Astrometry and Photometry with HST WFC3. I. Geometric Distortion Corrections of F225W, F275W, F336W Bands of the UVIS Channel

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ABSTRACT. An accurate geometric distortion solution for the Hubble Space Telescope UVIS channel of Wide Field Camera 3 is the first step toward its use for high-precision astrometry. In this work we present an average correction that enables a relative astrometric accuracy of ∼1 mas (in each axis for well-exposed stars) in three broadband ultraviolet filters (F225W, F275W, and F336W). More data and a better understanding of the instrument are required to constrain the solution to a higher level of accuracy.

1. INTRODUCTION, DATA SET, MEASUREMENTS

The accuracy and stability of the geometric distortion (GD) correction of an instrument are critical to its use for high-precision astrometry. The particularly advantageous conditions of the Hubble Space Telescope (HST) observatory make it ideal for imaging astrometry of (faint) point sources. Not only are the point-spread functions (PSFs) sharp and (essentially) close to the diffraction limit—which directly results in high-precision positioning—but also the observations are unaffected by atmospheric effects (such as differential refraction, image motion, differential chromatic refraction, etc.), which severely limit ground-based astrometry. In addition, HST observations do not suffer from gravity-induced flexures on the structures of the telescope (and camera), which add (relatively) large instabilities in the GD of ground-based images, and make corrections more uncertain.

On 2009 May 14, the brand-new Wide Field Camera 3 (WFC3) was successfully installed during the Hubble Servicing Mission 4 (SM4, 2009 May 12–24). After a period of intense testing, fine tuning, and basic calibration, on 2009 September 9 the first calibration and science demonstration images were finally made public.

Our group is active in bringing HST to the state of the art of its astrometric capabilities, which we have used for a number of scientific applications (e.g., from King et al. 1998, to Bedin et al. 2009, i.e., the first and the most recently accepted papers). Now that the “old” Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) is successfully repaired, and the new instruments are installed, our first step is to extend our astrometric tools to the new instruments (and to monitor the old ones). This article is focused on the geometric distortion correction of the UV/Optical (UVIS) channel of the WFC3. Since the results of these efforts might have some immediate public utility (e.g., relative astrometry in general, stacking of images, UV identification of X counterparts such as pulsars and CVs in globular clusters, etc.), we made our results available to the WFC3/UVIS user community.

We immediately focused our attention on a deep-UV survey of the core of the Galactic globular cluster ω Centauri (NGC 5139), where some well-dithered images were collected. The dense—and relatively flat—stellar field makes the calibration particularly suitable for deriving and monitoring the GD on a relatively small spatial scale. In addition, while most of the efforts to derive a GD correction will be concentrated on relatively redder filters, we undertook a study to determine the GD solutions of the three bluest broadband filters (with the exception of F218W): F225W, F275, and F336W.

The WFC3/UVIS layout is almost indistinguishable from that of ACS/WFC: two e2v thinned, backside illuminated, and UV optimized 2k × 4k CCDs contiguous on the long side of the chip, and covering a field of view (FOV) of ∼160 × 160 arcsec2. The ω Cen data set used here consists of 9 × 350 s exposures in each of the filters F225W, F275W,
and F336W. The nine images follow a squared $3 \times 3$ dither pattern with a step of about 40″ (i.e., ~1000 pixels), and were all collected on 2009 July 15.

We downloaded the standard pipeline-reduced FLT files from the archive. The FLT images are debiased and flat-field corrected, but no pixel resampling is performed on them. The FLT files are multiextension fits (MEF) on which the first slot contains the image of what, hereafter, we will call chip 1 (or simply [1]). The second chip, instead, is stored in the fourth slot of the MEF, and we will refer to it as chip 2 (or [2]). (Note that others might choose a different notation.) Our GD corrections refer to the raw pixel coordinates of these images.

The fluxes and positions were obtained from a code mostly based on the software img2xym WFI by Anderson et al. (2006). This is essentially a spatially variable PSF-fitting method. We were pleased to see that for the WFC3/UVIS images of this data set, the PSFs were only marginally undersampled. The left panel of Figure 1 shows a preliminary color-magnitude diagram in the three filters for the bright stars in the WFC3/UVIS data set. In a future article in this series we will discuss the PSF and its spatial variation and stability, as well as L-flats, 4 pixel-area corrections, and recipes for deep photometry in stacked images.

Fig. 1.—Left: Preliminary color-magnitude diagram of the bright stars in the new WFC3/UVIS data set (fluxes are neither pixel-area- nor L-flat corrected). Right: Color-magnitude diagram of the stars in our ACS/WFC master frame (from Villanova et al. 2007). Both plots are in instrumental magnitudes.

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4 Residual low-frequency flat-field structure (L-flat) cannot be accurately determined from ground-based calibration data or internal lamp exposures. L-flats need to be determined from on-orbit science data, for example, from multiple observations of stellar fields with different pointings and roll angles (van der Marel 2003).
2. THE GEOMETRIC DISTORTION SOLUTIONS

The most straightforward way to solve for the GD would be to observe a field where there is a priori knowledge of the positions of all the stars in a distortion-free reference frame. (A distortion-free reference frame is a system that can be transformed into any other distortion-free frame by means of conformal transformations.) Geometric distortion would then show itself immediately as the residuals between the observed relative positions of stars and the ones predicted by the distortion-free frame (on the basis of a conformal transformation).

Thankfully, we possess such an “astrometric flat field,” moreover with the right magnitude interval, source density, and accuracy. This reference frame is the mosaic of $3 \times 3$ ACS/WFC fields collected at the end of 2002 June under the program GO-9442 (PI: Cool), reduced by Jay Anderson, and published in Villanova et al. (2007). This reference frame was obtained from a total of 18 short and 90 long ACS/WFC exposures in the filters: F435W, F625W, and F658N (see Villanova et al. 2007 for details). The entire field covers an area of $10 \times 10 \text{arcmin}^2$, and can be considered distortion-free at the $\sim 0.5 \text{mas}$ level. The catalog contains more than 2 million sources, and we will refer to it as master frame, and to the coordinates of each i-source in it with the notation $(X_i^{\text{master}}, Y_i^{\text{master}})$. A color-magnitude diagram for the stars in the master frame is shown in the right panel of Figure 1.

To derive the WFC3/UVIS GD corrections we closely follow the procedures described in Anderson & King (2003, hereafter AK03) used to correct the GD for each of the four detectors of WFPC2. We represent our solution with a third-order polynomial, which is able to provide our final GD correction to the $\sim 0.025 \text{ pixel}$ level in each coordinate ($\sim 1 \text{ mas}$). Higher orders proved to be unnecessary.

Having a separate solution for each chip, rather than one that uses a common center of the distortion in the FOV, allows a better handle of potential individual detector effects (such as a different relative tilt of the chip surfaces, relative motions, etc.). We adopted as the center of our solution, for each chip,
the point \((x, y)\) is given by \((x', y') = (x, y) + \delta(x, y)\). For each \(i\) star of the master list, in each \(k\) chip of each \(j\)-MEF file, the distortion corrected position \((x'^{\text{corr}}, y'^{\text{corr}})\) is the observed position \((x, y)\) plus the distortion correction \((\delta x, \delta y)\):

\[
\begin{align*}
\delta x_{i,j,k} &= x_{i,j,k} - x_{i,j,k}^0, \\
\delta y_{i,j,k} &= y_{i,j,k} - y_{i,j,k}^0,
\end{align*}
\]

where \(x_{i,j,k}^0\) and \(y_{i,j,k}^0\) are the normalized positions, defined as

\[
\begin{align*}
x_{i,j,k}^0 &= \frac{x_{i,j,k} - \langle x_{i,j,k} \rangle}{\sigma_{x_{i,j,k}}}, \\
y_{i,j,k}^0 &= \frac{y_{i,j,k} - \langle y_{i,j,k} \rangle}{\sigma_{y_{i,j,k}}}.
\end{align*}
\]

Normalized positions make it easier to recognize the magnitude of the contribution given by each solution term, and their numerical round-off.

The final GD correction for each star, in each chip/image, is given by these two third-order polynomials (we omitted here \(i, j, k\) indexes for simplicity):

\[
\begin{align*}
\delta x &= a_1 x^3 + a_2 y^3 + a_3 x^2 + a_4 x y^2 + a_5 y^3 + a_6 y^2 + a_7 x y + a_8 x + a_9 y + a_{10}, \\
\delta y &= b_1 x^3 + b_2 y^3 + b_3 x^2 + b_4 x y^2 + b_5 y^2 + b_6 x y + b_7 x + b_8 y + b_{10},
\end{align*}
\]

Our GD solution is thus fully characterized by 18 coefficients: \(a_1, \ldots, a_9, b_1, \ldots, b_{10}\). However, as done in AK03, we constrained the solution so that, at the center of the chip, its \(x\)-scale is equal to the one at the location \((x_0, y_0)\), and the corrected axis \(y'^{\text{corr}}\) is aligned with its \(y\)-axis at the location \((x_0, y_0)\). This is obtained by imposing \(a_{1, k} = 0\) and \(a_{2, k} = 0\). Since the detector axes do not necessarily have the same scales nor are they perpendicular to each other, \(b_{1, k}\) and \(b_{2, k}\) must be free to assume whatever values fit best. Therefore, we have to compute only 16 coefficients (per chip) to derive our GD solution.

Each \(i\) star in the master frame is conformally transformed into each \(k\) chip/image, and cross-identified with the closest source. We indicate such transformed positions with \((X_i^{\text{master}})^{T_{i,k}}\) and \((Y_i^{\text{master}})^{T_{i,k}}\). Each of such cross-identifications, when available (of course not all the red sources in the master list were available in the WFC3 UV-filters), generates a pair of positional residuals

\[
\begin{align*}
\Delta x_{i,j,k} &= x_{i,j,k}^{\text{corr}} - X_i^{\text{master}}^{T_{i,k}}, \\
\Delta y_{i,j,k} &= y_{i,j,k}^{\text{corr}} - Y_i^{\text{master}}^{T_{i,k}},
\end{align*}
\]

which reflect the residuals in the GD (with the opposite sign), and depend on where the \(i\) star fell on the \(k/j\) chip/image (plus random deviations due to nonperfect PSF fitting and photon noise). Note that our calibration process is an iterative procedure, and that necessarily, at the first iteration, we have to impose \((x_{i,j,k}^{\text{corr}}, y_{i,j,k}^{\text{corr}}) = (x, y)\). In each chip/image we have typically \(\approx 5500\) high-signal unsaturated stars in common with the master frame, leading to a total of \(\approx 50000\) residual pairs chip\(^{-1}\). (A color-magnitude diagram of the stars actually used to compute the GD solution is shown, for each filter, in Fig. 2.)

For each chip, these residuals were then collected into a look-up table made up of \(37 \times 19\) elements, each related to a region of 110 \( \times \) 110 pixels. We chose this particular grid setup because it offers the best compromise between the need for an adequate number of grid points to model the GD, and an adequate sampling of each grid element, containing at least 60 pairs of residuals. For each grid element, we computed a set of five \(\sigma\)-clipped quantities: \(\Delta x_{m,n,k}, \Delta y_{m,n,k}, \Delta x_{m,n,k}', \Delta y_{m,n,k}'\), and \(P_{m,n,k}\); where \(\Delta x_{m,n,k}\) and \(\Delta y_{m,n,k}\) are the averaged positions of all the stars within the grid element \((m, n)\) of the \(k\) chip, and \(\Delta x_{m,n,k}', \Delta y_{m,n,k}'\) are the average residuals, and \(P_{m,n,k}\) is the number of stars that were used to calculate the previous quantities. These \(P_{m,n,k}\) quantities will also serve in associating a weight to the grid cells when we fit the polynomial coefficients.

### Table 1: Coefficients of the Third-Order Polynomial for Each Chip and Filter

| Term \((q)\) | Polynomial | \(a_{1,q}\) | \(a_{2,q}\) | \(a_{3,q}\) | \(a_{4,q}\) | \(a_{5,q}\) |
|-------------|-----------|-------------|-------------|-------------|-------------|-------------|
| WFC3/UVIS Filter F275W | \(\bar{x}\) | 0.000 | 129.230 | 0.000 | 140.270 |
| | \(\bar{y}\) | 0.000 | 0.000 | 1.935 | 0.000 | -4.215 |
| | \(x^2\) | 12.120 | 0.039 | 0.000 | 0.000 | 0.773 |
| | \(x\) | 6.279 | 5.533 | 6.057 | 5.496 |
| | \(y^2\) | 0.064 | -3.227 | 0.001 | -3.058 |
| | \(x\) | 0.176 | 0.046 | 0.149 | 0.000 | 0.156 |
| | \(y\) | -0.075 | 0.033 | 0.022 | -0.009 |
| | \(x^2\) | 0.004 | -0.041 | 0.061 | 0.000 | -0.026 |
| | \(y\) | 0.035 | -0.023 | 0.032 | 0.0280 |

**WFC3/UVIS Filter F275W**

| Term \((q)\) | Polynomial | \(a_{1,q}\) | \(a_{2,q}\) | \(a_{3,q}\) | \(a_{4,q}\) | \(a_{5,q}\) |
|-------------|-----------|-------------|-------------|-------------|-------------|-------------|
| WFC3/UVIS Filter F336W | \(\bar{x}\) | 0.000 | 129.270 | 0.000 | 140.285 |
| | \(\bar{y}\) | 0.000 | 1.925 | 0.000 | -4.221 |
| | \(x^2\) | 12.102 | 0.581 | 0.000 | 0.000 | 0.781 |
| | \(x\) | 6.284 | 5.547 | -6.040 | 5.493 |
| | \(y^2\) | 0.061 | -3.241 | 0.001 | -3.048 |
| | \(x\) | 0.178 | 0.033 | 0.144 | 0.000 | 0.163 |
| | \(y\) | -0.056 | 0.034 | 0.026 | 0.007 |
| | \(x^2\) | 0.005 | -0.041 | 0.051 | 0.000 | -0.025 |
| | \(y\) | 0.033 | -0.012 | 0.032 | 0.0200 |

**WFC3/UVIS Filter F336W**

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To obtain the 16 coefficients describing the two polynomials \((a_{q,k} \text{ with } q = 3, \ldots, 9, \text{ and } b_{q,k} \text{ with } q = 1, \ldots, 9)\), which represent our GD solution in each chip, we perform a linear least-squares fit of the \(N = m \times n = 37 \times 19 = 703\) data points. Thus, for each chip, we can compute the average distortion correction in each cell (\(\delta x_{p,k}, \delta y_{p,k}\)) with \(N\) relations of the form

\[
\begin{align*}
\delta x_{p,k} &= \sum_{q=1}^{9} a_{q,k} t_{q,p,k} \\
\delta y_{p,k} &= \sum_{q=1}^{9} b_{q,k} t_{q,p,k}
\end{align*}
\]

(where \(t_{1,p,k} = \tilde{x}_{p,k}, t_{2,p,k} = \tilde{y}_{p,k}, \ldots, t_{9,p,k} = \tilde{y}_{p,k}\)), and where the 16 unknown quantities—\(a_{q,k}\) and \(b_{q,k}\)—are our fitting parameters (16 for each chip).

In order to solve for \(a_{q,k}\) and \(b_{q,k}\), we formed, for each chip, one \(9 \times 9\) matrix \(M_k\) and two \(9 \times 1\) column vectors \(\mathbf{v}_a\) and \(\mathbf{v}_b\):

\[
M_k = \begin{pmatrix}
\begin{array}{cccc}
\sum_{p} P_{p,k} t_{1,p,k}^2 & \sum_{p} P_{p,k} t_{1,p,k} t_{2,p,k} & \cdots \\
\sum_{p} P_{p,k} t_{2,p,k} t_{1,p,k} & \sum_{p} P_{p,k} t_{2,p,k}^2 & \cdots \\
\vdots & \vdots & \ddots \\
\sum_{p} P_{p,k} t_{9,p,k} t_{1,p,k} & \sum_{p} P_{p,k} t_{9,p,k} t_{2,p,k} & \cdots \\
\end{array}
\end{pmatrix}

\begin{pmatrix}
\begin{array}{c}
\sum_{p} P_{p,k} t_{1,p,k} \Delta x_{p,k} \\
\sum_{p} P_{p,k} t_{2,p,k} \Delta x_{p,k} \\
\vdots \\
\sum_{p} P_{p,k} t_{9,p,k} \Delta x_{p,k}
\end{array}
\end{pmatrix}

\begin{pmatrix}
\begin{array}{c}
\sum_{p} P_{p,k} t_{1,p,k} \Delta y_{p,k} \\
\sum_{p} P_{p,k} t_{2,p,k} \Delta y_{p,k} \\
\vdots \\
\sum_{p} P_{p,k} t_{9,p,k} \Delta y_{p,k}
\end{array}
\end{pmatrix}

\mathbf{v}_a = \begin{pmatrix}
\begin{array}{c}
a_{1,k} \\
a_{2,k} \\
\vdots \\
a_{9,k}
\end{array}
\end{pmatrix}

\mathbf{v}_b = \begin{pmatrix}
\begin{array}{c}
b_{1,k} \\
b_{2,k} \\
\vdots \\
b_{9,k}
\end{array}
\end{pmatrix}

The solution is given by two \(9 \times 1\) column vectors \(A_k\) and \(B_k\), containing the best-fitting values for \(a_{q,k}\) and \(b_{q,k}\), obtained as:

\[
A_k = \mathbf{M}_k^{-1} \mathbf{v}_a, \quad B_k = \mathbf{M}_k^{-1} \mathbf{v}_b.
\]

With the first set of calculated coefficients \(a_{q,k}\) and \(b_{q,k}\) we computed the corrections \(\delta x_{i,j,k}\) and \(\delta y_{i,j,k}\) to be applied to each \(i\)-star of the \(k\)-chip in each \(j\)-MEF file, but actually we corrected the positions only by half of the recommended values, to guarantee convergence. With the new improved star positions, we start-over and recalculated new residuals. The procedure is iterated until the difference in the average correction from one iteration to the following one—for each grid point—became smaller than 0.001 pixel. Convergence was reached after \(\sim 100\) iterations. The coefficients of the final GD solutions for the two chips, and for the three different filters, are given in Table 1.

In Figure 3 we show for the intermediate filter F275W the total residuals of uncorrected star positions versus the predicted positions of the master frame, which is representative of our GD solutions. For each chip, we plot the \(37 \times 19\) cells used to model the GD, each with its distortion vector magnified (by a factor of \(\times 8\) in \(x\), and by a factor of \(\times 1.5\) in \(y\)). Residual vectors go from the average position of the stars belonging to each grid cell \((\bar{x}, \bar{y})\) to the corrected one \((\bar{x}_{\text{corr}}, \bar{y}_{\text{corr}})\). Side panels show the overall trends of the individual residuals \(\delta x, \delta y\) along \(x\) and \(y\) directions (where for clarity we plot only a 40% subsample, randomly selected). It immediately strikes the large linear terms in \(y\), reaching up to \(\sim 140\) pixels.

In Figure 4 we show, in the same way, the remaining residuals after our GD solution is applied. This time we magnified the distortion vectors by a factor \(\times 1500\) in both axes.

At this point it is very interesting to examine the r.m.s. of these remaining residuals, which shows a rather large \(\sim 0.15\) pixel dispersion. We will see that this dispersion can be interpreted as the effect of the internal motions of the cluster stars on the time baseline of \(\sim 7\) yr between the ACS/WFC observations of the reference frame, and the new WFC3/UVIS data set. Indeed, assuming (1) a distance of 4.7 kpc for \(\omega\) Cen (van der Marel & Anderson 2009), (2) an internal velocity dispersion of \(\sim 18\) km s\(^{-1}\) in our fields (van de Ven et al. 2006), and (3) an anisotropic velocity dispersion for stars, in \(\sim 7\) yr we would expect to observe a dispersion of the displacements of \(\sim 5.5\) mas. This dispersion, assuming a pixel scale of \(\sim 40\) mas for WFC3/UVIS, corresponds to a displacement of \(\sim 0.14\) pixel (also in good agreement with the recent measurements by Anderson & van der Marel 2009).

To show this more clearly we intercompare the average positions of the nine WFC3/UVIS corrected catalogs in the filter F275W with those in the F336W, for the stars in common between the two filters. All these images were taken at the same epoch, and so positions of stars are not affected by internal motion effects. The one-dimension dispersion should reflect our accuracy, and indeed the observed residuals in this case have a dispersion of \(\sim 0.025\) pixels (i.e., \(\sim 1\) mas). Figure 5 illustrates the two situations. On the left panel we plot the displacements between the ACS/WFC epoch of the reference frame and the new WFC3/UVIS epoch, while on the right panel we show the displacements between our corrected position in filter F275W and the corrected positions in F336W. On the left panel
the internal motions of \( \omega \) Cen dominate the dispersion, while on the right panel, there are no internal motions at all, and what we are left with are our errors only.

Unfortunately the WFC3/UVIS images were either not enough, or not sufficiently well dithered to perform a pure auto-calibration, and we had to use the ACS/WFC reference frame. Nevertheless, even a dispersion of 0.15 pixel within a given cell should be reduced to less than 0.02 pixel if averaged over more than 60 residuals. And this should be regarded as an upper limit, since we are using 703 grid points to constrain 16 parameters.

For this reason, the estimated 0.025 pixel accuracy is larger than we would have expected. We cannot exclude the possibility that these residuals could be due to a deviation from an isotropic distribution of the internal motion of \( \omega \) Cen (i.e., at the level of

Fig. 3.—Predicted vs. uncorrected positions. The size of the residual vectors is magnified by a factor of \( \times 8 \) in \( x \) and \( \times 1.5 \) in \( y \). For each chip we also plot individual residuals as function of \( x \) and \( y \) axes. Units are expressed as WFC3/UVIS pixels in the reference positions \((x, y)\). For clarity, only a random 40% of the residuals are plotted. See the electronic edition of the PASP for a color version of this figure.
\( \lesssim 3 \text{ km s}^{-1} \), or simply to unexpectedly large errors in the adopted ACS/WFC astrometric flat field (the master frame). Another possibility is that there could be some unexpected (and so far undetected) manufacturing artifact in the WFC3/UVIS detectors that could affect the positions (such as those identified on WFPC2 CCDs, and characterized by Anderson & King 1999, or those of ACS/WFC found by Anderson 2002). Finally, it could simply be a higher-frequency spatial variation that cannot be properly represented by a polynomial of a reasonable order, but rather requires a residual table as done in Anderson (2006) for ACS/WFC. Surely, more data are needed to further improve the GD solutions presented in this work, as well as a better time baseline for the understanding of its variations. We want to end this section by pointing out that the detection of the internal motions among the stars of a Galactic globular cluster is a rather challenging measurement,

Fig. 4.—Same as Fig. 3 after the correction was applied. The size of the residuals is now magnified by a factor of 1500. See the electronic edition of the PASP for a color version of this figure.
and it could well be one of the best demonstrations of the goodness of our derived geometric distortion solutions.

### 3. INTERCHIP TRANSFORMATIONS

For many applications it would be useful to transform the GD corrected positions of each chip into a common distortion-free reference frame. We could then simply conformally transform the corrected positions of chip \([k]\) into the distortion corrected positions of chip \([1]\), using the following relations

\[
\begin{align*}
(x^{\text{corr}}_{k}) &= \frac{\alpha_{[k]}}{\alpha_{[1]}} \left[ \cos(\theta_{[k]} - \theta_{[1]}) \sin(\theta_{[k]} - \theta_{[1]}) \right] \\
(y^{\text{corr}}_{k}) &= \frac{\alpha_{[k]}}{\alpha_{[1]}} \left[ -\sin(\theta_{[k]} - \theta_{[1]}) \cos(\theta_{[k]} - \theta_{[1]}) \right] \\
&\times \left( x^{\text{corr}}_{[k]} - 2048 \right) + \left( x^{\text{corr}}_{[1]} \right) \\
&\times \left( y^{\text{corr}}_{[k]} - 1025 \right) + \left( y^{\text{corr}}_{[1]} \right)
\end{align*}
\]

where—following the formalism in AK03—we indicate the scale factor as \(\alpha_{[k]}\), the orientation angle with \(\theta_{[k]}\), and the positions of the center of the chip \((x_{c}, y_{c})\) in the corrected reference system of chip \([1]\) as \((x^{\text{corr}}_{[1]})(y^{\text{corr}}_{[1]})\). Of course, for \(k = 1\), we end up with the identity. The values of the interchip

| \(k\)-chip | \(\alpha_{[k]} / \alpha_{[1]}\) (number) | \(\theta_{[k]} - \theta_{[1]}\) (°) | \((x^{\text{corr}}_{[k]})_{[1]}\) (pixel) | \((y^{\text{corr}}_{[k]})_{[1]}\) (pixel) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| [1] ....... | 1.00000 | 0.0000 | 2048.00 | 1025.00 |
| [2] ....... | 1.00595 | 0.0654 | 2046.00 | 3098.34 |
| \[\pm 2/100,000 \] | \[\pm 0.001 \] | \[\pm 0.03 \] | \[\pm 0.03 \] |

**Note.**—Chip [1] parameters are indicated only for clarity. For chip [2], formal errors are given.

![Fig. 5.](image1)

**Fig. 5.**—*Left:* Vector-point diagram of displacements for the stars in common between the ACS/WFC epoch of the master catalog, and the average of the corrected WFC3/UVIS new data in filter F275W. The internal motions of \(\omega\) Cen dominate the observed dispersions, but do not prevent a GD solution accurate to \(\sim 0.025\) WFC3 pixel. *Right:* Vector-point diagram of displacements for the stars in common between the corrected WFC3/UVIS data in filter F336W, and those corrected for F275W. The images are collected at the same epoch, and no sizable internal motions are present. In this case, the dispersion reflects our errors. The circles in both panels indicate the one-dimensional dispersion of the residuals, and all quantities are expressed as WFC3/UVIS pixels. See the electronic edition of the *PASP* for a color version of this figure.

**Fig. 6.**—Interchip transformation parameters as obtained from individual images. Data points from F225W are indicated with circles, F275W with triangles, and F336W with crosses. The averages are indicated with solid lines, while the dashed lines give the formal uncertainties.
transformation parameters are given in Table 2, and shown for individual images in Figure 6.

4. AVERAGE ABSOLUTE SCALE RELATIVE TO ACS/WFC

The final step is to link, for each filter, the WFC3/UVIS chip [1] to an absolute plate scale in mas. For this purpose we adopt an average plate scale for our ACS/WFC master frame of 49.7248 mas ACS/WFC-pixel\(^{-1}\) (from van der Marel et al. 2007), and multiplied it by the measured scale factor between the WFC3/UVIS chip [1] and the master frame (which is expressed in ACS/WFC pixels). The results for the individual images and the averages for each filter, are shown in Figure 7, while Table 3 gives the average values in mas pixel\(^{-1}\). We believe that the differences in the relative values for the three filters are significant. The fact that the plate scales correlate with the wavelength suggests that refraction introduced by either the filters, or by the two fused-silica windows of the dewar, could have some role.

Concerning their absolute values, instead, we have to consider that the velocity of \(HST\) around the Earth (\(\pm 7 \text{ km s}^{-1}\)) causes light aberration which induces plate-scale variations up to 5 parts in 100,000 (Cox & Gilliland 2002), and that our master frame (from Villanova et al. 2007) was not corrected for it.

The ACS/WFC plate scale for the Anderson’s (2006, 2007) GD solution, once corrected for the temporal variations of the linear terms, has proved to be stable at a level of accuracy better than these velocity aberration variations (van der Marel et al. 2007). However, since we are not attempting to correct for this effect on our adopted ACS/WFC master frame, we simply limit the accuracy of the WFC3/UVIS plate-scale absolute values derived here to these accuracies, i.e., 12 parts in 100,000.

5. CONCLUSIONS

By using a limited (but best available) number of exposures with large dithers, and an existing ACS/WFC astrometric flat field, we have found a set of third-order correction coefficients to represent the geometric distortion of WFC3/UVIS in three broadband ultraviolet filters. The solution was derived independently for each of its two CCDs.

The use of these corrections removes the distortion over the entire area of each chip to an average accuracy of \(\sim 0.025\) pixel (i.e., \(\sim 1\) mas), the largest systematics being located in the \(\sim 200\) pixels closest to the boundaries of the detectors (and never exceeding 0.06 pixel). We advise the use of the inner parts of the detectors for high-precision astrometry. The limitation that has prevented us from removing the distortion at an even higher level of accuracy is the lack of sufficient observations collected at different roll angles and dithers which could enable us to perform an autocalibration.

Nevertheless, the comparison of the mid-2002 ACS/WFC positions with the new WFC3 observations corrected with our astrometric solutions is good enough to clearly show the internal motions of \(\omega\) Centauri. The positions from 2002 proved to be in perfect agreement with the most recent determinations.

We also derived the average absolute scale of the detector with an accuracy limited by the uncertainties in the plate-scale variations induced by the velocity aberration of the telescope motion in the Earth-Sun system.

For the future, more data with a longer time baseline are needed to better characterize the GD stability of \(HST\) WFC3/UVIS detectors in the medium and long term.

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4If we add to this the Earth velocity around the Sun, the plate-scale variations can reach up to 12 parts in 100,000 (Cox & Gilliland 2002).

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![Figure 7](image-url)
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Note added in proof.—We want to state clearly to the reader that this is not the official calibration which will be delivered on the IDC tab file. The WFC3 team is working independently on an official GD correction suitable for DRZ pipeline-reduced DRZ images also in these filters.