 \, s + 10 \times 423 \, s$ ACS/WFC images in F606W filter and observations were carried out between 25 April and 9 July 2006 (mean epoch $t \sim 2006.39$). A catalogue of sources was extracted for each image by using the software hst1pass (Anderson 2022). These catalogues were matched with Gaia DR3 catalogue of the same region by using 6-parameter global transformations to orient and transform all the positions of the stars in the same reference system; the transformed positions were then (3σ-clipped) averaged to obtain a catalogue of stars with positions referred to the epoch 2006.39. We performed the same transformations with the JWST GD corrected catalogues in F090W; the final product consists of a catalogue with positions corresponding to the epoch 2022.53. We matched the HST ACS/WFC/F606W catalogue from 2006.39 with the F090W catalogue obtained with JWST in 2022.53, by using 6-parameter global (i.e., not local) transformations.

The displacements converted in proper motions assuming a time baseline of $\delta t = 16.14$ yr, are shown in Fig. 12. Beside the flip of the $\mu_\alpha$ axis, and the zero of the motions referred to LMC stars rest frame, the VPD distribution we obtained employing JWST is completely consistent with the one characterised in great detail by Anderson et al. (2021), for the same region of the LMC. The VPD has the same strongly non-Gaussian distribution in both $\alpha$ and $\delta$, with three-lobed shape, clearly recognisable also in our Fig. 12. This further, demonstrate that our NIRCam GD correction enables us to obtain high-precision results comparable to what obtainable with HST.

As a final note, a more solid estimate of the internal velocity dispersion within LMC would be obtained by performing a local transformation approach (as for example in Bedin et al. 2014).

5. PUTTING DETECTOR-BASED POSITIONS INTO A COMMON REFERENCE SYSTEM

To derive the transformations to put the positions measured in each detectors of a given image into a common reference system (which arbitrarily we chose to be that of A1) we exploited the Gaia catalogue. We considered each of the nine dithers separately, and we treated every filter independently. We proceeded as follows:

– first, we downloaded a portion of the Gaia DR3 catalogue large enough to cover both modules A and B of the considered exposure;

– we projected it onto the plane tangent to A1 in its central pixel;

– we transformed Gaia positions into the reference system of A1;

– finally, we used the Gaia positions on A1 to derive the six parameters transformations to bring all the other detectors on the reference system of A1.

At the end of this procedure, for each filter, we have nine transformations for each detector (one for each of
the nine dithers). We checked the consistency between the coefficients derived from each dither, and given the general agreement among them, we computed the final transformation averaging all the nine estimates. Furthermore, as the coefficients were compatible even in different filters, we also averaged the coefficients obtained in the three filters for the SW-channel, and average those in the two filters for the LW channel; in the end, resulting in six parameters for the transformation of each detector into a common reference frame, independently of the adopted filter.

In Sect. 6, we describe the Python software, which we release with this publication, that enables users to put all the 10 individual detectors of NIRCam into a common distortion-free meta-chip frame.

5.1. The absolute scale

The transformation between A1 and Gaia let us infer the pixel scale of our GD-corrected pixel reference system. For each of the filters, we observe the nine dithers to agree within few $10^{-5}$, with a pixel scale of about 31.23 mas/px (see Table 2).

In the case of HST the telescope was orbiting at 7 km s$^{-1}$ around the Earth, a speed that causes scale variation due to velocity aberration of about 7/300 000 parts, i.e., also of few $10^{-5}$, and every 2 hours (Cox & Gilliland 2003); therefore variations of the same order of what we observe here for JWST. However, unlike HST, JWST it is not orbiting at 7 km/s around the Earth. Nevertheless, JWST (as well as HST) is still orbiting the Sun with a velocity slightly less than 30 km s$^{-1}$, i.e., causing scale variations due to velocity aberration of about 30/300 000, or 1 part in 10 000, a very sizeable effect, although with a much slower ∼6-months timeframe. These effects (of 1 part in 10 000) needs to be properly accounted for in all applications which blindly rely on the absolute scale of the telescope (assuming JWST will prove to have a scale stable down to this level). For this purpose, the calibration pipeline includes in the header of each image the expected velocity aberration scale factor (VA_SCALE) calculated on the base of the expected absolute velocity of the Observatory. We note that the values of the VA_SCALE reported in the header of each image of the here-employed 1476 dataset, remains well below the few $10^{-5}$ scatter observed. In the lack of other observations, we assumed this to be the limit of the plate-scale stability for JWST.

We are deriving our absolute scales comparing directly to the absolute astrometric reference frame of Gaia DR3, therefore, to retrieve the true scale of our GD solution we should first divide for the VA_SCALE factor. The results obtained for the average of the scale of detector A1 compared to GaiaDR3, for all images collected in filters F090W, F150W, and F150W2, are shown in Table 2. The values for each filter are the averaged values obtained from the nine dithers. Note that the scale for filter F090W is significantly different (at ∼14 σ) from the one for the two filters F150W and F150W2, which are instead marginally consistent (∼2.8 σ) among them.

Finally, we note that this is the scale to apply to our here-derived GD solution, that is normalised to a specific chip location. Other GD solutions might refer to different pixels, and therefore might have slightly different scales.

6. CONCLUSION

In this work, we have exploited JWST observations of a field in the LMC and Gaia DR3 to calibrate the geometric distortion of the ten NIRCam detectors. We exploited the calibrated positions coupling them with archival HST observations to measure the proper motions of sources within a field in the core of the Galactic globular cluster M92. Our measurements were able to clearly disentangle field objects from cluster members, and even to measure their internal kinematic. We also were able to measure the internal dispersion of stars within one extra-galactic system, the LMC.

In all cases, our results are in agreement with the literature and in line with state-of-the-art astrometry.

Finally, we publicly release two Python tools to apply our geometric distortion correction to the raw coordinates of NIRCam detectors, and to put all the detector-based positions into a common, distortion-free, global reference system. The routine raw2cor.py takes as input a list of raw coordinates, the module (A or B) and the detector (1-5), and applies the third-degree polynomial, the linear terms, and the fine-scale table, giving as output the corrected coordinates. The routine xy2meta.py requires the same input as raw2cor.py, but in addition to the GD corrections it also applies the transformations to bring all the coordinates into a common reference system, which are given as output. These routines are released as electronic material with this paper and are also downloadable from the following url: https://oapd.inaf.it/bedin/files/PAPeR_s_eMATERIALs/JWST/Paper_02/Python.

Table 2: Mean pixel scale and VA_SCALE.

| Filter     | Scale [mas/px] | σScale [mas/px] | VA_SCALE − 1 |
|------------|----------------|-----------------|--------------|
| F090W      | 31.23227       | 0.00005         | 3.65488 $\times 10^{-6}$ |
| F150W      | 31.23115       | 0.00006         | 3.64514 $\times 10^{-6}$ |
| F150W2     | 31.23087       | 0.00008         | 3.64028 $\times 10^{-6}$ |
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