WFC3 SMOV Proposal 11445 - IR Geometric Distortion Calibration

V. Kozhurina-Platais, C. Cox, B. McLean,

L. Petro, L. Dressel, H. Bushouse

November 17, 2009

Abstract

The goal of WFC3 SMOV program 11445 is to obtain a coordinate system free of distortion to a precision level of 0.2 pixels or $\sim$ 26 mas. The astrometric calibration of WFC3/IR 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 F160W filter and with dither patterns, have been used to determine the geometric distortion in WFC3/IR. We used a 4th order polynomial model to derive the geometric distortion in the IR 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 8 mas, which is three 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 in *HST* during Servicing Mission 4 in May 2009. The SMOV observations (11445, PI L. Dressel) with the WFC3/IR channel (*IR*) are used to

derive the geometric distortion of the detector. Preliminary optical ray-tracing model demonstrated that the geometric distortion in *WFC3/IR* camera is severe, on the order of $\sim 10\%$ 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 10 pixels or $\sim$2 arcseconds. The knowledge of accurate geometry distortion is important **not only** for deriving accurate positions, parallaxes and proper motions of scientifically interesting objects **but also to rectify the WFC3/IR images**, and to stack multiple exposures of dithered *IR* images. The MultiDrizzle software (Koekemoer 2002), currently installed in the STScI on-the-fly pipeline (OTFR), requires a high accuracy geometry distortion in order to combine dithered WFC3/IR images, to enhance spatial resolution, and to deepen the detection limit. If the geometry distortion correction implemented in Multidrizzle is not accurate enough, then the IR 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/IR* images with MultiDrizzle and to mitigating the under-sampled PSF.

Thus, the goal of SMOV program 11445 is to calibrate the geometric distortion to 0.2 pixels or 26mas, which is sufficient to combine dithered and mosaicked WFC3/IR images using the STSDAS Multidrizzle software. During the Cycle 17, WFC3/IR calibration program (11928, PI - Kozhurina-Platais) the WFC3/IR geometric distortion will be characterized 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 of geometry distortion calibration for WFC3/IR channel.

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 to them as *U,V* rectangular coordinate system) of stars in these two catalogs are free of any systematic and are globally accurate to $\sim$0.02 ACS/WFC pixels or 0.1 mas (Anderson 2006). In the following description of our analysis we will call them as an "astrometric standard catalog".

Thus, the globular cluster 47 Tuc and the LMC field were observed with WFC3/IR near the center of each astrometric standard field and with the different dither POSTARGS as shown in Table 1. The observations of 47 Tuc and LMC were taken through the F160W filter with exposure times of 274 and 92 sec, respectively, in order to obtain a large number

of high S/N star images per IR detector.

Table 1: SMOV-11445 Observations

Image Name	Target Name	α (°)	δ (°)	POSTARG1 ($''$)	POSTARG2 ($''$)	Filter	Exp.time (sec)
iabi02mcq	LMC-FIELD-1	80.490208	-69.498363	0.00	12.43	F160W	92.94
iabi02meq	LMC-FIELD-1	80.490208	-69.498363	27.83	24.87	F160W	92.94
iabi02mfq	LMC-FIELD-1	80.490208	-69.498363	27.83	0.00	F160W	92.94
iabi02mhq	LMC-FIELD-1	80.490208	-69.498363	27.83	-24.87	F160W	92.94
iabi02mjq	LMC-FIELD-1	80.490208	-69.498363	0.00	-12.43	F160W	92.94
iabi02mkq	LMC-FIELD-1	80.490208	-69.498363	-27.83	-24.87	F160W	92.94
iabi02mmq	LMC-FIELD-1	80.490208	-69.498363	-27.83	0.00	F160W	92.94
iabi02mnq	LMC-FIELD-1	80.490208	-69.498363	-27.83	24.87	F160W	92.94
iabi01u9q	NGC104	5.660416	-72.067777	-9.28	8.29	F160W	274.23
iabi01udq	NGC104	5.660416	-72.067777	9.28	8.29	F160W	274.23
iabi01ufq	NGC104	5.660416	-72.067777	9.28	8.29	F160W	274.23
iabi01uqq	NGC104	5.660416	-72.067777	9.28	-8.29	F160W	274.23
iabi01usq	NGC104	5.660416	-72.067777	9.28	-8.29	F160W	274.23
iabi01uwq	NGC104	5.660416	-72.067777	-9.28	-8.29	F160W	274.23
iabi01uyq	NGC104	5.660416	-72.067777	-9.28	-8.29	F160W	274.23
iabi01v0q	NGC104	5.660416	-72.067777	-9.28	-8.29	F160W	274.23
iabi01v2q	NGC104	5.660416	-72.067777	-9.21	-8.29	F160W	274.23
iabi01v4q	NGC104	5.660416	-72.067777	-9.21	-8.22	F160W	274.23
iabi01v6q	NGC104	5.660416	-72.067777	-9.28	-8.22	F160W	274.23
iabi01v8q	NGC104	5.660416	-72.067777	-27.83	-8.29	F160W	274.23
iabi01vaq	NGC104	5.660416	-72.067777	-27.83	8.29	F160W	274.23
iabi01vcq	NGC104	5.660416	-72.067777	-27.83	24.87	F160W	274.23
iabi01veq	NGC104	5.660416	-72.067777	-9.28	24.87	F160W	274.23
iabi01vgq	NGC104	5.660416	-72.067777	9.28	24.87	F160W	274.23
iabi01viq	NGC104	5.660416	-72.067777	27.83	24.87	F160W	274.23
iabi01vkq	NGC104	5.660416	-72.067777	27.83	8.29	F160W	274.23
iabi01vmq	NGC104	5.660416	-72.067777	27.83	-8.29	F160W	274.23
iabi01vsq	NGC104	5.660416	-72.067777	27.83	-24.87	F160W	274.23
iabi01vvq	NGC104	5.660416	-72.067777	9.28	-24.87	F160W	274.23
iabi01vxq	NGC104	5.660416	-72.067777	-9.28	-24.87	F160W	274.23
iabi01w0q	NGC104	5.660416	-72.067777	-27.83	-24.87	F160W	274.23

The first step in the analysis of geometric distortion is to measure the positions of each star in each exposure. It is a well known that the PSF of the WFC3/IR is severely

under-sampled. The FWHM of the IR PSF is $\lesssim$1.3 pixels, and varies across the IR detector. Thus, the precision of the geometric distortion calibration depends on the accuracy of measured pixel positions of images, which should be precise and free of systematic errors.
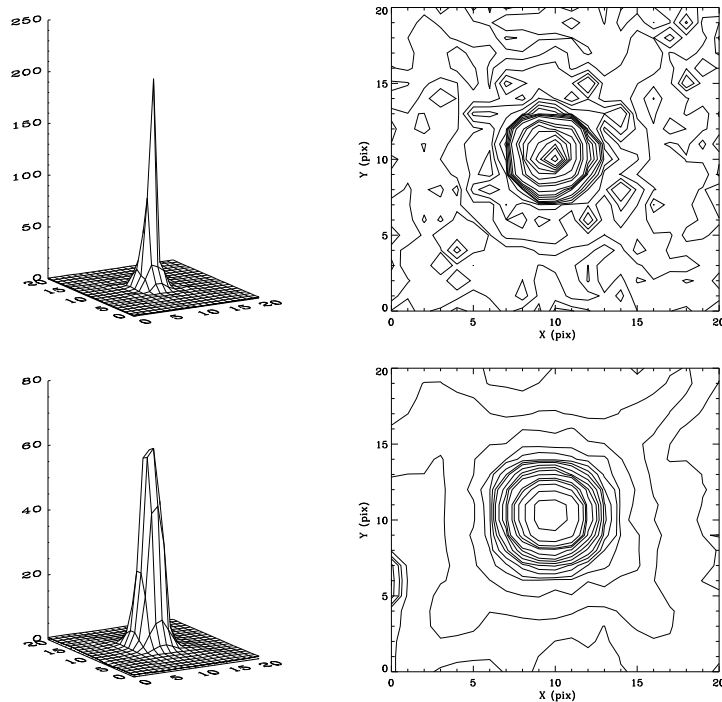

Fig. 1.— 2-D surface and contour plots of the original IR PSF and smoothed PSF with boxcar of 3×3 pixels. The top row shows the surface and contour plots of the original IR PSF and the bottom row, the surface and contour plots of the smoothed PSF. The units are WFC3/IR pixels.

At the time of our analysis, right after the Servicing Mission, there were no high precision tools available such as an *effectivePSF* library as in the case of ACS/WFC camera (Anderson, 2002). In order to improve the measurement of under-sampled PSF, we used the same technique, as described by Dulude & Dressel (2009). The images of 47 Tuc and LMC from SMOV 11445 observations were smoothed with the IRAF/BOXCAR task, using a flat-topped rectangular kernel of 3×3 pixels. Figure 1 represents the 2-D surface plots together with contour plots of the original and smoothed PSF. As can seen in Figure 1, the FWHM of the smoothed PSF is 3.3 pixels compared with FWHM=1.3 pixels of the original IR PSF.

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 30 IR images. As seen in Figure 2, the astrometric errors from Gaussian fit to X and Y positions as a function of instrumental magnitude shows a good formal measuring accuracy even for the severe under–sampled IR PSF.
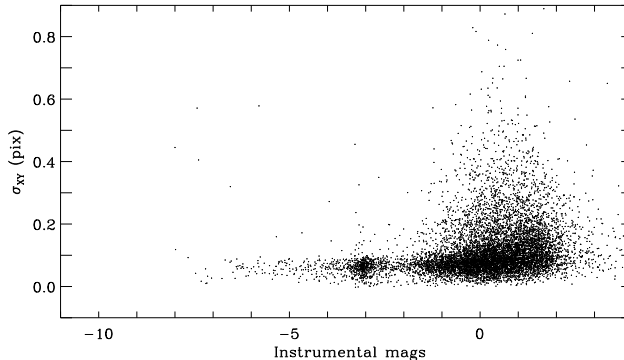

Fig. 2.— Centering errors of X & Y positions as a function of instrumental magnitude for stars in F160W images of LMC. The positions errors (σ_{XY}) are calculated as $\sqrt{(\sigma_X^2 + \sigma_Y^2)}$.

About 2,000 stars were detected in each IR image for 47 Tuc and about 15,000 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

Similar to the WFC3/UVIS geometric distortion calibration (Kozhurina-Platais *et.al.*, 2009), we used two astrometric standard frames, 47 Tuc and LMC, to calibrate the WFC3/IR channel. A relatively easy way to find the distortion model and then solve for it, is to use the positions of stars from a distortion-free astrometric standard catalog. The residuals between the observed positions of stars and the matching positions from an astrometric standard catalog essentially contain the optical distortion. A similar approach was used to derive the geometric distortion for WFC3/UVIS channel (Kozhurina-Platais *et.al.* 2009)

In the case of the WFC3/IR, preliminary optical ray-tracing model demonstrated that the IR detector has a considerable linear distortion, which is mainly a difference in scale between two principal axes. Because of this large linear distortion, almost square IR detector pixels will be projected onto the sky as elongated rectangles. Addition to that,

there is a small departure from non-orthogonality between the two principal axes known as the skew term. Therefore, the high precision astrometric standard catalog is essential to derive an accurate solution of the geometric distortion for IR detector.

3.2. Matching the Stars

First, the measured positions of stars from IR observed images should be matched with the same stars in the astrometric standard frame. This is not easy task because of the arbitrary orientation of the WFC3/IR images with respect to the astrometric standard catalog, and the difference in the scale, between the astrometric standard and IR images. To preserve the maximum precision all data manipulations are performed in the original pixel coordinates, as described by Kozhurina-Platais *et.al.* (2009). Because of that and the fact of very crowded images, the manual matching of stars was chosen for the first WFC3/IR image from the SMOV 11445 program About 20 bright stars were matched manually with the same stars in the astrometric standard catalog. This set of stars provided the initial shifts, rotation and scale, which is sufficient to identify automatically the remaining thousands of 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 in IR images, interactively rejecting poorly–measured and saturated stars. 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 is on the order of 0.06 pixels. The set of fixed reference stars always contains the original full-precision X & Y pixel positions of stars from the observed frame as well as the U & V coordinates from the astrometric standard catalog. The following observed WFC3/IR frames have the same orientation but different shifts in RA and DEC (dither POSTARG) in comparison to the starting image, therefore it is 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, which substantially speeds up reduction of the remaining frames.

3.3. The Model of Geometric Distortion

After all measured stars from the IR images are matched with the same stars in the astrometric standard catalog and the original positions from both coordinate systems (observed and astrometric standard) were saved, we proceed with deriving of the 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 positions in the astrometric standard catalog, and X,Y are the measured pixel positions in the observed IR 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 the 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. However, in the case of a substantial skew term ($A_2 \neq B_3$), the classical distortion odd-terms actually migrate to the lower order odd- and cross-terms. In essence, it means that we have to employ a full polynomial model to fully describe the geometric distortion. Thus, a key to the determination of the geometric distortion is to find a good alignment between the two coordinate systems.

In order to properly align the observed and catalog coordinate systems (X & Y pixel and U & V respectively), we made a few assumptions:

- the IR X-axes define as a primary reference axes because of the presence of large skew term in IR images;

- the zero-point of the IR CCD chips at $X = (x - 507.0)$ and $Y = (y - 507.0)$ is adopted as the global zero–point for the entire IR image, thus defining that all geometric distortions are zero at this specific point;

- the astrometric standard must be rotated and shifted so that there are zero offsets in X & Y between the IR and the astrometric standard catalog and there are no rotation between the X-axes in both systems, 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 IR CCD chip was used to find the initial offsets and the rotation center of the astrometric standard. The final offsets, the location of a rotation center, and the amount of rotation

were obtained through iterative least-squares solutions and successive small adjustments to the offset/rotation parameters. The process of minimization is non-trivial because of a skew term between the X & Y–axes. Therefore, we chose the X-axis as a reference with respect to which there is no rotation, *i.e.* when the ratio of the linear terms A_3/B_3 is minimal. Thus, the positions of stars from astrometric standard, matched to the X & Y positions from *IR*, were rotated with respect to this center, eliminating the rotation between the *IR* X-axis and the U-axis of the astrometric standard. The detailed description of the procedure is given in Kozhurina-Platais *et.al.* (2009). Once the rotation center is found and the $X\&Y$-offsets 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 *IR* detector.

Each coefficient of Eqs.(1) and (2) was examined by its value and the formal error, as returned by a least squares minimization of a 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 and significant with respect to the errors; except for the fifth-order, which is very small (on the order of 10^{-15}) and varies from one solution to another. Thus, the final geometric distortion for IR detector is represented by a fourth-order polynomial in X and Y positions for each solution.
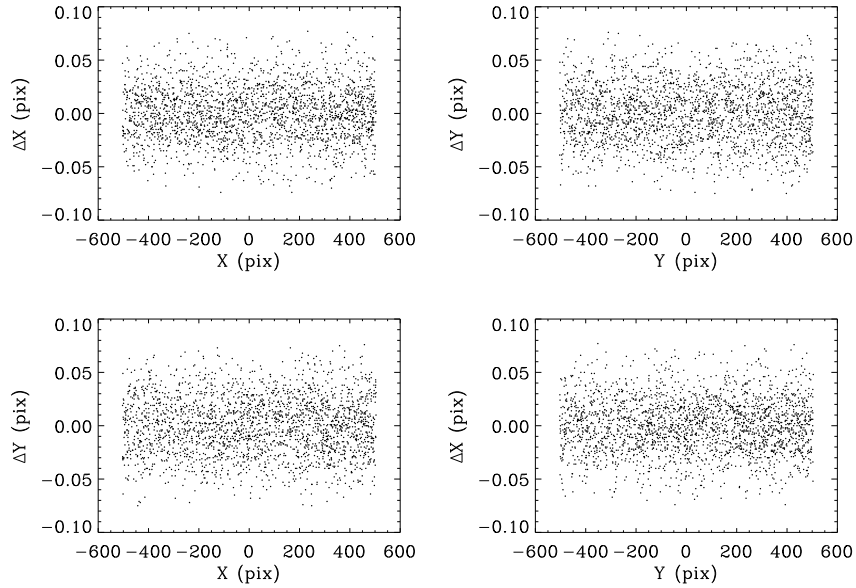

Fig. 3.— XY-residuals as function of X and Y positions between the standard astrometric catalog (47 Tuc) and the observed 47 Tuc positions after applying the best polynomial fit. The coordinates X,Y are given in the units of WFC3/IR pixels.

As seen in Figure 3, after applying the best polynomial fit, the residuals of X and Y positions between the observed 47 Tuc positions and the standard astrometric catalog (47 Tuc) are essentially flat, i.e. all large–scale residuals are successfully removed. The RMS of the best polynomial fit for each solution is 0.03 pixels or 5 *mas*. There is no evidence of the fine-scale systematic residuals from the best–fit polynomial solutions, as was noticed for the WFC3/UVIS (Kozhurina-Platais *et.al.*, 2009) or for the ACS/WFC and ACS/HRC (Anderson 2002).

A product from WFC3/IR geometric distortion calibration is color-magnitude diagram of globular cluster 47 Tuc (Fig.4), the comparison of ACS B (F606W) magnitudes from the astrometric standard and WFC3/IR H (F160W) magnitudes. This is a first CMD for globular cluster derived with WFC3/IR detector, which has a large magnitude range, five magnitudes below the main sequence turn off and 2.5 magnitudes range in the color. The curvature and the large slope of the main sequence in this diagram can be beneficial to analysis of stellar population in globular clusters, as 47 Tuc (Anderson *et.al* 2009).
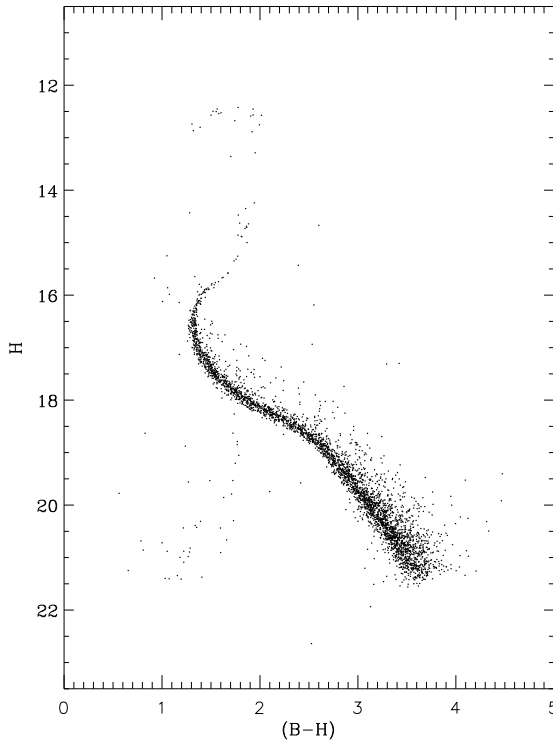

Fig. 4.— Color-Magnitude Diagram of globular cluster 47 Tuc as a product of the comparison of WFC3/IR photometry in F160W filter with ACS/WFC photometry in F606W filter.

3.4. Polynomial Coefficients

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

$$U = A_1 + A_2X + A_3Y + A_4X^2 + A_5XY + A_6Y^2 + A_7X^3 + ... + A_{21}Y^4 \tag{3}$$
$$V = B_1 + B_2X + B_3Y + B_4X^2 + B_5XY + B_6Y^2 + B_7Y^3 + ... + B_{21}Y^4 \tag{4}$$

These 30 separate 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 IR detector are listed in Tables 2.

Table 2: The 4th order polynomial terms for IR

Order	A	σ_A	B	σ_B
CONST	0.6465691E-01	0.449E+00	-0.9040401E-01	0.273E+00
X	0.1058096E+01	0.888E-05	0.3212205E-02	0.110E-04
Y	-0.5249698E-07	0.697E-09	0.9448773E+00	0.991E-05
XX	-0.1939060E-06	0.222E-07	0.6642154E-05	0.307E-07
XY	0.2591698E-04	0.223E-07	-0.1259990E-06	0.311E-07
YY	0.7850266E-07	0.281E-07	0.2842660E-04	0.339E-07
XXX	-0.1753322E-09	0.222E-10	0.1740409E-10	0.342E-10
XXY	0.1150480E-09	0.319E-10	-0.2220895E-09	0.345E-10
XYY	0.8208991E-10	0.294E-10	0.9723588E-11	0.338E-10
YYY	0.3765804E-10	0.229E-10	-0.1371008E-09	0.435E-10
XXXX	-0.5112961E-12	0.978E-13	-0.5441890E-12	0.138E-12
XXXY	0.7508959E-12	0.809E-13	0.2362620E-12	0.161E-12
XXYY	0.3999507E-13	0.140E-12	0.1418080E-12	0.976E-13
XYYY	0.7001390E-12	0.112E-12	-0.2469907E-13	0.135E-12
YYYY	-0.3430553E-12	0.115E-12	0.7375051E-12	0.148E-12

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 890×830 pixels in X and Y, respectively. These X and Y positions corrected for distortion with newly derived coefficients, 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 and 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. shift (the X & Y offset between frames), rotation between two frames and scale. The RMS of such solutions is about 0.05 pixels or *8mas*. The 2-D residual map shown in Figure 4, indicates that the residuals do not have any systematics as a function of X & Y positions or, in other words, the geometric distortion is properly removed even better than the original specifications on the accuracy of geometry distortion determination.
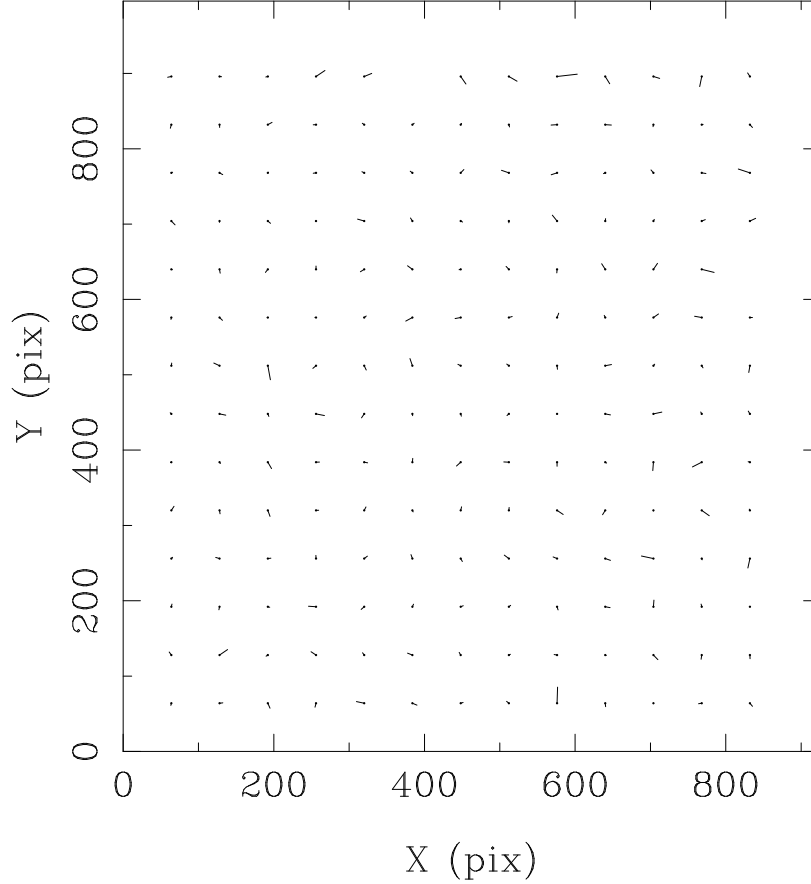

Fig. 5.— 2–D XY-residual map between two LMC images overlapped by 890×830 pixels in X and Y, respectively, after applying the newly derived geometry distortion coefficients. The largest vector has an amplitude of 0.15 pixels. The size of the residuals are scaled by a factor of 300. The units are WFC3/IR pixels.

4. **V2V3 System and IDCTAB**

The newly derived coefficients of geometric distortion for the WFC3/IR channel are in the system of X and Y detector coordinates that can be used to correct the X and Y positions obtained from any WFC3/IR (*_flt.fits) image with arbitrary pointing and orientation. The geometric distortion coefficients are fundamental for on-the-fly OTFR calibration in the STScI pipeline in order to remove the distortion from WFC3/IR (*_flt.fits) images. These coefficients are stored in a reference file, the Instrument Distortion Corrections Table (IDCTAB) which are in HST-based coordinate system – *V2V3*. The detailed description of the IDCTAB reference file can be found in 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 detailed description of the transformation of the geometric distortion coefficients from the detector coordinate system into the *V2V3* system are given in Kozhurina-Platais *et.al.* (2009, see Fig.8).

The calculated parameters of geometric distortion are compared to the ZEMAX optical ray-tracing model and presented in Table 3. As seen in this table, the derived geometric distortion parameters such as X_{scale} and Y_{scale} are in good agreement with the predictions from the model, accept for non-orthogonality of the axis, i.e. $(\beta_Y - \beta_x)$ is slightly greater then predicted at about $0°.17$.

Table 3: Parameters of IR geometric distortion

Parameters	Measured	Model
$X scale$	$0.''1354$	$0.''1355$
$Y scale$	$0.''1209$	$0.''1211$
β_X	$-44°.8161$	$-45°.1474$
β_Y	$45°.0099$	$44°.8528$

Thus, after transforming the coefficients from the detector pixels into the sky tangential plane or to reference file as IDCTAB, we are ready to use them in Multidrizzle.

5. Multidrizzle Test with derived WFC3/IR 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). Multiddrizzle 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 800×800 pixels in X & Y respectively, A plot of the residuals between these two overlapping LMC drizzled images (Fig.6), indicates that the IDCTAB in Multidrizzle is properly removing the geometric distortion. The RMS of a linear fit is 0.07 pixels, which means that the accuracy of the geometry distortion implemented in the IDCTAB is at about 0.08 pix, which is four times better than requirements of the WFC3/IR images alignment in Multidrizzle. were compared to each other, applying only a linear transformation.
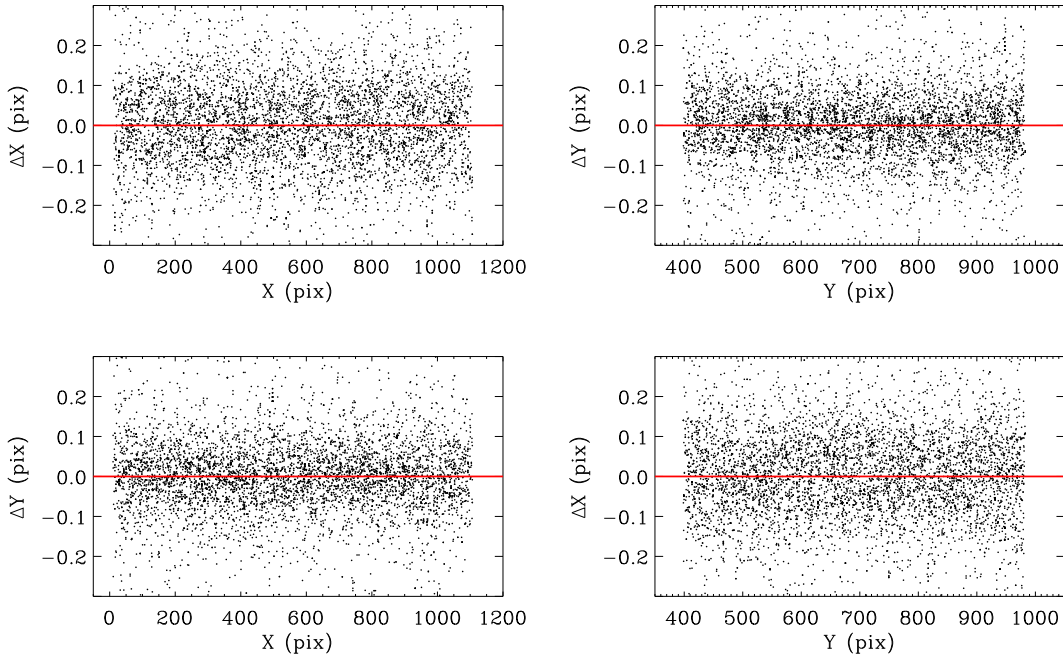

Fig. 6.— XY-residuals as a function of X and Y positions from two overlapping LMC drizzled images. The RMS of the linear transformation in X positions is 0.07 pixels and 0.05 pixels in Y. The over-plotted red solid line in each residual plots, shows no systematic trend in the residuals. The units are WFC3/IR pixels.

Another way to check the implementation of the geometry 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. The 2–D residual map in Figure 7, shows no indication of any large-scale systematic error.
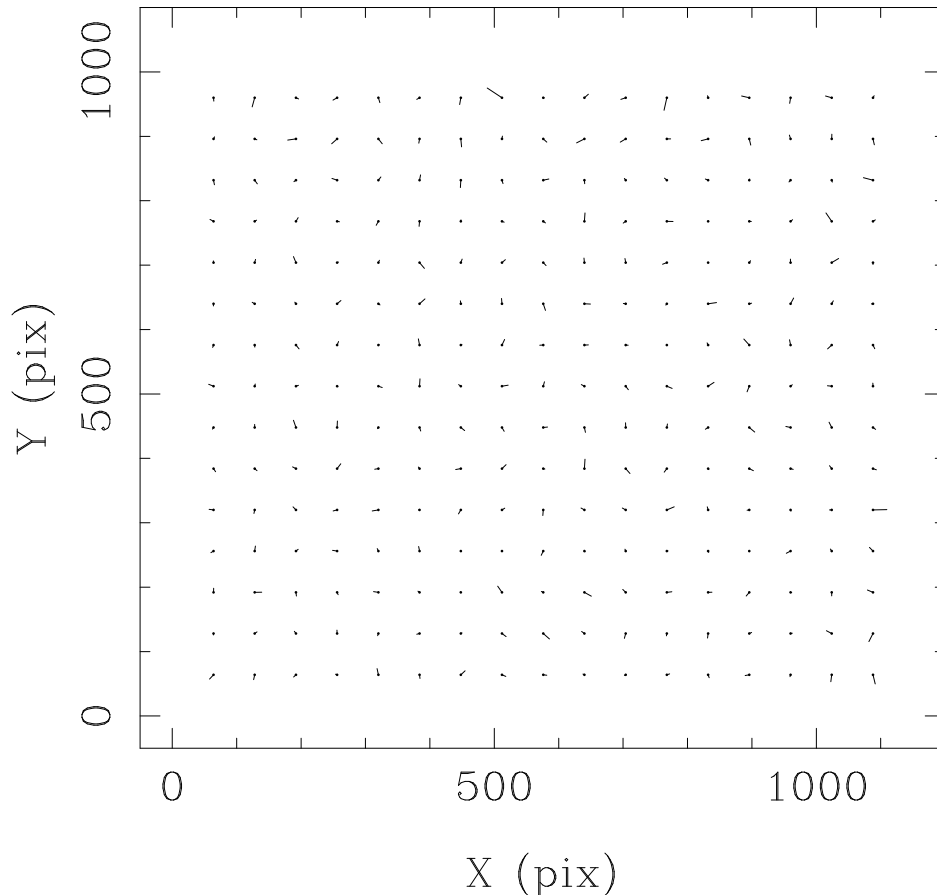

Fig. 7.— 2–D XY-residual map between a drizzled LMC image and the astrometric standard catalog. The largest vector has an amplitude of 0.3 pixels. The size of the residuals are scaled by a factor of 100. The units are WFC3/IR pixels.

6. Conclusions and Recommendations

This report presents a detailed description of the results of geometric distortion calibration of the WFC3/IR 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/IR geometric distortion down to the 8 mas precision

level, which is four times better than the required precision for SMOV. Summarizing the precision of the geometric distortion solution for WFC3/IR, we conclude that precision and accuracy of the geometric distortion depends on how accurate and precise is the centering technique for measurement of X and Y positions of severely under-sample PSF. Because of that, the effective PSF library and PSF fitting technique would allow us to better characterize the WFC3/IR geometric distortion down to $1mas$ precision level.

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

7. Acknowledgments

References

Anderson, J., 2002, in "2002 HST Calibration Workshop", eds. A.Arribas, A. Koekemoer, B.C. Whitmore (Baltimore:STScI)

Anderson, J., 2005, in "2005 HST Calibration Workshop", eds A. Koekemoer, P. Goudfrooij, L. Dressel (Baltimore:STScI), p.11

Anderson, J., & King, I., 2006, ACS Instrument Science Report, ACS/ISR - 06-01 (Baltimore:STScI)

Anderson, J., 2007, ACS Instrument Science Report, ACS/ISR - 07–08 (Baltimore:STScI)

Dulude, M., Dressel, L., 2009, WFC3 Instrument Science Report, WFC3/ISR - 2009–11 (Baltimore:STScI)

Hack, W., Cox, C., 2001, ACS Instrument Science Report, ACS/ISR - 01–08 (Baltimore:STScI)

Koekemoer, A.,M., Fruchter, A., Hook, R.,N., Hack, W., 2002, in "2002 HST Calibration Workshop", eds A.Arribas, A. Koekemoer, B.C, Whitmore (Baltimore:STScI), p.337

Kozhurina-Platais,V., Cox, C., McLean, B., Petro, L., Dresel, L., Bushouse, H., 2009, WFC3/ISR - 09–34 (Baltimore:STScI)

van de Kamp, P., 1967, "Principles of Astrometry", by W. H. Freeman & Company (San Francisco and London)