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WFC3 SMOV Proposal 11444 - UVIS Geometric Distortion Calibration

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Abstract

The goal of the WFC3 SMOV4 astrometric calibration program –11444 is to obtain a coordinate system free of distortion to a precision level of 0.2 pixels or ∼ 8 mas. The astrometric calibration of WFC3/UVIS is based on two astrometric standard fields: a reference frame in the globular cluster 47 Tuc and in the Large Magellanic Cloud. Both 47 Tuc and the Large Magellanic Cloud, observed with the F606W filter and with different dither patterns, have been used to determine the geometric distortion in WFC3/UVIS. We used a 4th-order polynomial model to derive the geometric distortion in the UVIS channel relative to the distortion–free coordinates of our astrometric fields. As a result, the geometric distortion can be successfully corrected down to the precision level of 2 mas, which is four times better than the required precision.

1. Introduction

A new instrument, *Wide Field Camera 3* (WFC3), a fourth generation imaging instrument of *HST*, was installed on *HST* during Servicing Mission 4 in May 2009. The

Servicing Mission Orbital Verification (SMOV) observations (proposal 11444, PI L. Dressel) with the *WFC3/UVIS* channel are used to derive the geometric distortion of the detector. Preliminary optical ray-tracing model demonstrated that the geometric distortion in *WFC3/UVIS* camera is severe, on the order of $\sim 7\%$ across the detector. This distortion in the form of displacement of celestial sources from their true positions on the sky can reach up to about 120 pixels or ∼5 arcseconds. The knowledge of accurate geometric distortion is important **not only** for deriving accurate positions, parallaxes and proper motions of the scientifically interesting objects **but also to rectify the WFC3/UVIS images**, and to stack multiple exposures of dithered *UVIS* images. The Multidrizzle software (Koekemoer 2002), currently installed in the STScI on-the-fly pipeline (OTFR), requires an accurate distortion correction in order to combine dithered *WFC3/UVIS* images, to enhance spatial resolution, and to deepen the detection limit. If the geometric distortion correction implemented in Multidrizzle is not accurate enough, then the UVIS combined frames can produce blurred images and distorted under-sampled Point Spread Function (PSF). Any significant uncertainty in geometric distortion is detrimental to alignment of *WFC3/UVIS* images with MultiDrizzle and to mitigating the under-sampled PSF.

The goal of the SMOV 11444 astrometric calibration program right after the Servicing Mission, is to derive an accurate geometric distortion to a precision level of 0.2 pixels, which is sufficient to combine dithered and mosaicked *WFC3/UVIS* images using the STSDAS Multidrizzle software. During the Cycle 17 calibration (CAL-11911, PI. E. Sabbi), when more observations with *WFC3/UVIS* program will acquired, and once an accurate PSF models will be available, the *WFC3/UVIS* geometric distortion will be characterized down to 1 mas precision level, which is necessary to obtain accurate positions for scientific programs with various astrometric goals – parallaxes, proper motions. In this report, we present the analysis and results of geometry distortion calibration sufficiently accurate to use in Multidrizzle with observations of the new *HST* camera *WFC3/UVIS*.

2. Observations and Reductions

Two high-precision dense astrometric standard catalogs were available prior to SMOV, obtained from multiple observations of the globular cluster *47 Tuc* and *Large Magellanic Cloud* (LMC) field with ACS/WFC. The tangential–plane positions (we will further refer as U, V rectangular coordinate system) of stars in these two catalogs globally are accurate to ∼0.02 ACS/WFC pixels or 0.1 mas (Anderson 2006). In the following description of our analysis we will call as the “astrometric standard catalogs”.

The globular cluster 47 Tuc and a LMC field were observed with *WFC3/UVIS* near the center of each astrometric standard field with the different dither POSTARGS as shown in Table 1. The observations were taken through the F606W filter with exposure times of 350 sec in order to achieve a large number of high S/N star images per each UVIS chip.

Table 1: SMOV-11444 Observations

Image Name	Target Name	α (°)	δ (°)	POSTARG1 (″)	POSTARG2 (″)	Filter	Exp.time (sec)
iabj02a6q	LMC-FIELD-1	80.490208	-69.4983638	0.00	10.96	F606W	349.00
iabj02a7q	LMC-FIELD-1	80.490208	-69.4983638	0.00	-10.96	F606W	349.00
iabj02a9q	LMC-FIELD-1	80.490208	-69.4983638	-21.92	-21.92	F606W	349.00
iabj02abq	LMC-FIELD-1	80.490208	-69.4983638	-21.92	21.92	F606W	349.00
iabj02adq	LMC-FIELD-1	80.490208	-69.4983638	21.92	21.92	F606W	349.00
iabj02afq	LMC-FIELD-1	80.490208	-69.4983638	21.92	-21.92	F606W	349.00
iabj01a2q	NGC104	5.660416	-72.0677777	0.80	0.80	F606W	350.00
iabj01a4q	NGC104	5.660416	-72.0677777	0.80	-0.80	F606W	350.00
iabj01yuq	NGC104	5.660416	-72.0677777	-10.96	10.96	F606W	350.00
iabj01yvq	NGC104	5.660416	-72.0677777	10.96	10.96	F606W	350.00
iabj01yxq	NGC104	5.660416	-72.0677777	10.96	-10.96	F606W	350.00
iabj01yzq	NGC104	5.660416	-72.0677777	-10.96	-10.96	F606W	350.00
iabj01z1q	NGC104	5.660416	-72.0677777	-32.88	-10.96	F606W	350.00
iabj01z3q	NGC104	5.660416	-72.0677777	-32.88	10.96	F606W	350.00
iabj01z5q	NGC104	5.660416	-72.0677777	-32.88	32.88	F606W	350.00
iabj01z7q	NGC104	5.660416	-72.0677777	-10.96	32.88	F606W	350.00
iabj01z9q	NGC104	5.660416	-72.0677777	10.96	32.88	F606W	350.00
iabj01zbq	NGC104	5.660416	-72.0677777	32.88	32.88	F606W	350.00
iabj01zdq	NGC104	5.660416	-72.0677777	32.88	10.96	F606W	350.00
iabj01zfq	NGC104	5.660416	-72.0677777	32.88	-10.96	F606W	350.00
iabj01zhq	NGC104	5.660416	-72.0677777	32.88	-32.88	F606W	350.00
iabj01zjq	NGC104	5.660416	-72.0677777	10.96	-32.88	F606W	350.00
iabj01zlq	NGC104	5.660416	-72.0677777	-10.96	-32.88	F606W	350.00
iabj01znq	NGC104	5.660416	-72.0677777	-32.88	-32.88	F606W	350.00
iabj01zpq	NGC104	5.660416	-72.0677777	-2.96	-2.96	F606W	350.00
iabj01zrq	NGC104	5.660416	-72.0677777	-2.96	2.96	F606W	350.00
iabj01ztq	NGC104	5.660416	-72.0677777	2.96	2.96	F606W	350.00
iabj01zvq	NGC104	5.660416	-72.0677777	2.96	-2.96	F606W	350.00
iabj01zxq	NGC104	5.660416	-72.0677777	-0.80	-0.80	F606W	350.00
iabj01zzq	NGC104	5.660416	-72.0677777	-0.80	0.80	F606W	350.00

The first step in the analysis of geometric distortion is to measure the positions of each star in each chip and in each exposure. It is well known that the PSF of *WFC3/UVIS* is under-sampled and, similar to ACS/WFC, varies across the CCD chips. Because of that, the *WFC3/UVIS* PSF may suffer from systematic errors, which in turn affect the positional measurement of a star, depending on its location on the chip. Thus, the precision of the geometric distortion calibration depends on the accuracy of measured pixel positions of images, which ideally should be precise and free of systematic errors. At the time of our analysis, right after the Servicing Mission, there were no high precision tools available such as an *effectivePSF* library as has been derived for the ACS/WFC camera (Anderson, 2002). Therefore, the IRAF/DAOPHOT/PHOT task, which includes a Gaussian fit to the PSF centroid and simultaneous aperture photometry was used to obtain the X & Y positions of stars on each of the UVIS CCD chips for a total of 30 images. As seen in Figure 1, a Gaussian fit to X and Y positions as a function of instrumental magnitude shows a good formal measuring accuracy even for the under–sampled UVIS PSF.

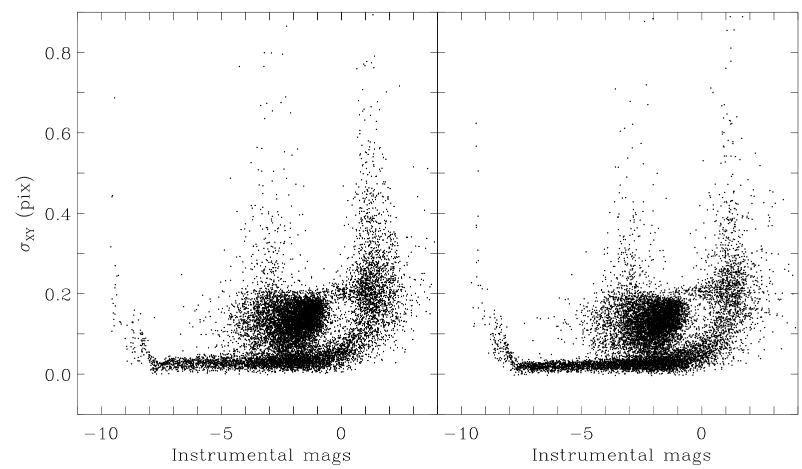

Fig. 1.— Centering errors of X & Y positions as a function of instrumental magnitude for stars in F606W images of 47Tuc in UVIS2 (left panel) and UVIS1 (right panel). The points above the astrometric error trend ($\sigma_{XY} \gtrsim 0.05$ for -5.0 $\lesssim$ mag $\lesssim 0$) are likely to be cosmic rays. The stars brighter than about -8 magnitude are saturated. The position errors (σ_{XY}) are calculated as $\sqrt{(\sigma_X^2 + \sigma_Y^2)}$.

About 3,000 stars were detected in each CCD chip for 47 Tuc and about 20,000 stars for the LMC observations – a sufficient number to model properly the geometric distortion with a high-order polynomial.

3. Geometric Distortion Solution

3.1. Master Catalog

A relatively easy way to find the distortion model and then solve for it, is to use the positions of stars in a distortion-free astrometric standard catalog. The residuals between the observed positions of stars and the corresponding positions in an astrometric standard catalog reveal the optical distortion directly.

A similar approach was used to examine the systematic residuals in X and Y positions in three other *HST* imaging cameras: WFPC2 filter-dependent geometric distortion (Kozhurina-Platais *et al.*, 2002); ACS/HRC polarized filters distortion (Kozhurina-Platais & Biretta 2004) and ACS/WFC CTE-induced centroid shift (Kozhurina-Platais *et al.*, 2007), where the star positions, corrected for the known distortion, were compared against the distortion-free coordinate system applying only shift, rotation and scale, or the so-called four parameter transformation (Anderson 2006).

In the case of the *WFC3/UVIS* detector, preliminary optical ray-tracing model demonstrated, that the camera has a considerable linear distortion, known as the skew terms, which manifest them-selfes as a departure from non-orthogonality between the two principle axes and as a difference in scale between two principal axes. Because of a large linear distortion, nearly square UVIS detector will be projected onto the sky in a rhombus shape. For a such complicated model for the optical distortion in *WFC3/UVIS* a high precision astrometric standard catalog is essential to derive an accurate geometric distortion.

3.2. Matching the Stars

The first step to solve for distortion is to match the observed and measured positions of stars from UVIS images with the same stars in the astrometric standard frame, which is not an easy task due to the arbitrary orientation of the *WFC3/UVIS* images with respect to the standard, differences in the scale, the presence of numerous cosmic rays, and, most important, unknown geometric distortion. Although it would be much easier to use the sky positions RA and DEC (α and δ) of the astrometric standard catalog and compare them with calculated α and δ from the header WCS information of the *WFC3/UVIS* images. However, we want to avoid using the WCS information from the header as much as possible, because right after SM4 it is not calibrated accurately yet and should be treated with caution if we wish to reach the accuracy and precision of pixel coordinates. Second, the maximum precision is preserved only if all data manipulations are performed in the original pixel coordinates. It is well-known that transformation from one coordinate system to another one introduces model-dependent systematics, also known as a modelling error, depending on how complicated the transformation is.

Because of this and the fact of very crowded images, we chose a manually matching stars for the first *WFC3/UVIS* images of the SMOV observations from calibration program 11444.

About 20 bright stars were matched manually from the first *WFC3/UVIS* image to stars in the astrometric standard catalog. This set of stars provided the initial shifts, rotation and scale, which were sufficient to identify automatically the other several thousands common stars. A general transformation with high order polynomial terms (up to 3rd order) was used in the least-squares minimization to find the common reference stars for each UVIS CCD chip, interactively rejecting poorly–measured, saturated stars and cosmic rays. This provided the first-cut "plate" solution and a very important fixed set of all good-quality reference stars. The standard error of the least-squares solutions was on the order of 0.05 pixels. The sets of fixed reference stars always contain the original full-precision X & Y pixel positions of stars from the observed frame as well as U & V coordinates from the astrometric standard catalog. The following observed *WFC3/UVIS* frames have the same orientation but different shifts in α and δ relative to the starting image, therefore it was possible to predict linear transformation coefficients using the plate constants from a previous manually matched frame and avoid the step of initial manual identification of stars and substantially speed up reductions of the remaining frames.

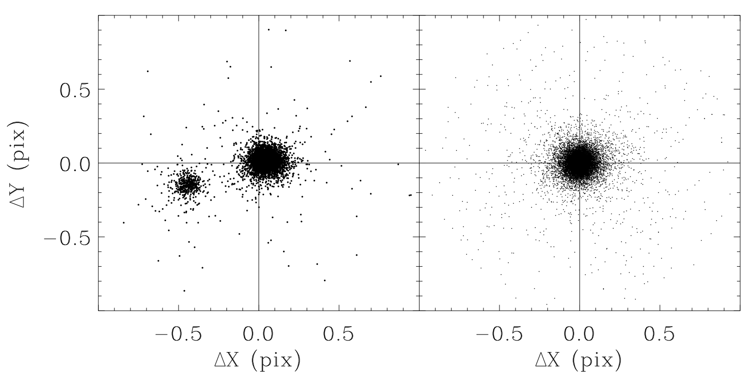

Fig. 2.— XY-residual plot between an observed UVIS frame and the standard astrometric catalog. The left panel shows the 47 Tuc stars and Small Magellanic Cloud stars separated by large proper motions of 47 Tuc over few years. The right panel shows stars from the Large Magellanic Cloud only. The units are *WFC3/UVIS* pixels.

In the case of a standard astrometric field in the vicinity of the globular cluster 47 Tuc it is crucial to eliminate the stars from the Small Magellanic Cloud (SMC). As seen from Figure 2, the stars from 47 Tuc and the SMC form two very distinctive clumps in the X & Y residuals between the observed UVIS frame and the astrometric standard, separated by about 0.5 pixels (left panel). The separation of two distinctive clumps in the X & Y residuals of globular cluster 47 Tuc shows proper motion over a few years of these two stellar systems. In contrast, the positional residuals between the LMC UVIS observed frame and the LMC standard astrometric catalog are very tight and centered on $\Delta X = 0.0$ and $\Delta Y = 0.0$ pixels (right panel).

3.3. The Model of Geometric Distortion

After all measured stars from the UVIS images were matched to the same stars in the astrometric standard catalog and the original positions from both coordinate systems (observed and astrometric standard) were saved, we proceeded with actual solutions for geometric distortion.

The general form of geometric distortions is a polynomial containing all terms up to 5th-order, as follows:

$$U = A_1 + A_2X + A_3Y + A_4X^2 + A_5XY + A_6Y^2 + A_7X^3 + ... + A_{21}Y^5 \qquad (1)$$

$$V = B_1 + B_2X + B_3Y + B_4X^2 + B_5XY + B_6Y^2 + B_7Y^3 + ... + B_{21}Y^5 \qquad (2)$$

where U and V are tangential-plane positions in the astrometric standard catalog, and X,Y are measured pixel positions in the observed UVIS frame. An examination of various terms in Eqs. (1) and (2) helps to illustrate the strategy of finding the distortion correction. If the (U, V) and (X, Y) are well aligned, then, for example, in the X solution: A_1 is an arbitrary offset between the two coordinates systems, A_2 is the relative plate scale, A_4 and A_5 are plate tilt terms (van de Kamp, 1967), A_7 through A_{21} are classical cubic- and fifth-order distortion terms, respectively. If the centers of the two coordinate systems are not properly matched, and/or there is rotation between the two frames, the quadratic and 4th order terms will be nonzero. Thus, a key to determine of the geometric distortion is to find a good alignment between two coordinate systems.

In order to properly align the two coordinate systems UVIS X & Y pixel and U & V astrometric standard catalog), we made the following assumptions:

- UVIS CCD chip 2 (UVIS2) was chosen as a basic reference frame and its X-axes as a primary reference axes because of the presence of large skew term in UVIS images;
- the zero-point of the UVIS CCD chips at $X = (x - 2048.0)$ and $Y = (y - 1026.0)$, where x and y are measured positions from each chips, were adopted as the zero–point, defining that all geometric distortions are zero only at this specific point;
- the astrometric standard catalog must be rotated and shifted so that there is zero offset in X & Y between UVIS2 and the astrometric standard catalog and there is no rotation between the X-axes in both systems, (UVIS2 and the astrometric standard catalog), following precisely the definition of geometric distortion correction as applied to ACS/WFC by Anderson (2006).

In order to put these assumptions into practice, the nearest star to the center of the UVIS2 CCD chip was used to find the initial offsets and the rotation center of the astrometric standard. The final offsets, the location of the rotation center, and the amount of rotation are obtained through iterative least-squares solutions and successive small adjustments to the offset/rotation parameters. But this process of minimization is non-trivial because of a skew term between X and Y axis. In order to account for this, we chose the X axis as a reference with respect to which there is no rotation, *i.e.* minimazing the ratio of the linear terms A_3/B_3. Therefore, the positions of the stars U and V from the astrometric standard, which were matched to the X and Y positions from UVIS2, were rotated with respect to the center of UVIS2, thus eliminating the rotation between the UVIS2 X-axis and the U-axis of the astrometric standard.

Once the rotation center and the X & Y–offset between UVIS2 and the standard astrometric catalog are found and rotation are eliminated, a new full least-square solution is performed which includes all necessary high-order polynomial terms. This solution constitutes the geometric distortion for UVIS2.

Once the geometric distortion is solved for UVIS2, we can solve it for the other CCD chip UVIS1. However, the presence of the inter-chip gap, which is ∼40 pixels derived from ground-based geometric distorion test, complicates the task of finding the geometric distortion solution for UVIS1 CCD chip. Similar to ACS/WFC inter-chip gap, required an united geometric solution, so, that X & Y positions corrected for distortion would assembled a single entity of coordinats system.

Global Solution. Our first approach was similar to the one described in Platais *et.al.* (2002), where the ground-based technique considers the entire imaging instrument as a single detector, utilizing a unique geometric distortion solution which affects all CCD chips simultaneously. This approach requires the so-called chip constants (center of a chip cx, cy and the rotation angle θ, around this center) for each individual chip, which allows us to construct a unified global coordinate system – X,Y, and then solve for the global geometric distortion. The method of deriving the chip constants of a CCD mosaic – the center of the chips and their rotation – involves an astrometric standard: the measured pixel coordinates X,Y of the reference stars must be adjusted to their standard coordinates U,V (Eqs. 1 and 2). If approximate values for the chip centers and rotation angles – (cx,cy and θ) are derived, then we have the global coordinate system $\tilde{X}, \tilde{Y}$. The least-squares adjustment $\tilde{X}, \tilde{Y} \Rightarrow U$,$V$ using an initial guess of chip constants will produce large residuals between these two coordinate systems. To improve the first guess of chip constants, we minimize χ^2 iteratively through the parameter space cx,cy and θ, one at a time. This process is repeated until a global minimum is reached. In the case of *WFC3/UVIS* images only one chip, UVIS1, requires its constants to be determined (because with the two chips only one of them can be adopted as a reference chip). As a results, we have a set of constants cx,cy defined as follows:

$$cx = dx \tag{3}$$

$$cy = dy + 2052 \tag{4}$$

where dx and dy represent the variable part of the chip constants cx,cy and dx corresponds to the sideways displacement of UVIS1 relative to UVIS2, and dy corresponds to the physical gap between the chips. The rotation of the chip is defined as

$$x_n = (x - 2048)cos\theta - (y - 1026)sin\theta + 2048 \tag{5}$$

$$y_n = (x - 2048)sin\theta + (y - 1026)cos\theta + 1026 \tag{6}$$

where x and y are original pixel coordinates from UVIS1 chip, and x_n and y_n are new rotated pixels coordinates. Transformations (5)-(6) must be done before applying the constants (3)-(4). For UVIS2 chip, since it is a reference chip, we simply use its own pixel coordinates "$as it is$". The final transformation of UVIS1 chip pixel coordinates to the global *united* pixel coordinate system $\tilde{X}$ and $\tilde{Y}$ with a proper orientation is following:

$$\tilde{X} = x_n + cx \tag{7}$$
$$\tilde{Y} = y_n + cy \tag{8}$$

When the minimum of the standard error σ of the solution is reached, it means that the chip constants are found. Performing such solutions for all 30 *WFC3/UVIS* images taken in the SMOV calibration program 11444, we have found that the gap between the UVIS2 and UVIS1 CCD chips is 31±0.1 pixels and the rotation angle between the chips is 0.00067±0.00005 radians or $2\farcm3$. Now the united coordinate system – $\tilde{X}$ and $\tilde{Y}$ – can be solved directly into the standard frame for a global geometric solution. However, the global geometric solution produced systematically biased residuals as a function of X and Y positions up to 0.2 pixels. We outlined here the global solution only because we found the accurate value of the inter gap chips and rotation angle between UVIS1 and UVIS2.

Meta–Chip Solution. Since, the global solution decribed above produced X,Y residuals up to 0.2 pixels, our next approach was a meta-chip solution, very similar to the ACS/WFC meta-chip geometric solution (Anderson, 2002). The key point here is that at the same time with UVIS2 we shifted and rotated the matching astrometric standard coordinates for UVIS1 as well. As it is described above, the astrometric standard frame in UVIS2 was rotated about the central point by the angle required to align the U-axes to the X-axes at that point. At the same time we relate X,Y on UVIS2 and X,Y on UVIS1 to the same astrometric standard frame in UVIS2. In this way, we achieved the meta-chip configuration for both chips *simultaneously* and directly into the system of our reference chip UVIS2. A straightforward least-squares solution provides the coefficients of geometric distortion for UVIS1 in the same system as for UVIS2. It is important to note here that the inter-chip gap and rotation between the two chips is now implicitly included in the coefficients.

Each coefficient of Eqs. (1) and (2) was examined by its value and the formal error, as returned by a least squares minimization of the high-order polynomial. Careful analysis of the polynomial terms in each solution led us to the conclusion that all terms – linear, quadratic and classical distortion terms are consistent from one solution to another and significant with respect to its errors, except for the fifth-order, which are very small (on the order of 10^{-17}) and vary from one solution to another. Thus, for each solution in X and Y the final geometric distortion for each UVUS CCD chip is represented by a fourth-order polynomial. As shown in Figure 3, after applying the best polynomial fit, the residuals of X and Y positions between the observed LMC frame and the astrometric standard catalog (LMC) for the UVIS2 CCD chip are essentially flat, i.e. all large–scale residuals are successfully removed.

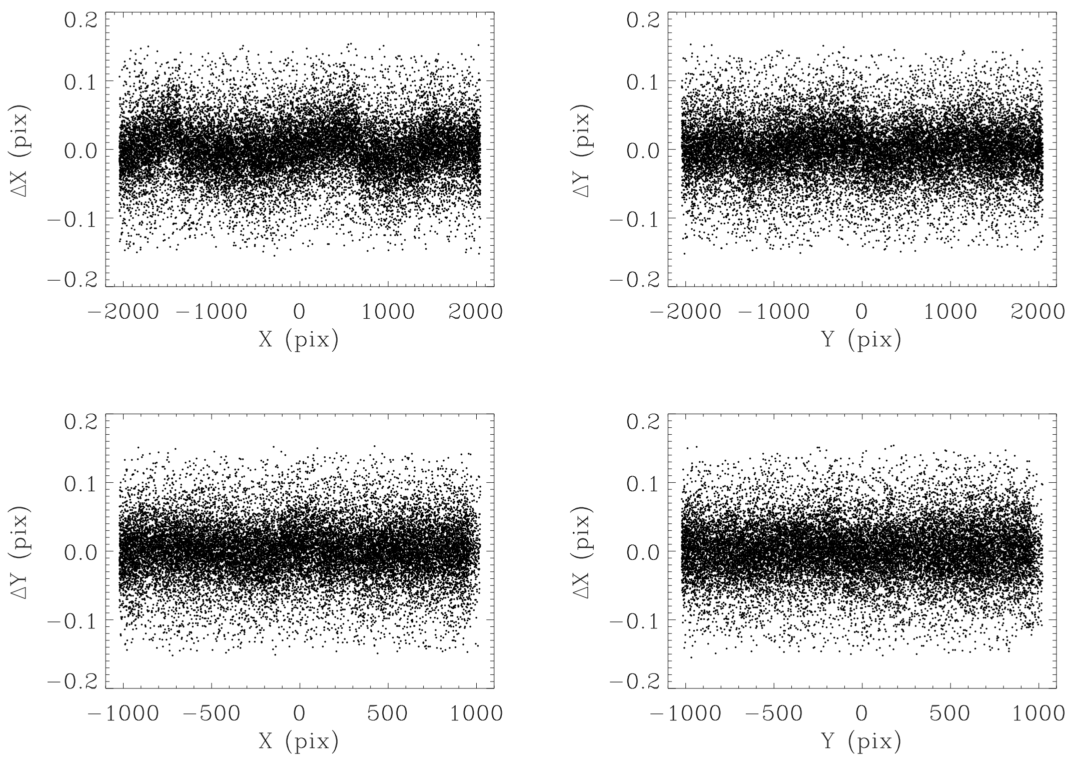

Fig. 3.— XY-residuals as function of X and Y positions from one of the observed LMC image and the standard astrometric catalog (LMC) for the UVIS2 CCD chip. The units are *WFC3/UVIS* pixels.

Nevertheless, there are noticeable fine-scale systematic residuals from the best–fit polynomial solutions. In order to visualize these residuals, we examined the X and Y residuals in vertical and horizontal slices through UVIS1 and UVIS2 in steps of δX=512 pixels in X and δY=256 pixels in Y with a width of 128 and 64 pixels, respectively.

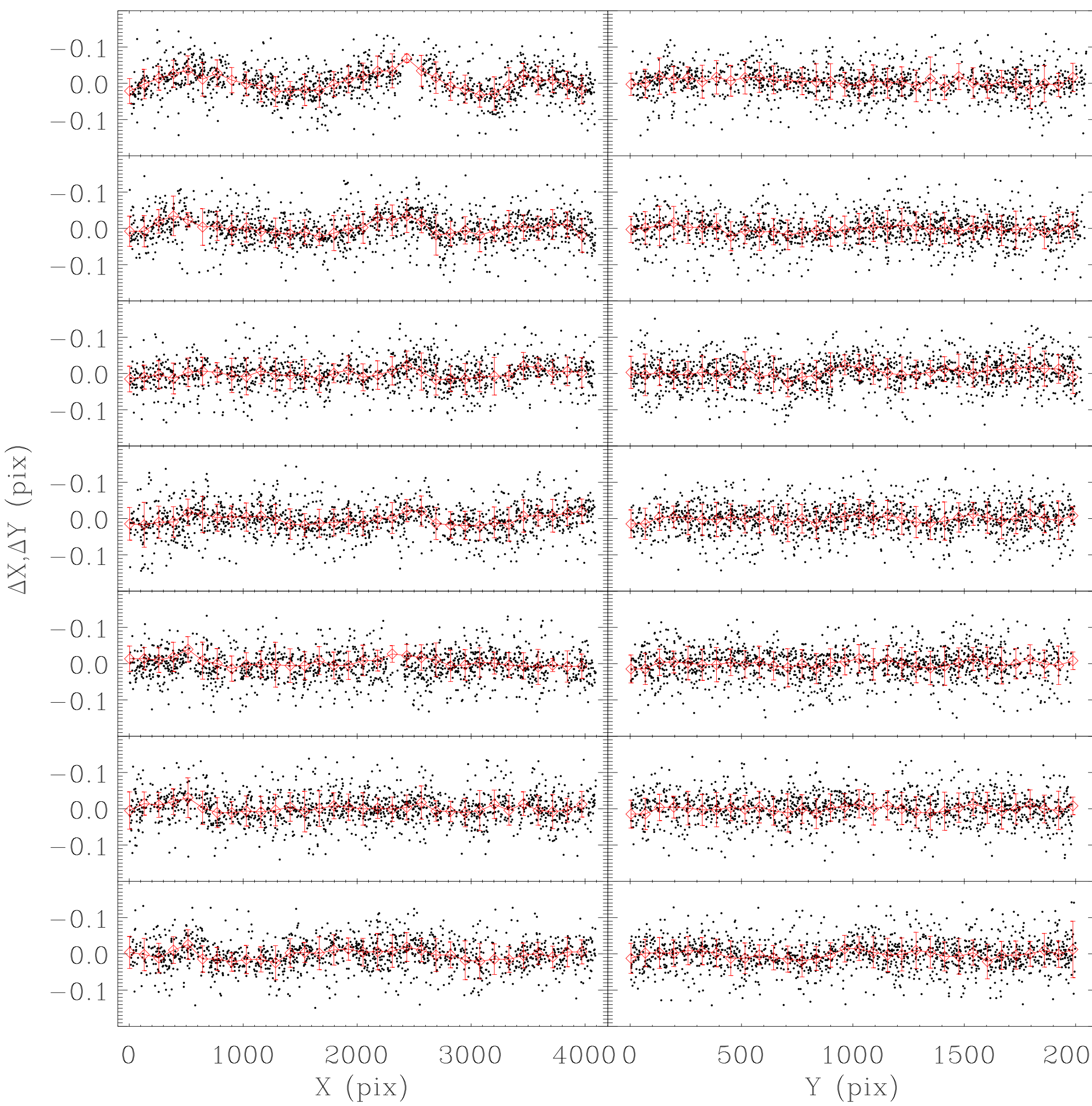

Fig. 4.— Narrow slices of X and Y residuals centered at the selected δX with step of 512 pixels in X and at the selected δY (from the top to the bottom – 1792, 1536, 1280,1024, 768, 512, 256) with a step of 256 pixels in Y through the UVIS2 chip. The residuals are from the best–fit polynomial solution. The coordinates X,Y are given in *WFC3/UVIS* pixels.

As seen in Figures 4 and 5, the XY residuals for UVIS1 and UVIS2 CCD chips show a complicated structure, depending on the location of the CCD, with a typical amplitude of 0.05 pixels, which would require a polynomial of greater then 5th order or so to remove it. Such a high order polynomial would be hard to deal in the least square minimization. These fine–scale residuals seen in Fig.4 and Fig.5 are probably due to some fine-structure in the F606W filter itself during the manufacturing process. A similar effect of filter dependence in geometric distortion was also noticed in the ACS/WFC and ACS/HRC filters (Anderson 2002). The observations from the calibration SMOV program 11444 were taken only through the F606W filter because of that, in Cycle 17 we have planned observations of

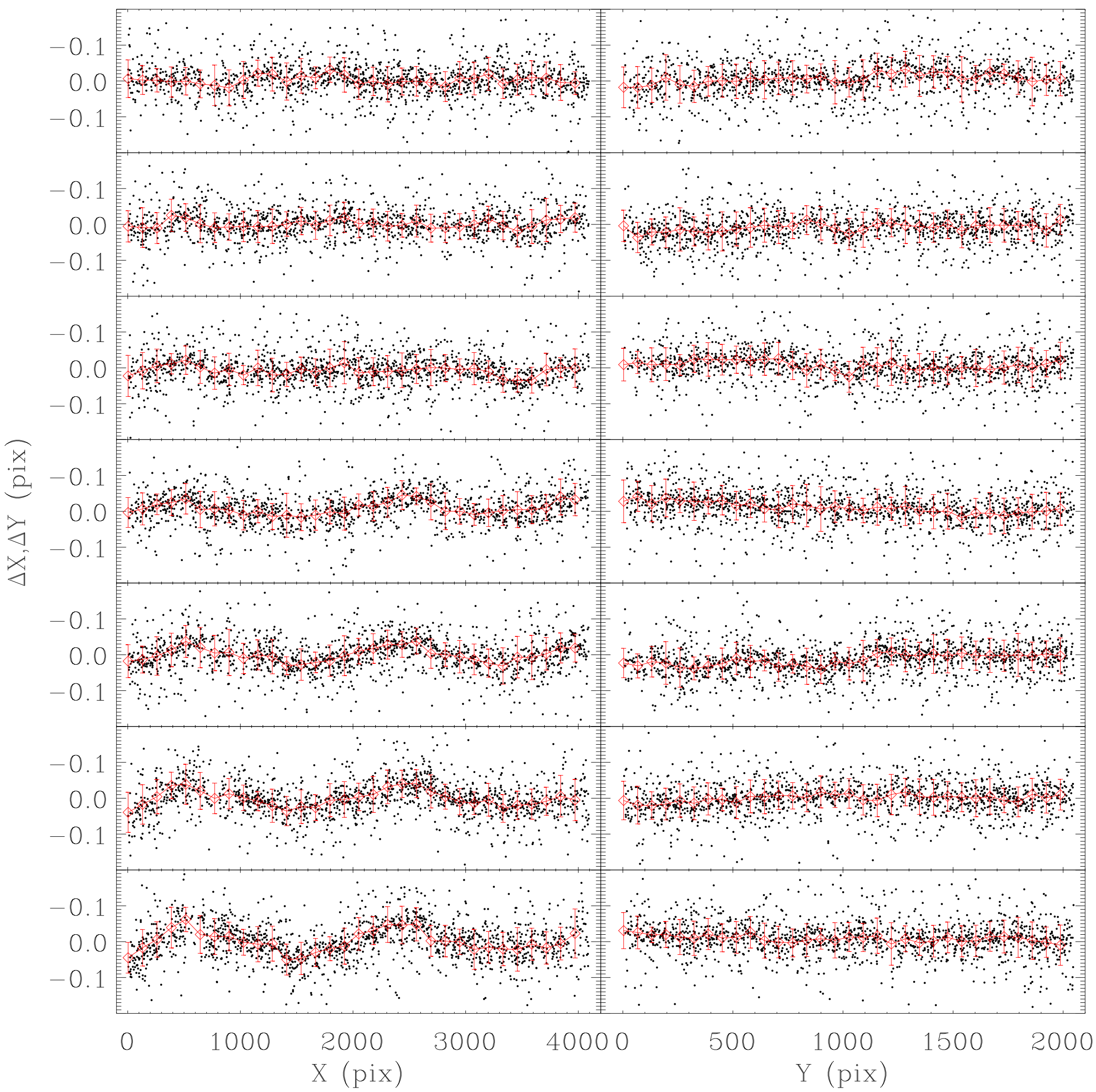

Fig. 5.— The same as in Fig. 4, now for UVIS1.

dense star field through various filters of *WFC3/UVIS*, which then will allow us to derive an accurate filter-specific geometric distortion in the form of look-up tables.

3.4. Polynomial Coefficients

For each of the thirty WFC3/UVIS images (24 observations in 47 Tuc and 6 observations in LMC), and for each UVIS chip, an independent solution was calculated, using the least squares minimization of the fourth-order polynomial:

$$U = A_1 + A_2X + A_3Y + A_4X^2 + A_5XY + A_6Y^2 + A_7X^3 + ... + A_{21}Y^4 \tag{9}$$

$$V = B_1 + B_2X + B_3Y + B_4X^2 + B_5XY + B_6Y^2 + B_7Y^3 + ... + B_{21}Y^4 \tag{10}$$

These 30 sets of newly derived coefficients were then averaged and the standard deviation of the coefficients calculated. The coefficients of a fourth-order polynomial representing the geometric distortion for each chip are listed in Tables 2 and 3.

Table 2: The 4th order polynomial terms for UVIS1

Order	A	σ_A	B	σ_B
CONST	-0.1985295E+01	0.85E-02	0.2061278E+04	0.20E-01
X	0.9882444E+00	0.91E-05	0.6884967E-01	0.55E-05
Y	-0.1105318E-02	0.36E-05	0.9842041E+00	0.12E-04
XX	0.2807940E-05	0.27E-08	0.1812170E-06	0.20E-08
XY	-0.2895120E-05	0.34E-08	0.2581759E-05	0.12E-08
YY	-0.3447714E-08	0.56E-08	-0.2897681E-05	0.38E-08
XXX	0.6866515E-11	0.10E-11	0.1770888E-10	0.11E-11
XXY	0.6053346E-11	0.10E-11	-0.1868423E-11	0.15E-11
XYY	0.1712952E-10	0.20E-11	-0.7816541E-11	0.28E-11
YYY	0.8375285E-11	0.33E-11	0.4569925E-10	0.49E-11
XXXX	0.4967988E-14	0.65E-15	-0.3918184E-15	0.47E-15
XXXY	0.8232215E-14	0.12E-14	-0.1301928E-14	0.43E-15
XXYY	-0.1221402E-14	0.15E-14	0.4096568E-14	0.24E-14
XYYY	0.1462033E-13	0.12E-14	-0.2984833E-14	0.18E-14
YYYY	0.1668299E-13	0.50E-14	-0.2930571E-14	0.42E-14

Table 3: The 4th order polynomial terms for UVIS2

Order	A	σ_A	B	σ_B
CONST	0.6997726E-05	0.76E-04	-0.2450114E-04	0.50E-03
X	0.9941676E+00	0.12E-04	0.6279832E-01	0.40E-05
Y	-0.5544527E-09	0.36E-09	0.9959910E+00	0.10E-04
XX	0.2855580E-05	0.27E-08	0.1421154E-06	0.10E-08
XY	-0.2953815E-05	0.36E-08	0.2624561E-05	0.20E-08
YY	0.9000204E-07	0.32E-08	-0.3058222E-05	0.65E-08
XXX	0.2035511E-10	0.89E-12	0.3702375E-11	0.72E-12
XXY	-0.1080719E-10	0.16E-11	0.1606399E-10	0.12E-11
XYY	0.1471166E-10	0.17E-11	-0.1009220E-10	0.19E-11
YYY	0.2266466E-10	0.27E-11	0.1053757E-10	0.24E-11
XXXX	0.1675142E-14	0.64E-15	0.6514074E-15	0.22E-15
XXXY	0.7029921E-15	0.14E-14	0.1256815E-14	0.64E-15
XXYY	-0.1692394E-13	0.15E-14	0.1142159E-13	0.13E-14
XYYY	-0.4298677E-14	0.12E-14	-0.8605310E-14	0.12E-14
YYYY	-0.1533064E-13	0.37E-14	-0.1362531E-14	0.55E-14

The newly derived coefficients of geometry distortion were applied to X & Y positions obtained with IRAF/DIGIPHOT/PHOT Gaussian fit from two LMC `(*_flt.fits)` images overlapped by 4000×3000 pixels in X and Y, respectively. These X and Y positions were compared to each other, applying only linear transformation. It is important to mention here, that if the geometry distortion is removed from two frames and they are rectangular, i.e. X & Y axes have the same scale and they are perpendicular, then these two frames can be transformed into each other using only a linear transformation, i.e. a shift (the X & Y offset between frames), rotation between two frames and the scale. The RMS of such solutions is about 0.05 pixels or *2mas*. The residual map is illustrated in Figure 6, and indicates that residuals do not have any systematics as a function of X & Y positions, in other words, the geometric distortion is properly removed even better than the SMOV requirement on the accuracy of geometric distortion calibration.

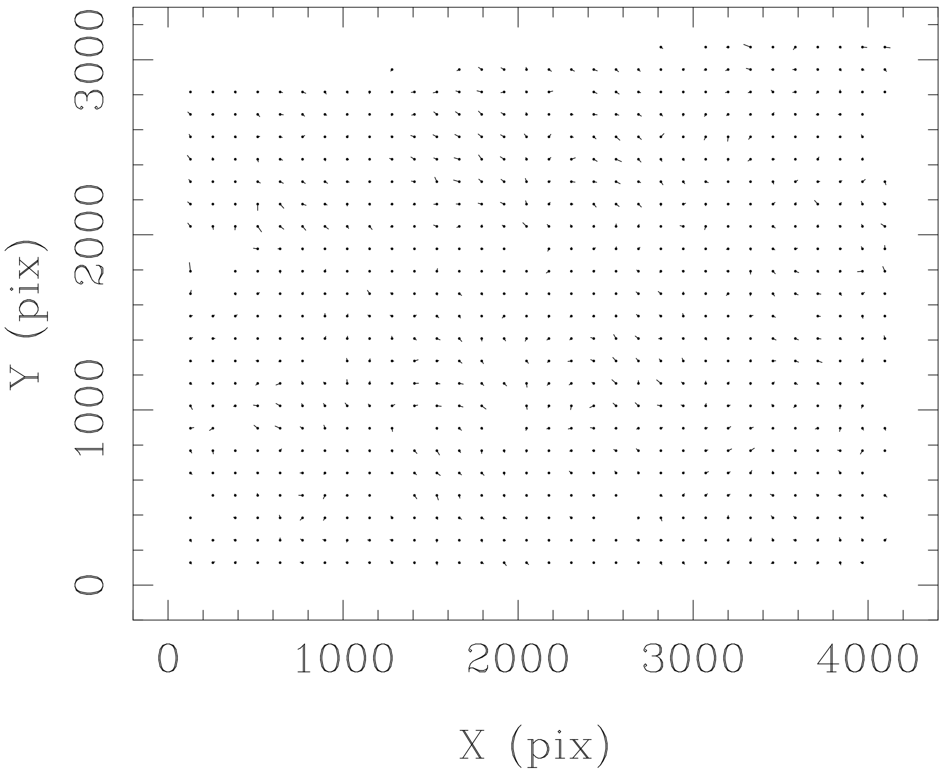

Fig. 6.— 2–D XY-residual map between two LMC images overlapped by 4000×3000 pixels in X and Y, respectively, after applying the newly derived geometric distortion coefficients. The largest vector has an amplitude of 0.17 pixels. The vectors are scaled by a factor of 500. The units are *WFC3/UVIS* pixels.

4. V2V3 System and IDCTAB

The newly derived coefficients of geometric distortion for the WFC3/UVIS channel are in the system of X and Y detector coordinates, which can be used to correct the X and Y positions obtained from any WFC3/UVIS `(*_flt.fits)` images with arbitrary pointing and orientation. The geometric distortion coefficients are fundamental for on-the-fly calibration in the STScI (OTFR) pipeline in order to remove the distortion from WFC3/UVIS `(*_flt.fits)` images. These coefficients are stored in a reference file – the Instrument Distortion Corrections Table (IDCTAB), which is in the system of HST-based coordinate system – *V2V3*. The detailed description of the IDCTAB reference file can be found in a paper by Hack & Cox (2001). Thus, the geometric distortion coefficients in the XY detector coordinate system must be converted into the *V2V3* system (equivalent to the sky tangential plane) including the scaling and distortion correction with the origin at the reference position where the detector and the sky axes are exactly parallel.

The *V2V3* system and the related coordinate system of the UVIS channel is schematically illustrated in Figure 7, where the angle between North and the V3-axis is the *PA_V3* angle as kept in the image header. The angle between North-axis and detector Y-axis is ORIENTAT and also kept in the image header. As seen from Figure 7, in order to convert the derived geometric distortion coefficients into the *V2V3* system, the angle between the Y-axis and the V3-axis is used to rotate the coefficients.

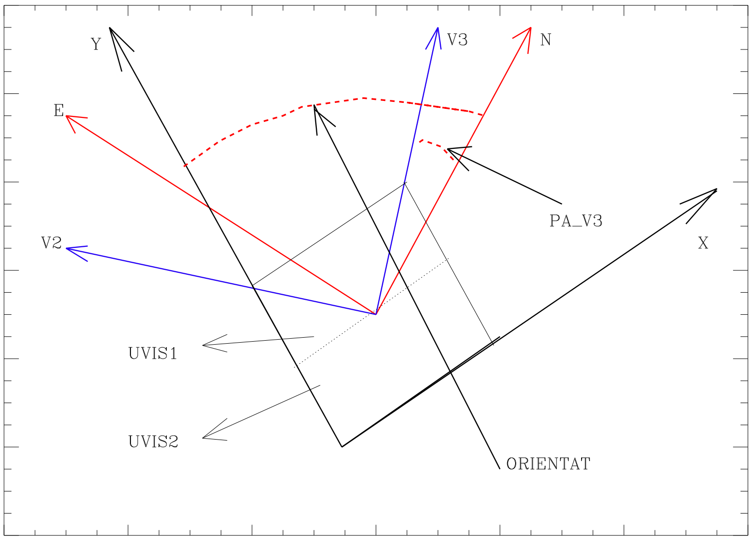

Fig. 7.— Schematic illustration of the *WFC3/UVIS* detector *XY* coordinate system with respect to the North-East axes (indicated by red line), *V2V3* system is shown in blue. The angles *PA_V3* and ORIENTAT are also indicated.

Let's define the angle between the detector Y-axis and the V3-axis as $\theta =$ ORIENTAT-PA_V3. Then rotation of the coefficients from the XY system into the *V2V3* system can be performed as follows:

$$CX = -A \times cos\theta + B \times sin\theta \tag{11}$$

$$CY = A \times sin\theta + B \times cos\theta \tag{12}$$

where, A, B are an array of coefficients in X and Y solutions from Eqs.(9) and (10).

After the coefficients have been rotated into the *V2V3* system, they are averaged. These averaged coefficients in the *V2V3* system should be scaled by the adopted plate scale of exact $0\farcs04$, in order to put them into the sky tangential plane. This also allows us to calculate the X,Y scale as follow:

$$X\text{scale} = \sqrt{A_2^2 + B_2^2} \tag{13}$$
$$Y\text{scale} = \sqrt{A_3^2 + B_3^2} \tag{14}$$

The angle of the X and Y–axes, or so–called β_X and β_Y can be calculated as follows:

$$\beta_X = \arctan\left(\frac{A_2}{B_2}\right) \tag{15}$$
$$\beta_Y = \arctan\left(\frac{A_3}{B_3}\right) \tag{16}$$

The calculated parameters of geometric distortion and comparison with the optical ray-tracing model using ZEMAX are presented at Table 4.

Table 4: Parameters of geometric distortion

Parameters	Measured		Model	
	UVIS1	UVIS2	UVIS1	UVIS2
$X scale$	0.″0396	0.″0399	0.″0396	0.″0398
$Y scale$	0.″0393	0.″0398	0.″0393	0.″0398
β_X	-41.°121	-41.°492	-41.°023	-41.°362
β_Y	44.°957	44.°893	44.°890	44.°862

As seen from this table, the derived geometric distortion parameters are in good agreement with the predictions from the ground-based tests using optical ray tracing.

After transforming the coefficients from the detector pixels into the sky tangential plane, we are ready to use them in Multidrizzle.

5. Multidrizzle Test with derived WFC3/UVIS IDCTAB

In order to test how the newly–derived geometry distortion is implemented in IDCTAB to be used in Multidrizzle, we used 4 LMC images with POSTARGS $\sim \pm 21''$ (see Table 1). Multidrizzle parameters were set to default values and the output from Multidrizzle was set to single drizzled images (`*_single_sci.fits`), as well as one combined drizzled image (`*_drz.fits`). The X & Y positions were derived from the drizzled images with the IRAF/DAOPHOT/PHOT task which includes a Gaussian fit to X & Y positions. Two sets of X & Y positions from two drizzled LMC images overlapping by 4000×3000 pixels in X & Y respectively, were compared to each other, applying only a linear transformation. A plot of the residuals between these two overlapping LMC drizzled images (Fig.8), indicates that the IDCTAB in Multidrizzle is properly removing the geometric distortion and there are no displacements or discontinuities of the inter-chip gap. The RMS of a linear fit is 0.05 pixels, which means that the accuracy of the geometry distortion implemented in the IDCTAB is at about 0.05 pix, which is four times better than requirements of the WFC3/UVIS images alignment in Multidrizzle.

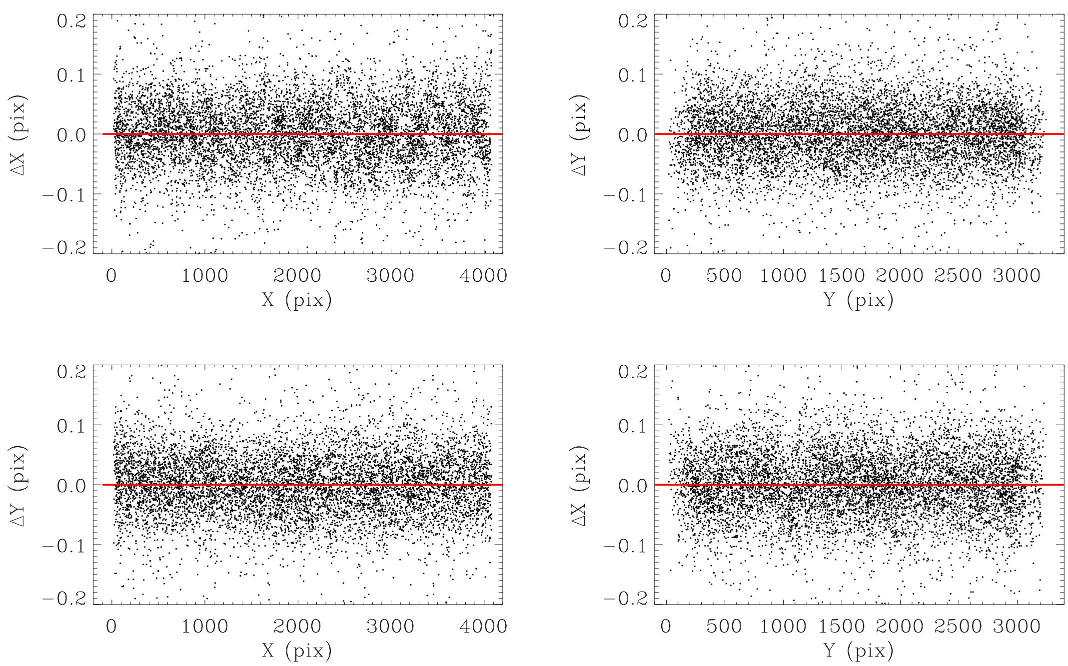

Fig. 8.— XY-residuals as a function of X and Y positions from two overlapping LMC drizzled images. The RMS of the linear transformation is 0.05 pixels or 2mas. The overplotted red solid line in each residual plots, shows no systematic trend in the residuals. The units are *WFC3/UVIS* pixels.

Another way to check the implementation of the geometric distortion in Multidrizzle is to use the same X,Y positions derived from the drizzled image and compare them with the astrometric standard catalog, applying only a linear transformation, as described above. Figure 9, where we present the 2–D residual map, shows no indication of any large-scale systematic error. The remaining small–scale residual is due to the filter-dependent geometric distortion. The RMS of a linear fit is about 0.05 pixels.

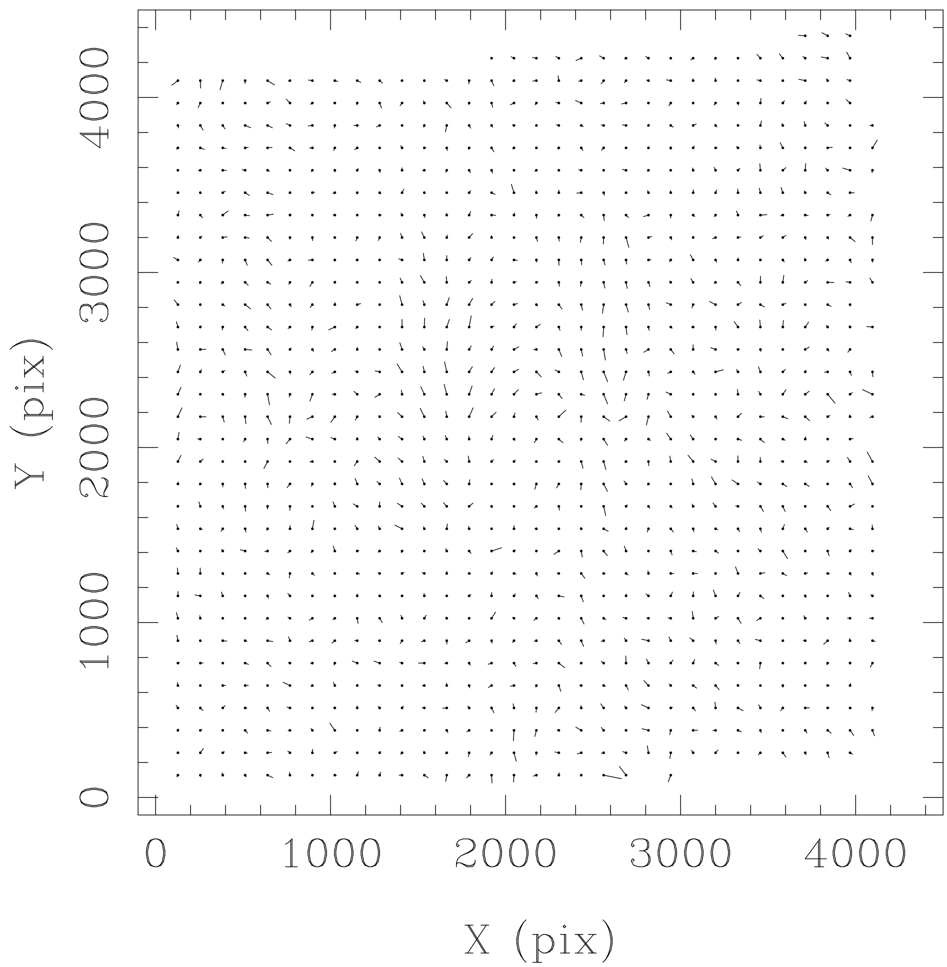

Fig. 9.— 2–D XY-residual map between a drizzled LMC image and the astrometric standard catalog. The largest vector has an amplitude of 0.16 pixels.The vectors are scaled by a factor of 1000. The units are *WFC3/UVIS* pixels.

6. Conclusions and Recommendations

This report presents a detailed description of the results of geometric distortion calibration of the *WFC3/UVIS* channel. The well-planned observations of 47 Tuc and LMC in various dither patterns in combination with the techniques of an astrometric standard fields allow us to characterize the *WFC3/UVIS* geometric distortion down to the 2 *mas* precision level, which is four times better than the required precision at SMOV activity

WFC3-031. Summarizing the newly derived results of the geometric distortion solution for *WFC3/UVIS*, we conclude that besides of the optical geometric distortion, there is a strong hint of filter-dependence geometric distortion.

The derived geometric distortion coefficients in the form of IDCTAB can be already successfully used in STSDAS/Multidrizzle software for: 1) stacking of *WFC3/UVIS* images with different dither pattern; 2) rejecting the CRs; 3) enhance the spatial resolution; 4) deepen the detection limit.

As it was mentioned in Sect.3.3, the WFC3 SMOV observations are exposed through the F606W filter. In Cycle 17 (CAL–11911, PI–E.Sabbi), the observations of the astrometric standard field in *Omega Cen* will be taken through various *WFC3/UVIS* filters, which then will allow us to derive the filter dependent geometry distortion in the form of look-up tables, similar to ACS/WFC camera. The filter-dependencies geometric distortion will then allow us to characterize the *WFC3/UVIS* geometric distortion down to 1 mas precision level and even better once accurate PSFs model will be available.

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