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Revised IDCTAB Definition: Application to HST data

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ABSTRACT

The new reference table, IDCTAB, will support the description of geometric distortion models for instruments. This report describes the columns in the table and how the coefficients in the table can be used. Examples are then provided on how this table will be used on HST data; specifically, ACS and STIS.

Introduction

Many instruments require some sort of reference file for describing the geometric distortion, yet a single format has not yet been developed that satisfies each instrument's needs. The description of the geometric distortion can take many different forms, ranging from images of pixel area variations to polynomial fits. One common element shared by all the instruments is the Science Instrument Aperture File (SIAF) which contains descriptions of the distorted and undistorted aperture positions. The conversion between distorted and undistorted positions in the SIAF is controlled by a polynomial fit performed by the instrument teams. This commonality provides the basis for generating a small and simple reference file which can be used by any instrument to describe the detector's geometric distortion using the same fitting method.

This report describes the format of this common reference file based on the polynomial fit used by the SIAF. The IDCTAB, as referenced by the ACS, contains the coefficients for this fit along with other information necessary for applying to each image. The format has been developed to be as general as possible so that instruments other than ACS can also use it along with any software designed to work with this table.

Distortion Model

A single model for the geometric distortion has been used for WFPC2, STIS and ACS in the SIAF. This model ties in the aperture position to the detector pixel positions and accounts for geometric distortion to support accurate target acquisitions, image processing, and photometry. The X and Y pixel coordinates for the reference pixel for this model gets recorded in the science headers as CRPIX1 and CRPIX2.

The translation from detector pixel coordinates to sky position includes the scaling and distortion correction with the origin at the reference position where the detector and sky Y axes are assumed to be exactly parallel. The relationship between these systems is defined for the SIAF as

$$x_c = \sum_{i=0}^{k}\sum_{j=0}^{i} a_{i,j}(x-x_r)^j(y-y_r)^{i-j} \qquad y_c = \sum_{i=0}^{k}\sum_{j=0}^{i} b_{i,j}(x-x_r)^j(y-y_r)^{i-j}$$

where (x,y) is the original pixel position from the image, (x_r,y_r) is the reference pixel position, (x_c,y_c) is the corrected position in arcseconds and k is the polynomial order of the fit. For the SIAF, the orientation of the (x_c,y_c) system is normally chosen so that the corrected y_c axis is parallel to the input y axis. For displaying the ACS images, we choose the x_c, y_c axes where:

- x_c is parallel to V2 and y_c anti-parallel to V3 for the WFC, and
- x_c is anti-parallel to V2 and y_c is parallel to V3 for the HRC and SBC.

In this way, we do not explicitly involve the exact detector orientations which are different for each of the WFC chips. The interface document ICD-26 limits the SIAF polynomial order to 5. Fortunately, this limit does not prevent us from using higher order fits in the IDCTAB should it be necessary. These polynomials expand out to the forms

$$x_c = a_{00} + a_{10}d_y + a_{11}d_x + a_{20}d_y^2 + a_{21}d_xd_y + a_{22}d_x^2 + \ldots \qquad (1)$$

$$y_c = b_{00} + b_{10}d_y + b_{11}d_x + b_{20}d_y^2 + b_{21}d_xd_y + b_{22}d_x^2 + \ldots \qquad (2)$$

where $d_x = (x - x_r)$ and $d_y = (y - y_r)$. The values of a_{00} and b_{00} will always be zero, since $x_c=0$ and $y_c=0$ at the reference position $(x,y) = (x_r,y_r)$. For the purposes of mosaicing the separate WFC chips, a display coordinate system (x_u,y_u) is defined, shifted and scaled with respect to the (x_c,y_c) coordinates for each detector, but aligned with them.

A similar form is used for the inverse relation using coefficients *c* and *d* for the x and y fits respectively; specifically,

$$x = x_r + \sum_{i=0}^{k}\sum_{j=0}^{i} c_{i,j}x_c^jy_c^{(i-j)} \qquad y = y_r + \sum_{i=0}^{k}\sum_{j=0}^{i} d_{i,j}x_c^jy_c^{(i-j)}$$

Although this description appears asymmetric, the origin of each set of coefficients is the same point. This inverse relation provides the conversion from units of arcseconds to distorted input pixels.

File Format

The IDCTAB will be stored as a FITS file with a FITS table in the first extension. The primary header will only contain basic FITS keywords along with information about the generation of the reference file. Additional keywords in the primary header would include:

INSTRUME	S	Name of the Instrument
DETECTOR	S	Name of the detector used
NORDER	I	Order of the polynomial fit used for the distortion
PARITY	I	Parity value for conversion from (x,y) to (V2,V3)

The INSTRUME and DETECTOR keywords provide a way to tie the distortion model found in the table with a specific instrument and detector. These can then be used to select which IDCTAB is appropriate for an observation so that the right model gets applied to the data. The keyword NORDER provides a way to ascertain up front what order of polynomial has been stored in the table. The PARITY keyword describes the relationship between pixel coordinates and V2,V3, having a value of either 1 or -1. This value exists primarily as documentation for the instrument, and does not directly enter into the application of the model to the observational data.

The first extension to the FITS file would then hold the table with the description of the geometric distortion. The table itself would at least consist of the columns:

DETCHIP	S	%8s	ID of chip/detector used for observation
DIRECTION	S	%8s	Application direction of coefficients (FORWARD or INVERSE)
WAVELENGTH	R	%12.4f	Central wavelength of fit
XSIZE	I	%8d	Raw image size in pixels in X direction
YSIZE	I	%8d	Raw image size in pixels in Y direction
XREF	R	%12.4f	X position of reference point (pixels)
YREF	R	%12.4f	Y position of reference point (pixels)
V2REF	R	%12.4f	V2 position of reference point (arcsec)
V3REF	R	%12.4f	V3 position of reference point (arcsec)
SCALE	R	%12.4f	Scale of square corrected pixel in arcsec
CX10,CY11,...	R	%20.6e	Distortion Coefficients for X position

CY10,CY11,...	R	%20.6e	Distortion Coefficients for Y position

The table contains one row for each part of the detector that has its own distortion correction. For example, the ACS WFC table would contain 1 row for each 2048x4096 chip that makes up a WFC observation where each row would have a different value of DETCHIP. An additional row for each chip may be included for the inverse fit and they would be flagged with the DIRECTION value of ‘INVERSE’. Naturally, instruments with only one detector (such as STIS CCD) would only have 1 row for the forward fit and an optional row for the inverse fit. There may also be separate sets of these rows for different central wavelengths, as determined by the optical elements used for the observation, with each set having its own value for WAVELENGTH. The units of WAVELENGTH can vary for each instrument since IR detectors operate in microns as opposed to Angstroms for a UV imager.

Reference Position Columns

A primary problem that arises when working with multiple chips that make up a single observation comes in when trying to assemble the chip’s data into a single image. The distortion coefficients provide a correction for each pixel relative to the chip’s or detector’s reference point as specified in the XREF and YREF columns. The relationship between each chip or detector in the entire observation must be factored in separately. HST relies on a V2/V3 coordinate system to define the metrology for each instrument and its apertures. It specifies each detector’s position in terms of arcseconds from the center of the HST primary’s field of view. The position of each detector’s reference position in this coordinate system then provides the absolute position of each chip in the final observation. The V2REF and V3REF columns contain the position of each detector’s reference position in these coordinates. The absolute values of the V2REF and V3REF positions are not as important as the relative positions, as they are only used to compute relative positions of the chips/detectors used to take the observation.

The use of the V2/V3 coordinate system for the reference positions would seem, at first glance, to preclude the application of this table to any non-HST instrument’s data. This obviously does not present any problem for use of this table within HST calibration pipelines for HST data. However, this table could potentially be used to allow dither-combining of non-HST data through the STSDAS dither package. In these cases, the V2REF and V3REF positions would be computed to represent deltas in arcseconds between the different chips in multi-chip observations, and in the case of single chip/ detector observations, they could simply be set to zero. Ultimately, the nomenclature attempts to make it clear that both the XREF/YREF and V2REF/V3REF positions represent the same point in the images in different coordinate systems allowing the possibility of combining the data into a single image.

Distortion Coefficients Columns

Applying the fit to an image will result in an image where the pixels are shifted around to correct for the distortion, but a couple of decisions remain to be made: output size and output pixel scale. Both of these are completely up to the end-user, however, this reference file contains the column SCALE to provide the calibrated value for the model. The value for SCALE will specify a canonical, calibrated value which would be applied to the output image in lieu of any end-user overrides. This will allow data to be processed automatically with this reference table to produce output images of consistent pixel scale suitable for astrometric purposes subject to the errors in the correction.

The final columns CX*nn* and CY*nn* contain the values for the polynomial fit for the distortion for that chip alone. The precision of these coefficients should largely be driven by the fit, using either single- or double-precision as necessary. These values would convert an input pixel position to an undistorted position assuming the value of the DIRECTION column were ‘FORWARD’. Alternatively, if DIRECTION was specified as ‘INVERSE’ for the row, the coefficients would specify the application of the distortion to undistorted pixel positions resulting in a distorted image. The column names for the coefficients contain the indices for the coefficients from the polynomial fit, such as CX11 corresponding to the a_{11} coefficient for the forward fit and c_{11} coefficient for the inverse fit. This allows a direct correlation between the columns and the coefficients used in the fit with little ambiguity. These columns can then be read into a polynomial of order NORDER (specified for the fit in the table header). For subarray data, the pixel position from the observation should be corrected for the offset of the subarray to put it into the coordinate frame of the entire chip.

Optional Columns

The IDCTAB provides nearly all the necessary functionality through the default columns. However, some instruments require additional information specific to the situation, information which can be added as optional columns to the default IDCTAB. Examples of some optional columns used in the IDCTAB are:

PEDIGREE	S	%-67s	Source of calibrated values: ground, on-orbit,...
DESCRIP	S	%-67s	Indication of how these calibrated values were generated
OPT_ELEM	S	%15s	Optical elements for which these values are valid
CXSIZE,CYSIZE	I	%8d	Default calibrated image size (in pixels)
CXREF,CYREF	I	%8d	Default reference position in output image (in pixels)
THETA	R	%12.4f	Angle between calibrated and uncalibrated Y axes

These optional columns can be found in the STIS IDCTAB being used within the STIS calibration software, CALSTIS. The column ‘OPT_ELEM’ provides a more exact way to match the observation with a distortion model as some filters/elements result in different scales. This sort of distinction would not be possible by selecting by wavelength alone. The other columns provide default values that can be used when applying the model to allow for automatic processing in a robust, standardized manner.

In short, additional columns can be added to the base set of columns defined for the IDCTAB to provide greater flexibility in how the IDCTAB describes the distortion for an observation. The default columns should always be present in the IDCTAB whenever additional columns are added to insure that some common functionality be available to software that might try to access this table.

Application of the IDCTAB

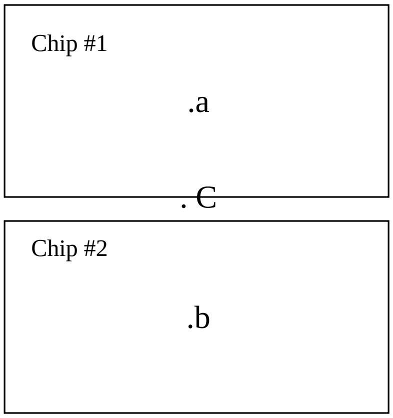
The IDCTAB file represents the geometric distortion of any given observation with a detector for removal during calibration and analysis of the data. Therefore, it will find its uses in tasks which provide a means of correcting images for their distortions, such as calibration pipeline software and image combination tasks such as ‘drizzle’. Some routines, like ‘drizzle’, will not understand this table, so the coefficients need to be converted into a format suitable for use by that task. Current efforts have focussed on developing software that would allow this table to be used for ACS observations in the application of the ‘drizzle’ software to provide the geometric correction during routine pipeline calibration. Other instruments, such as STIS, have also started using this table for their calibration purposes as well. In each situation, the IDCTAB provides basic information which must be interpreted for use in the software. The following sections provide some details on IDCTAB files for a couple of HST instruments and how they are used to calibrate their instrument’s observations. These examples should serve as examples on how to not only set up an IDCTAB for an instrument, but also on how to set up the software to apply it to the instrument’s data.

ACS IDCTAB

ACS actually requires three separate IDCTABs, one for each detector: WFC, HRC, and SBC. The HRC and SBC IDCTABs only have to provide the coefficients for a single chip/detector resulting in a table with a single row for the FORWARD correction. The WFC, on the other hand, requires a table with 2 rows for the FORWARD direction: one for each chip, WFC1 and WFC2. The initial tables derived from ground-testing calibrations can be found in “Appendix A” on page 10.

The model given in the table covers the entire instrument’s field of view, but the WFC uses 2 chips for each non-subarray observation. The fits for each chip are combined into a global fit with the same common point (x_{com}, y_{com}). This common point can be defined as the average of the (V2REF,V3REF) positions and converted to pixel positions using the plate scale, by default using the value provided in the SCALE column; specifically, 0.05 arcseconds/pixel. Figure 1 shows how the common point C relates to each chip in an ACS WFC observation. The distance in arcseconds for each reference point from the common point, (X_{delta}, Y_{delta}), provides the offset to be applied when combining the chips into a single image.

Figure 1: Schematic of Reference Points for ACS WFC observation.



Combining both chip's data into a single image would require the transformation:

$$(X_u, Y_u) = (X_c, Y_c) / \text{scale} + (X_{delta}, Y_{delta}) \qquad (3)$$

The basic steps performed in the application of the IDCTAB for 'drizzle' operation can be specified in the following steps.

- The pixel positions relative to the reference pixel position for the chip are computed. The reference position is given by (XREF,YREF). We then get $d_x = x - XREF$ and $d_y = y - YREF$, where x and y are original (distorted) detector pixel positions.
- These deltas, (d_x, d_y), are then used in Equation (1) and Equation (2) to compute the undistorted positions (x_c, y_c). At this point, the undistorted position will be in units of arcseconds.
- These positions are then divided by the desired output plate scale, which by default is given by the SCALE column value of 0.05.
- Finally, combine both chips into a single image by adding the offset (X_{delta}, Y_{delta}) to each pixel position to get the final position (X_u, Y_u).

Ideally, all chips for the observation will be perfectly parallel with each other. The fit for each chip only insures that the distorted and corrected Y axes for a chip remain at the same angle with respect to the telescope V3 axis. This allows each chip to have different rotations relative to each other. Typically, though, this mis-alignment between the chips will be less than a degree for ACS observations.

STIS IDCTAB

The pipeline calibration software for STIS, *calstis*, has recently updated to correct for the distortion in the optics. The software relies on an IDCTAB for the specification of the model, although the STIS IDCTAB contains more than just the default columns. All the optional columns described earlier are used, except THETA, along with the default columns. The columns CX10, CX11, CY10, and CY11 must be present for *calstis* to operate properly, with additional coefficients columns (CX*ij*, CY*ij*) being read if present (up to fifth order). Some optical elements in STIS affect the plate scale, so calstis actually relies on OPT_ELEM instead of WAVELENGTH to unambiguously select which model applies to the data.

In calstis, the IDCTAB actually gets used to compute the original distorted pixel positions from the corrected image.   The ‘raw’ coordinate gets computed by:

- transforming the corrected pixel coordinates (X_u,Y_u) from pixel position to arcseconds (X_c,Y_c) using

$$X_c = (X_u - CXREF) \times SCALE \tag{4}$$

$$Y_c = (Y_u - CYREF) \times SCALE \tag{5}$$

- computing the undistorted pixel position (d_x,d_y) by applying the (CX*ij*, CY*ij*) coefficients to (X_c,Y_c) in manner described by Equation (1) and Equation (2).
- then shifting the undistorted pixel position (d_x,d_y) back into the reference frame by applying the reference position to get the initial ‘raw’ distorted position (x,y):

$$x = d_x + XREF \tag{6}$$

$$y = d_y + YREF \tag{7}$$

The STIS coefficients used in the IDCTAB were derived using the method described at the STScI Calibration Workshop (Malumuth and Bowers, 1997, HST Calibration Workshop, p 144).

Summary

The geometric distortion for many instruments can be described using the IDCTAB which contains the coefficients for the SIAF polynomial fit. This table has been defined so that any instrument whose distortion has been modelled using a polynomial fit can use this table as a reference file. In fact, it would be possible to extend this to other forms of models by referencing a keyword in the header which describes the form; such as, legendre, chebyshev, spline. The coefficient columns would then be applied to the form of the model specified in the header, with the default model being a polynomial.

The table contains information about the reference positions used for the fit and used for applying that fit to single- and multiple-chip observations. Each instrument has its own set of unique requirements that may not be fully met by this specification. Those requirements can therefore be met with the addition of columns specific to the instrument, as demonstrated by the use of an IDCTAB with additional columns with STIS data. Overall, this table should support a wide-range of instruments and should be easily applied with software.

Appendix A

This appendix contains the data from the initial IDCTAB tables for the ACS.

Column Name	WFC1	WFC2	HRC	SBC
DETCHIP	1	2	1	1
DIRECTION	FORWARD	FORWARD	FORWARD	FORWARD
WAVELENGTH	5500	5500	5500	5500
XSIZE	4096	4096	1024	1024
YSIZE	2048	2048	1024	1024
XREF	2048.0	2048.0	512.0	512.0
YREF	1024.0	1024.0	512.0	512.0
V2REF	256.1759	252.4010	202.9552	202.9552
V3REF	202.9818	307.2501	476.9087	476.9087
SCALE	0.0500	0.0500	0.0250	0.0250
CX10	2.043000E-03	1.716000E-03	3.456965E-05	3.456965E-05
CX11	4.936900E-02	4.998800E-02	2.829400E-02	2.829400E-02
CX20	1.039763E-07	1.009187E-07	-2.963941E-08	-2.963941E-08
CX21	-3.581642E-07	-2.512996E-07	2.489537E-07	2.489537E-07
CX22	4.260882E-07	4.323974E-07	-1.017438E-07	-1.017438E-07
CX30	1.083901E-12	9.808750E-13	6.038382E-11	6.038382E-11
CX31	-2.534018E-11	-2.609675E-11	-3.352572E-11	-3.352572E-11
CX32	-7.050180E-12	3.504677E-13	1.764284E-11	1.764284E-11
CX33	-2.084135E-11	-2.185396E-11	-1.808337E-11	-1.808337E-11
CY10	4.874700E-02	5.045900E-02	2.484900E-02	2.484900E-02
CY11	2.241000E-03	1.587000E-03	2.806000E-03	2.806000E-03
CY20	-4.869958E-07	-3.655885E-07	2.777439E-07	2.777439E-07
CY21	2.950638E-07	3.059341E-07	-5.324632E-08	-5.324632E-08
CY22	-1.322498E-07	-7.903063E-08	4.102039E-08	4.102039E-08
CY30	-1.784890E-11	-1.925362E-11	2.863611E-11	2.863611E-11
CY31	-4.502763E-12	-2.690682E-12	2.160897E-11	2.160897E-11
CY32	-2.015181E-11	-2.613851E-11	1.298933E-12	1.298933E-12
CY33	3.224006E-12	4.491541E-12	-1.712582E-13	-1.712582E-13