Instrument Science Report WFC3 2021-07

Accuracy of the HST/WFC3 Standard Astrometric Catalog *w.r.t* Gaia EDR3

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June 14, 2021

Abstract

The Gaia early data release three (EDR3) with its average high positional accuracy of 0.05 (milli-arc-second) has been used to evaluate the fidelity of the HST standard astrometric catalog in the vicinity of globular cluster ω Cen based on ACS/WFC observations. This standard astrometric catalog was used for calibration of the WFC3/UVIS and IR geometric distortions. We found that there are significant positional offsets, rotation, and scale correction in the HST standard astrometric catalog and, hence, these systematic errors have propagated in the WFC3/UVIS & IR distortion model. Here we present a detailed analysis of the HST standard astrometric catalog relative to the Gaia EDR3. The standard astrometric catalog appears to contain significant systematic errors, and the new improved version of the standard catalog is accurate to the level of 10 mas. Therefore, the WFC3/UVIS & IR distortion models should be accounted and corrected for existing uncertainties, so that the high-precision HST/UVIS & IR positions would be free of any systematic errors.

1 Introduction

The high level of astrometric precision and accuracy of the early data release (EDR3) of the European Space Agency Gaia mission provides an opportunity to evaluate the accuracy of the HST standard astrometric catalog which is regularly used for astrometric calibration of WFC3/UVIS and IR. The most straightforward technique to solve for accurate and reliable astrometric calibration is to use the positions of stars from the standard astrometric catalog, where stellar X&Y positions are free of optical distortion. Then, the residuals between the observed stellar positions and the corresponding positions in the standrad astrometric catalog reveal the optical distortions of the basic geometry of the optical projection, possible deviation in the focal length, optical aberrations, etc., as discussed by Kozhurina-Platais et al. (2009a), Kozhurina-Platais et al. (2009b).

The high positional precision of the standard astrometric catalog was instrumental in the discovery of of the high-frequency systematics in the raw X&Y measured positions from WFC3/UVIS (Kozhurina-Platais, *et al.*, 2010) [1], confirmed later by (Bellini et al., 2011), and also in the raw X&Y measured positions from ACS/WFC observations (Kozhurina-Platais et al., 2016). These fine-scale distortions are inherent to the CCD detector itself, as the CCD pixel-grid irregularities due to the lithographic-mask pattern in the detector as fine-scale and correlated systematic offsets in the residuals from the best-polynomial solution. Such systematic offset across the CCD chip introduced astrometric errors at the level of 0.1pixels. The correction for this distortion is performed using a 2-D look-up table implemented in the HST pipeline by Kozhurina-Platais et al. (2013) and Kozhurina-Platais et al. (2015) as a reference files for distortion correction of HST WFC3/UVIS images and ACS/WFC.

On the other hand, if the stellar positions in the standard astrometric catalog (SAC) contain systematic errors and have inaccurate positions with respect to the International Celestial Reference System (ICRS), then these errors will generate an additional distortion in the catalog and consequently these errors will be propagated into the instrument geometric distortion model. The high accuracy of $sub-mas$ astrometry, radial velocity and photometry of more than 1 billion stars down to the 21 magnitude of Gaia EDR3 catalog provides a new opportunity to evaluate the accuracy of the HST satndard astrometric catalog in the vicinity of globular cluster ω Cen. Therefore, we present a detailed analysis of the stellar positions in the HST standard astrometric catalog in comparison to the stellar positions in the Gaia EDR3. First, we provide a short description of the standard catalog. Second, we present the detailed account of the astrometric errors found in the HST SAC. Third, we describe the improvements and corrections for the HST SAC and how that will affect of the accuracy of the WFC3 geometric distortion correction. And fourth, we compare the current WFC3/UVIS distortion in the HST pipeline $w.r.t$ Gaia EDR3.

2 HST Standard Astrometric Catalog

Right after the installation of the HST WFC3/UVIS and IR by SMO4 at 2009, the astrometric calibration of the latest cameras were based on observations of the globular cluster 47Tuc and the Large Magellanic Cloud (Dressel (2009b), Dressel (2009a)). After SMO4

[1] https://www.stsci.edu/contents/events/hst/2010/july/2010-hst-calibration-workshop

in the HST Cycle 18 (2009-2010), the calibration field has been chosen in the vicinity of globular cluster ω Cen. The same field has been observed early with the HST ACS/WFC in 3×3 mosaic pointing from GO-9442 (PI–Cool), covering the center of the cluster within $10' \times 10'$ at the reference point α=201°.697006 and δ=-47°.479473. Afterward, the observations from GO-9442 were combined with GO-10252 and GO-10766 astrometrically assembled and characterized into the reference frame within the range of $[1:14000, 1:14000]$ pixels with the center at X=7011 and Y=6960 with the pixel scale of 50mas/pixel (Anderson & van der Marel (2010)). The reference frame described above has been aligned with the Two Micron All Sky Survey (2MASS, Skrutskie et al. (2006)), which was the best representative of the International Celestial Reference System (ICRS) prior to the Gaia era. Thus, this reference frame was adopted as the standard astrometric catalog for the astrometric calibration of the WFC3/UVIS and IR. The large 3×3 mosaic pointing of ACS/WFC observations were essentially for astrometric calibration of WFC3/UVIS and IR providing the overlap of the standard catalog for observations of large dither patterns. As a results it provided an accurate characterization of the optical distortion presented by the high-order polynomial distortion and the multi-wavelength geometric distortion, almost for all calibrated UVIS and IR filters (Kozhurina-Platais (2014), Martlin et al. (2018)).

3 Gaia Early Data Release 3

The earlier data from the ESO Gaia mission Data Release 1 (DR1) were available in 2018 (Gaia Collaboration et al., 2016). Back then the sources from DR1 were used to evaluate the HST standard astrometric catalog in the vicinity of globular cluster ω Cen. However, Gaia DR1 has a limiting astrometric performance for the globular cluster ω Cen due to extreme stellar density and crowding issues in the core of the cluster as discussed by Pancino et al. (2017). The extracted Gaia sources in the vicinity of ω Cen showed non-uniform spatial distribution and some visible traces from left to right and from top to bottom as an indication of the prevalent directions of scanning. Thus, the location of the HST standard catalog in the vicinity of ω Cen, was poorly sampled in Gaia DR1, which were difficult to compare as it described in Kozhurina-Platais et al. (2018).

The Gaia Early Data Release 3 (EDR3, December 2020) has a significant astrometric (positions, parallaxes, proper motions) and photometric (integrated G, GBP, GRP) improvements (Gaia Collaboration et al., 2020). All Gaia sources in EDR3 were retrieved from the Gaia Archive Core System ESA Center, around the reference point of the HST SAC within 0°.25. Figure 1 shows the spatial distribution of all retrieval sources from Gaia DR1 (left panel) and Gaia EDR3 (right panel). It is evident from Figure 1 that the spatial distribution of Gaia EDR3 sources are uniformly distributed over the field of view and there is a sufficient number of stars over all parts of the field to permit an accurate calibration of the HST Standard Astrometric Catalog.

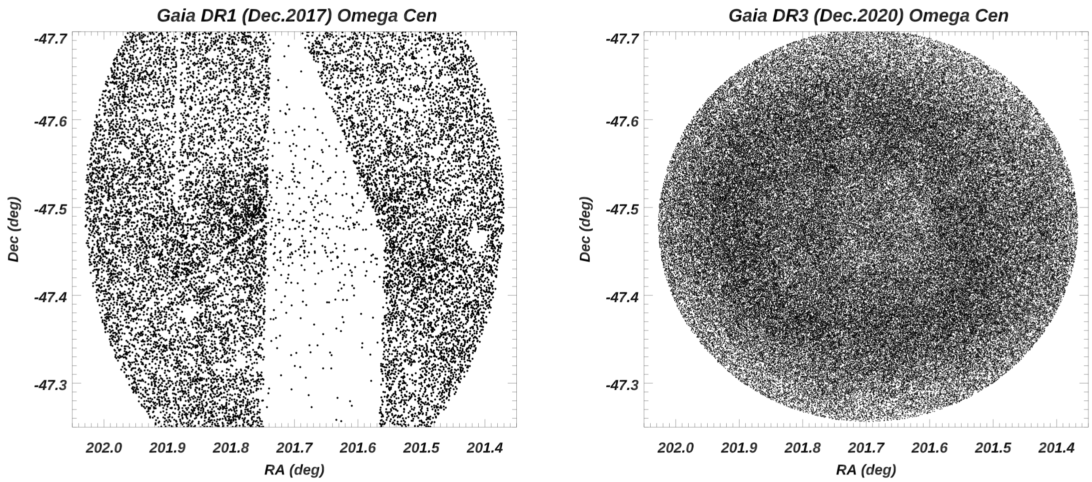

Figure 1: Spatial distribution of Gaia sources in the vicinity of globular cluster ω Cen. The left panel is Gaia sources from DR1 and the right panel is Gaia sources from EDR3. The sky positions α and δ are in decimal degrees.

The first step in the comparison of the HST SAC with EDR3 is to estimate the accuracy of sources positions. To keep high astrometric accuracy of Gaia positions, only stars with positional errors $\lesssim$ 2mas were used in this analysis. Figure 2 shows positional errors $\lesssim$ 2mas in α and δ for all selected stars in the vicinity of ω Cen. Even distribution of the errors along the red line is an indication of equal precision in both celestial coordinates.

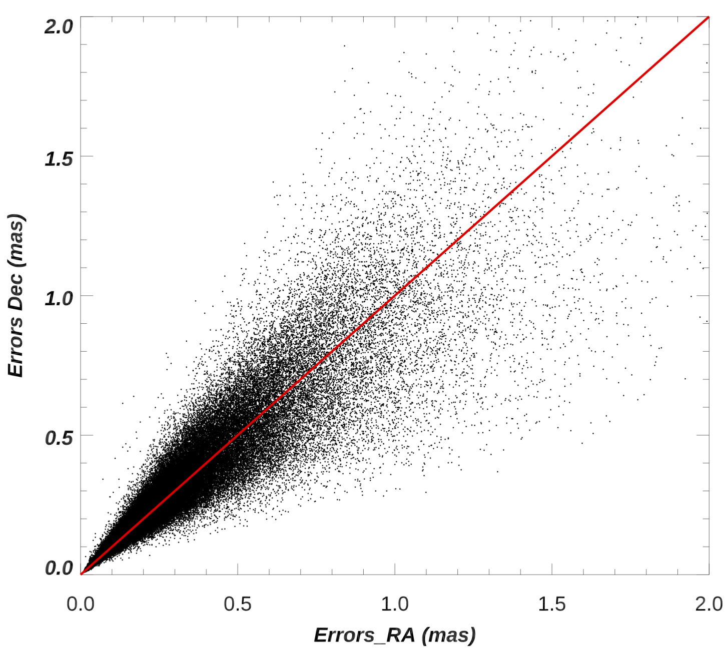

Figure 2: Positional errors of selected Gaia stars in the vicinity of ω Cen. The diagonal red line indicates an even distribution of the errors. The positional errors are in milli-arc-seconds (mas).

As expected, the positional errors are increasing as a function of stellar magnitudes. Figure 3 shows the position errors calculated as $\sqrt{(\sigma_\alpha{}^2 + \sigma_\delta{}^2)}$ as function of Gaia's G-magnitude. The distribution of the errors in Figure 3 shows a good formal accuracy of Gaia even for a faint stars.

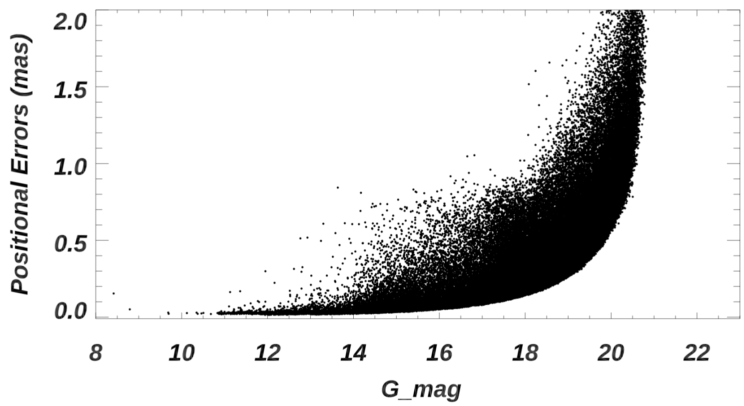

Figure 3: Errors of α and δ as a function of G-band magnitude of Gaia stars in the vicinity of ω Cen. The position errors calculated as $\sqrt{(\sigma_\alpha{}^2 + \sigma_\delta{}^2)}$ are in *mas*.

The errors of the proper motions calculated as $\sqrt{(\sigma_{\mu\alpha}{}^2 + \sigma_{\mu\delta}{}^2)}$ are the indication of the positional accuracy. Hence the stars with the proper motion errors in the range of $0 \lesssim \sigma_\mu \lesssim 2$ *mas* were used to select the accurate proper motion. As seen in Figure 4, there are stars with proper motion errors equal to zero, these stars are excluded from Gaia DR3 for the evaluation of the HST SAC.

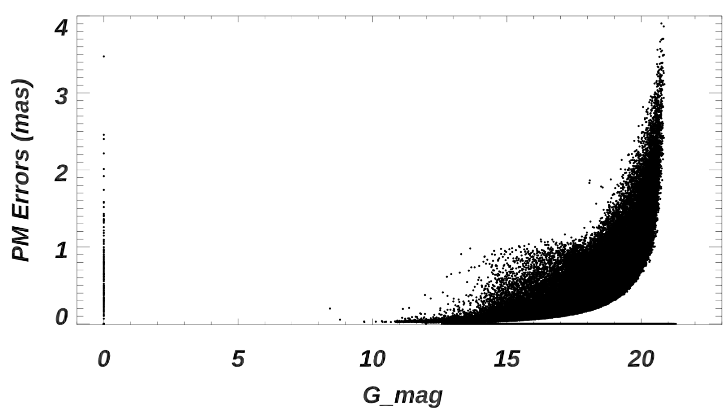

Figure 4: Proper motion errors as function of G-band magnitude of Gaia stars in the vicinity of ω Cen. The proper motion errors calculated as $\sqrt{(\sigma_{\mu\alpha}{}^2 + \sigma_{\mu\delta}{}^2)}$ are in *mas*.

4 HST Standard Astrometric Catalog Assessment

In order to validate the HST standard astrometric catalog *w.r.t* to Gaia positions, these two coordinates systems have to be properly aligned by employing the general linear transformation between these two coordinates systems. Gaia source positions are given in the equatorial system which is specified as right ascension α and declination δ. On the other hand, the HST Standard Astrometric Catalog positions are in the tangent-plane X&Y positions. It would be much easier to compare two coordinates system if the SAC tangent-plane X&Y positions were also in the sky positions, α and δ. Then we would compare the sky positions α and δ of the catalog with Gaia α and δ positions. The calculation of the sky positions α and δ in the HST catalog is required the header information of the World Coordinate System. However, we want to avoid using the WCS information as much as possible because: 1) we wish to reach the accuracy and precision of the original pixel coordinates; 2) the maximum precision is preserved only if all data manipulations are performed with the original pixel coordinates; 3) the transformation from one coordinate system (X&Y) to another (α and δ) may introduce model-dependent systematics, also known as a modeling error, depending on how complicated the transformation is.

Taking into consideration all the points above, the tangent-plane projection was performed to the Gaia equatorial position. Specifically, the Gaia equatorial α and δ positions were transformed into the X-Y plane. The tangent-plane (gnomonic) projection to X-Y plane was performed in the reference point of the catalog α=201$^{\circ}_{.}$690979 and δ=-47$^{\circ}_{.}$4774658 at the frame coordinate corresponding to pixel (7011, 6960) with the scale factor of 50mas/pixel. Thus, the X&Y tangent-plane positions from the Gaia EDR3 were used to match the stars with catalog positions, employing the linear transformation in the least-squares minimization (shift, scale and rotation) to find the common reference stars, interactively rejecting poorly–measured and saturated stars from the HST SAC if needed.

4.1 Linear Transformation between two systems

The evaluation of the HST catalog was done by employing the linear transformation of X&Y catalog positions into the system of the orthogonal reference coordinates U and V, which represent Gaia positions here. Then the linear terms in this transformation between two coordinate systems are used to detect possible residual systematic in the catalog positions and its characterization of an accuracy. The following linear transformation between two systems was used:

$$U = A_1 + A_2 X + A_3 Y \tag{1}$$

$$V = B_1 + B_2 X + B_3 Y \tag{2}$$

where U & V are the positions of the orthogonal coordinate system (tangent-plane Gaia positions), and X& Y are the HST standard catalog positions to be evaluated. A general linear transformation from one system (X,Y) into another (U,V) are specified by 3×2 parameters. The meaning of these parameters have been discussed in several articles e.g., Eichhorn (1974), Taff (1981), van Altena (2013), Kiselev (1989), and define the basic geometry between two coordinates systems; the parameters A_1 and B_1 are the constant terms and

represent an arbitrary offset between two sets of coordinates systems; parameters A_2, A_3, B_2, B_3 are the linear terms characterizing the scale and rotation between two coordinates systems. The rotation angle between these two systems then can be defined as:

$$\tan(\theta) = \frac{A_3}{B_3} \tag{3}$$

The skew term, which is the total amount of non-orthogonality between the principal X & Y axes, can be derived from the following ratio of linear terms:

$$\tan(\gamma) = -\frac{A_2A_3 + B_2B_3}{A_2B_3 - B_2A_3} \tag{4}$$

The scale term is proportional to:

$$\mathcal{M} = \sqrt{(A_2B_3 + B_2A_3)} \tag{5}$$

These linear terms were re-parametrized by Anderson (2007), in the HST context, and were used by van der Marel et al. (2007), in the calibration of the ACS/WFC absolute scale. These parameters were adopted by Sahlmann et al. (2019) for the validation of the JWST calibration field catalog. To be consistent with these authors, the linear terms of Eqs.1-2 were used here again.

The off-axis skew, representing non-perpendicularity between the X, Y axes is defined as

$$Skew_{off-axis} = (A_2 - B_3)/2 \tag{6}$$

The on-axis skew, representing the scale difference between the X, Y axes is defined as :

$$Skew_{on-axis} = -(A_3 + B_2)/2 \tag{7}$$

The scale in X&Y axes are: $Scale_X = \sqrt{({A_2}^2 + {A_3}^2)}$ and $Scale_Y = \sqrt{({B_2}^2 + {B_3}^2)}$, respectively. The global scale then is similar as calculated in Eq.5.

The rotation in X axis is calculated as following

$$Rot_X = arctan(-A_2/B_2) \tag{8}$$

And that in Y-axis is

$$Rot_Y = arctan(A_3/B_3) \tag{9}$$

The global rotation is calculated as

$$Rot = arctan((A_3 - B_2)/(A_2 + B_3)) \quad (10)$$

The deviation from non-perpendicularity between X&Y axes is global skew and defined as $Skew = (Rot_X - Rot_Y)$.

Table 1 shows the numerical values of the derived parameters and their uncertainties as described it above. The parameters were calculated by least-squares minimization using 9990 common stars between the two catalogs, from Gaia and HST SAC. The RMS of solution is equal to 7.5mas and 7.0mas in X and Y respectively. The main contribution to the RMS of solution is the proper motion dispersion in the globular cluster ω Cen. The epoch difference of ∼6.5 years between the HST SAC and Gaia EDR3 contributes to the RMS as much as ∼6 mas (the internal velocity dispersion from the proper motion of ω Cen is at the level of 0.9 mas per year according to Anderson & van der Marel (2010). The proper motions in the HST SAC were not available at that time and as a result the stellar positions in the catalog were not updated for the effect of proper motions of stars in ω Cen in the operation of calculation by least-squares minimization.

The calculated parameters shown in Table 1 indicate a significant rotation, shift and scale difference between the two catalogs, Gaia and the HST SAC, and marginally significant skew terms.

Table 1: The values of the parameters and its standard errors from Eqs 1–5

Parameter	Values	STD. Errors	Units
Global offset in X	25.81	0.075	mas
Global offset in Y	136.35	0.070	mas
Global Scale	0.99994198	0.53e-07	pix
Global Rotation	0.10096719	0.31e-07	deg
Global Skew	0.000965	0.21e-07	deg
Rotation in X	0.10144986	0.38e-07	deg
Rotation in Y	0.10048452	0.39e-07	deg
Scale in X	0.99994347	0.40e-06	pix
Scale in Y	0.99994049	0.40e-06	pix
Skew - on-axis	1.51e-06	0.52e-07	–
Skew -off-axis	8.43e-06	0.63e-07	–

The estimated arbitrary offsets of $\sim 1''$ in X & Y and $\sim 0\overset{\circ}{.}1$ angle of rotation between the HST catalog and Gaia EDR3 are in good agreement with Anderson & van der Marel (2010), where similar offset between the adopted reference frame and 2MASS (Skrutskie et al., 2006) reported.

Two-dimensional X&Y residuals maps were used to visualize directly the contribution of each of the linear terms of transformation in the following sections.

4.1.1 Effect of Rotation

Figures shows a 2-D map of the positional differences between two coordinates systems, with vectors indicated a significant solid-body type rotation. As seen in Figure 5, the rotation at HST catalog relative to Gaia EDR3 catalog is positive (rotation angle measured from North to East). The global rotation between two catalogs calculated from the linear parameters (Eq.10) is equal to $0\overset{\circ}{.}101 \pm 0.31e\text{-}07$ as seen in Table 1.

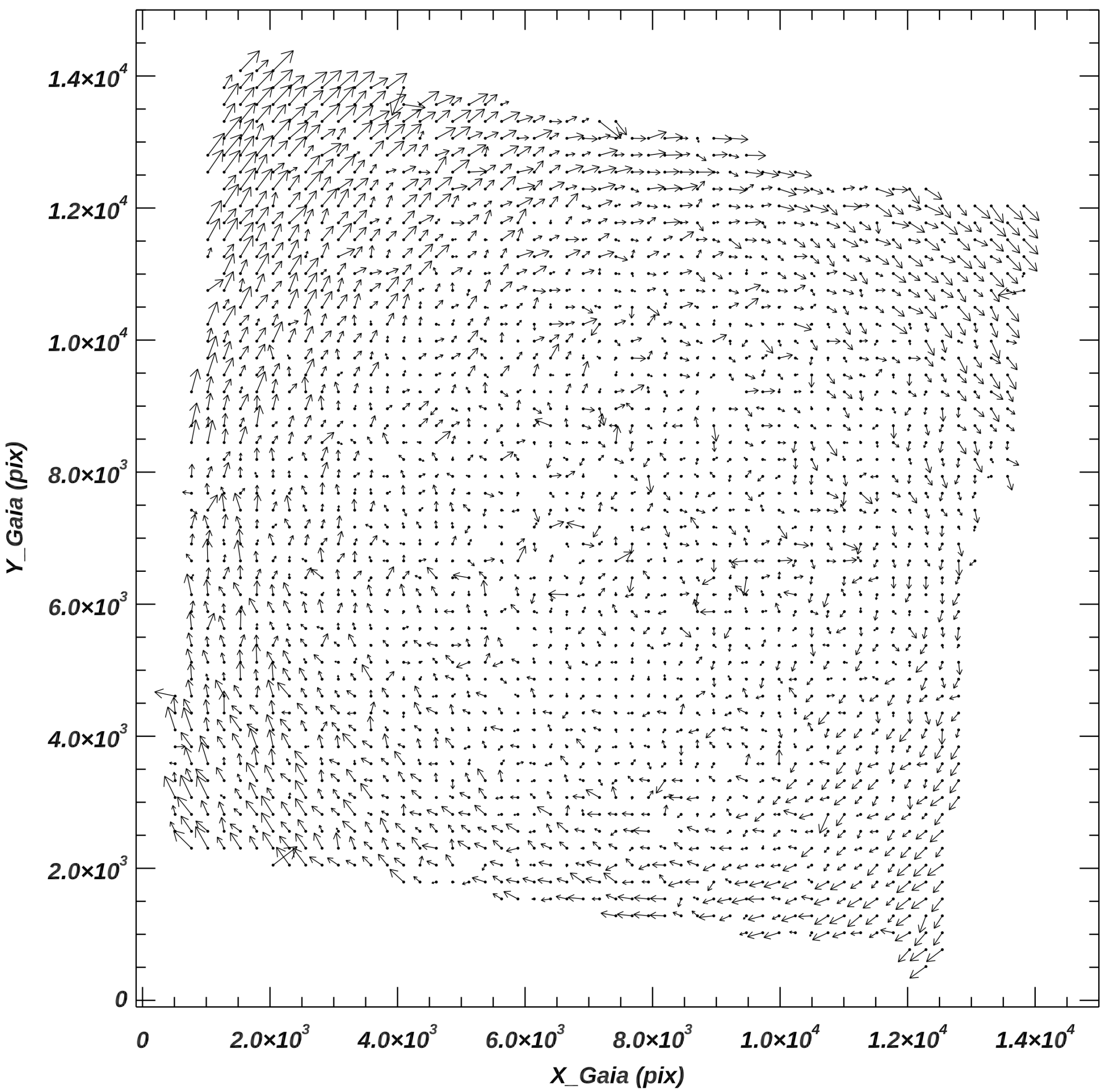

Figure 5: The difference in position between the Gaia and HST coordinates systems before applying global rotation and global offsets in X and Y positions. The maximum length of the vector is 19 pixels (950 mas) and each vector magnified by a factor 30. The tangent-plane positions X and Y are in units of the ACS/WFC pixels

4.1.2 Effect of X & Y Shifts

The correction for the rotation reveals the positional difference between two coordinate systems. Figure 6 shows 2-D map of positional differences with the vector flow indicates that the global offset is dominating in Y-axis at about 136 mas (or 2.73 pixels) which is 5 times less than the shift in X (25 mas).

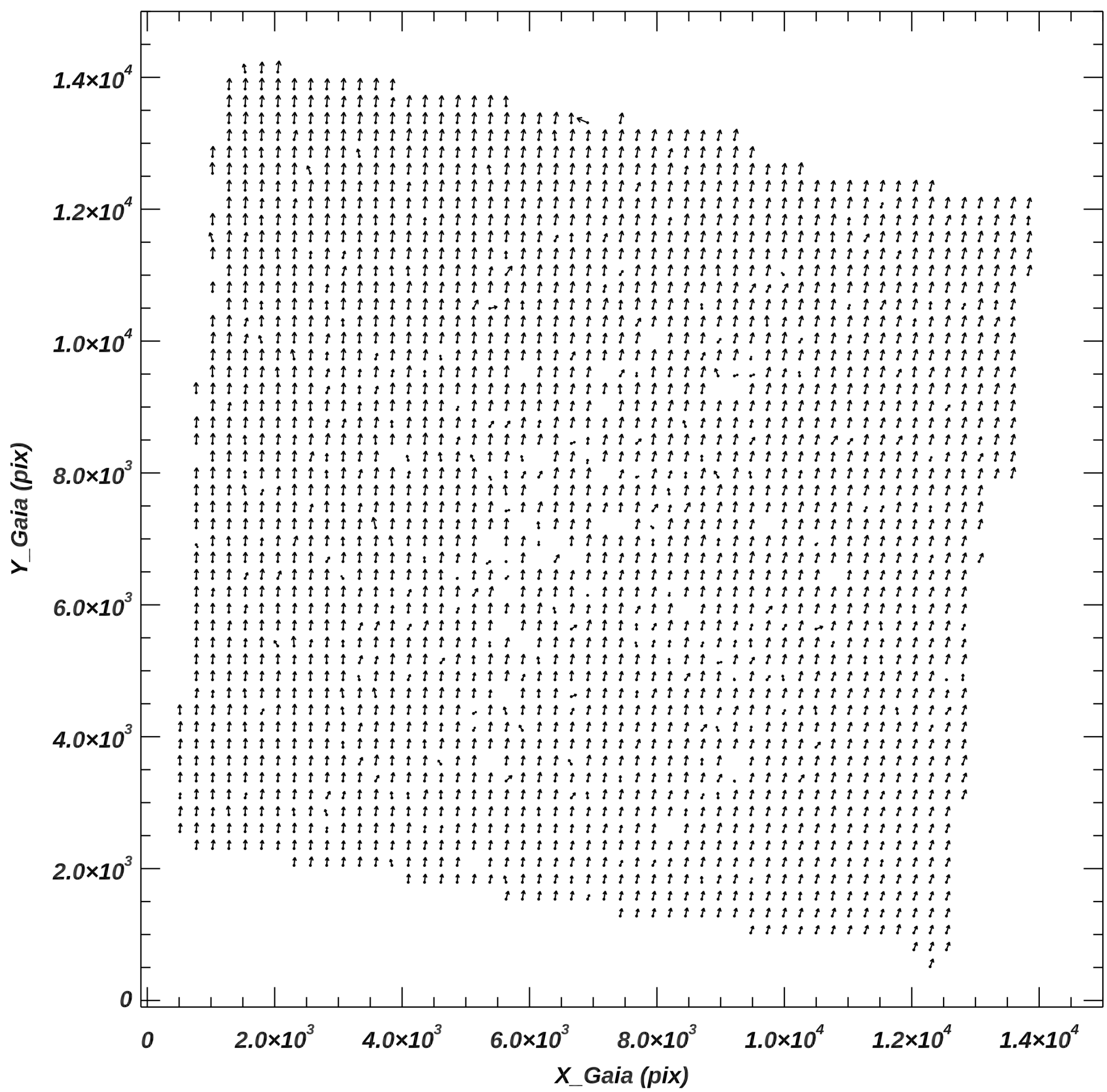

Figure 6: The difference in position between the Gaia and HST coordinates systems applying the global solid-body type rotation. The maximum length of the vector is 3 pixels (or 150 mas) and each vector magnified by a factor 50. The tangent-plane positions X and Y are in units of the ACS/WFC pixels

4.1.3 Effect of Scale

After applying both global shift and rotation, the pattern of X&Y residuals shows a vector growing from the central point towards the edges and varies with position over the field. According to Anderson & van der Marel (2010), this catalog was constructed from the set of ACS/WFC F435W, F625W and F658N images (GO-9442) taken at same pointing with large dither, the same roll-angle, and at the same observation time-span. The reference point corresponding to the center of the catalog located at X=7011 and Y=6960 pixels chosen as the tangential point for transformation of all sets of F625W images into the tangential X&Y

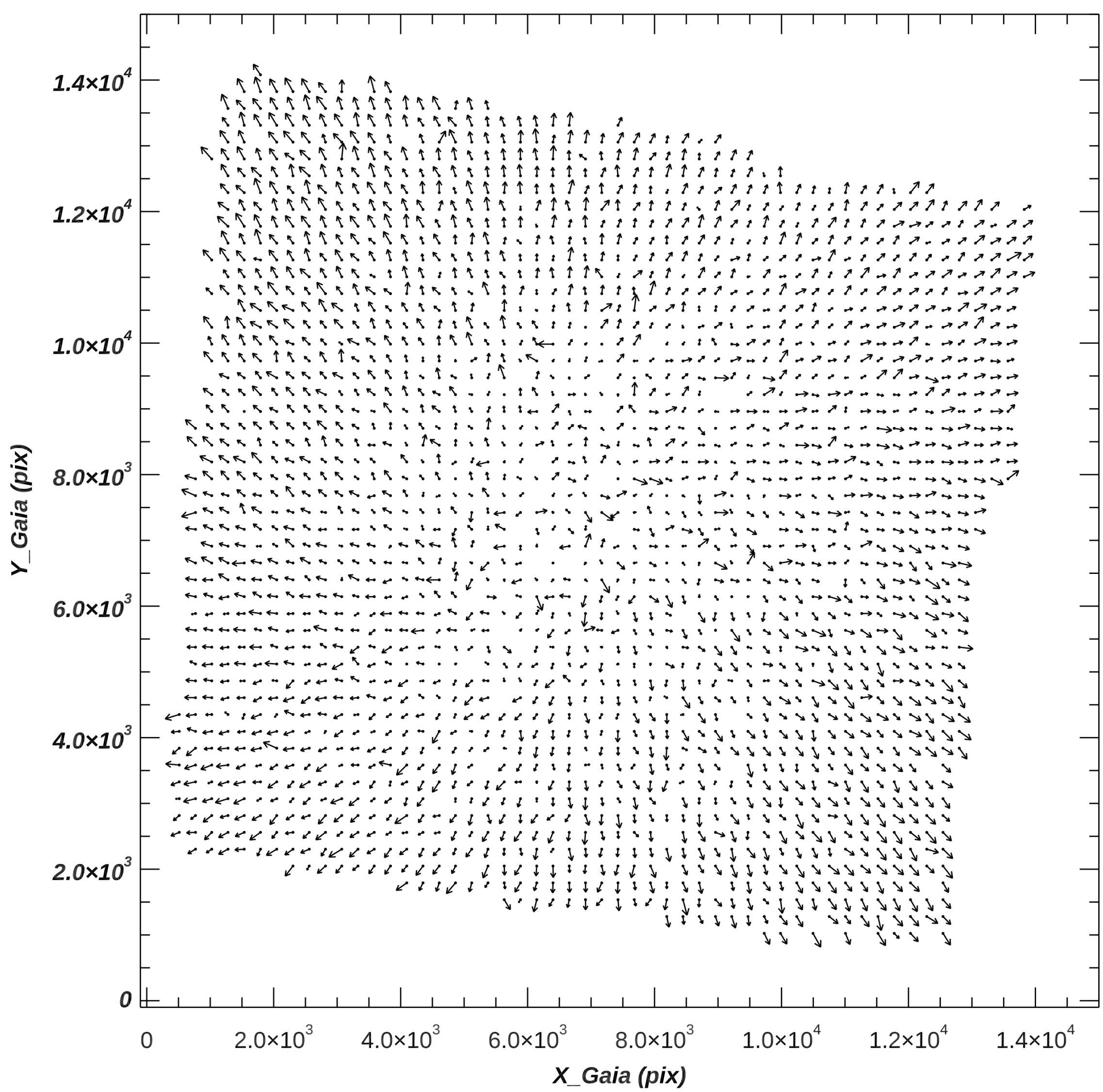

Figure 7: The difference in position between the Gaia and HST coordinates systems after subtracting of both global rotation and global positional shifts. There is a clear indication of a difference in scale. The size of the maximum vector is 0.5 pixels (or 25mas) and each vector magnified by a factor 500. The tangent-plane positions X and Y are in units of the ACS/WFC pixels.

positions to this reference point. Adding 4000 pixel to each coordinates so that entire catalog have the range of 1:14000 pixels for both axes with adopted scale of 50 *mas* per pixel. The global scale of the HST catalog is calculated as $\sqrt{(A_2B_3 + A_3B_2)}$, and is equal to 0.99994198 at the adopted reference point (see also Table 1). However as seen in Figure 7, the scale is not constant over the field. The variation of the global scale from the center to the far edges of the standard catalog is of the level of 8×10^{-5}. To calculate the difference in scale between the Gaia and the HST catalog, we took the ratio of (1.0/0.99994198), where the denominator is the calculated global scale (eq. 1,2 and Table 1) and multiplied by the adopted scale of 50 *mas*, will equal to the true scale. Thus, the true scale of the HST catalog is larger by 0.0029 *mas* than previously assumed and that introduces ∼11 *mas* (0.25 pix) error at the catalog edge (∼ 4000 pixels far away from the catalog center) which approximately equal to the maximum vector as seeing in Figure 7.

4.2 Validation of the HST Standard Astrometric Catalog

The derived transformation parameters from Eqs.1-2 in Sec.4.1 were used to compute inverse transformations to the positions of the HST catalog. These positions were then linearly transformed into the system of the Gaia reference frame, i.e. a corrected HST X&Y catalog of positions aligned to the Gaia reference frame.

Figure 8 shows the difference between the two coordinates systems after the correction of the HST standard catalog. Figure 8 shows that the large structural residual pattern seen in Figures 5, 6, 7 is now completely eliminated. The distribution of larger residuals is random mostly concentrated in the center of the catalog, with the largest *accidental* errors of ∼0.25 pixel. As shown in Figure 1, the spatial distribution of stars in the center of the cluster now is uniform comparing to Gaia DR1. Nevertheless, there are some non-uniform distribution of stars in the core of the cluster as seen in Figure 8. There are some cells with no stars at the center of the SAC. The applied strict quality filters to select stars with the reliable astrometric measurements in Section 3 reduced the number of sampled stars and particularly at the center of extreme stellar density and crowding issues in the core of ω Cen. Although the astrometric measurements significantly improved in EDR3 and the statistical uncertainties are reduced by 2 times, there also appear some spatially correlated systematic errors associated with the Gaia scanning law (Lindegren et al., 2020). Nevertheless, the precision and accuracy of the Gaia EDR3 is adequate for the final assessment of the accuracy of the HST standard astrometric catalog.

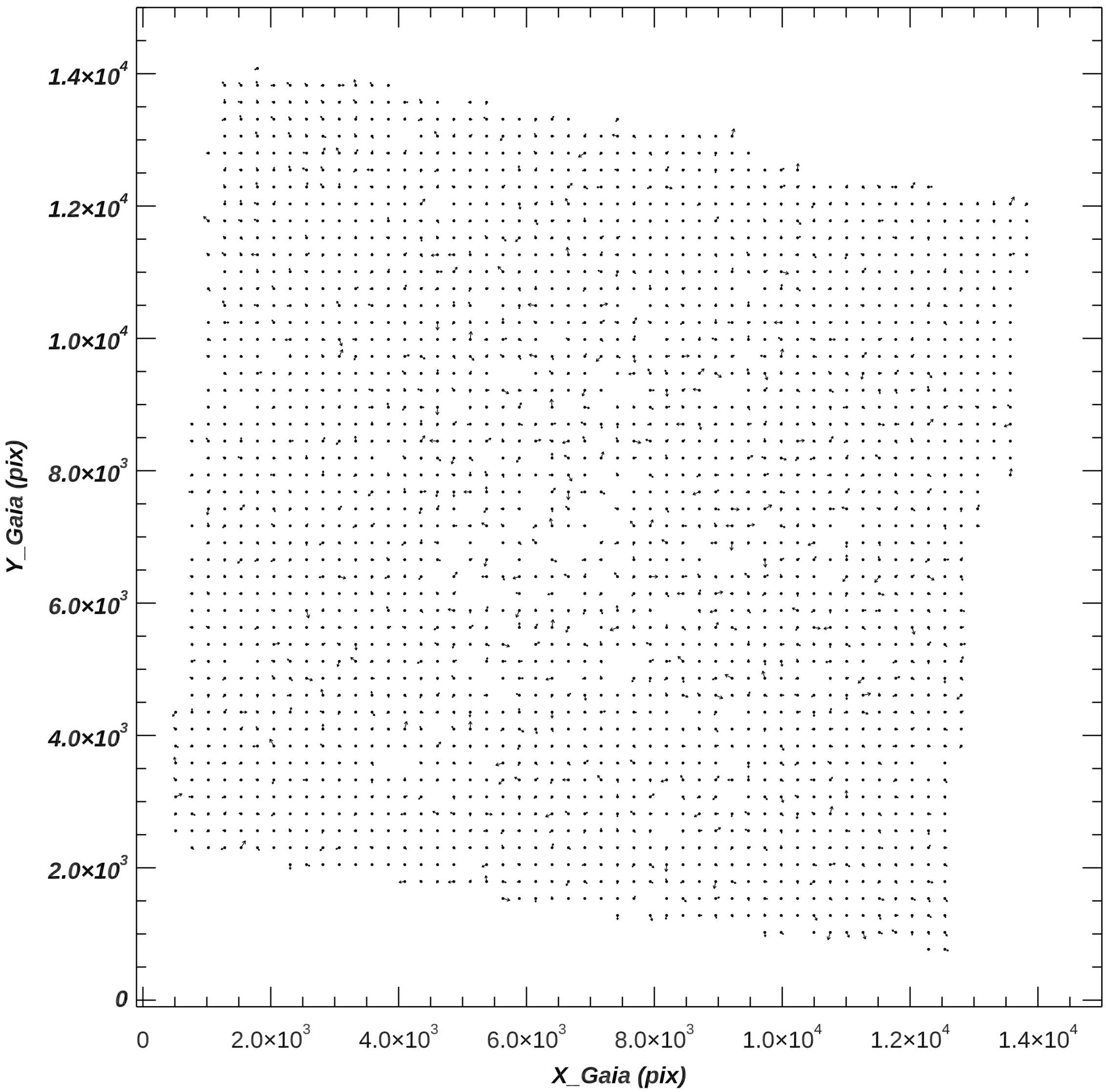

Figure 8: The difference in position between the Gaia and HST coordinates systems after accounting for both global rotation, global positional shifts and scale. Residuals are clearly now random, the large structural patterns are eliminated. The largest accidental vector is ~ 0.25 pixel (12 mass) and and each vector magnified by a factor 500. The tangent-plane positions X and Y are in units of the ACS/WFC pixels.

5 The WFC3/UVIS & IR geometric distortion and its application

5.1 IDCTAB correction for distortion

Instrument Distortion Coefficients Table (IDCTAB) is the reference file populated into the primary of the UVIS and IR images during the HST pipeline calibration and used in the HST

software DrizzlePac [2] (Hoffman *et al*, 2021) to correct the images for geometric distortion. The initial test of IDCTAB, back in 2010 have shown a significant amount of global rotation between the two coordinate systems. There were confidence in the accuracy of the chosen standard astrometric catalog in the vicinity of ω Cen based on ACS/WFC observations. The foundation of the confidence is based on the fact that the reference frame of the catalog have been aligned according to Anderson & van der Marel (2010) with the system of absolute astrometry from the Two Micron All Sky Survey (2MASS, Skrutskie et al. (2006)), which was the best representation of the International Celestial Reference System (ICRS) prior to the Gaia era. For the sanity test the graound-based observations of ω Cen by van Leeuwen et al. (2000a) and van Leeuwen et al. (2000b) were used to compare with the HST SAC. This independent comparison also found that there is a global rotation at the level of $0\overset{\circ}{.}085$. Thus, if the reference catalog used for the geometric distortion calibration has such offset in rotation, then this offset is transferred into the distortion model. Specifically, the polynomial coefficients are affected by the same amount of rotation. Therefore instead of rotation of the standard catalog, the polynomial coefficients of the geometric distortion were rotated as the following:

$$A'_n = A_n cos(\theta) - B_n sin(\theta) \tag{11}$$

$$B'_n = A_n sin(\theta) + B_n cos(\theta) \tag{12}$$

where, A_n and B_n are the 5th-order polynomial coefficients in X and Y solutions from Eq. 9-10 (Kozhurina-Platais et al., 2009b), θ is the angle of rotation between two coordinates systems and, A'_n & B'_n are rotated polynomial coefficients of the geometric distortion. These rotated polynomial coefficients were then transformed into the HST V2V3 coordinate system and converted into FITS format as reference file IDCTAB. *Hence since 2010* the WFC3/UVIS and IR reference file were delivered to the HST pipeline and used for the geometric distortion correction of the WFC3/UVIS and IR images.

5.2 Test of the WFC3/UVIS IDCTAB in DrizzlePac

The geometric distortion implemented in the HST software DrizlePac is designed to correct for the distortion and then align and combine HST images. One of these tasks is TweakReg in the DrizzlePac, which is an automated interface to compute the transformation parameters between HST images such as shift, rotation and scale. The Gaia EDR3 in the vicinity of ω Cen was used to test the current UVIS IDCTAB in the HST pipeline. In order to do so all WFC3/UVIS images of ω Cen from multi-cycle astrometric calibration program over 12 years were selected from the MAST (Mikulski Archival for Space Telescopes), a total of about 180 images. Thus, the Gaia EDR3 in the vicinity of ω Cen has been used as reference frame and the selected HST/WFC3/UVIS images were input images to find the transformation parameters, as described by Martlin et al. (2019). One of the systematic errors in the geometric distortion model is the error related to the rotation angle between the standard catalog and the images corrected for distortion. That angle in the geometric distortion is defined in a linear part of the distortion which has to be accurately calibrated. If there

[2] https://hst-docs.stsci.edu/drizzpac

are errors in the linear part of distortion, they will be introduced in the angle between the standard astrometric catalog and any UVIS drizzle images. Figure 9 shows the calculated angle from TwekReg between the Gaia EDR3 as the absolute reference coordinate system and each individual UVIS image as a function of time.

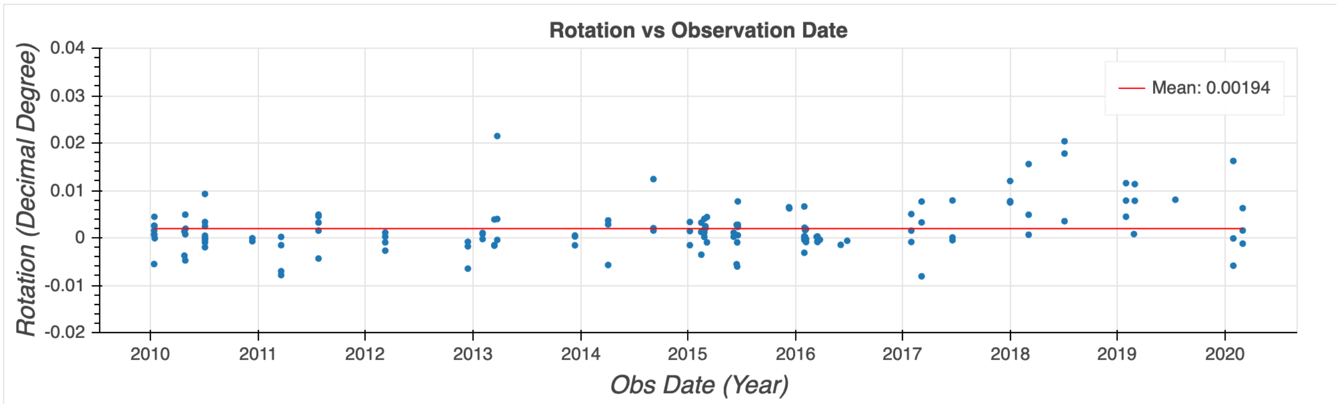

Figure 9: Rotation angle between Gaia EDR3 and each individual WFC3/UVIS image corrected for distortion as a function of time. Each point represents the calculated rotation angle from the corresponding TweakReg solution. The over-plotted red line shows the mean offset in the rotation angle, which equal to $\sim 0\overset{\circ}{.}002$ degree.

As seen in Figure 9, the angle between the Gaia EDR3 and each single UVIS image is close to zero with the maximum deviation from $-0\overset{\circ}{.}01$ to $0\overset{\circ}{.}02$. The largest deviation and scatter of these angles is around of 2018 and after when two gyros have failed and the implementation of the hybrid gyro mode. At that time, the HST encountered increased jitters in its pointing stability. The RMS of this jitters increased from 4 to 18 in 2019, and as a result there was instability in the angle between each individual WFC/UVIS image and Gaia EDR3. The mean angle of rotation between each UVIS image and Gaia EDR3 is 0.002 degree which correspond to $\sim 7''$. The offset by this amount could be explained by the linear part of the geometric distortion is being not accurately calibrated due to the errors in the standard astrometric catalog. On the other hand, the absolute astrometric coordinates system of the HST is known to be good to the level of 0.1-0.3$''$ by Koekemoer et al. (2005).

Another error in the geometric distortion model is the scale also defined in the linear part of distortion. Figure 10 shows the plate-scale for each WFC3/UVIS image calculated from the linear transformation of two coordinates systems, EDR3 and each individual WFC3/UVIS image corrected for distortion. As seen in Figure 10, the plate scale is not exactly equal 1 pixel. The difference between the ideal plate scale and the calculated plate scale introduces errors near the far edges of UVIS image at the level of 0.1 pixel or 4 *mas* which is on the verge of the accuracy specification for alignment of HST images. There is also some deviation from the mean scale, as seen in Figure 10, for example between 2010-2011 and 2015-2016. This scatter is due to the orbital breathing effect during the sequential HST orbits.

Thus, the current IDCTAB as a reference frame for the UVIS distortion correction with the comparison to the Gaia EDR3 have shown the error of rotation and plate-scale in the UVIS drizzle images at the level of 5-10 %.

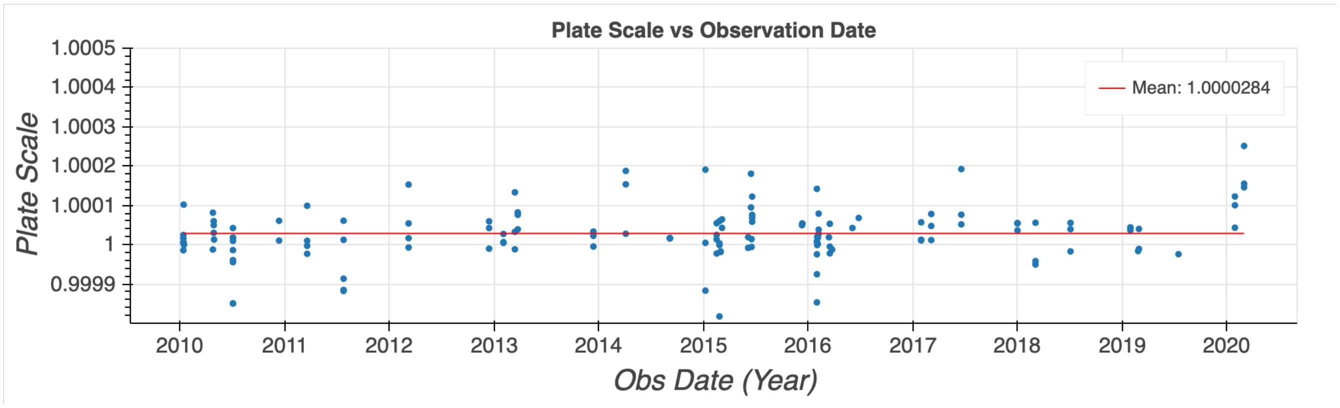

Figure 10: Calculated plate-scale from the linear transformation between two coordinates systems. Each point represents the calculated scale for each individual WFC3/UVIS image. The red line corresponds to the mean plate-scale equal to 1.0000284 UVIS pixel.

6 Conclusion

The Gaia EDR3 catalog was used here to validate the accuracy of the HST standard astrometric catalog in the vicinity of globular cluster ω Cen. The comparison of the two coordinate systems shows a significant distortion of the HST standard catalog based on ACS/WFC observations of ω Cen aligned to 2MASS astrometry. First, we found offsets in RA and Dec, at about -28 mas, and 136 mas respectively. These offsets are likely due to the errors in the absolute astrometry of the Two Micron All Sky Survey (2MASS, Skrutskie et al., 2006), which was the best representative of the International Celestial Reference System (ICRS) prior to the Gaia era. The global rotation between the HST standard catalog and Gaia EDR3 coordinate systems at the adopted reference point is about $0.^{\circ}1$, which is $\sim$100 times larger than the orientation uncertainty of the WFC3/UVIS. This comparison has also revealed a difference in scale between the HST standard astrometric catalog and the Gaia catalog, resulting by 0.0029 mas larger scale in the HST SAC. This difference introduces significant offsets of 12 mas (0.25pix) in positions at the distance of $\sim$4000 pixels from the center of the HST standard astrometric catalog.

Finalizing the components of low-order distortions in the HST standard catalogs and improving its average accuracy down to the level of 10 mas or better, will simultaneously improve the HST WFC3 astrometric calibration to the level of 1 mas. Consequently, the improved astrometric catalog will improve the calibration of the HST WFC3/UVIS and IR instruments and will finally remove existing uncertainties in several steps of the HST WFC3 images operation: 1) accurate stacking of various HST images taken with different dither patterns and at different orientations and inter-instruments; 2) cosmic-ray rejection with higher accuracy and precision in the drizzled-combined HST images; 3) enhancement of the spatial resolution; 4) deepening of the detection limit.

The improved astrometric calibration of the HST WFC3/UVIS and IR instruments relaying on Gaia EDR3 will reach a high and an accurate absolute astrometric precision level. The expected future Gaia data release will not further improved the HST astrometric calibration.

7 Acknowledgments

V.K-Platais sincerely expresses her gratitude for help with TexShop to N. Nikolov and Y. Cohen also for his help with new template of HST ISR in LaTex. V.K-Platais is grateful to Joel Green for careful reading of the preliminary version of the text and his useful comments & suggestions which improved significantly the clarity of ISR. V.K-Platais is grateful to I. Platais for useful discussion of the Gaia EDR3 product and its accuracy. We also acknowledge K. Sahu for reading the early version of ISR and his suggestions.

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