The SIP Convention for Representing Distortion in FITS Image Headers

David L. Shupe, Mehrdad Moshir, Jing Li,[1] David Makovoz, and Robert Narron

Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125, USA

Richard N. Hook[2]

Space Telescope European Coordinating Facility, Karl-Schwarzschild-Str. 2, D-85748, Garching, Germany

Abstract.   The SIP (Simple Imaging Polynomial) convention provides a convenient means for representing non-linear geometric distortion as polynomials in FITS header keywords. This scheme has been incorporated by the Spitzer Science Center (SSC) into its imaging products, and it is under consideration for wider use. The SIP keywords are read and applied by the SSC's MOPEX mosaicking software, and by several standard analysis tools, including WCSTools, SAOImage, DS9, GAIA/Starlink AST, IDL ASTROLIB, and Drizzle. We provide definitions of how these keywords are used together with standard FITS World Coordinate System (WCS) keywords to relate pixel coordinates to the sky. Some examples illustrate the application of this scheme to actual distorted data.

1.   Introduction

Images from the instruments on board the *Spitzer Space Telescope* are distorted by a few percent relative to a regular sky grid. These distortions are well-represented by polynomials, and the Spitzer Science Center (SSC) has developed a convention for inserting the coefficients into the FITS headers of each Basic Calibrated Data (BCD) product. The post-BCD processing software MOPEX[3] developed by the SSC (Makovoz & Khan 2004) accounts for the distortions in regridding and coadding the images. Writing the coefficients to the FITS headers was motivated particularly by the optics of the Multiband Imaging Photometer for Spitzer (MIPS) instrument (Rieke et al. 2004)—the distortion changes with scan mirror position, and hence from one image to the next.

The development of the SIP convention proceeded in parallel with work on the World Coordinate System (WCS) standard. The first two papers in this series (Greisen & Calabretta 2002, "Paper I"; and Calabretta & Greisen 2002,

---

[1]Princeton, NJ, USA

[2]currently based at STScI, Baltimore, MD 21212, USA

[3]http://ssc.spitzer.caltech.edu/postbcd/

"Paper II") specifying the WCS keywords (sans distortion) have been approved by the IAU FITS Working Group. "Paper IV" will address distortion–it has been drafted[4] but is not yet final (cf. Calabretta et al. 2004). The Spitzer keywords are compliant with the first two papers, and have been influenced by discussions of Paper IV, but are distinct from the proposed keywords in Paper IV.

2. Definitions of the Distortion Keywords

The SIP convention derives its name from the four characters '`-SIP`' that are appended to the values of `CTYPE1` and `CTYPE2`. These extra characters were included in early drafts of Paper IV to denote the distortion representation; however, the most recent draft has dropped this form. We chose '`-SIP`' to be distinct from the '`-PLP`' that was to be used in Paper IV for polynomials, and because it has the useful mnemonic "Simple (or Spitzer) Imaging Polynomial".

We define u, v as relative pixel coordinates with origin at `CRPIX1`, `CRPIX2`. Following Paper II, x, y are "intermediate world coordinates" in degrees, with origin at `CRVAL1`, `CRVAL2`. Let $f(u, v)$ and $g(u, v)$ be the quadratic and higher-order terms of the distortion polynomial. Then

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \texttt{CD1\_1} & \texttt{CD1\_2} \\ \texttt{CD2\_1} & \texttt{CD2\_2} \end{pmatrix} \begin{pmatrix} u + f(u, v) \\ v + g(u, v) \end{pmatrix} \tag{1}$$

We define `A_p_q` and `B_p_q` as the polynomial coefficients for polynomial terms $u^p v^q$. Then

$$f(u, v) = \sum_{p,q} \texttt{A\_p\_q} u^p v^q, \quad p + q \leq \texttt{A\_ORDER}, \tag{2}$$

$$g(u, v) = \sum_{p,q} \texttt{B\_p\_q} u^p v^q, \quad p + q \leq \texttt{B\_ORDER}. \tag{3}$$

For example, for a third-order polynomial,

$$f(u, v) = \texttt{A\_2\_0} u^2 + \texttt{A\_0\_2} v^2 + \texttt{A\_1\_1} uv + \texttt{A\_2\_1} u^2 v + \texttt{A\_1\_2} uv^2 + \texttt{A\_3\_0} u^3 + \texttt{A\_0\_3} v^3$$

The `CDi_j` keywords encode skew as well as rotation and scaling. The CD-matrix values together with the higher-order distortion polynomials, as in Equations 1, 2, and 3, define a unique transformation from pixel coordinates to the plane-of-projection.

For Spitzer, we also provide polynomials for the reverse transformation, for fast inversion. Corrected pixel coordinates U, V are found from

$$\begin{pmatrix} U \\ V \end{pmatrix} = CD^{-1} \begin{pmatrix} x \\ y \end{pmatrix} \tag{4}$$

then the original pixel coordinates are computed by

$$u = U + F(U, V) = U + \sum_{p,q} \texttt{AP\_p\_q} U^p V^q, \quad p + q \leq \texttt{AP\_ORDER}, \tag{5}$$

$$v = V + G(U, V) = V + \sum_{p,q} \texttt{BP\_p\_q} U^p V^q, \quad p + q \leq \texttt{BP\_ORDER}. \tag{6}$$

---

[4]`http://www.atnf.csiro.au/people/mcalabre/WCS/index.html`

3. Example: Spitzer-IRAC Channel 4

We take as an example the distortion of the Spitzer Infrared Array Camera (IRAC) instrument (Fazio et al. 2004), which is characterized by quadratic coefficients. Polynomial distortion of this form (plus linear terms) was fit to data taken during In-Orbit Checkout (see Spitzer Observer's Manual). The linear terms are folded into the CDi_j. An excerpt from an actual BCD header produced by the SSC pipeline (Moshir et al. 2004) for IRAC Channel 4 is shown below.

```
CTYPE1  = 'RA---TAN-SIP'          / RA---TAN with distortion
CTYPE2  = 'DEC--TAN-SIP'          / DEC--TAN with distortion
CRVAL1  =      248.588845714283 / [deg] RA at CRPIX1,CRPIX2
CRVAL2  =      -46.7664545714299 / [deg] DEC at CRPIX1,CRPIX2
CD1_1   = 3.79787003748175E-05
CD1_2   = 0.000336011759341397
CD2_1   = 0.000337467809645458
CD2_2   = -3.6366440945003E-05
CRPIX1  =                 128.
CRPIX2  =                 128.
A_ORDER =                     2 / polynomial order, axis 1
A_0_2   =            1.569E-05 / distortion coefficient
A_1_1   =            5.232E-05 / distortion coefficient
A_2_0   =             3.31E-05 / distortion coefficient
B_ORDER =                     2 / polynomial order, axis 2
B_0_2   =            4.172E-05 / distortion coefficient
B_1_1   =            2.213E-05 / distortion coefficient
B_2_0   =           -9.819E-07 / distortion coefficient
AP_ORDER=                     2 / polynomial order, axis 1
AP_0_1  =            5.677E-05 / distortion coefficient
AP_0_2  =           -1.569E-05 / distortion coefficient
AP_1_0  =            5.871E-05 / distortion coefficient
AP_1_1  =           -5.231E-05 / distortion coefficient
AP_2_0  =           -3.309E-05 / distortion coefficient
BP_ORDER=                     2 / polynomial order, axis 2
BP_0_1  =            4.432E-05 / distortion coefficient
BP_0_2  =           -4.172E-05 / distortion coefficient
BP_1_0  =            2.091E-05 / distortion coefficient
BP_1_1  =           -2.213E-05 / distortion coefficient
BP_2_0  =            9.814E-07 / distortion coefficient
```

In this case, the reverse coefficients have the opposite sign and roughly the same absolute values as the corresponding forward coefficients. However, this is not true for some more distorted fields of view, so the Spitzer headers retain the reverse coefficients in general.

The SSC has developed library routines to implement this coefficient naming scheme. The functions key off the extended CTYPEn. The order in which the keywords are displayed in the example is the order in which the software searches for them and is the most efficient for lookups using CFITSIO.

4.   Software that Reads and Applies the Coefficients

The SSC's mosaicking package MOPEX (Makovoz & Khan 2004) applies the SIP distortion coefficients in the SSC pipelines. Support has also been added to IPAC's Skyview display program[5]. Doug Mink has implemented Spitzer distortion support in his WCS routines[6]. SAOimage and DS9 use these routines and hence automatically handle the SIP distortions. The Montage software[7] (Laity et al. 2004) also uses Mink's routines and applies the coefficients. Support in the GAIA viewer has been added via David Berry's ASTLIB. Wayne Landsman has added support to the IDL ASTROLIB. The Drizzle software (Fruchter & Hook 2002) has also recently been modified to read these coefficients.

5.   SIP for Hubble

Of the active cameras on board the Hubble Space Telescope, the distortion is largest by far for the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) where it amounts to more than fifty pixels at the corner of the image in addition to an even larger (linear) skew term.

   The image distortion for Hubble cameras is currently characterized by a FITS table known as the Image Distortion Correction Table (IDCTAB) which includes information about the positioning of the instrument aperture in the telescope focal plane as well as the distortion polynomial coefficients. Software has been developed that will combine the IDCTAB information with the normal information from the telescope's pointing control software to write out a header which makes the header WCS keywords fully compatible with the table values and also populates the SIP-keywords (or at least the most important ones). An example of the resultant header is given in Table 1.

   Currently the writing of these SIP keywords is an unsupported feature for Hubble data. However, it would be very easy to formally include such headers in future to provide users with a full, self-describing distortion model without the need for access to external files in non-standard formats. The software to read the coefficients and apply them to remove image distortion already exists within the standard Hubble data processing tools.

---

[5]http://www.ipac.caltech.edu/Skyview/

[6]http://tdc-www.harvard.edu/software/wcstools

[7]http://montage.ipac.caltech.edu

Table 1.   SIP coefficients for the Hubble ACS Wide Field Channel.

Keyword	Value	Keyword	Value
CTYPE1	'RA---TAN-SIP'	CTYPE2	'DEC--TAN-SIP'
CRPIX1	2048.0	CRPIX2	1024.0
CRVAL1	5.6260667398471	CRVAL2	-72.076963036772
CD1_1	-7.8481866550866E-06	CD2_1	1.1406694624771E-05
CD1_2	1.0939720432379E-05	CD2_2	8.6942510845452E-06
A_0_2	2.1634068532689E-06	B_0_2	-7.2299995118730E-06
A_1_1	-5.194753640575E-06	B_1_1	6.1778338717084E-06
A_2_0	8.543473309812E-06	B_2_0	-1.7442694174934E-06
A_0_3	1.0622437604068E-11	B_0_3	-4.2102920235938E-10
A_1_2	-5.2797808038221E-10	B_1_2	-6.7603466821178E-11
A_2_1	-4.4012735467525E-11	B_2_1	-5.1333879897858E-10
A_3_0	-4.7518233007536E-10	B_3_0	8.5722142612681E-11
A_0_4	1.4075878614807E-14	B_0_4	6.5531313110898E-16
A_1_3	-1.9317154005522E-14	B_1_3	1.3892905568706E-14
A_2_2	3.767898933666E-14	B_2_2	-2.9648166208490E-14
A_3_1	5.0860953083043E-15	B_3_1	-2.0749495718513E-15
A_4_0	2.5776347115304E-14	B_4_0	-1.812610418272E-14
A_ORDER	4	B_ORDER	4

References

Calabretta, M.R., & Greisen, E.W. 2002, A&A, 395, 1077 (Paper II)

Calabretta, M.R., Valdes, F., Greisen, E.W., & Allen, S.L. 2004, in ASP Conf. Ser., Vol. 314, ADASS XIII, ed. F. Ochsenbein, M. Allen, & D. Egret (San Francisco: ASP), 551

Fazio, G., et al. 2004, ApJS, 154, 10

Fruchter, A.S. & Hook, R.N. 2002, PASP, 114, 144

Greisen, E.W., & Calabretta, M.R. 2002, A&A, 395, 1061 (Paper I)

Laity, A.C., Anagnostou, N., Berriman, B., Good, J.C., Jacob, J.C., & Katz, D.S. 2004, in ASP Conf. Ser., Vol. 347, ADASS XIV, ed. P. L. Shopbell, M. C. Britton, & R. Ebert (San Francisco: ASP), 34

Makovoz, D., & Khan, I. 2004, in ASP Conf. Ser., Vol. 347, ADASS XIV, ed. P. L. Shopbell, M. C. Britton, & R. Ebert (San Francisco: ASP), 81

Moshir, M. 2004, in ASP Conf. Ser., Vol. 347, ADASS XIV, ed. P. L. Shopbell, M. C. Britton, & R. Ebert (San Francisco: ASP), 434

Rieke, G., et al. 2004, ApJS, 154, 25