ASTRO-H

ASTRO-H COORDINATES DEFINITIONS
ASTH-SCT-020

Version 0.28

25 September 2017

ISAS/ GSFC

Prepared by: Hans Krimm, Robert Hill, Lorella Angelini, Tahir Yaqoob

Table of Contents

CHANGE RECORD

DOCUMENT TITLE : Coordinate definition

ISSUE	DATE	PAGES AFFECTED	DESCRIPTION
Version 0.0	June 2011	All	First draft
Version 0.1	Oct 2011	All	Included basic description of SXI coordinates
Version 0.2	Nov 14 2011	SXS,HXI, SGD	Added basic description of SXS, HXI, SGD coordinates
Version 0.3	Nov 23 2011	All	Modified to include instrument specification.
Version 0.4	Dec 23 2011	All	Revision after GSFC meeting Dec 12-16 2011
Version 0.5	Jan 26 2012	Sec 2.3 2.4	Modified based on teldef files for SXS, HXI
Version 0.6	Mar 14 2012	Sec 2.2,2.3, 2.4	Modified coordinate levels for SXI, SXS, HXI based on discussions with SCT team.
Version 0.7	Mar 23 2012	All but sec 2.5	Additional mods based on simulations.
Version 0.8	Apr 26 2012	All but sec 2.5	Modified descriptions and diagrams based on decisions made in discussion with instrument and SCT teams.
Version 0.9	May 20 2012	Sec 2.2 and 2.4	2.2: Changed default readout nodes from A,D to A,C. Added description of window mode 2.4: Corrected description of derivation of FOC_XOFF and FOC_YOFF
Version 0.10	Jun 8 2012	Sec 2.4	Modified the HXI coordinates to include ACT system.
Version 0.11	Nov 8 2012	Several	Minor corrections throughout document.
Version 0.12	Dec 5 2012	Several	Changed sizes of SXI and HXI coordinate systems. Added ACT system to SXS. Minor corrections throughout document.
Version 0.13	Dec 21 2012	Several	Fixed some remaining inconsistencies and inaccuracies. In SXI section corrected ACT system to run 1:640. In HXI FOC transformation clarified pixel sizes. Added new figures showing channel mapping.
Version 0.14	May 28 2013	Several	Modified discussion to reflect changes to teldef files for FOC systems. Fixed some other residual errors.
Version 0.15	Jul 2 2013	Sec 2.1	Added discussion that is general to all instruments about FOC -> SKY transformations

Version 0.16	Dec 6 2013	Sec 2.1 2.2 Sec 2.3 Sec 2.6 Appendices	a) Added more details about FOC->SKY transformations and split this out to separate Section; later sections renumbered. b) Various small corrections c) Added new section about aberration correction d) Added three appendices: teldef, CAMS, Suzaku
Version 0.17	Jan 27 2014	Sec 2.1 2.2 All	Revised figures to show SXI switch of CCD 3 & 4 Removed personal pronouns: I, we, us
Version 0.18	Jan 31 2014	Sec 2.1	Moved Sec 2.2 after Sec 2.5. Moved Sec 2.6 to Appendix. Added new figures to Sec 2.1
Version 0.19	Jul 3 2014	Several	Modified discussion of DET->FOC transformations for all instruments, based on as-built SXI locations.
Version 0.20	Dec 16 2014	Several	Modified various figures and discussions to match the as-built from the instrument teams.
Version 0.21	Jun 9 2015	Several	Modified description of the FOC system based on new TelDef with FOC centered on SXS and not SXI.
Version 0.22	Sep 10 2015	Appendix F	Added descriptions of how TelDef parameters are derived from alignment values.
Version 0.23	Nov 23 2015	Sect 2 split	Rearranged tables and text in Section 2. Moved Appendix F to other sections. Added new Section 3 on alignment.
Version 0.25	May 9 2016	Sect 2	Added section on post-launch alignment
Version 0.26	Sep 28 2016	Appendix B	Deleted redundant CAMS description and added description of derivation of TelDef keyword
Version 0.27	Jun 19 2017	Sect 2	Corrections to inflight alignment values to reflect latest teldef files.
Version 0.28	25 Sep 2017	All	Document Format change

1 Introdution

1.1 Overview

Astro-H is equipped with four different instruments that together cover a wide energy range 0.3-600 keV. The Soft X-ray Spectrometer (SXS), which pairs a lightweight Soft X-ray Telescope (SXT) with a X-ray Calorimeter Spectrometer, provides non-dispersive spectroscopy with < 7 eV resolution in the 0.3-12 keV energy range with a field of view of about 3 arcmin. Three additional scientific instruments extend the energy bandpass of the observatory. The Soft X-ray Imager (SXI) expands the field of view with a new generation CCD camera in the energy range of 0.5-12 keV at the focus of the second lightweight SXT ; the Hard X-ray Imager (HXI , two units) performs sensitive imaging spectroscopy in the 5-80 keV band; the non-imaging Soft Gamma-ray Detector (SGD, two units) extends Hitomi's energy band to 600 keV. In addition there are three subsystems: two for the SXS, the Modulated X-ray Source (MXS to calibrate the gain) and the anti-coincidence system; and one for the HXI, the Canadian Astro-H Metrology System (CAMS) that tracks the movement of the Extended Optical Bench (EOB).

This document describes the coordinates of the three instruments which work in conjunction with a focusing optics.

2 Definition of coordinates

2.1 General definition

The following coordinates are defined to describe event locations in the telemetry, on the detector, or on the sky. All the coordinates are written in the Astro-H event files.

- RAW coordinates:

Original digitized values in the telemetry to identify pixels of the events. May reflect the physical locations of the pixels on the sensor. For example, in the SXI CCD, the RAW X and Y coordinates have values from 0 to 640 on each CCD segment to cover the full logical pixel range of 320 × 640. For SXS, the RAW pixel IDs, from 0 to 35, are arranged in terms of readout, not physical location, so the conversion to DET coordinates is through a remapping table. In the HXI, there are only one-dimensional strip locations, which are converted to physical coordinates during the event reconstruction stage into a version of RAW coordinates. The HXI event reconstruction program may make use of internal strip X, Y, Z coordinates.

For the HXI and SXI the RAW coordinates are defined by looking-down the sensors. In other words, these coordinates have the same sense as the spacecraft coordinates (i.e. they can be transformed from spacecraft coordinates by a rotation alone.) This is not true for the SXS since the raw coordinates are pixel IDs that require a remapping table for conversion to a look-down system.

- ACT coordinates:

ACT coordinates are coordinates based in an individual sensor or sub unit of a sensor. Like the RAW coordinates, the SXI ACT coordinates are defined by looking-down the sensors. The SXI includes four separate ACT coordinates, one for each CCD in the SXI focal plane. These coordinates are intermediate between RAW (from the telemetry) and DET. They are calculated from the RAW coordinates by a simple conversion using coefficients common to all SXI chips. The ACT X and Y values are defined to represent actual pixel locations in an entire SXI CCD chip. ACT XY takes 1 to 640 to denote the 640 × 640 pixels in the chip. The SXI RAW to ACT conversion depends on the window modes and choice of readout node and so requires housekeeping information to be present in the event file. For the HXI, the ACT coordinate is the RAW coordinate corrected for time-dependent misalignments by the CAMS. For the SXS, the ACT coordinates are look-down linearized coordinates that are in the same sense as the instrument or array coordinates used by the SXS Instrument Team.

- DET coordinates:

DET coordinates are defined as physical positions of the pixels within each ASTRO-H sensor. Misalignments between the sensors are not taken into account. However, in the SXI, the conversion from ACT to DET must take into account the misalignments among the four individual CCD chips and the different orientations of the four individual ACT coordinates. The DETX/Y coordinates are defined by looking up the sensor, such that the satellite +Y direction becomes the -DETY direction (the same as the Suzaku convention). The SXI and SXS DET X and Y values are defined with respect to a virtual focal plane at the nominal location of the SXI focal plane. (This allows for shifts or misalignments of the as-flown SXI focal plane.) The origin for each set of DET coordinates for HXI and SXS is taken at the lower left of the individual sensor such that the pixel or equivalent closest to the origin has value (1,1). However, for SXI, it was decided to center the DET system on the physical center of the four CCDs (see Section 2.2.3).

- FOC coordinates:

This is the Focal plane coordinate system common to all the sensors. Since the SXI has the largest field and smallest detector pixel size, the FOC coordinates for all sensors must have the scale and range appropriate to the SXI. Misalignments between the sensors are taken into account so that the FOC images of different sensors (SXS, SXI and HXI) can be superposed. FOC is calculated from DET by linear transformation to represent the instrumental misalignment, i.e., the offset and the rotation angle. Full information about these misalignments is written in the teldef files.

- SKY coordinates:

SKY coordinates are the positions of the events on the sky in the same unit as FOC. The conversion from FOC to SKY is made using the satellite attitude in the attitude file and the alignment matrix (3 × 3) written in the teldef file. For each SXI event, the equatorial coordinates of the pixel center projected on a tangential plane are given. For each SXS event, the equatorial coordinates of the pixel center as well as the roll angle of the pixel are given. The roll angle is necessary since the SXS pixel size is finite. For the HXI, the equatorial coordinates of the reconstructed event location is given.

There are several assumptions regarding the spacecraft attitude file, which is represented as both quaternions and Euler angles. First, although the star tracker (STT) systems are aligned such that their Z-axes are tilted by 5° relative to the spacecraft Z-axis, the values in the spacecraft attitude file are defined relative to the Satellite system and not the STT system. Therefore there is no need for an alignment matrix to correct for this 5° tilt. Second, the quaternions are in the format consistent with the existing attitude software, namely (q0,q1,q2) represent the imaginary component (rotation axis) and q3 is the real component. Finally, the Euler angles are defined in the Z-Y-Z system (as was the case for Suzaku).

Coordinate System	Direction	Extent	Brief Description
RAW	Look-down	Individual sensor or chip	Most basic system. Pixel numbering corresponds to readout electronics.
ACT	Look-down	Individual chip	Remapped system corresponding to the physical location of pixels within a sensor. Corrected for relative movement between the mirror and detector.
DET	Look-up	Entire Instrument	Remapped system covering the entire extent of an instrument detector.
FOC	Look-up	All instruments	System combining the detector planes of all instruments into a single, unified system.
SKY	Look-up	All instruments	Remapped system where orientation corresponds to satellite sky pointing.

Table 1. Brief descriptions of the coordinate systems. All coordinate systems are used for each of the Astro-H instruments.

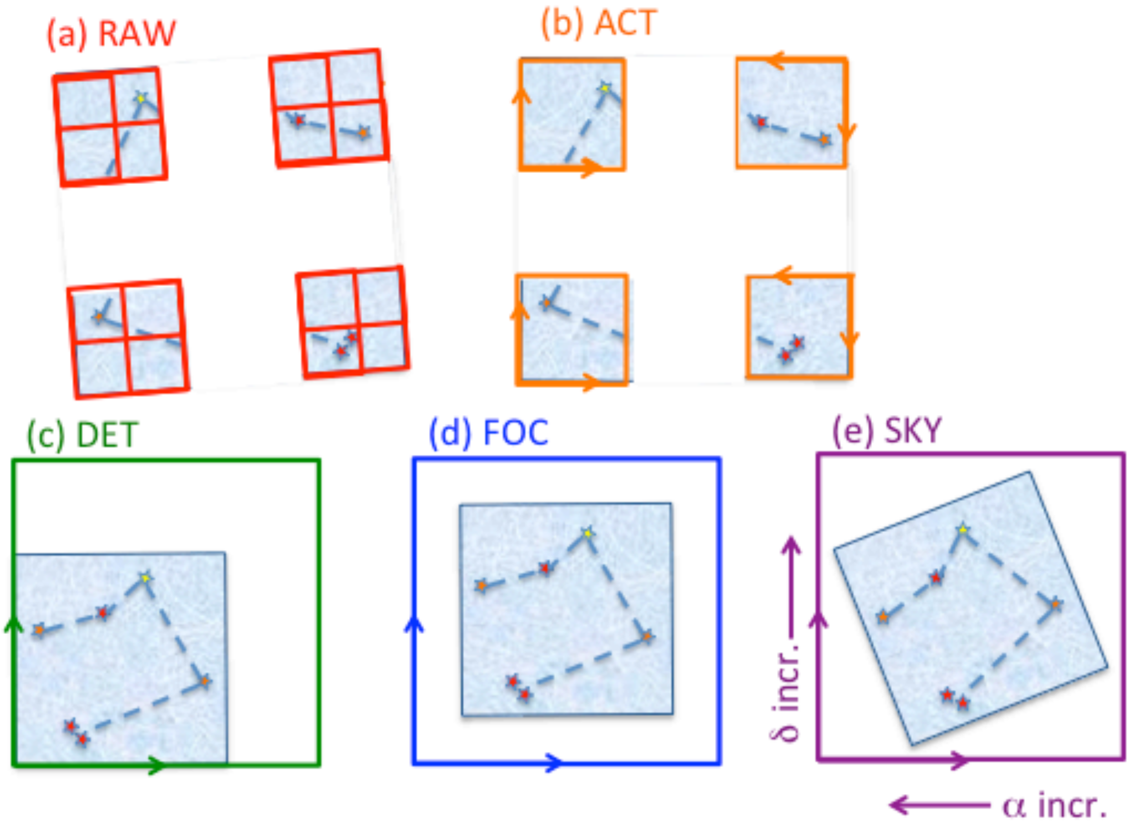


Figure 1. Schematic view of the five standard coordinate systems. (a) RAW system. There are often multiple versions of this system for a single instrument. This coordinate is linked to the electronic readout of the sensor. (b) The ACT system combines and refines the RAW system and is linked to the physical layout of the sensor. There can also be multiple ACT systems with different orientations for a single instrument, if it has more than one detector. It is also possible for there to be an offset between RAW and ACT. (c) The DET system combines all ACT coordinates into a single system for a given detector, accounting for any misalignments among them. Note that the mock star field is reversed between ACT and DET. This represents the flip from look-down (ACT) to look-up (DET). (d) The FOC system combines all of the individual DET systems from all of the instruments on a satellite, accounting for misalignments among them. Typically the FOC system is centered on the instrumental reference point, which in the example is the center of the star image. (e) The SKY system is a tangent plane referenced to WCS coordinates. It is normally oriented such that declination (δ) increases in the +Y direction and Right Ascension (α) increases in the –X direction as shown. Thus there is a relative rotation (position angle or roll) between the FOC and SKY systems.

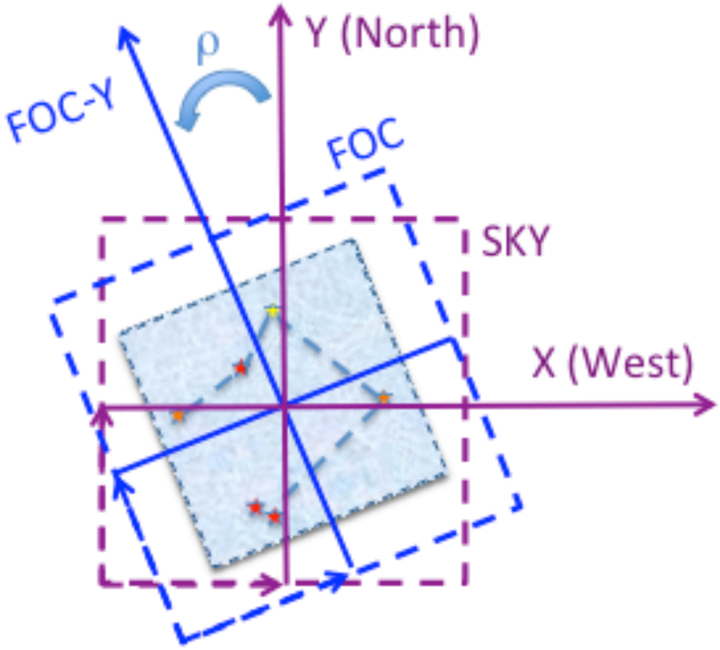


Figure 2. Detail showing the correspondence between FOC (blue) and SKY (purple) systems. The FOC system is oriented square to the detector, while the SKY system is oriented such that +Y points to the North and –X points to the East. The rotation between the (SKY-)Y and FOC-Y axes is the position angle ρ. The sign of ρ is such that a positive ρ takes Y into FOC-Y.

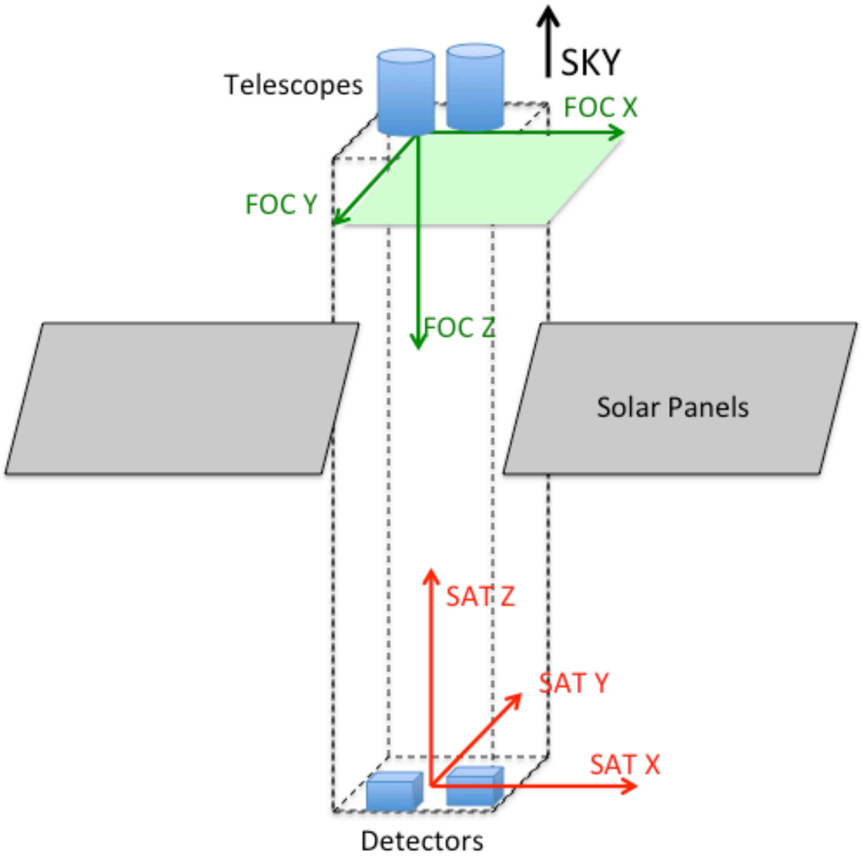


Figure 3. Diagram showing the definitions of the SATellite coordinate system (look-down; red) and the FOC system (look-up; green). The SAT system is oriented with the X-axis pointing toward the solar panels and the Z-axis pointing to the sky. The FOC system is flipped with respect to the SAT system: the X-axes coincide and the Y- and Z-axes are flipped.

The tables on the following pages summarize the coordinate systems for each instrument and the conversions between them. The keywords associated with each coordinate system are given in the Appendix B.

Instrument		Field of View			Focal length (mm)
		(pixels)	(mm)	(arcmin)	
SXS (incl gaps)		6 × 6	4.974 × 4.974	3.053 × 3.053	5600
SXI	Single chip	640 × 640	30.72 × 30.72	18.858 × 18.858	5600
	Entire array (incl gaps)	1280 × 1280	61.54 × 61.54	37.778 × 37.778	5600
HXI-1		128 × 128	32.0 × 32.0	9.167 × 9.167	12000
HXI-2		128 × 128	32.0 × 32.0	9.167 × 9.167	12000

Table 2. Physical parameters of the Astro-H instruments.

Instrument		RAW/PIXEL coords (look-down)		ACT coords (look-down)		DET coords (look-up)		FOC coords (look-up)	
		size	pixel arc sec	size	pixel arc sec	size	pixel arc sec	size	pixel arc sec
SXS		0:35	--	1:8, 1:8	29.982	1:8, 1:8	29.982	1:2430 1:2430	1.768
SXI	segment	0:639 0:319	1.768	--	--	--	--	--	--
	chip	--	--	1:640, 1:640	1.768	--	--	--	--
	array	--	--	--	--	1:1810, 1:1810	1.768	1:2430 1:2430	1.768
HXI-1		1:128, 1:128	4.297	1:256, 1:256	4.297	1:256, 1:256	4.297	1:2430 1:2430	1.768
HXI-2		1:128, 1:128	4.297	1:256, 1:256	4.297	1:256, 1:256	4.297	1:2430 1:2430	1.768

Table 3. Dimensions of the coordinate systems. Note that the FOC system is common to all. The numbers in each cell indicate the range of values the coordinate can take. The coordinate system is in two dimensions except for the SXS RAW. The SXS ACT and DET pixel sizes do not include the gaps between pixels. The SXI array consists of 4 chips and 8 total segments.

Instrument	RAW (PIXEL) ➔ ACT	ACT ➔ DET	DET ➔ FOC
SXS	Single pixel list to two-dimensional array	Flip about Y-axis	Translation, resampling
SXI	Remapping from segment to chip using coefficients	Remapping from chip to full array plus alignment	Translation
HXI-1	Translation and rotation using Δ-attitude	Flip about Y-axis	Translation, rotation by 22.5°, resampling
HXI-2	Translation and rotation using Δ-attitude	Flip about Y-axis	Translation, rotation by -22.5°, resampling

Table 4. Types of transformations between coordinate systems for each instrument.

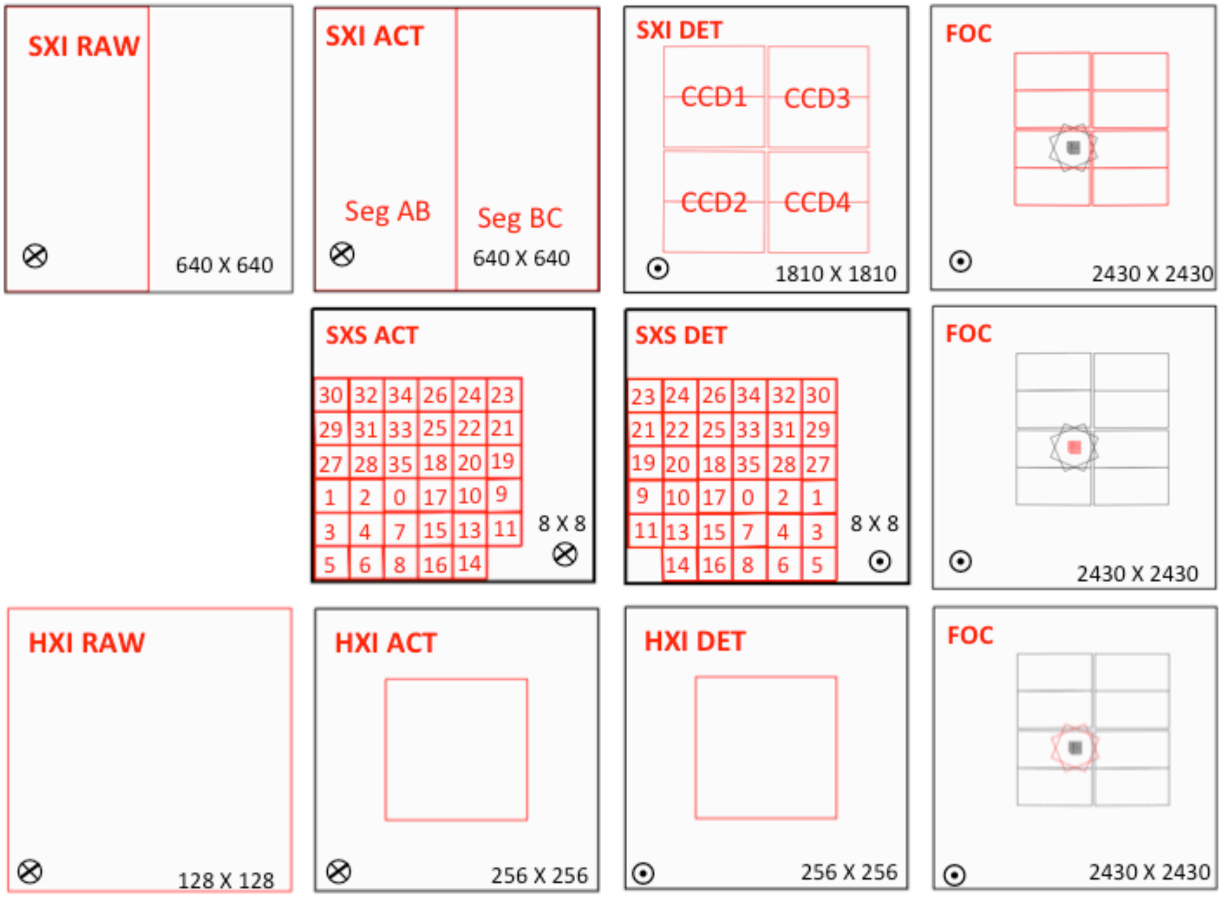


Figure 4. The physical size of each instrument plotted on the full coordinate system. The symbols ⦸ and ⊙ represent look-down and look-up coordinate systems, respectively.

In the following table, the scales for each of the ASTRO-H instruments are shown.

The values are calculated as follows:

(1) Calculate the plate scale in arcsec/mm (inverse is mm/arcsec):

Scale (HXI) = 1/FL = 1/12,000 = 83.33 μrad X (180/π) = 0.00477° X 3600 = 17.189 arcsec/mm

Scale (SXI/SXS) = 1/FL = 1/5,600 = 178.6 μrad X (180/π) = 0.0102° X 3600 = 36.833 arcsec/mm

(2) The pixel size (mm/pixel or pixel/mm) is known for each instrument.

(3) Finally, the pixel angular scale (arcsec/pixel; inverse is pixel/arcsec) is derived from:

(arcsec/pixel) = (arcsec/mm)*(mm/pixel)

Instrument	ACT system (instrument scale)				FOC system (resampled scale)			
SXS with no gaps	Col/ row	pixel	mm	arcsec	Col/ row	pixel	mm	arcsec
	pixel/	1.0	1.229	0.0336	pixel/	1.0	20.833	0.566
	mm/	0.814	1.0	0.0271	mm/	0.048	1.0	0.0271
	arcsec/	29.982	36.833	1.0	arcsec/	1.768	36.833	1.0
SXS with gaps between pixels	Col/ row	pixel	mm	arcsec	Col/ row	pixel	mm	arcsec
	pixel/	1.0	1.202	0.0326	pixel/	1.0	20.833	0.566
	mm/	0.832	1.0	0.0271	mm/	0.048	1.0	0.0271
	arcsec/	30.645	36.833	1.0	arcsec/	1.768	36.833	1.0
SXI	Col/ row	pixel	mm	arcsec	Col/ row	pixel	mm	arcsec
	pixel/	1.0	20.833	0.566	pixel/	1.0	20.833	0.566
	mm/	0.048	1.0	0.0271	mm/	0.048	1.0	0.0271
	arcsec/	1.768	36.833	1.0	arcsec/	1.768	36.833	1.0
HXI	Col/ row	pixel	mm	arcsec	Col/ row	pixel	mm	arcsec
	pixel/	1.0	4.0	0.233	pixel/	1.0	9.722	0.565
	mm/	0.250	1.0	0.0582	mm/	0.103	1.0	0.0582
	arcsec/	4.297	17.189	1.0	arcsec/	1.768	17.189	1.0
CAMS	Col/ row	pixel	mm	--	--	--	--	--
	pixel/	1.0	66.7	--	--	--	--	--
	mm/	0.015	1.0	--	--	--	--	--
	--	--	--	--	--	--	--	--

Table 5. Scales for all of the Astro-H instruments. The tables are read as follows. A number in the grid represents the [row heading] per [column heading]. For example, in the HXI instrument scale table, the scale is 4.0 pixel/mm, or 0.250 mm/pixel.

Instrument	Keyword	ACT	DET	FOC
SXS	TCRPX	4.5	4.5	1215.5
	TCRVL	0.0	0.0	0.0
	TCDLT	0.832	0.832	0.048
	TCTYP	ACTX,ACTY	DETX,DETY	FOCX,FOCY
	TCUNI	mm	mm	mm
SXI	TCRPX	320.5	905.5	1215.5
	TCRVL	0.0	0.0	0.0
	TCDLT	0.048	0.048	0.048
	TCTYP	ACTX,ACTY	DETX,DETY	FOCX,FOCY
	TCUNI	mm	mm	mm
HXI	TCRPX	128.5	128.5	1215.5
	TCRVL	0.0	0.0	0.0
	TCDLT	0.250	0.250	0.048
	TCTYP	ACTX,ACTY	DETX,DETY	FOCX,FOCY
	TCUNI	mm	mm	mm

Table 6. Coordinate reference keywords for each Astro-H instrument and coordinate system.

The figures on the next two pages show the relative positions of the fields of view of the four instruments. Figure 5 shows the relative orientation of the SXI and SXS fields of view in the DET (look-up) orientation. Figure 6 is the same picture with the fields of view of the two HXI sensors added.

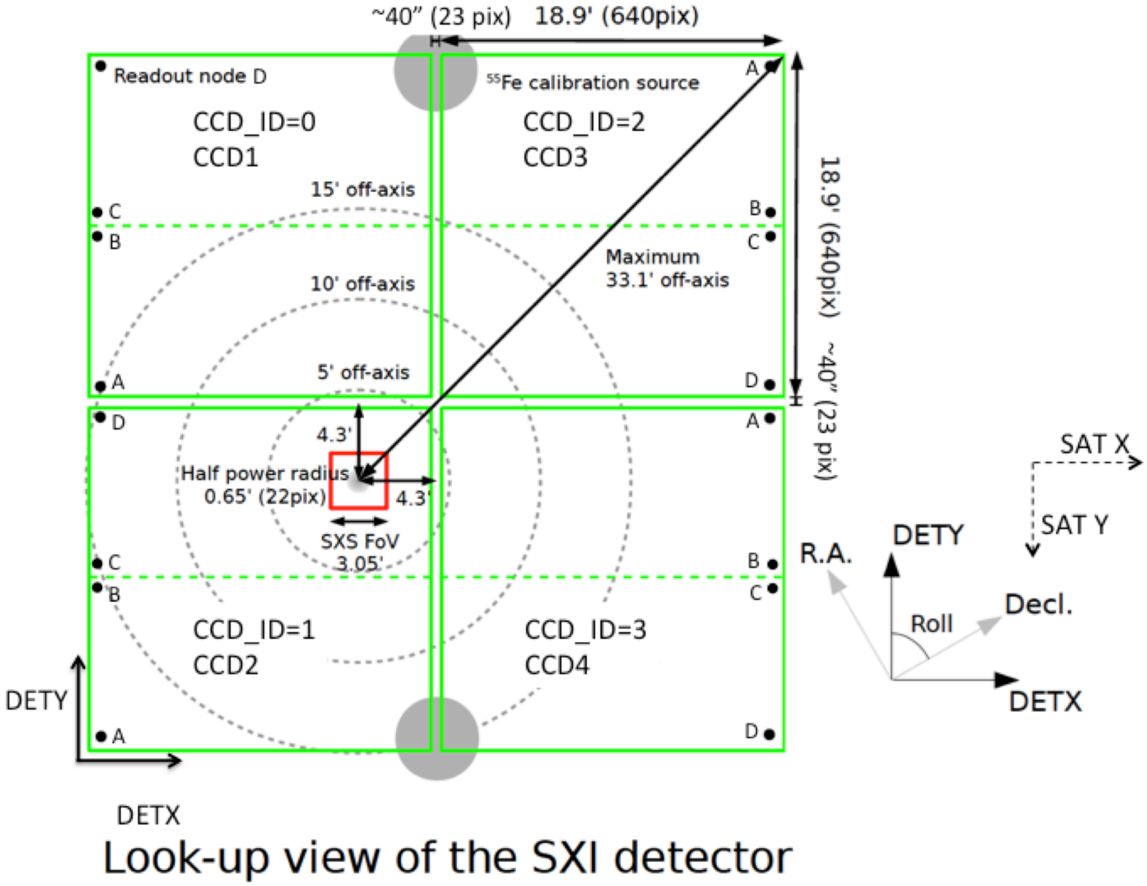


Figure 5. Idealized look-up view of the SXI detector. SXI consists of 4 CCD chips. This shows the orientation of the four SXI CCD chips along with the relative location of the SXS field of view. The origin of the SXI DET coordinates is to the lower left of CCD1. The orientation of the satellite coordinates is also shown. The large grey circles represent the placement of the calibration sources. Note that this is an idealized view for reference. In actuality, the four SXI chips are farther apart (average gap of ~24 pixels) and show slight relative rotations.

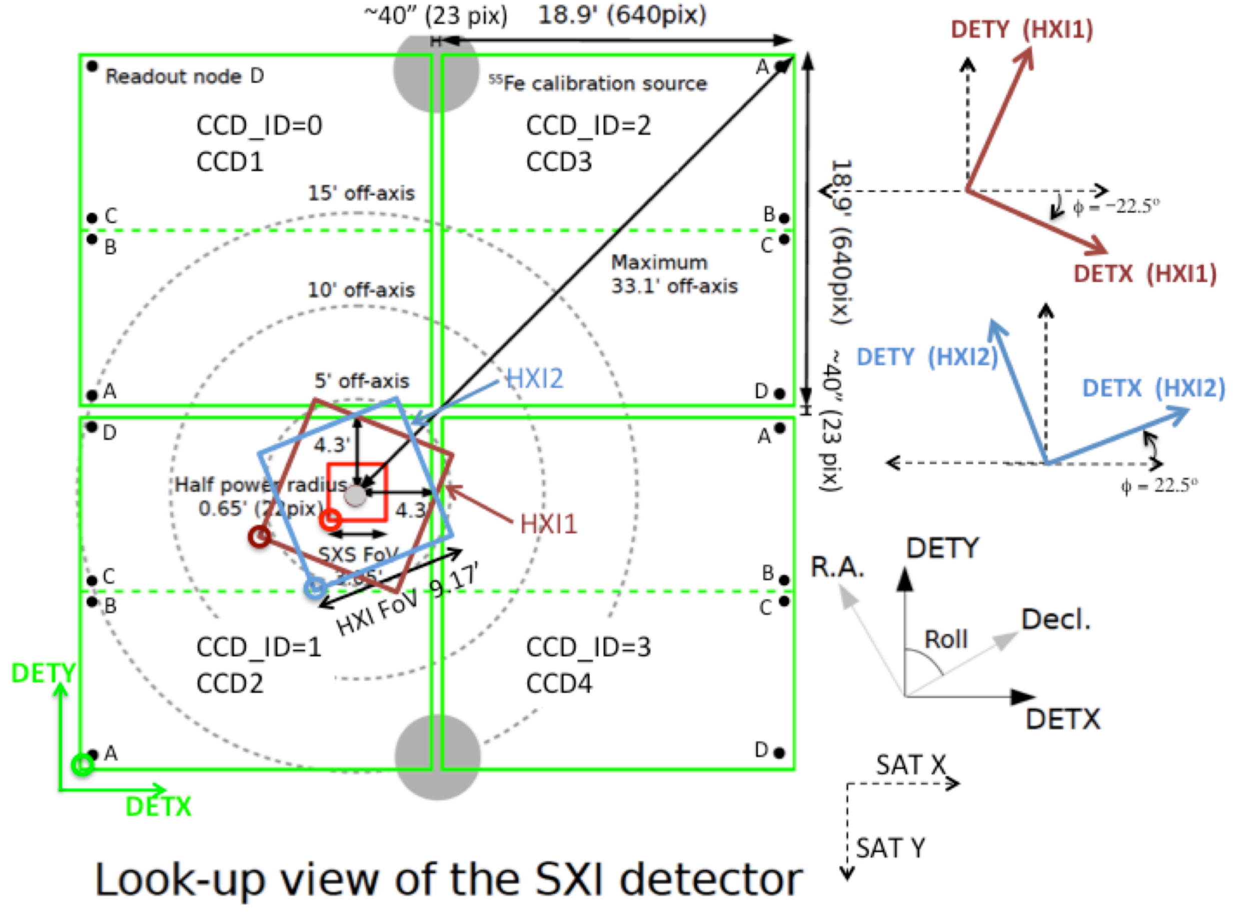


Figure 6. Idealized look-up view of the SXI detector with the HXI fields of view overlaid. The centers of the fields of view of the two HXI sensors and of the SXS are coincident. The DET coordinates of all four sensors are also indicated (SXS is the same as SXI). The origins of the coordinate systems are indicated by color-coded circles (although the physical corners are actually at coordinates (0.5,0.5) instead of (0,0)). The large grey circles represent the placement of the calibration sources.

2.2 Alignment of instrument into a common FOC frame : Ground Alignment

Observatory level alignment determines the positions of the instrument optical axes relative to each other and to the spacecraft pointing direction. This also includes determination of the rotation angles of the HXI detectors relative to the other instruments. The alignment of the individual instruments is covered in the instrument coordinate sections.

Definitions:

Telescope Axis is the line connecting the center of the Detector to the center of the Mirror. A source on the Telescope Axis will fall on the center of the Detector. For the SXI, this is not to the center of the detector, but rather to the "sweet spot" on the detector, where the mirror aim point is located.

Mirror (Optical) Axis is defined by the maximum effective area of the mirror. It can fall anywhere on the detector.
The Spacecraft (Z) Axis may not be parallel to the Telescope or Mirror Axis.

The pointing (current assumption) is along the Z-Axis. The center of the FOC system must be the pointing direction and is thus the Z-Axis. Then the center of ALL instruments including the SXS must be shifted relative to the FOC Center (Z-Axis).

For each instrument, the co-alignment calibration provides two important pieces of information. First is the relative orientation (tilt) of the instrument Mirror Axis relative to the common Z-Axis (Figure 7, left). To get a projection onto the focal plane, these angles must be divided by the focal length. Second is the relative differences between the instrument detector centers and the common Z-Axis (Figure 7, right).

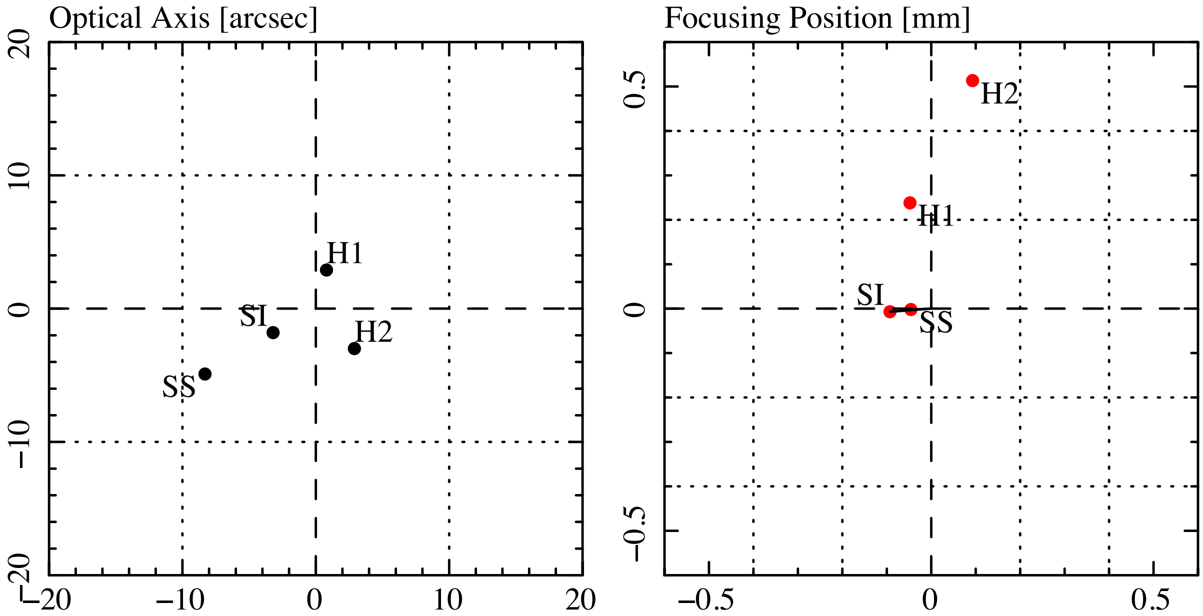


Figure 7. The left panel shows the tilt in two dimensions of each instrument Mirror Axis relative to the common Z-Axis. This is a look-up figure. The figure is oriented so that a tilt in the direction of Spacecraft X is to the right and a tilt in the direction of Spacecraft Y is downward (toward the bottom). Note that this figure is not a projection. The right panel shows the position on each instrument detector where a source located along the Z-Axis would fall relative to the center of that detector. The center of the figure represents the center of the SXS, HXI1 and HXI2 and represents the "sweet spot" for the SXI, which is the design aim point of the SXT-I and the origin of the SXI Telescope Axis. The figure is shown in common spacecraft "look-up" coordinates with Spacecraft +X to the right and Spacecraft -Y up.

The information in Figure 7, right is used to derive the offset correction factors between each instrument DET system and the common FOC system. The FOC system is defined to be centered at the projection of the Spacecraft Z-Axis, which is also defined to be the pointing direction. The first step is to redraw Figure 7 to show, in a look-down view, the relative positions of the detector centers and the Z-Axis. This is given in Figure 8. Also added are the positions of the projections of each instrument Mirror (optical) axis relative to the Spacecraft Z axis.

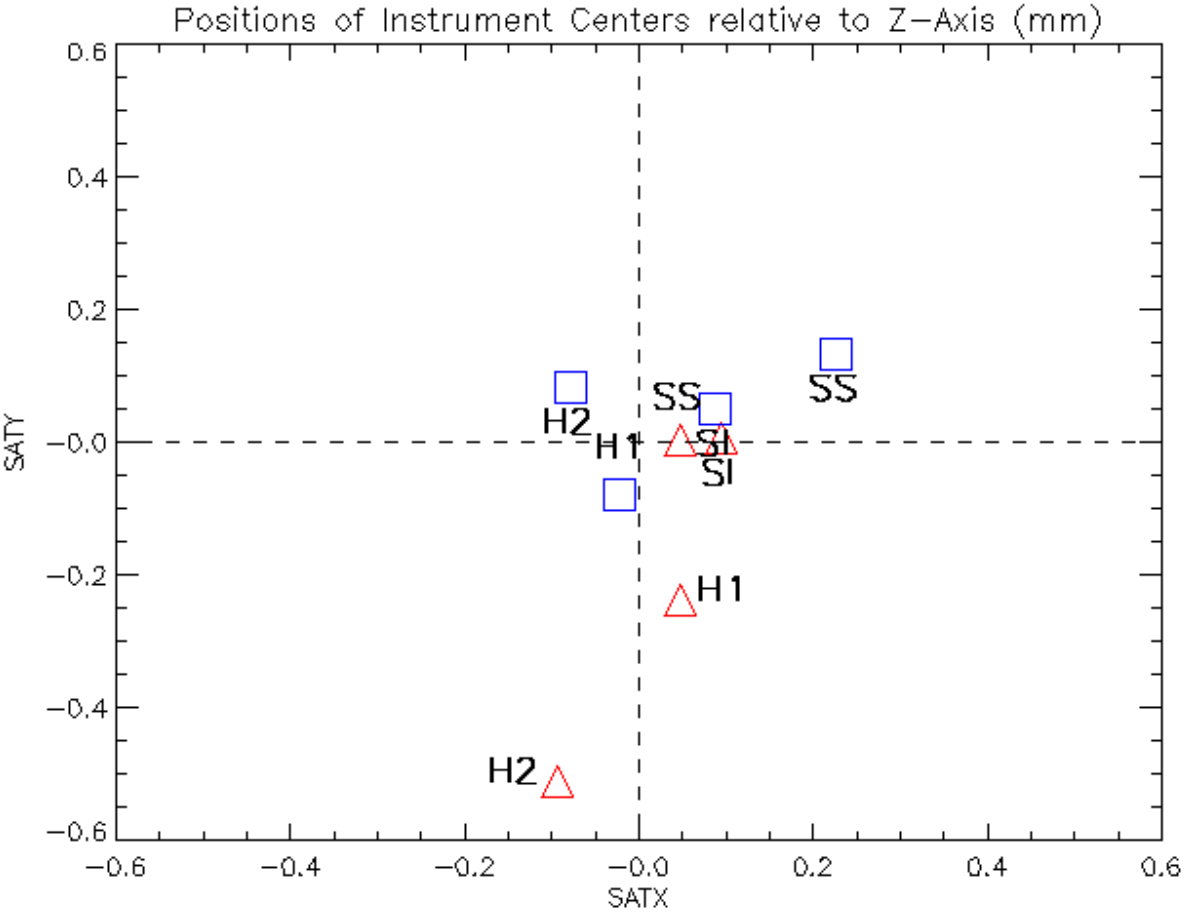


Figure 8. Positions of the four instrument detector centers relative to a common origin in the look-down SAT system.

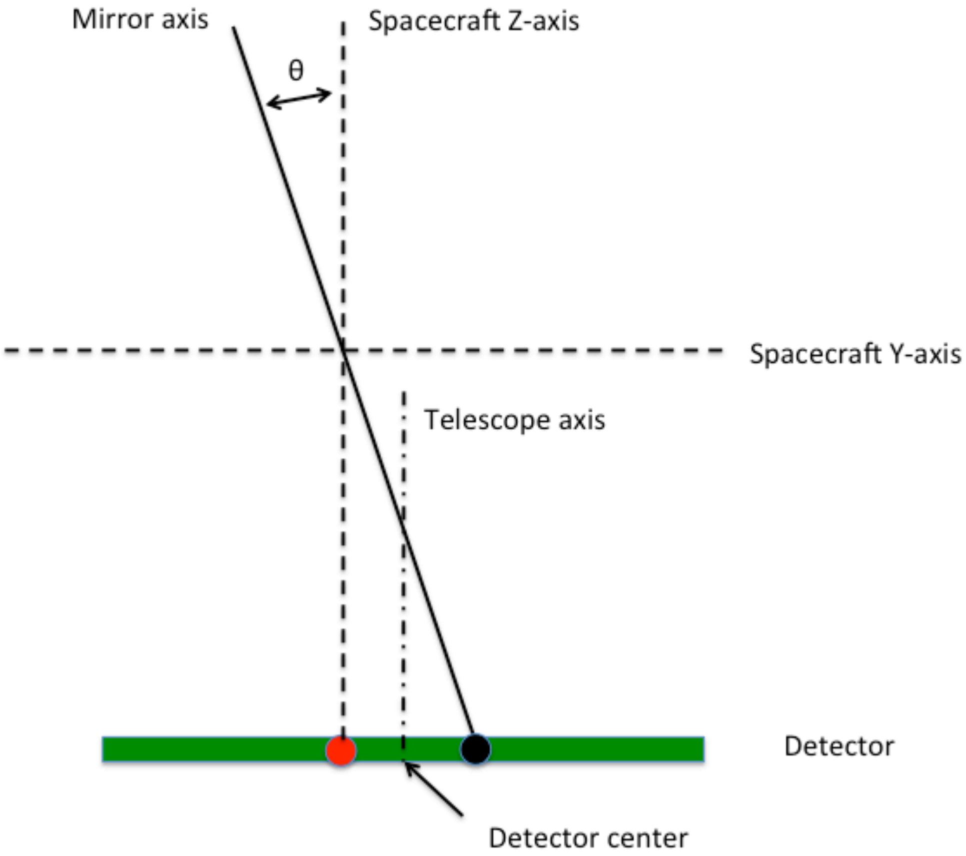


Figure 9. Side view showing the three axes (Mirror, Telescope, Spacecraft Z-). An example of one of the red dots in Figure 7 right (Z-axis) is shown here relative to the detector center. An example of one of the black dots in Figure 7 left is shown here relative to the Z-axis.

In order to produce Figure 8, two inversions are done. First, Figure 7, right, shows the Z-axis relative to the detector centers while Figure 8 shows the dectector centers relative to the Z-axis. Secondly.

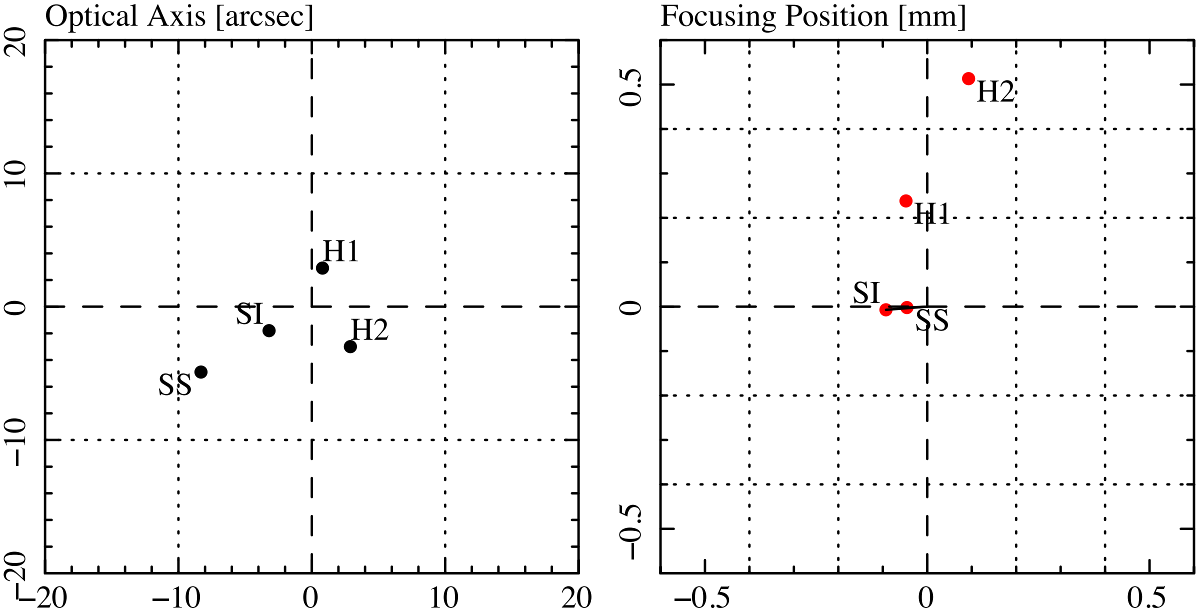


Figure 7, left, shows the offsets (tilts) of the Mirror Axes relative to the Z-axis. In order to project this offset angle onto the detector plane,

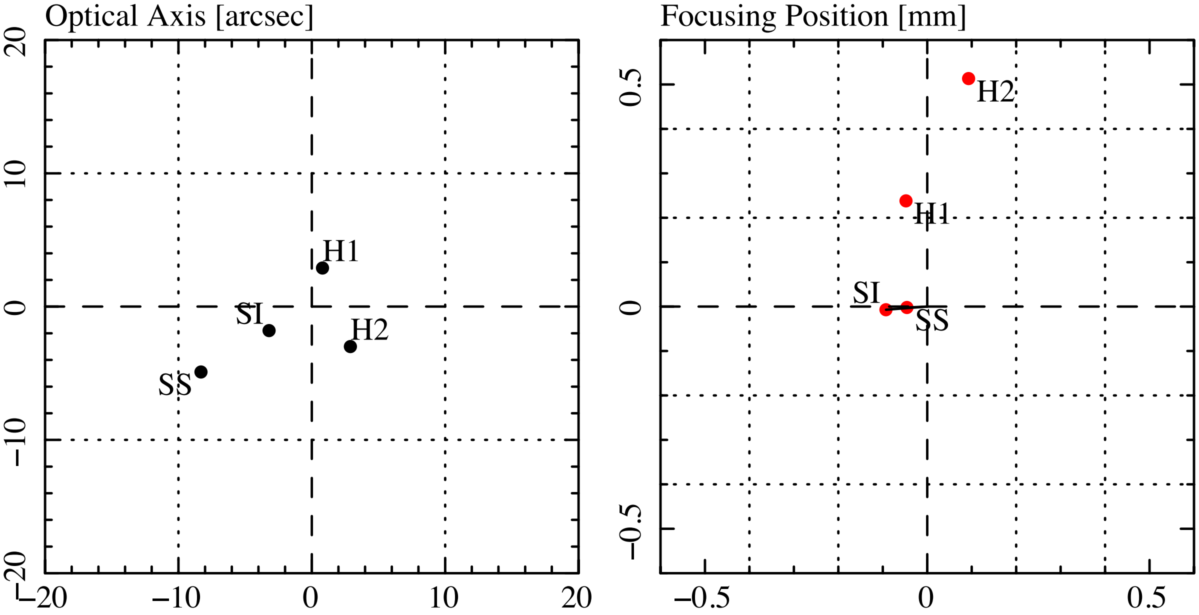


Figure 7, left, must also be inverted.

Next we must transform this to a look-up system in which the common center is the center of the FOC system. As shown in Figure 6, the SAT system and DET/FOC system have a common X-axis, but the Y-axis is flipped when going from look-down to look-up. Figure 10 shows the relative detector center locations in FOC pixels. We also plot on this figure, the projections of the instrument optical axes (Figure 7, left) converted to FOC pixels (0.566 pixel/arcsec).

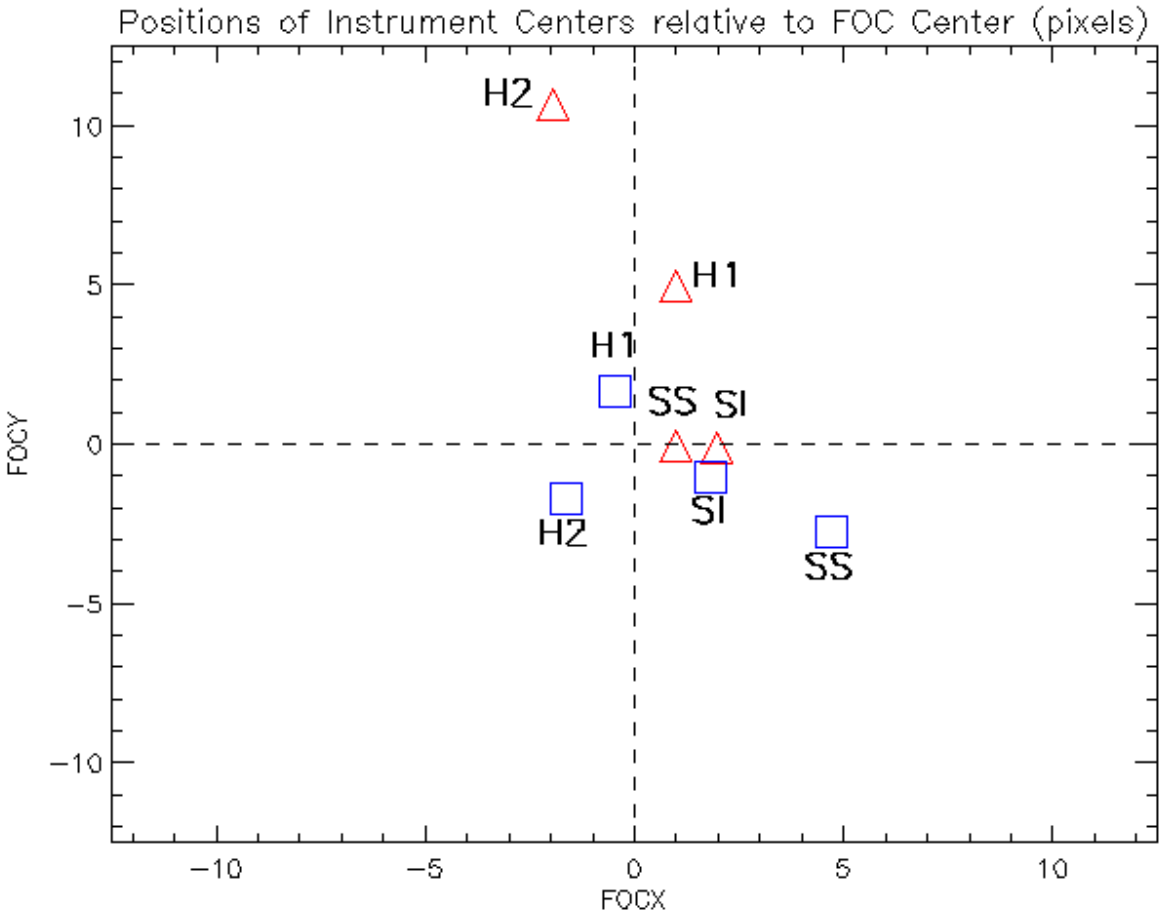


Figure 10. Positions of the four instrument detector centers relative to a common origin in a look-up system, parallel to the FOC system, displaced by 1215.5 pixels in X and Y, are shown as red triangles. The positions of the projections of the four Mirror Axes are shown as blue squares. The positions are now shown in FOC pixels (20.833 pixels/mm).

The next step is to derive, for each instrument, the offset required to convert a point in the DET system to the FOC system. The offset is given in units of the DET system. We have, as shown on Figure 10, the positions of the DET system centers in offset FOC; we need to invert this for each detector to find the position of the FOC system center in DET.

For each instrument, we must convert the values from the calibration (in mm for the mirror axes and in arcsec for the optical axes), first to FOC pixels and then to DET pixels for the individual instrument. For the HXI, this also includes a rotation.

Taking (Rx, Ry) as the given values in mm for the locations of the DET centers in FOC. These values are shown in the right panel of Figure 7.

Step 1. Convert from mm to FOC pixels. This involves a flip of the Y-values to go from look-down to look-up and a negation of both X and Y-values in going from Figure 7 to Figure 8. (which is equivalent to a flip of the X-coordinate).

SXI/SXS
$Fx = - Rx * (1\ \text{pixel}/0.048\ \text{mm})$
$Fy = Ry * (1\ \text{pixel}/0.048\ \text{mm})$

HXI
$Fx = - Rx * (1\ \text{pixel}/0.048\ \text{mm}) * (5600/12000)$
$Fy = Ry * (1\ \text{pixel}/0.048\ \text{mm}) * (5600/12000)$

Step 2. Convert from FOC pixels to DET pixels.

$Dx = Fx * \text{Det2Foc} = Fx * (\text{FOC\_scale}/\text{DET\_scale})$
$Dy = Fy * \text{Det2Foc} = Fy * (\text{FOC\_scale}/\text{DET\_scale})$

FOC_scale = 0.048 mm/pixel
SXI DET_scale = FOC_scale; Det2Foc = 1.0
SXS DET_scale = 0.832 mm/pixel; Det2Foc = 0.05769
HXI DET_scale = 0.250 mm/pixel; Also must scale by the ratio of the HXI to SXI focal length = (12000/5600); Det2Foc = (0.048/0.250)*(12000/5600) = 0.4114.

Step 2a. For HXI, also rotate (Dx, Dy) into HXI DET frame.

$$\begin{pmatrix} Dx(rot) \\ Dy(rot) \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Dx \\ Dy \end{pmatrix}$$

Where $\theta = 22.5°$ for HXI-1 and $-22.5°$ for HXI-2.

Step 3. The FOC_[XY]OFF is defined as the offset required to co-align each instrument with the common FOC frame. Its effect is to put the Spacecraft Z Axis into a common point in the common frame. The FOC_[XY]OFF is calculated as the inverse (negative) of (Dx,Dy) plus the offset between the physical center of each instrument and the center of its DET coordinate system. Define the physical center in local DET coordinates as (Px, Py)

FOC_XOFF = Px – DET_XCEN - Dx
FOC_YOFF = Py – DET_YCEN - Dy

For SXI, DET_XCEN = DET_YCEN = 905.5
Px = Py = 748.5
Px – DET_XCEN = Py – DET_YCEN = -157
For SXS, DET_XCEN = DET_YCEN = 4.5
Px = Py = 3.5
Px – DET_XCEN = Py – DET_YCEN = -1
For HXI, DET_XCEN = DET_YCEN = 128.5
Px = Py = 128.5

Px – DET_XCEN = Py – DET_YCEN = 0
(Note that for HXI, (Dx(rot), Dy(rot)) is substituted for (Dx,Dy))

Calculate the Optical Axis location in the DET coordinate system for each instrument. Taking (Ox, Oy) as the given values in arcsec for the locations of the Mirror Axes in FOC. These values are shown in the left panel of

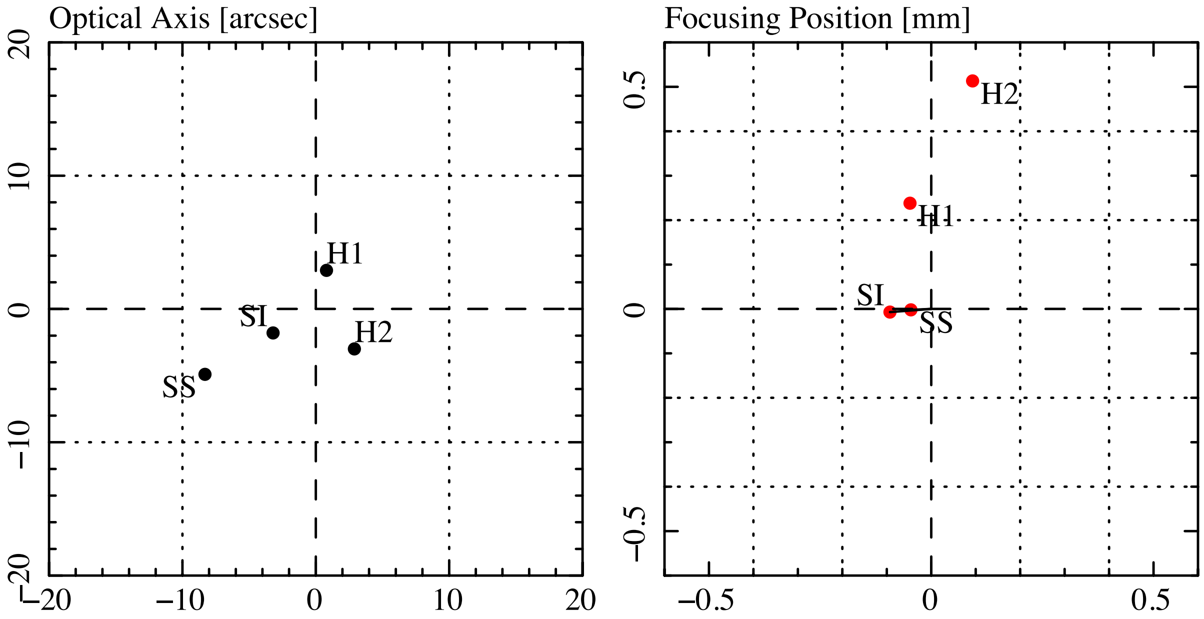


Figure 7.

Step 4. Convert the Optical Axis positions in arcsec to mm as projected onto the instrument detector plane. The conversion factor is the focal length defined for the FOC system, 5600 mm. Then convert to FOC pixels. Also apply the effective flip of the X-values (see step 1).

$$Ox(FOC) = -Ox * (5600\ mm/rad) / ((180/\pi)*3600) * (1\ pixel/0.048\ mm)$$
$$Oy(FOC) = Oy * (5600\ mm/rad) / ((180/\pi)*3600) * (1\ pixel/0.048\ mm)$$

Step 5. The offsets given in the Figure 7 are relative to the common Z-axis. Thus the offsets of each detector center must be subtracted. This procedure is done in the FOC system and the result converted to the DET system (and rotated for the HXI).

$$\Delta x = [\ Ox(FOC) - Fx\ ] * Det2FOC$$
$$\Delta y = [\ Oy(FOC) - Fy\ ] * Det2FOC$$

Step 6. Calculate the optical axis location in DET, which is relative the physical detector center.

$$OPTAXISX = Px + \Delta x$$
$$OPTAXISY = Py + \Delta y$$

This Table shows the values of the parameters calculated in the steps above for each instrument.

	SXI	SXS	HXI1	HXI2
Rx (mm)	-0.093	-0.046	-0.048	0.093
Ry (mm)	-0.007	-0.002	0.238	0.513
Fx (FOC pixels)	1.9375	0.9583	1.0000	-1.9375
Fy (FOC pixels)	-0.1458	-0.04167	4.9583	10.6875
Dx (DET pixels)	1.9375	0.05529	0.4114	-0.7971
Dy (DET pixels)	-0.1458	-0.002404	2.0400	4.3971
Dx(rot)	1.9375	0.05529	-0.04006	0.9462
Dy(rot)	-0.1458	-0.002404	2.04216	4.3675
Px (DET pixels)	748.5	3.5	128.5	128.5
Py (DET pixels)	748.5	3.5	128.5	128.5
DET_XCEN	905.5	4.5	128.5	128.5
DET_YCEN	905.5	4.5	128.5	128.5
FOC_XOFF	-158.937	-1.055	0.401	-0.946
FOC_YOFF	-156.854	-0.998	-2.042	-4.367
Ox (arcsec)	-3.2	-8.3	0.8	2.9
Oy (arcsec)	-1.8	-4.9	2.9	-3.0
Ox (mm)	0.08688	0.2253	-0.02172	-0.07873
Oy (mm)	-0.04887	-0.1330	0.07873	-0.08145
Ox (FOC)	1.8100	4.6946	-0.4525	-1.6403
Oy (FOC)	-1.0181	-2.7715	1.6403	-1.6968
Δx (DET pixels)	-0.1275	0.2156	-0.5976	0.1223
Δy (DET pixels)	-0.8723	-0.1575	-1.3651	-5.0953
Δx (rot)	-0.1275	0.2156	-0.02969	-1.8369
Δy (rot)	-0.8723	-0.1575	-1.4899	-4.7542
OPTAXISX	748.372	3.716	128.470	126.663
OPTAXISY	747.628	3.343	127.010	123.746

Table 7. This table shows all of the calculated values for each instrument in Steps 1-6 above. Values in yellow are directly from the instrument calibration. FOC_XOFF and FOC_YOFF values (in green) were written to the first versions of the TelDef files but were replaced by values calculated from inflight data (see section 2.2.2). Optical axis values (in green) are also written to the Teldef files but the values for SXI were replaced by values obtained from inflight data (see section 2.2.2). All other values in the table are intermediate values.

2.3 Alignment of instrument into a common FOC frame : In flight alignment

After launch, it was determined that the ground alignment of the instruments was not consistent with the observations. Therefore, a second set of the (FOC_XOFF, FOC_YOFF) alignment parameters was derived for each instrument.

For each instrument, an image is made in the DET coordinate system. For the HXI, the data are first corrected for the EOB motion using CAMS offsets derived from the data (this derivation is described below). Using the following sets of equations, the offsets between DET and FOC systems are derived.

Translation from DECX/Y (pixel) to FOCX/Y (pixel)
Calculation done in coordevt (attitude library routine):

TMPX = (DETX - DET_XCEN - FOC_XOFF)/FOC_SCAL
TMPY = (DETY - DET_YCEN - FOC_YOFF)/FOC_SCAL
FOCX = FOC_XCEN + cos(FOC_ROTD)*TMPX - sin(FOC_ROTD)*TMPY
FOCY = FOC_YCEN + sin(FOC_ROTD)*TMPX + cos(FOC_ROTD)*TMPY

Solve these equations for FOC_XOFF, FOC_YOFF:

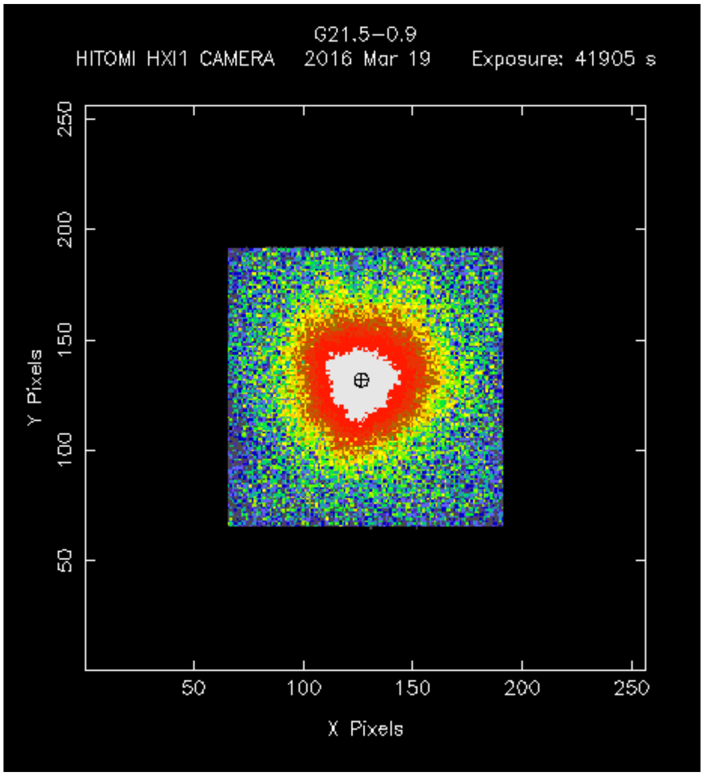
All of these values are given in the TelDef files:
fs = FOC_SCAL; fa = FOC_XCEN; fb = FOC_YCEN
da = DET_XCEN; db = DET_YCEN
c = cos(FOC_ROTD); s = sin(FOC_ROTD)

fx = FOCX; fy = FOCY; dx = DETX; dy = DETY
For the calculation, FOCX, FOCY are forced to equal FOC_XCEN, FOC_YCEN and DETX, DETY are taken from the flight data.

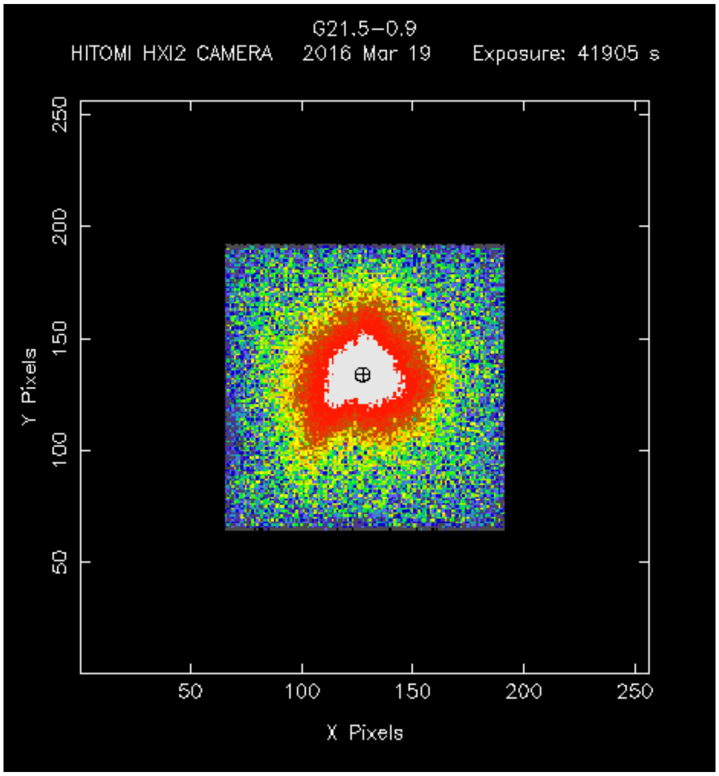
a = -fs*fx + c*dx - s*dy + (fa*fs - c*da + s*db)
b = -fs*fy + s*dx + c*dy + (fb*fs - s*da - c*db)

FOC_XOFF= a*c + b*s
FOC_YOFF = b*c - a*s

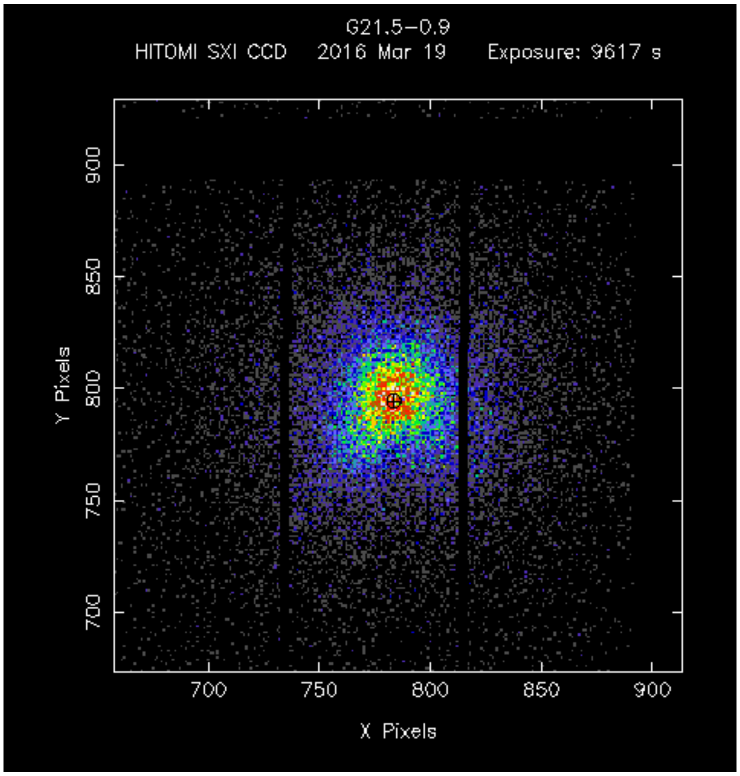
Here this procedure is followed for each of the instruments in turn. The DETX/DETY are derived as the Calculated centroid in the ximage program, DETX = Xpix, DETY = Ypix, and FOC_XOFF and FOC_YOFF are calculated using the equations immediately above.



```
HXI1  : ximage Calculated centroid:    X/Ypix = 125.412 128.388
        FOCXOFF =       -3.088
        FOCYOFF =       -0.112
```



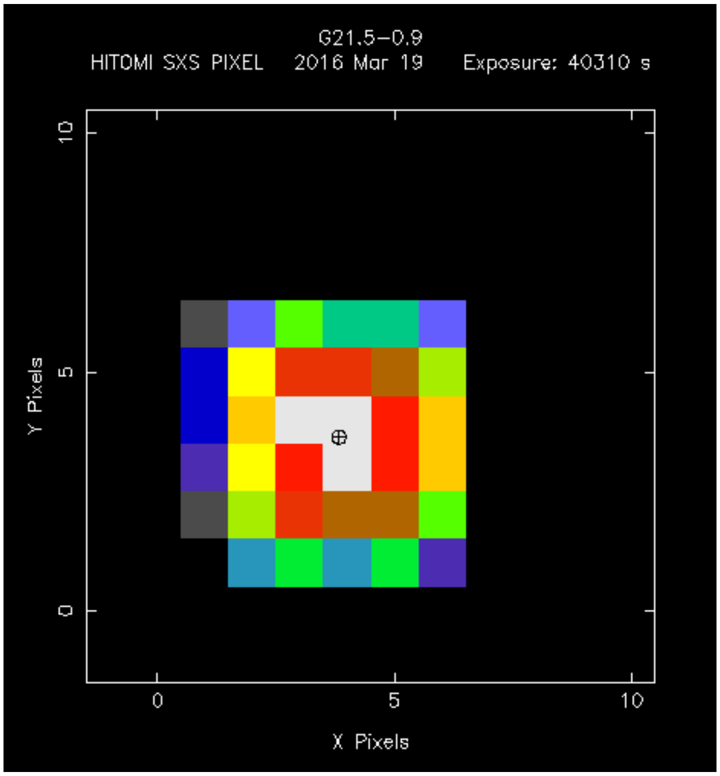
```
HXI2 : ximage Calculated centroid:    X/Ypix = 127.437 134.244
      FOCXOFF =       -1.063
      FOCYOFF =        5.744
```



```
SXI : ximage Calculated centroid:   X/Ypix = 782.854 791.837
      FOCXOFF =       -122.646
      FOCYOFF =       -113.663
```

For the SXI, the Optical axis was also updated using this centroid of the image in DET coordinates. This places the optical axis at the center of the image.

```
OPTAXISX=             783.464 /optical axis x in DET coordinates (pixel)
OPTAXISY=             794.180 /optical axis y in DET coordinates (pixel)
```



```
SXS : ximage Calculated centroid:  X/Ypix = 3.6363 3.6418
      FOCXOFF =       -0.8637
      FOCYOFF =       -0.8582
```

2.4 FOC to SKY transformation

The FOC coordinate system is common to all Astro-H instruments, the transformation from FOC to SKY is common to all instruments. Although in practice this transformation is carried out in a single step, the transformation quaternion is actually the product of three quaternions. The first is a static (time-independent) alignment quaternion $\mathbf{Q}_{\mathrm{M}}$ derived from the alignment matrix between the instrument FOC system and the spacecraft system. The second is a time-dependent attitude quaternion $\mathbf{Q}_{\mathrm{A}}$ that describes the attitude of the spacecraft relative to the celestial system. The third is a static (for a given observation) pointing quaternion $\mathbf{Q}_{\mathrm{B}}$ derived from the nominal pointing RA (α) and declination (δ) with roll set to zero.

The final transformation quaternion is derived as $\mathbf{Q} = (\mathbf{Q_B}^{-1} \times \mathbf{Q_A} \times \mathbf{Q_M}^{-1})$. **SKY** = **Q** × **FOC**. Since **FOC** and **SKY** are both tangent planes, in practice the transformation is done using the equivalent 2-d rotation (ROT) plus translation (TRN) (stored as a xform2d structure). The order is:

SKY = ROT × **FOC** + TRN. Therefore the translation is defined in the SKY system.

In component form, this is

$$\begin{bmatrix}\mathrm{SKY\_X}\\ \mathrm{SKY\_Y}\end{bmatrix} = \begin{bmatrix}\mathrm{ROT00} & \mathrm{ROT01}\\ \mathrm{ROT10} & \mathrm{ROT11}\end{bmatrix}\begin{bmatrix}\mathrm{FOC\_X}\\ \mathrm{FOC\_Y}\end{bmatrix} + \begin{bmatrix}\Delta \mathrm{X}\\ \Delta \mathrm{Y}\end{bmatrix}$$

This simple transformation is shown graphically in Fig 11. The aberration correction to the sky coordinates is carried out at the SKY stage (see Appendix A).

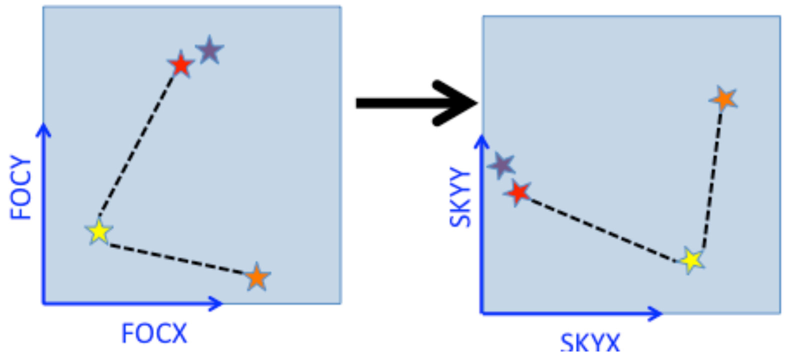


Figure 11. In Astro-H, the FOC and SKY systems are related by a simple 2-d rotation plus translation.

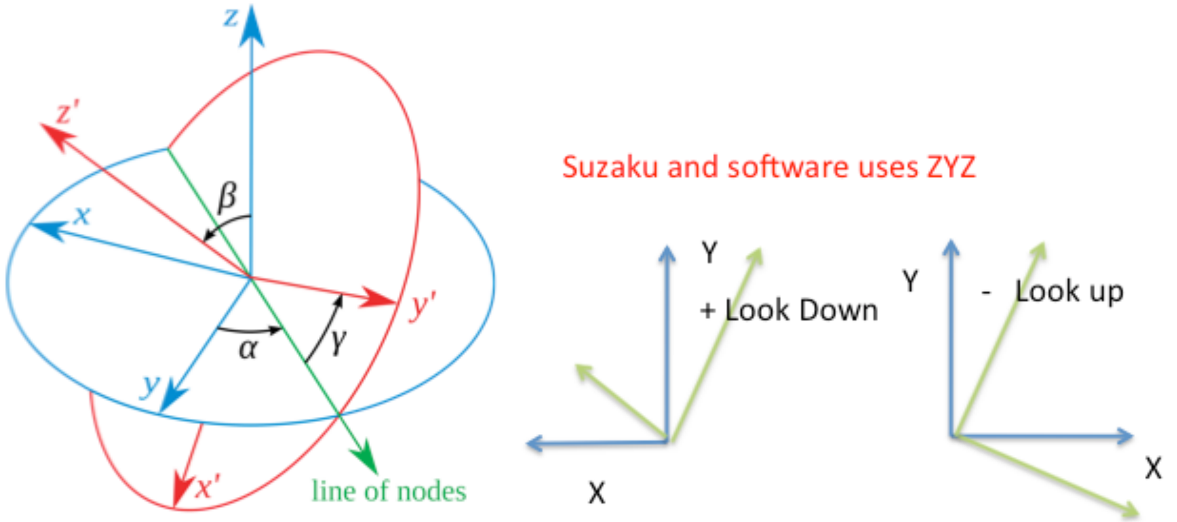


Figure 12. The definition of the Euler angles (left) in the Z-Y-Z system showing the conversion from FOC to SKY coordinates (common to all Astro-H instruments). The other figures show the sense of roll as shown as positive for look-down and negative for look-up.

The definition of the attitude and pointing quaternions needs explanation. Since the alignment quaternion and pointing quaternions are static, the discussion here concerns the spacecraft attitude part of the transformation.

It is easiest to understand the attitude quaternion when it is described in terms of three Euler angles (see Figure 12). In the Z-Y-Z system, these represent the following rotations. The first E_1 (α) is about the Z axis and takes the X-axis toward the Y-axis. In Figure , this is a rotation α in the blue plane, and the new Y-axis is indicated in green as the line of nodes. The second rotation E_2 (β) is about the new Y-axis (line of nodes) and takes the Z-axis toward the X-axis. In Figure , this takes the blue plane into the red plane. The final rotation E_3 (γ) is about the Z' axis in the red plane. The final X', Y' and Z' axes are shown in red.

The attitude transformation quaternion is defined as the quaternion that takes the SKY system from the origin to the pointing location and aligns the SKY image such that north (increasing declination) is up in the image. The first two Euler angles transform the coordinates of the center of the image and E_3 rolls the image. The relationship between Euler angles and celestial coordinates is given as $E_1 = \alpha$ (RA), $E_2 = 90° - \delta$ (where δ = declination), and $E_3 = 90° - \rho$ (where ρ = roll). Roll is defined as the angle between North (the direction towards the North Celestial Pole (NCP)) and the image FOCY axis and oriented such that a positive ρ takes North into FOCY (See Figure 2).

The origin of the pointing system is defined as pointing to the NCP and oriented such that SKYX points toward RA=18 hr (270°) and SKYY points toward RA=12 hr (180°). Since this is the origin, the quaternion of this pointing position is the identity $Q_0 = [\ 0, 0, 0, 1]$ and the Euler angles $E_1 = E_2 = E_3 = 0°$. By the definitions, this means that $\alpha = E_1 = 0$, $\delta = 90° - E_2 = +90°$, $\rho = 90° - E_3 = +90°$. This is shown in Figure 13 where SKYX points at α = 18 hr and there is a 90° roll between SKYY and FOCY.

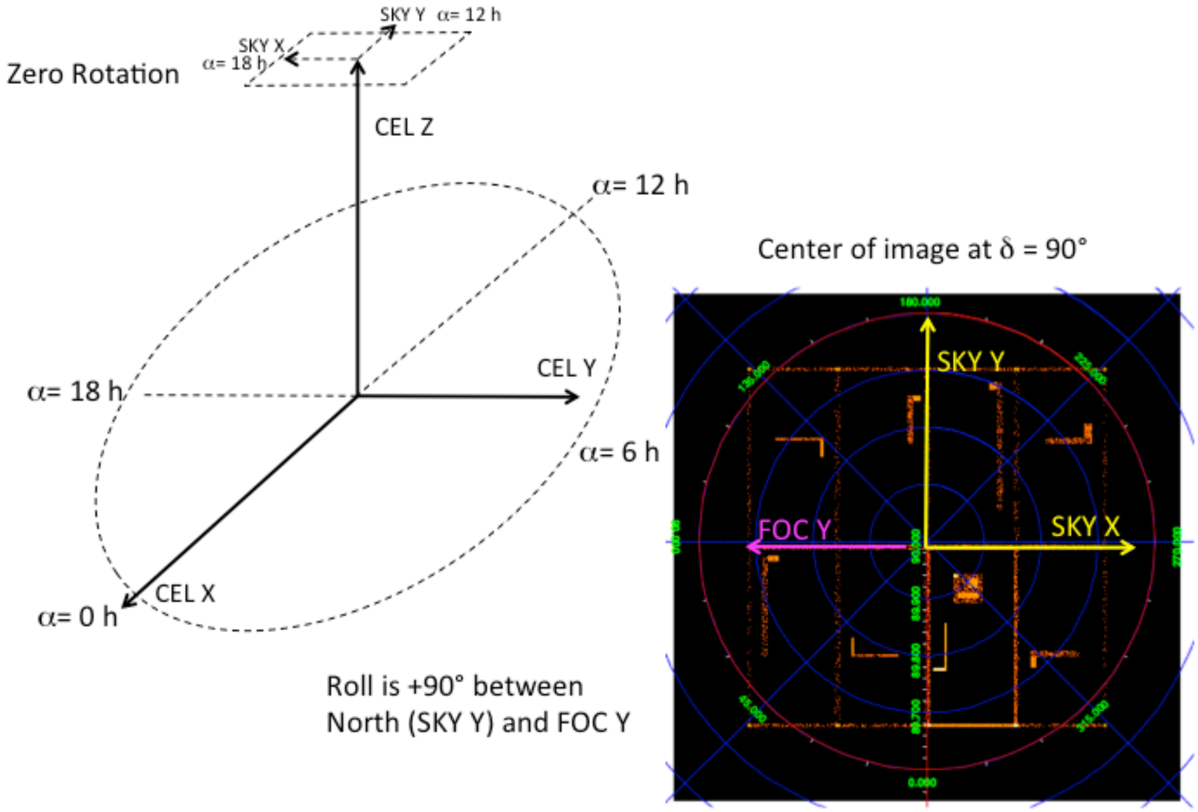


Figure 13. Origin of the SKY rotation system.

Also shown in Figure 14 – 16 are three different rotations, about each of the celestial coordinates. In each figure three views are shown: (a) the celestial coordinate system with the image fixed and coordinates rotated, (b) the celestial coordinate system with the coordinates fixed and the image rotated, and (c) the image as projected in tangent plane coordinates. In each case, the sky image is drawn as it would be seen by an observer at the celestial origin looking out toward the sky image. In each case the SKYZ axis is pointing toward the observer for a look-up coordinate frame. In the system thus defined, a positive rotation about a given axis takes the image from one sky pointing to another, as shown in the (b) drawings. The equivalent rotations of the coordinates ((a) drawings) are in the negative sense: for example, a rotation about Z takes the celestial Y axis toward the celestial X axis. The starting point for each rotation is always the Zero rotation figure (Figure 13) with ($\alpha = 0$ hr, $\delta = +90°$, $\rho = +90°$). (The (c) images are always oriented such that North is up (direction of increasing δ). This means that it is frequently the case that the SKY coordinates are rolled with respect to the FOC coordinates. The roll convention is that a positive roll means that a rotation from SKYY to FOCY is in the positive direction around the SKYZ/FOCZ axis.

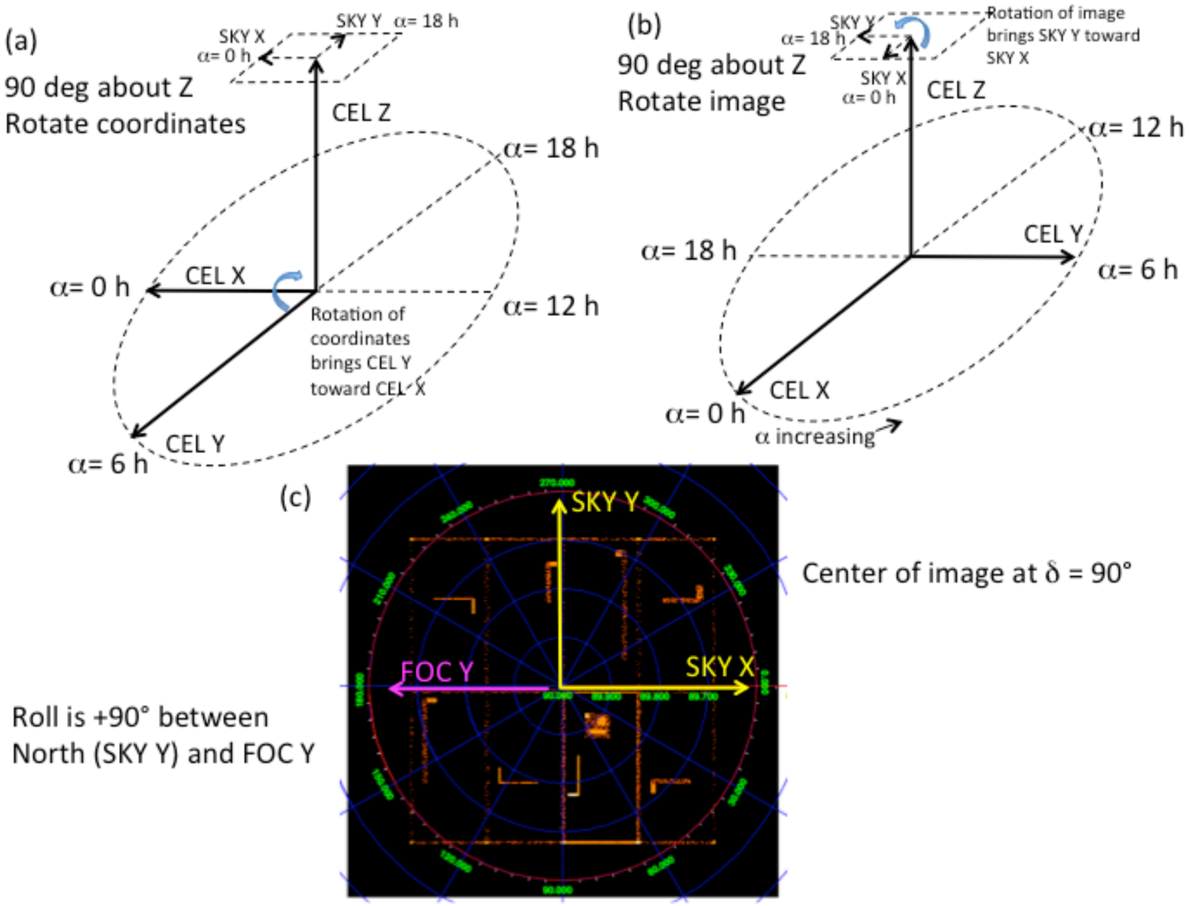


Figure 14. Rotation of 90° about the celestial Z axis.

Figure 14 shows a 90° rotation about the celestial Z axis with Euler angles (E_1, E_2, E_3) = (90°, 0°, 0°) and quaternion $Q = [0, 0, 1/\sqrt{(2)}, 1/\sqrt{(2)}]$. This positive rotation takes (a) celestial Y toward celestial X or (b) SKYY toward SKYX such that the angles are ($\alpha = 6$ hr, $\delta = +90°$, $\rho = +90°$). The image is oriented such that SKYX points at $\alpha = 0$ hr and there is a 90° roll between SKYY and FOCY. Of course, δ is still +90°.

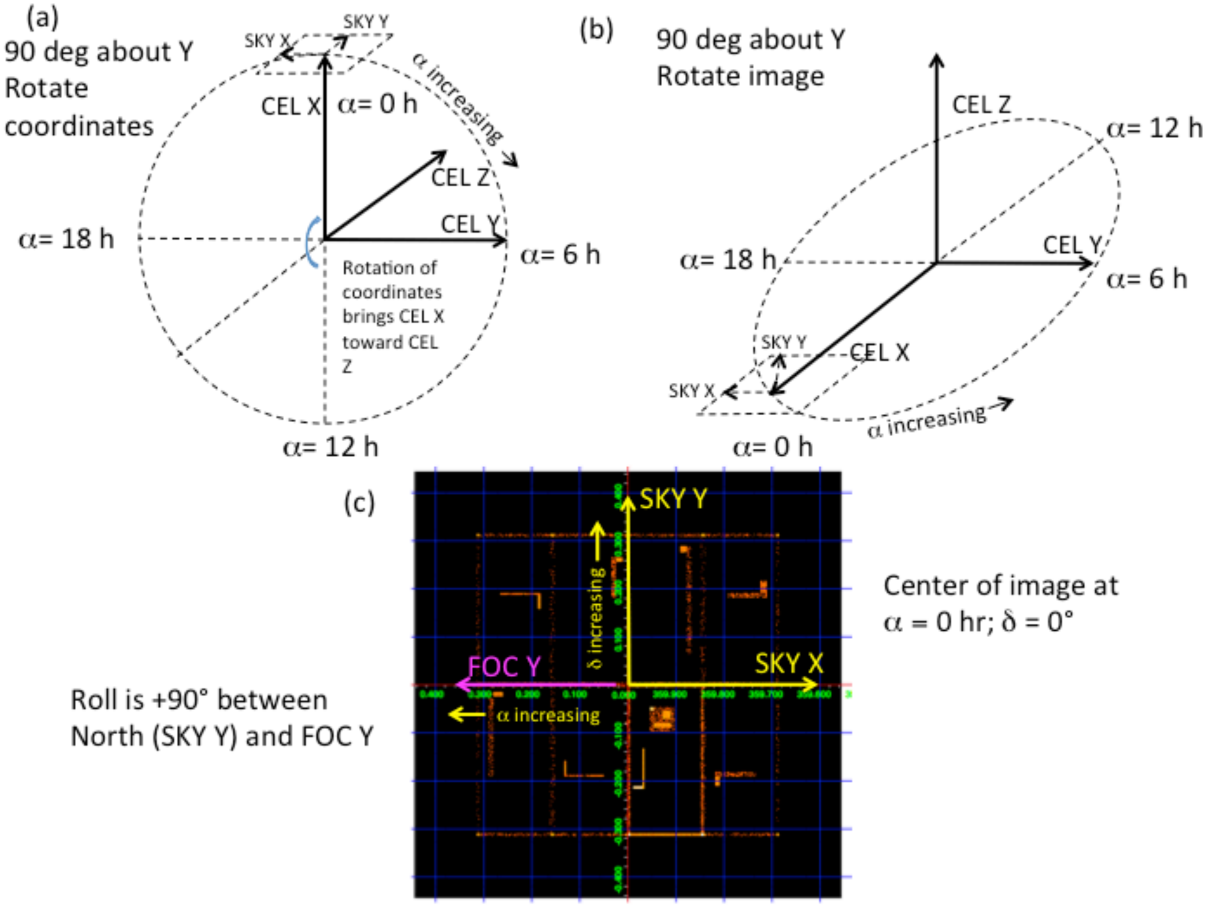


Figure 15. Rotation of 90° about the celestial Y axis.

Figure 15 shows a 90° rotation about the celestial Y axis with Euler angles (E_1, E_2, E_3) = (0°, 90°, 0°) and quaternion $Q = [0, 1/\sqrt{(2)}, 0, 1/\sqrt{(2)}]$. This positive rotation takes (a) celestial X toward celestial Z or (b) rotates the sky image around Y such that it is centered on the positive CELX axis rather than the positive CELZ as in Figure 13. This renders the center of the image at ($\alpha = 0$ hr, $\delta = 0°$, $\rho = +90°$). The image is oriented such that δ is increasing in the direction of SKYY and α is increasing in the direction of –SKYX. As in the Zero rotation case, there is a 90° roll between SKYY and FOCY.

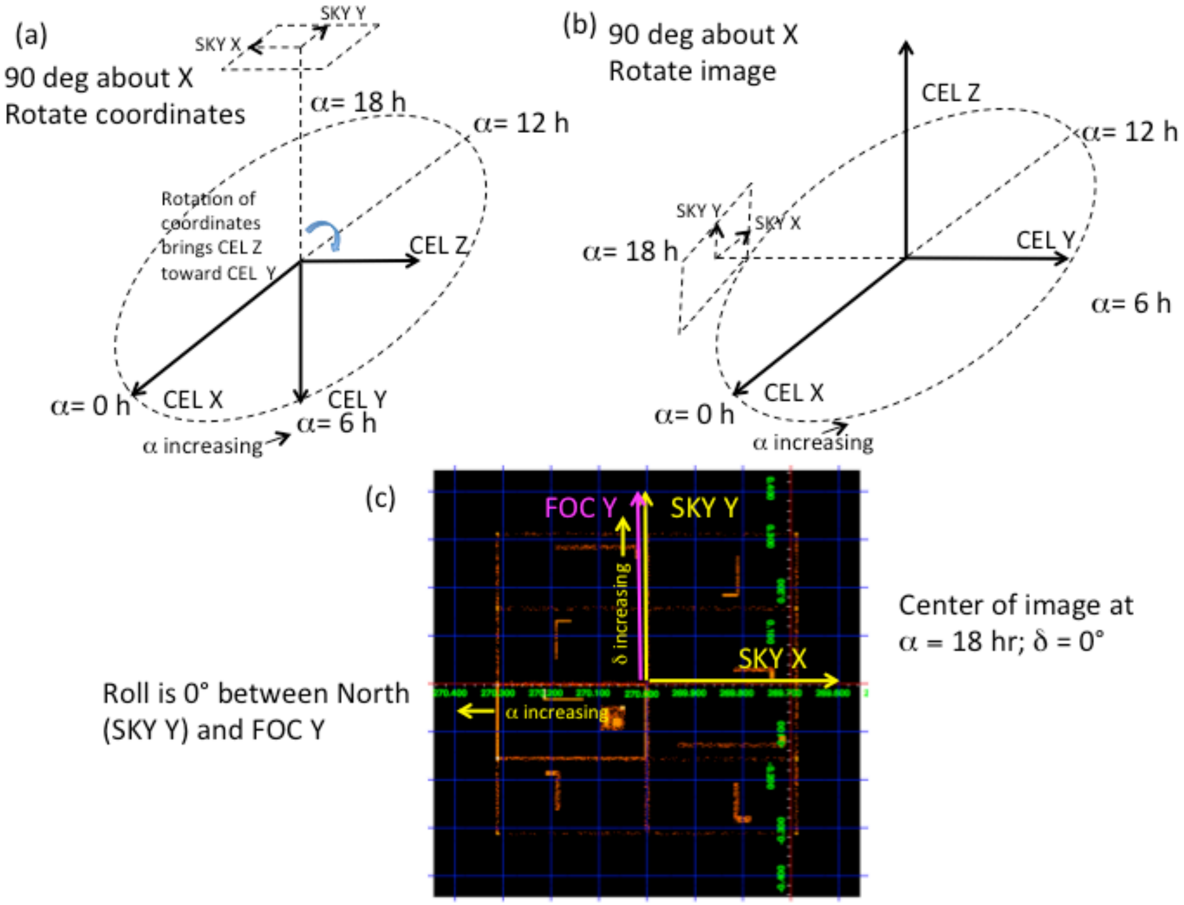


Figure 16. Rotation of 90° about the celestial X axis.

Figure 16 shows a 90° rotation about the celestial X axis with Euler angles (E_1, E_2, E_3) = (270°, 90°, 90°) and quaternion Q = [1/√(2), 0, 0, 1/√(2)]. This positive rotation takes (a) celestial Z toward celestial Y or (b) rotates the sky image around X such that it is centered on the negative CELY axis rather than the positive CELZ as in Figure 13. In order to preserve the convention that North is up in the image, there is a final E_3 = +90° roll around the SKYZ axis. This makes the center of the image at (α = 18 hr, δ = 0°, ρ = 0°). The image is oriented such that δ is increasing in the direction of SKYY and α is increasing in the direction of –SKYX. For this situation there is a 0° roll between SKYY and FOCY.

3 SXI Instrument Coordinates

The SXI consists of four CCD chips, each of which has two separate segments with two readout nodes (see Figure 5). Thus there are a total of eight segments and sixteen read-out nodes. There are two different, but closely related numbering systems for the SXI CCD chips. The instrument names for the chips are CCD1, CCD2, CCD3, CCD4. However in the TelDef file and in the software these chips are known by their CCD_ID value, which runs 0:3. The correspondence, which is shown in Figure 5 and Figure 18 , is that CCDn has CCD_ID = n-1.
Note that there can be a misalignment between the four individual chips since the CCDs are manually mounted; thus he positions and rotations of the CCDs are calibrated and included in the teldef file.

3.1 SXI RAW coordinates

There are eight separate raw coordinate definitions and conversions from RAW to DET, one for each SXI segment. This uses the capability in *coordevt* to have a coefficient-based conversion (see below). Each segment is 320 × 640 pixels on a side (binned), so the dimensions for RAW are 640 × 640, since for symmetry the coordinate system maintains a square shape. The physical dimensions of the binned pixels (bpix in the SXI instrument description document) are 48 μm (0.048 mm) square. With a 5600 mm focal length, this converts to 1.768″ per pixel (focal plane scale of 36.833″ per mm).

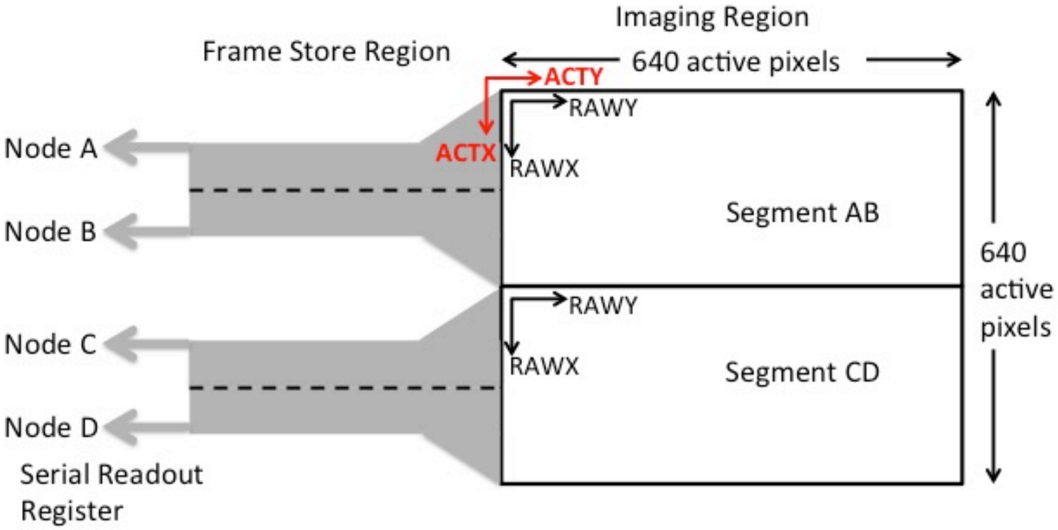


Figure 17 . This schematic drawing (look-down) shows the two segments of an individual SXI CCD chip. Each segment is read out through a separate serial register node. This view shows the “normal” readout through nodes A and C (see also Figure 19). Note that the orientations of the RAW CCD coordinates are different for different segments. The orientation and origin of the ACT coordinates for an SXI chip are shown in red.

3.2 SXI ACT coordinates

There are four separate sets of SXI ACT coordinates, one for each CCD chip, each with a different relationship to the DET coordinates. These are then converted to a single common DET system for the entire SXI. The dimensions in pixels for each chip is 640 × 640 pixels on a side (binned), and since there is no possible misalignment between segments, the dimensions for ACT are similarly 640 × 640. The definitions of the RAW, ACT and DET coordinates for the normal readout are shown in Figure 18 . The scale of ACT is the same as RAW.

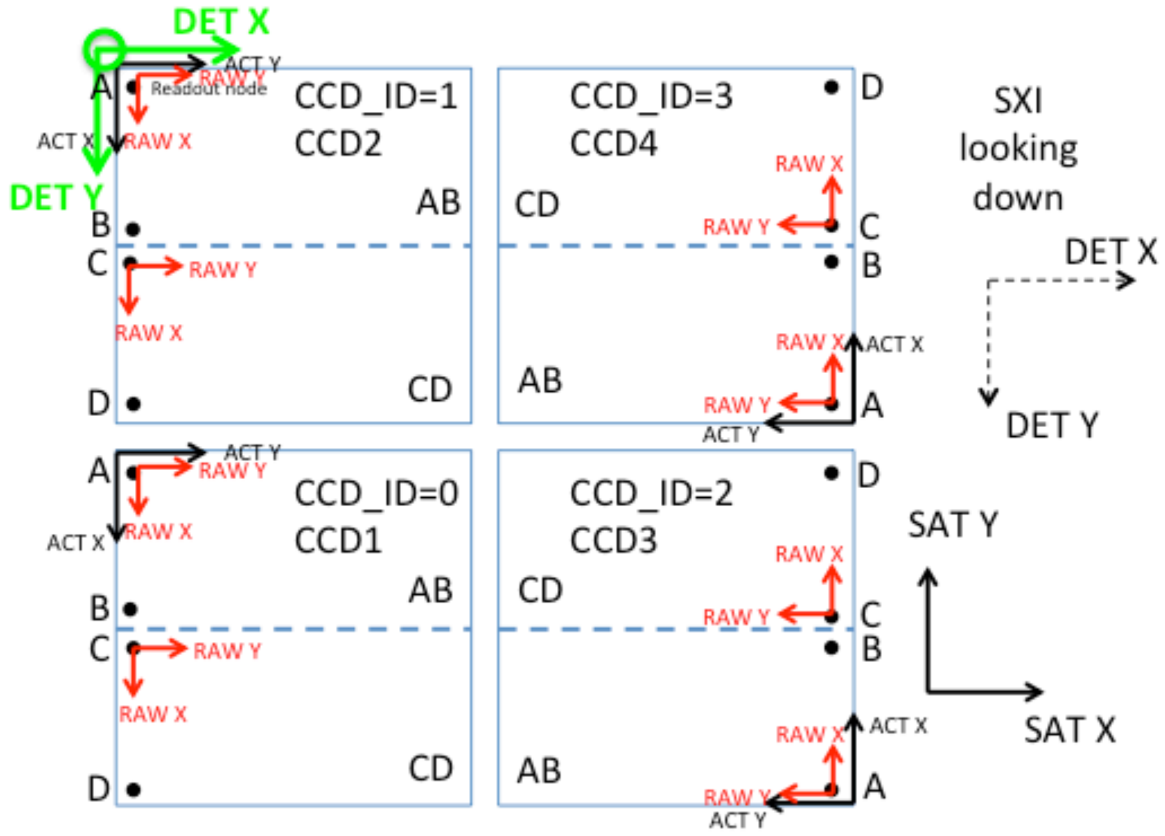


Figure 18. ACT and DET coordinates for SXI. This is a look-down view (since ACT coordinates are defined in look-down – same as the satellite coordinates) and so is flipped vertically with respect to the views in Figure 5 and Figure 6 and to the DET coordinates. The origins of the single DET, 4 ACT and 8 RAW coordinates are shown for the default operating case of readout nodes A and C.THe

There is a two-step process RAW → ACT → DET. The previous version of the **coordinator** tool only supports a coefficient-based transformation when converting from the first-level to the second-level coordinates. However, the new tool, **coordevt**, has been modified to allow coefficient-based transformations at additional stages. All subsequent conversions use only rotations, flips and translations to transform one monolithic coordinate system to another. In Suzaku, the four XIS sensors are separate instruments with separate telescope mirrors, so there are four separate teldef files and separate definitions of ACT and DET coordinates. In ASTRO-H, the four SXI sensors are on the focal plane of a single mirror and so must be treated as a single instrument with a single teldef file.

The conversion from RAW to ACT (all in look-down) is identical for all four SXI sensors. The first step in the conversion is from RAW to ACT, which is described as follows. Note that there are also "READ" coordinates internal to the sensors, but since the RAW coordinates are output in the telemetry, there is no need to be concerned with the READ coordinates in this discussion. The generic formulae are:

$$\mathrm{ACTX} = R_{XN\_a} + W_X + R_{XN\_b} * (\mathrm{RAWX} \mathbin{\%} R_{XN\_d}) + R_{XN\_c} * (\mathrm{RAWY} \mathbin{\%} R_{YN\_d})$$

$$\mathrm{ACTY} = R_{YN\_a} + W_Y + R_{YN\_b} * (\mathrm{RAWX} \mathbin{\%} R_{XN\_d}) + R_{YN\_c} * (\mathrm{RAWY} \mathbin{\%} R_{YN\_d})$$

The $\mathbf{R_{(X/Y)N\_n}}$ parameters depend on the CCD segment (Figure 17) and on the window mode. In the nomenclature above, N takes values A, B, C, D depending on segment. The $W_{(X,Y)}$ parameters depend on the window mode; these parameters are commandable, so they are read as keywords from the event data, rather than being stored in a CALDB table. For the SXI, there is no "mixing" between RAWX and RAWY, so the R_{XN_c} and R_{YN_b} coefficients are zero. In the x-direction there is no windowing, so W_X is also zero. This simplifies the formulae to:

$$\mathrm{ACTX} = R_{XN\_a} + R_{XN\_b} * (\mathrm{RAWX} \mathbin{\%} R_{XN\_d})$$

$$\mathrm{ACTY} = R_{YN\_a} + W_Y + R_{YN\_c} * (\mathrm{RAWY} \mathbin{\%} R_{YN\_d})$$

Mode	SEGMENT	READNODE	R_{XN_a}	R_{XN_b}	R_{XN_d}	W_Y	R_{YN_a}	R_{YN_c}	R_{YN_d}
w/o win	AB	A	1	+1	320	0	1	+1	640
w/o win	AB	B	320	-1	320	0	1	+1	640
w/o win	CD	C	321	+1	320	0	1	+1	640
w/o win	CD	D	640	-1	320	0	1	+1	640
1/4 win	AB	A	1	+1	320	414*	1	+1	160
1/4 win	AB	B	320	-1	320	414*	1	+1	160
1/4 win	CD	C	321	+1	320	414*	1	+1	160
1/4 win	CD	D	640	-1	320	414*	1	+1	160
1/8 win	AB	A	1	+1	320	454*	1	+1	80
1/8 win	AB	B	320	-1	320	454*	1	+1	80
1/8 win	CD	C	321	+1	320	454*	1	+1	80
1/8 win	CD	D	640	-1	320	454*	1	+1	80
1/16 win	AB	A	1	+1	320	474*	1	+1	40
1/16 win	AB	B	320	-1	320	474*	1	+1	40
1/16 win	CD	C	321	+1	320	474*	1	+1	40
1/16 win	CD	D	640	-1	320	474*	1	+1	40

Table 8. Parameters to convert from RAW to ACT coordinates. The values of W_Y indicated by * are the nominal offsets that would center on the window on the mirror design aim point. However, this value is commandable and must be read directly from the event file.

The properties in the first three columns of Table 8 , along with the window size are encoded in the SXI TelDef file as four Properties, defined as follows:

- PROPERTY0 = SEGMENT
  - Segment AB ➔ PROPERTY0 = 0
  - Segment CD ➔ PROPERTY0 = 1
- PROPERTY1 = READNODE
  - Readnode A ➔ PROPERTY1 = 0
  - Readnode B ➔ PROPERTY1 = 1
  - Readnode C ➔ PROPERTY1 = 1
  - Readnode D ➔ PROPERTY1 = 0
- PROPERTY2 = WINOPT
  - Mode without windowing ➔ PROPERTY2 = 0
  - Mode with ¼, 1/8 or 1/16 windowing ➔ PROPERTY2 = 1
- PROPERTY3 = WIN_SIZE
  - Mode without windowing ➔ PROPERTY3 = 640
  - 1/4 windowing ➔ PROPERTY3 = 160
  - 1/8 windowing ➔ PROPERTY3 = 80
  - 1/16 windowing ➔ PROPERTY3 = 40

For the mode without windowing, the conversions are (suppressing the $\mathbf{R}_{\mathbf{(X/Y)N\_d}}$ coefficients since no RAW(X/Y) values are > $\mathbf{R}_{\mathbf{(X/Y)N\_d}}$.):

AB node A (normal):	ACTX = 1 + RAWX	ACTY = 1 + RAWY
AB node B (modified):	ACTX = 320 - RAWX	ACTY = 1 + RAWY
CD node C (normal):	ACTX = 321 + RAWX	ACTY = 1 + RAWY
CD node D (modified):	ACTX = 640 - RAWX	ACTY = 1 + RAWY

In normal operations, each chip is read out from nodes A and C. However, nodes B and D are available for modified operations (in the case in which node A or C becomes inoperable). As seen above, the conversion from RAW to ACT changes depending on the read-out node in use. This is illustrated in Figure 19. Note that the choice of readout node can be made independently for each chip and for each segment. In other words it might be, for example, that SXI-1 and SXI-3 use nodes A and D, while

SXI2 uses nodes B and D, and SXI-4 uses nodes A and C.

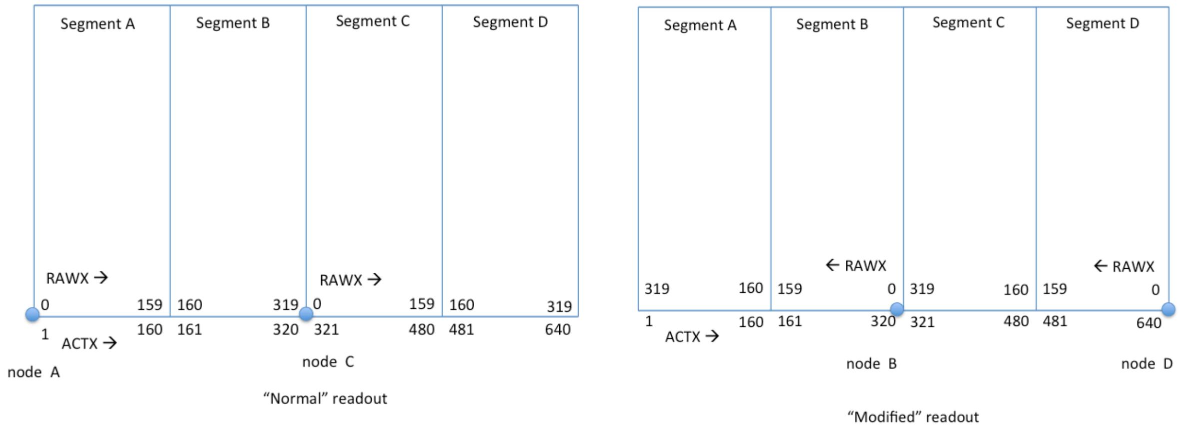


Figure 19. This schematic shows the conversion from RAWX to ACTX depending on the readout node in use. On the left is the "normal" readout mode in which nodes A and C are used. On the right is shown a "modified" readout mode in which node B is used instead of node A and node D instead of node C.

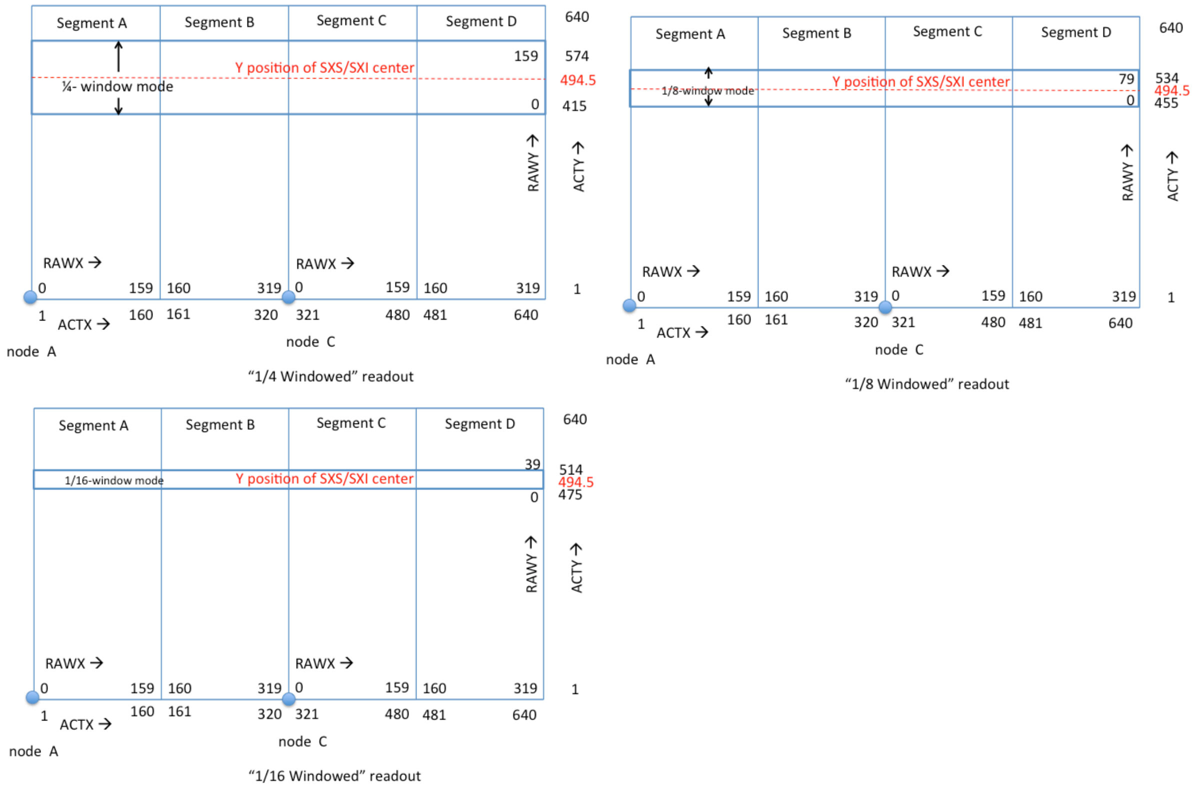


Figure 20. This schematic indicates the window modes for the SXI. Each window is centered in Y at the position of the SXT-I and SXT-S centers. The ¼ - window mode covers 160 pixels (4.72 arcmin), the 1/8-window covers 80 pixels (2.36 arcmin) and the 1/16-window mode covers 40 pixels (1.18 arcmin).

It is possible to operate the SXI in a "windowed" mode, for example ¼-window, 1/8-window or 1/16 window. In the windowed mode, only a section (1/4, 1/8 or 1/16) or window of each chip is read out in the Y-direction. The window is centered on the Y-position of the (coincident) centers of the SXT-S and SXT-I fields-of-view, which is at Y=494.5 pixels (see Figure 20). When windowing is applied, the RAWX → ACTX conversions remain the same. However, the conversion from RAWY → ACTY change to the following:

1/4-window mode: ACTY = 1 + 415[1] + (RAWY % 160)
1/8-window mode: ACTY = 1 + 455* + (RAWY % 80)
1/16-window mode: ACTY = 1 + 475* + (RAWY % 40)

The logic behind the different conversions for different window modes is as follows.

Full Mode.
No windowing. The pixel RAM buffer in the Y-direction (X-direction is unaffected by windowing) is 640 pixels and data is filled in row-by-row:

Physical 639 ==> RAWY = 639 ==> ACTY = 1 + RAWY = 640
Physical 638 ==> RAWY = 638 ==> ACTY = 1 + RAWY = 639
... ...
Physical 1 ==> RAWY = 1 ==> ACTY = 1 + RAWY = 2
Physical 0 ==> RAWY = 0 ==> ACTY = 1 + RAWY = 1

1/4-Windowing Mode.
In the 1/4-windowing, only 1/4 of the physical chip is read out (nominally from physical rows 414 to 573) but it is read out four times to fill the RAM buffer. Therefore one needs to subtract off a pedestal of either 0, 160, 320 or 480, depending whether the data were written first, second, third or fourth. The mathematical operation is thus (RAW % 160). Finally, in this example an offset of 415 is added to produce the correct physical location.
First (of four read-outs):
Physical 639 ==> unread
Physical 638 ==> unread
... ...
Physical 574 ==> RAWY = 159 ==> ACTY = 415 + (RAWY % 160) = 574
Physical 573 ==> RAWY = 158 ==> ACTY = 415 + (RAWY % 160) = 573
... ...
Physical 416 ==> RAWY = 1 ==> ACTY = 415 + (RAWY % 160) = 416
Physical 415 ==> RAWY = 0 ==> ACTY = 415 + (RAWY % 160) = 415
... ...
Physical 1 ==> unread
Physical 0 ==> unread

---

[1] Nominal value; this offset is commandable and must be read from the event file.

Second (of four read-outs):
Physical 639 ==> unread
Physical 638 ==> unread
... ...
Physical 574 ==> RAWY = 319 ==> ACTY = 415 + (RAWY % 160) = 574
Physical 573 ==> RAWY = 318 ==> ACTY = 415 + (RAWY % 160) = 573
... ...
Physical 416 ==> RAWY = 161 ==> ACTY = 415 + (RAWY % 160) = 416
Physical 415 ==> RAWY = 160 ==> ACTY = 415 + (RAWY % 160) = 415
... ...
Physical 1 ==> unread
Physical 0 ==> unread
etc.

1/8-Windowing Mode.
A similar scheme happens in the 1/8 windowing: only 1/8 of the physical chip is read out (nominally from physical rows 454 to 533) but it is read out eight times to fill the RAM buffer. Therefore one needs to subtract off a pedestal of either 0, 80, 160, 240, 320, 400 or 480, depending whether the data were written first, second, third through eighth. The mathematical operation is thus (RAW % 80). Finally an offset of 455 is added to produce the correct physical location.

First (of eight read-outs):
Physical 639 ==> unread
Physical 638 ==> unread
... ...
Physical 534 ==> RAWY = 79 ==> ACTY = 455 + (RAWY % 80) = 534
Physical 533 ==> RAWY = 78 ==> ACTY = 455 + (RAWY % 80) = 533
... ...
Physical 456 ==> RAWY = 1 ==> ACTY = 455 + (RAWY % 80) = 456
Physical 455 ==> RAWY = 0 ==> ACTY = 455 + (RAWY % 80) = 455
... ...
Physical 1 ==> unread
Physical 0 ==> unread
Second (of eight read-outs):
Physical 639 ==> unread
Physical 638 ==> unread
... ...
Physical 574 ==> RAWY = 159 ==> ACTY = 455 + (RAWY % 80) = 534
Physical 573 ==> RAWY = 158 ==> ACTY = 455 + (RAWY % 80) = 533
... ...
Physical 416 ==> RAWY = 81 ==> ACTY = 455 + (RAWY % 80) = 456
Physical 415 ==> RAWY = 80 ==> ACTY = 455 + (RAWY % 80) = 455
... ...
Physical 1 ==> unread
Physical 0 ==> unread

etc.

A similar scheme is used for the 1/16-mode, but this is not shown here.
Although the hardware supports all of the window modes described here, **the decision was made by the Instrument Team to support only Full and 1/8-Window modes.**

The window mode conversion keys off certain keywords in the event file, which, following the Suzaku convention, would be, for ASTRO-H:

WINOPT = 1 / window option (0:Off, 1:On)
WIN_ST = 415[2] / window start address in RAWY
WIN_SIZ = 160 / window size
WINOPT = 2 / window option (0:Off, 1:1/4, 2:1/8)
WIN_ST = 455* / window start address
WIN_SIZ = 80 / window size

3.3 SXI DET coordinates

The DET coordinates are the physical coordinates for the entire SXI (one system for all four chips.) Since the four individual chips are manually mounted, there are misalignments among them, which are measured and calibrated. This means that the conversion from ACT to DET in the SXI must involve this calibration through the teldef file, although the conversion from RAW to ACT does not need to involve the calibration. The conversion is from ACT to DET is different for each of the different sensors.

The first step is to define the four separate transformations from ACT to DET. The relative orientations of the ACT coordinates for the four SXI sensors are shown in Figure 18. The generic transformations are:

$$DETX = C_{XN\_a} + (C_{XN\_b} * ACTX) + (C_{XN\_c} * ACTY)$$

$$DETY = C_{YN\_a} + (C_{YN\_b} * ACTX) + (C_{YN\_c} * ACTY)$$

where the index N runs 1-4 for the four SXI sensors. In what is described below, there is no rotation of any of the CCDs with respect to each other or with respect to the DET coordinates. Such a misalignment can be taken into account by adjusting the parameters $\mathbf{C_{(X/Y)N\_b}}$ and $\mathbf{C_{(X/Y)N\_c}}$.

Given the orientations of the SXI sensors in the absence of rotational misalignment, each of the ACTX axes are either parallel or anti-parallel to the DETY axis and each of the ACTY axes are either parallel or anti-parallel to the DETX axis. Thus many of the $\mathbf{C_{(X/Y)N\_b}}$ and $\mathbf{C_{(X/Y)N\_c}}$ parameters are zero.

The offsets $\mathbf{A_{CX/Y)N\_a}}$ are derived by referring to Figure 21. Figure 5 is used as a baseline for the placement of the chips including gaps.

---

[2] Nominal value; this offset is commandable and must be read from the event file.

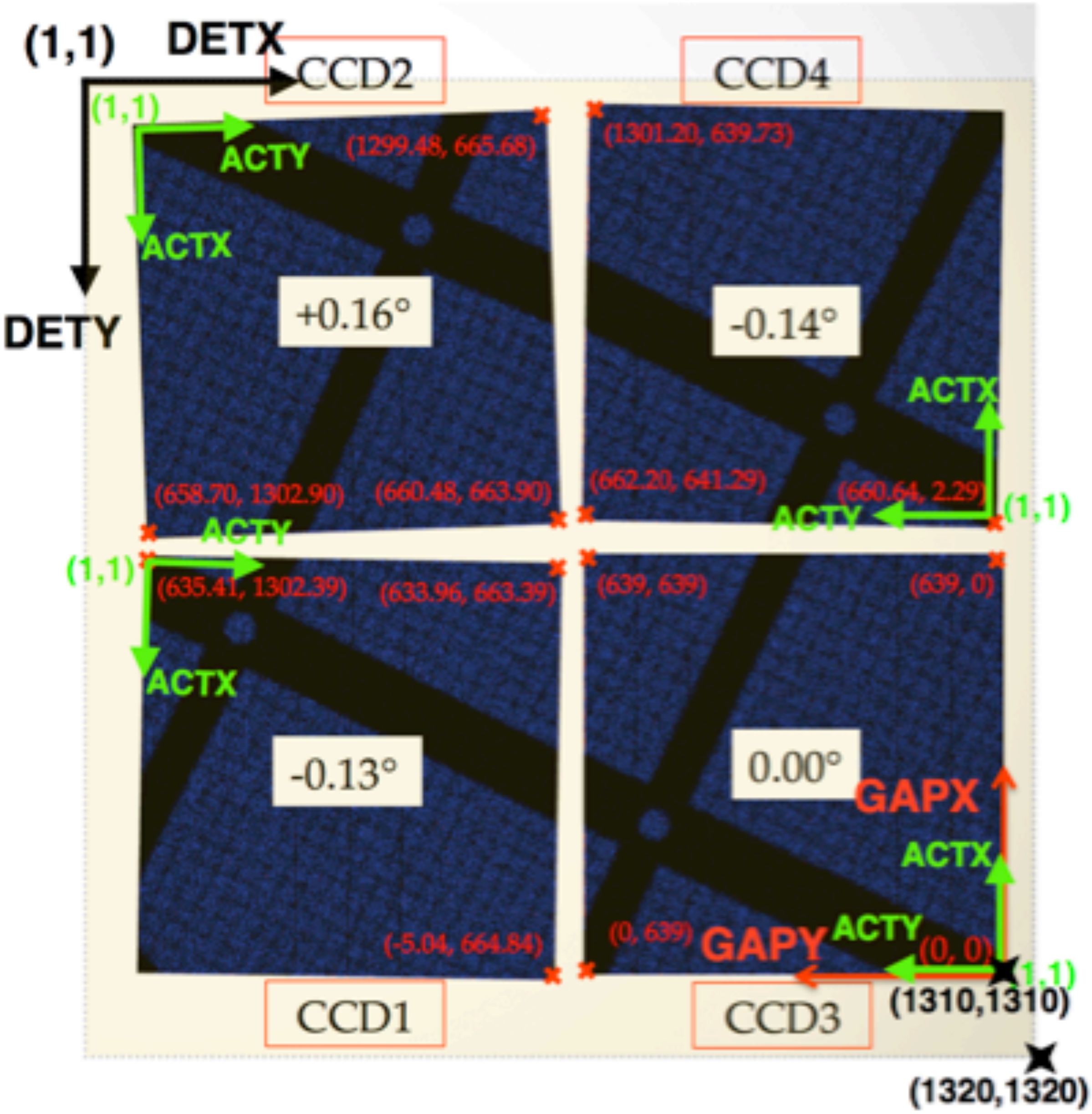


Figure 21. Look-down view showing the DET coordinates (black; universal to all four sensors) and the individual ACT coordinates for each sensor (green). The axes are shown along with the coordinates for the corner pixels of each CCD. The DET coordinates span the gaps between the detectors and take on fractional values because the gaps are not integral numbers of pixels. The offsets are derived by examining the ACT=(0,0) pixel for each sensor and comparing to the DET value for that pixel. There is an intermediate system used only for deriving the conversion parameters, called the GAP system. This system is oriented parallel to DET, but rotated and oriented look-down.

Expanding out gives:
CCD1 (CCD_ID=0):

DETX = C_{X0_a} + (C_{X0_b} * ACTX) + (C_{X0_c} * ACTY) = 254.217 - 0.00227 * ACTX + ACTY

DETY = C_{Y0_a} + (C_{Y0_b} * ACTX) + (C_{Y0_c} * ACTY) = 917.762 + ACTX + 0.00227 * ACTY
CCD2 (CCD_ID=1):
DETX = C_{X1_a} + (C_{X1_b} * ACTX) + (C_{X1_c} * ACTY) = 251.920 + 0.00279 * ACTX + ACTY
DETY = C_{Y1_a} + (C_{Y1_b} * ACTX) + (C_{Y1_c} * ACTY) = 255.481 + ACTX - 0.00279 * ACTY
CCD3 (CCD_ID=2):
DETX = C_{X2_a} + (C_{X2_b} * ACTX) + (C_{X2_c} * ACTY) = 1558.604 - ACTY
DETY = C_{Y2_a} + (C_{Y2_b} * ACTX) + (C_{Y2_c} * ACTY) = 1555.173 - ACTX
CCD4 (CCD_ID=3):
DETX = C_{X3_a} + (C_{X3_b} * ACTX) + (C_{X3_c} * ACTY) = 1556.310 + 0.00244 * ACTX - ACTY
DETY = C_{Y3_a} + (C_{Y3_b} * ACTX) + (C_{Y3_c} * ACTY) = 894.536 - ACTX - 0.00244 * ACTY

These coefficients take into account misalignments. Assuming that the four CCD chips are monolithic, the rotational misalignment are incorporated by setting the parameters **$C_{(X/Y)N\_b}$** and **$C_{(X/Y)N\_c}$** to represent rotation angles of the chips relative to a fiducial standard, which in this case is the orientation of CCD2 in Figure 21. Translational misalignment is accounted for by modifying the **$C_{(X/Y)N\_a}$** parameters to include additional offsets due to misalignment.

Putting all of this information into a table (9) gives:

Sensor	First coefficient	Second coefficient	Third coefficient	Fourth coefficient	Fifth coefficient	Sixth coefficient
CCD1	C_{X0_a}= 254.217	C_{X0_b} = -0.00227	C_{X0_c} = 1	C_{Y0_a}= 917.762	C_{Y0_b}= 1	C_{Y0_c} = 0.00227
CCD2	C_{X1_a} = 251.920	C_{X1_b} = 0.00279	C_{X1_c} = 1	C_{Y1_a}= 255.481	C_{Y1_b}= 1	C_{Y1_c} = - 0.00279
CCD3	C_{X2_a}=1558.604	C_{X2_b} = 0	C_{X2_c} = -1	C_{Y2_a}=1555.173	C_{Y2_b}= -1	C_{Y2_c}= 0
CCD4	C_{X3_a}=1556.310	C_{X3_b} = 0.00244	C_{X3_c} = -1	C_{Y3_a}= 894.536	C_{Y3_b}= -1	C_{Y3_c} = - 0.00244

Table 9. Coefficients for SXI chips and readout nodes.

The coefficients must be FLOAT or DOUBLE to accommodate non-integral gaps and misalignments.

The total size (in pixels) of the SXI focal plane is calculated as follows. Each chip is 640 X 640 pixels (30.72 mm; 18.86 arcmin). For a full four (2 X 2) plane without gaps, this gives a size of 1280 X 1280. From Figure 21, the maximum gap is 25.95 pixels ($45.9''$) in X and 26.52 pixels ($46.9''$) in Y. So the full size is 1306 X 1307 pixels. The DET space must be at least this large, plus a margin for misalignments of the chips. To cover this region and include room for misalignments, the DET space is defined as 1810 X 1810. This is large enough to include a full 45-degree rotation of the fields with respect to each other. The DET scale is the same as the SXI RAW scale: 0.048 mm. With a 5600 mm focal length, this converts to $1.768''$ per pixel (focal plane scale of $36.833''$ per mm).

The center of the DET system is defined as the geometric center of the four CCD chips and the origin is located to the lower left in look-up (Figure 5 6 and 22) or upper left in look-down (Figure 18 21). In keeping with past convention, all DET coordinate values are positive. Figure 22 shows the SXI transformation schematically with a cartoon star field.

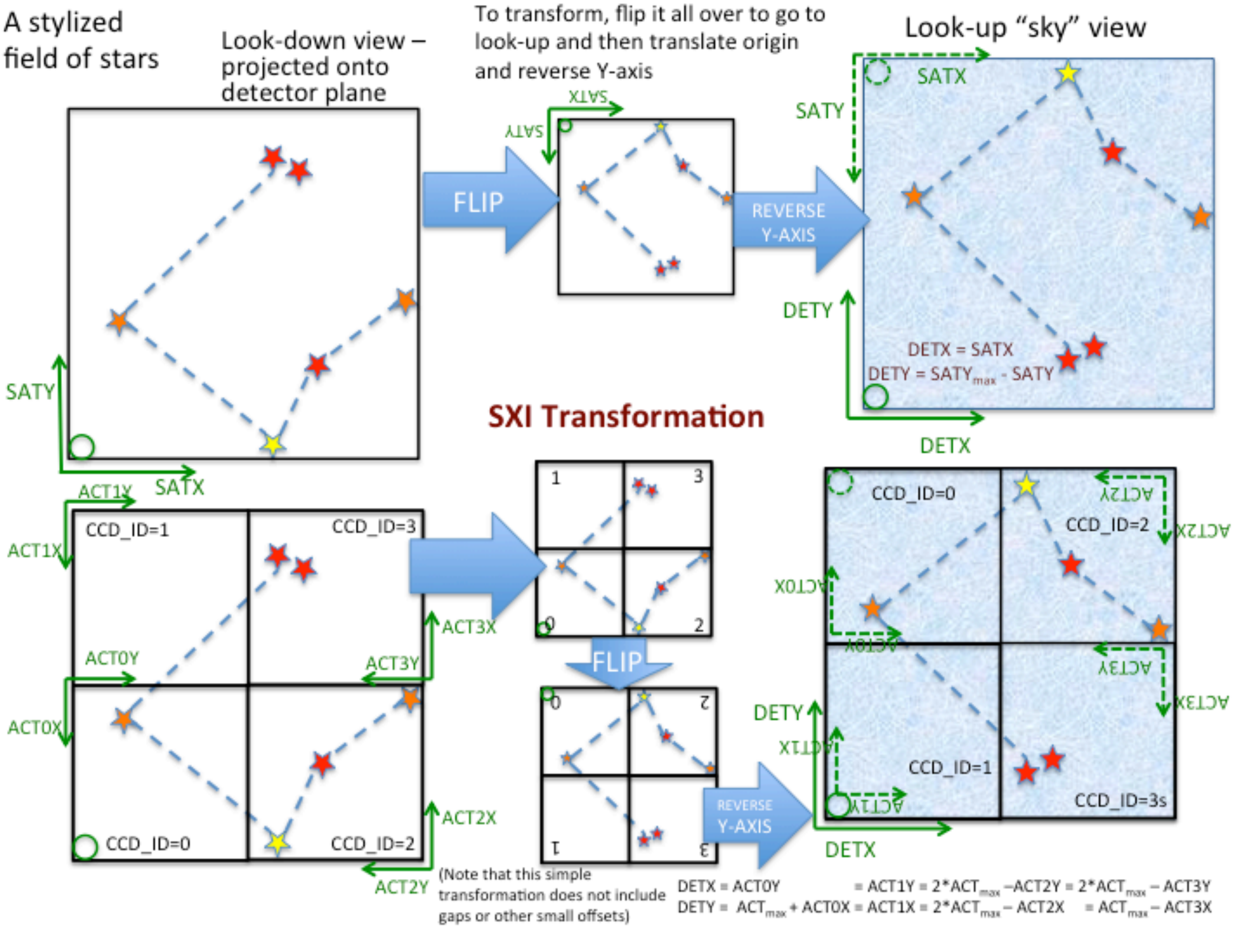


Figure 22. This shows schematically the transformation from SXI ACT to DET which includes an inversion to go from look-down (ACT) to look-up (DET), rotations of the separate ACT axes and then finally a flip of the Y-axis to bring the system into a right-handed look-up orientation.

3.4 SXI FOC coordinates

The FOC coordinates are common to all of the sensors and hence take into account misalignments among the sensors. Since the SXI and SXS have the same focal length (5600 mm) there is no need for a conversion factor on the pixel scales. (There is a conversion for the HXI.) The center of the FOC coordinates is defined to be the center of the SXS sensor (the gap among pixels 0, 17, 18, 35). The scale is the same between SXI DET and FOC, but the range must be larger for the FOC system to accommodate rotation when converting from FOC to SKY. In the current definition, there is no rotation between SXI DET and FOC, but the TelDef can accommodate a rotation if measured after launch. Figure 23 shows the relative size and orientation of the SXI DET and FOC systems.

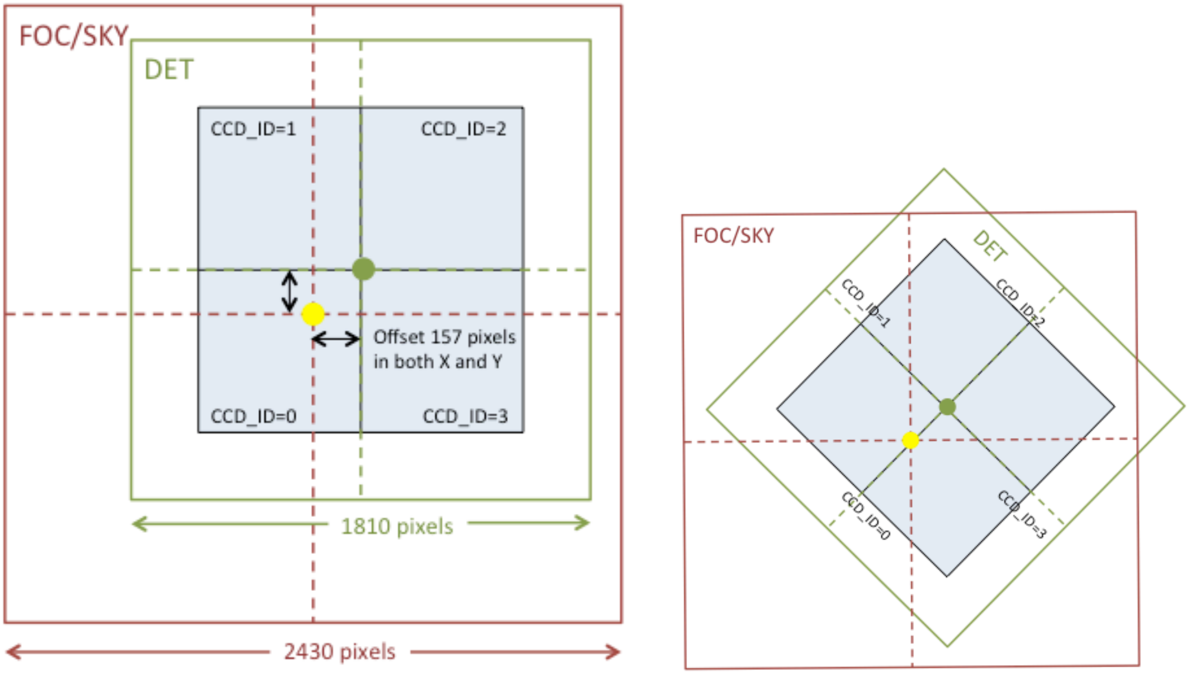


Figure 23. This shows the relative orientations of the SXI DET and FOC systems. Note that the SKY system is the same size as the FOC system. Left: The SXI DET system is centered on the gap among the four CCD detectors and its size is indicated by the green square. The FOC system is centered on the SXS detector (yellow circle) and is sized such that a maximum rotation of 45° (Right) will keep the actual detector within the FOC/SKY system. The offset between DET and FOC is based on the design and the actual value, and any rotation, will be determined by alignment.

Although it is not expected that there are any large time-dependent shifts in the position of the fixed optical bench on which the SXI is mounted with respect to the SXT-I, the transformation from DET to FOC for the SXI must take into account this possibility. Since there is no active monitoring of shifts of the fixed optical bench (as there are for the extensible optical bench) any such distortions are determined in-flight from observations of bright sources. If the distortions are determined to be dependent on sun angle, orbit location, etc., then they can be parameterized and applied as a "delta attitude" in the conversions. The conversion code includes a placeholder for the SXI (and SXS) delta attitude.

3.5 SXI Detector Alignment

The transformation between the ACT and DET coordinate systems for the SXI is described in Section 3.3. The coefficients listed in Table 9 are derived from the information given in Figure 21. This figure is based on measurements and shows accurately the relative positions and rotations of the individual CCD chips. The measurements shown in Figure 21are referenced to the lower right corner of the figure and given as "GAP" coordinates, which are aligned to CCD3. Thus the positions of the other CCDs are measured relative to CCD3. The rotation angle θ of each CCD is given directly on Figure 21, and the rotation coefficients are given as AXN_b = sinθ, AYN_c = -sinθ, and AXN_c = AYN_b = cosθ. The offset terms (AXN_a, AYN_a) for each CCD are derived in the following way. First the mean of the differences between the GAP coordinate and ACT coordinate for each corner of the CCD is calculated. Second, this mean difference vector is rotated by θ into the common DET system. Finally an offset is added to center the DET system at the center of the gap among the four CCDs.

4 SXS Coordinates

The SXS consists of 36 separate detectors (Figure 24), each of which is read out separately. There can be a small misalignment among the detectors (as there is for the XRS in Suzaku), so this misalignment is accounted for in the teldef file in a table similar to the PIXEL_MAP extension for the Suzaku/XRS teldef. The SXS has RAW, ACT, DET, FOC and SKY coordinates.

4.1 SXS Pixel (RAW) coordinates

The basic level coordinate for the SXS is a one-dimensional pixel number. The relative orientation of the SXS pixels is shown in Figure 24. The *coordevt* tool uses the PIXEL_MAP table extension to convert from the pixel number to the ACT coordinates. This table contains the physical locations relative to the center of the SXS array for each of the SXS pixels. This is converted directly to ACT coordinates, then to DET by including a 180° rotation and a "flip" of the Y-axis.

In the teldef file, each individual pixel is a segment. The corner locations in the PIXEL_MAP table account for the nominal placement of the pixels and their relative misalignments. It is appropriate that this table also account for overall misalignment of the SXS detector with the nominal FOC coordinates. This is what is done for the Suzaku/XRS since there are no misalignment values in the XRS DET → FOC transformations.

The values of the pixel corner positions for the teldef file are taken from measurements provided by SXS team NASA Goddard Space Flight Center on Sep. 26, 2012. The overall average pitch of the pixels in the plane are (size/pitch/gap = 814/832/18 μm, respectively). As in the Suzaku/XRS PIXEL_MAP table, the pixel corner positions are given with respect to the center of the pixel array at the corners of pixels 0, 17, 18 and 35 (see Figure 24). In the PIXEL_MAP table, the X and Y locations of the SXS pixels are in order (look-down) lower-left, lower-right, upper-right, upper-left.

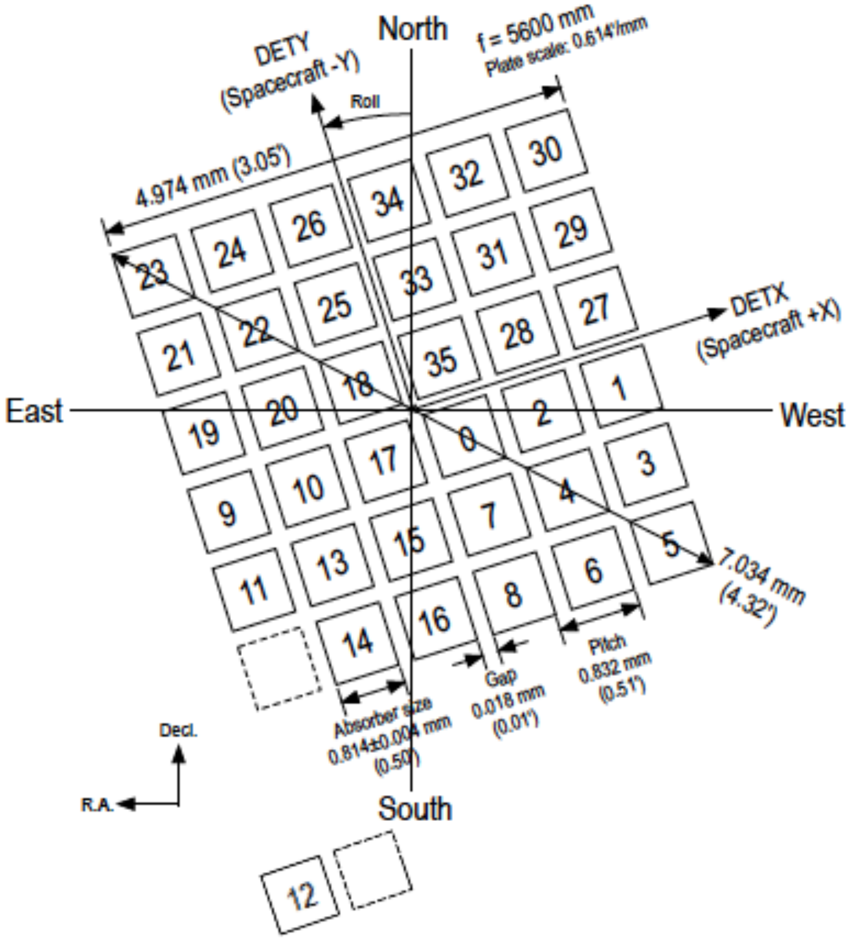


Figure 24. Look-up map of the SXS calorimeter array, showing the layout of the pixels (JAXA-XCS-E-007 "PSP Description Document"). Each has a dimension of 0.814 mm x 0.814 mm, corresponding to a sky projection of 0'.50 x 0'.50; the entire X-ray sensitive portion of the array projects a solid angle of 3'.05 x 3'.05 on the sky. Pixel 12 is the calibration pixel, which is located outside the field of view.

4.2 SXS ACT coordinates

The ACT coordinates are defined in terms of the physical positions of the individual pixels (in mm) in the SXS in a look-down orientation. The orientation of the ACT system is the same as the "instrument" or "array" system used by the instrument team (Figure 25) although the origin of the ACT system is near pixel 5 and not at the center of the SXS array. Therefore a small offset is required when transforming from RAW to ACT coordinates and a larger one when transforming from DET to FOC (see Section 2.2.4). Note that the ACT system is rotated by 180° from the dewar system, which is the same as the spacecraft system. The SXS ACT coordinates span the space (8×8).

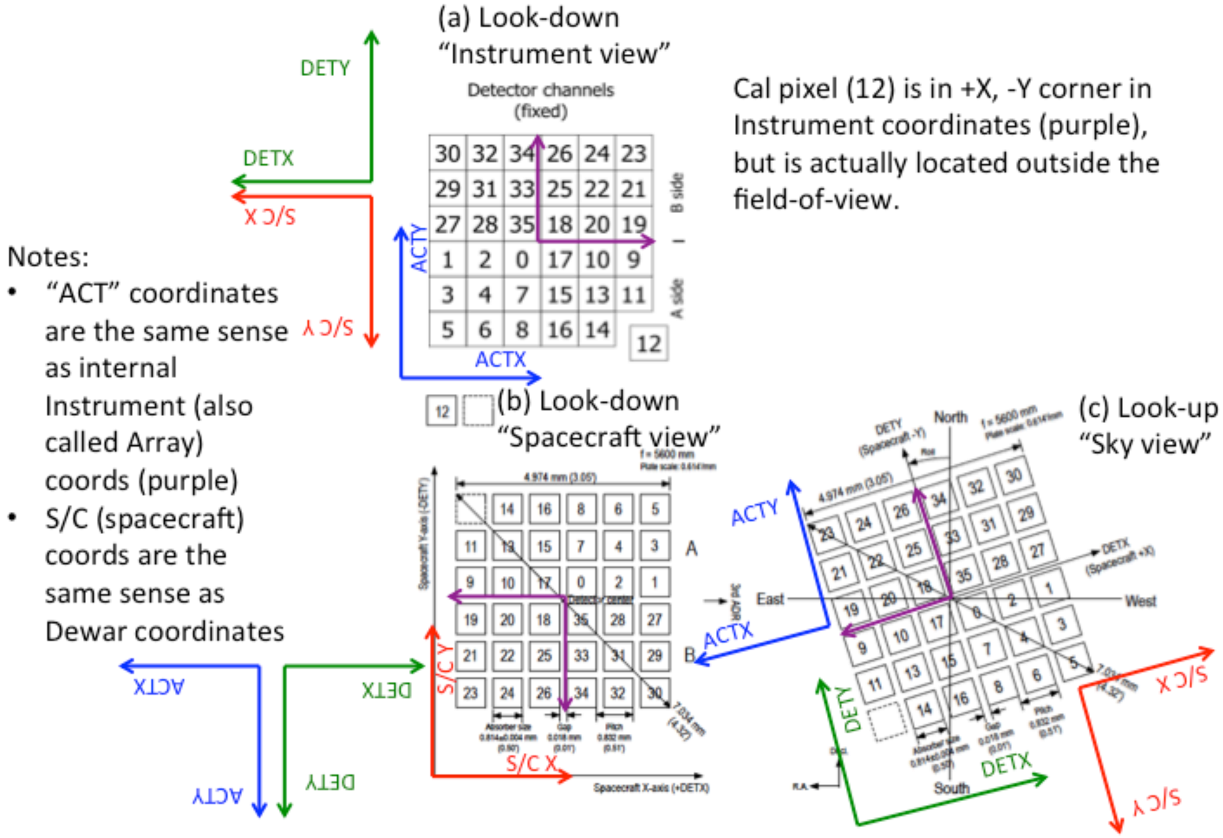


Figure 25 . Combined view showing the relationships between the ACT coordinates (blue) and the DET coordinates (green). Also shown for reference are two sets of engineering coordinates that are not included in the coordinate transformations or the teldef file: the spacecraft (S/C) coordinates (red) and the instrument or array coordinates (purple), which are used by the SXS Instrument Team. (a) Look-down "Instrument view." Figure (a) taken from ASTRO-H SXS Pulse Shape Processor (PSP) Description Document, JAXA-XCS-E-007. (b) Look-down "Spacecraft view." (c) Look-up "Sky view." Figures (b) and (c) taken from ASTRO-H SXS Dewar Description, JAXA-XCS-C-001.

4.3 SXS DET coordinates

The DET coordinates are look-up in the same sense as those for the other ASTRO-H sensors (DETX = S/C X; DETY = -S/C Y). The transformation from ACT-> DET consists of a 180° rotation about the Z-axis to align with the S/C system and then a flip of the Y-axis to convert to a look-up orientation. The SXS DET coordinates span the space (8 × 8). The origin and scale for the DET coordinates is at the lower left corner of the SXS (near the "missing" pixel 12). A subset of SXS detectors in the DET system is shown in Figure 26.

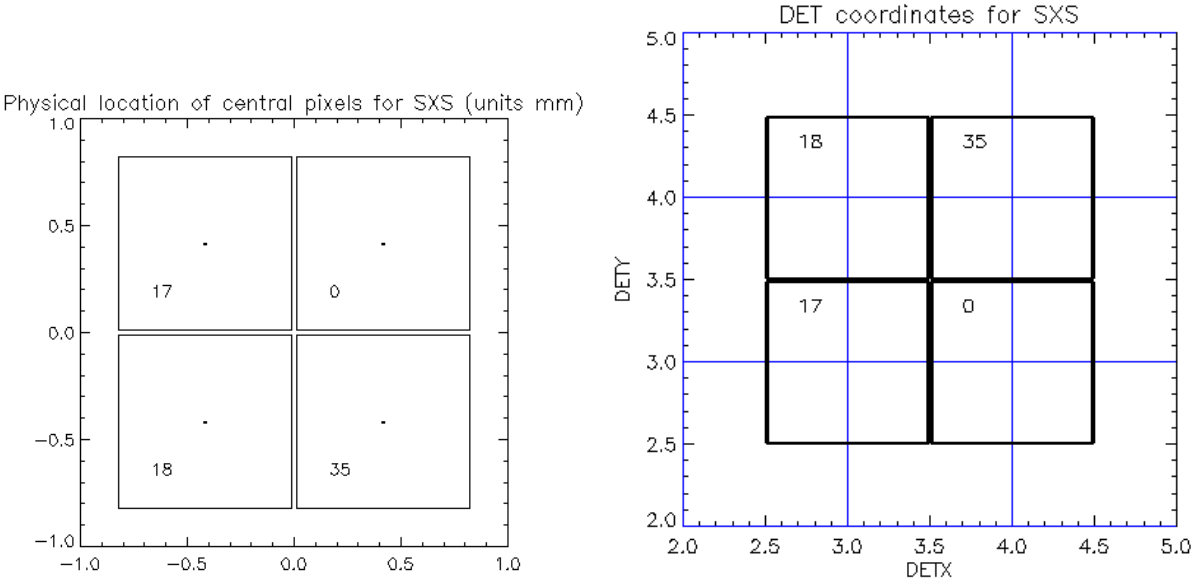


Figure 26. The four central pixels of the SXS showing their physical location relative to the array center (left) and the proposed DET coordinates (right). The DET origin is at the lower left of the SXS array. Note the flip in the Y-direction from look-down (left) to look-up (right).

4.4 SXS FOC coordinates

The FOC coordinates are common to all of the sensors and hence take into account misalignments among the sensors. The FOC system is defined such that its center is at the center of the SXS detector, which is seen in DET in Figure 26. There is an offset of one pixel between DET and FOC because the SXS is not at the center of DET. A rescaling is also necessary between DET and FOC due to the smaller size of the FOC pixels. The full scale of FOC is 2430 X 2430. Figure 27 shows the effect of oversampling on the SXS FOC coordinate system.

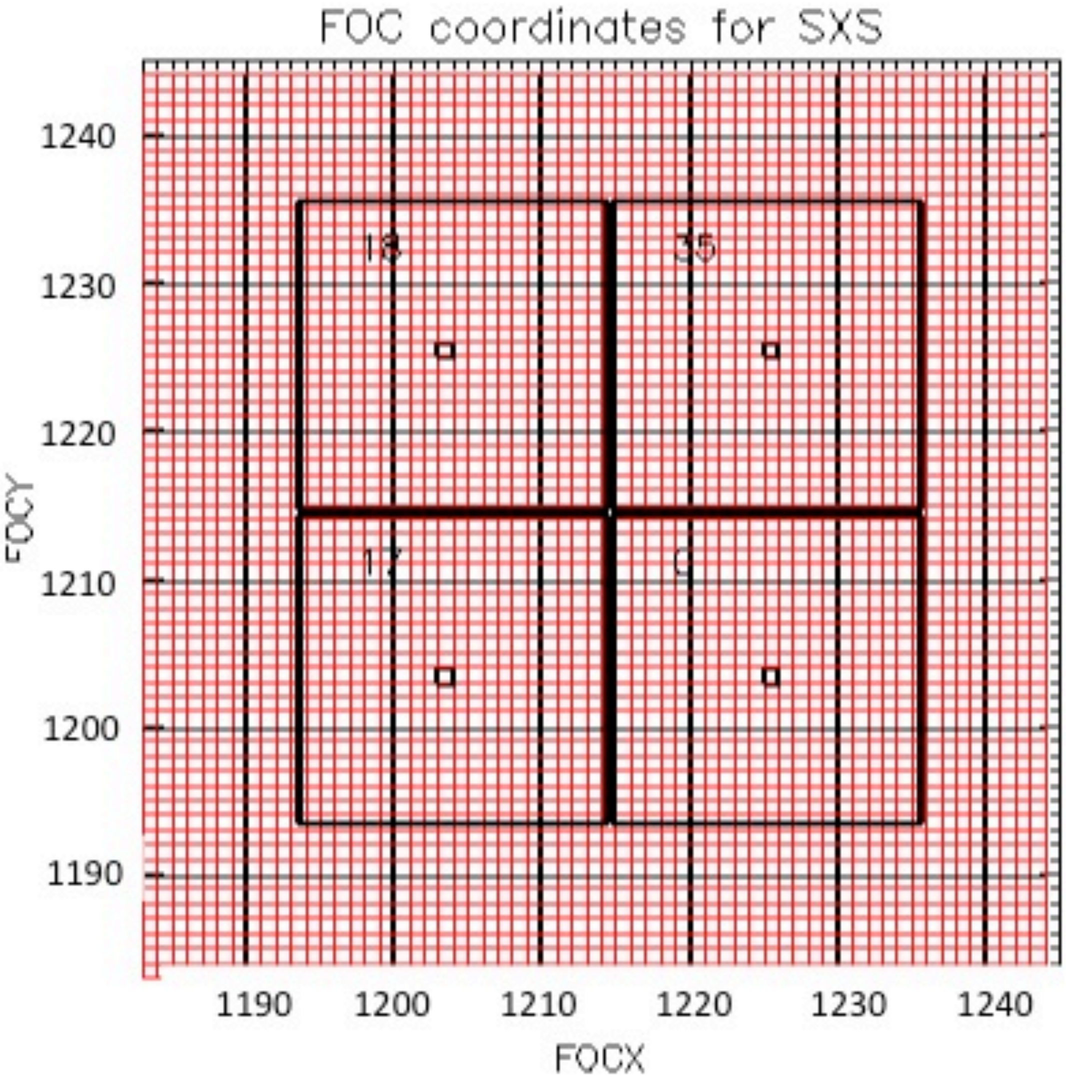


Figure 27. The central four pixels (same as in Figure 7) shown in the proposed FOC system which is defined at the pixel scale of the SXI. The oversampling is a factor of 832 mm/48 mm = 17 in each dimension. The small squares show the center of each detector.

For reference, Figure 28 gives the equivalent of Figure 26 and 27 for the Suzaku/XRS as derived from the published teldef files.

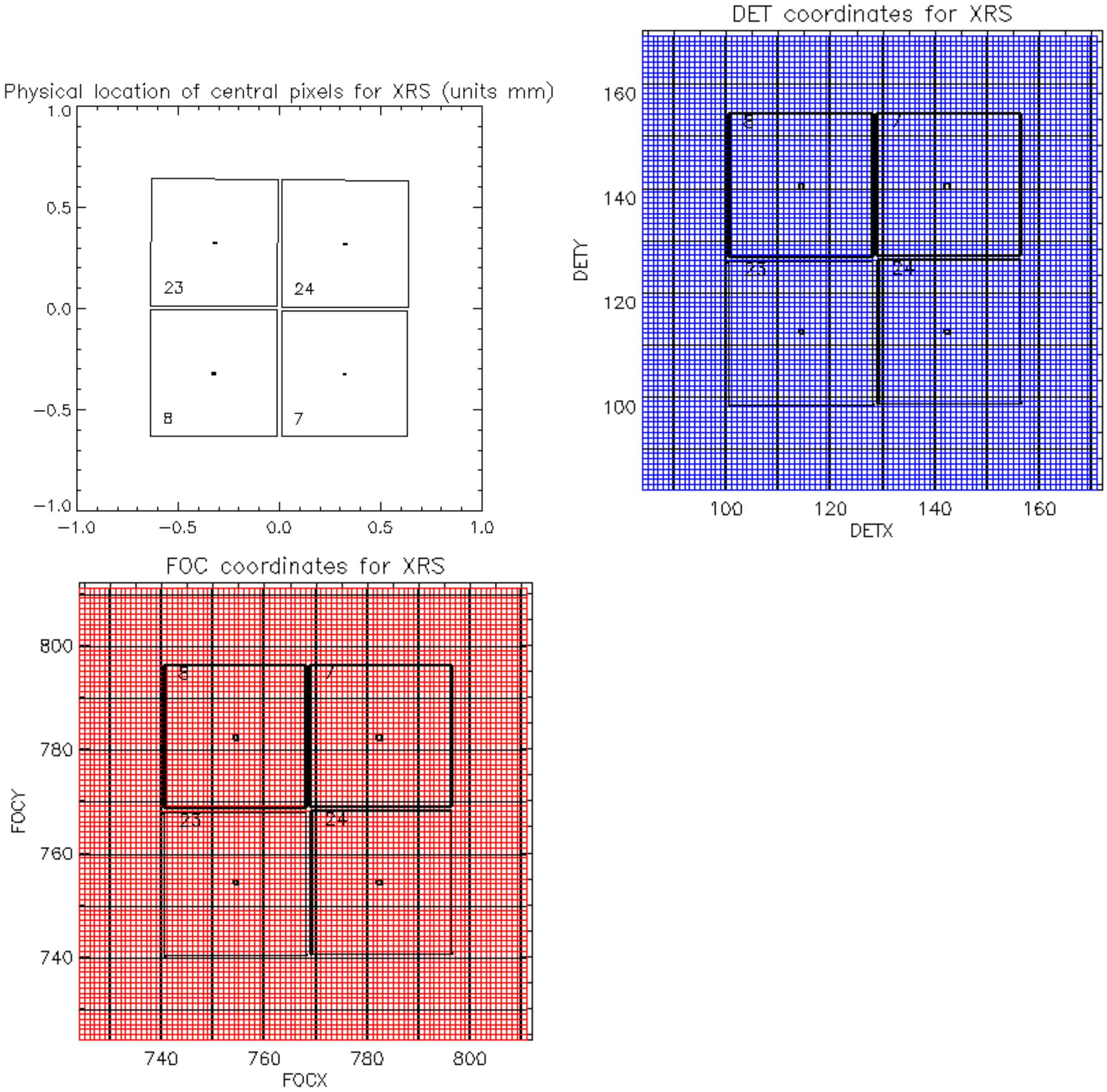


Figure 28 shows the physical locations, DET and FOC coordinates for the XRS on Suzaku. The oversampling is a factor of ~28.

4.5 SXS Detector Alignment

The positions of the 36 SXS pixels were measured on Sep. 26, 2012 by the SXS team at NASA Goddard Space Flight Center. The information was recorded in a spreadsheet containing the following notations: the measurements are in mm and the array is oriented down-looking, with the calibration pixel in the +x, -y quadrant. Pixel numbers are left-right, top-bottom, and are not PSP channel numbers. Pixel 36 (PSP channel 12) is not read out (that channel is used for the calibration pixel instead). The columns of the spreadsheet are X, Y, Pixel ID and each pixel has four rows, corresponding, in order, to the locations of the top-left, top-right, bottom-left, bottom-right corners of the pixel.

A mapping was made between spreadsheet pixel ID and PSP channel, since the measurements are given in the TelDef in order of PSP channel. This mapping is illustrated in Figure 29 (compare Figure 25).

1	2	3	4	5	6		30	32	34	26	24	23
7	8	9	10	11	12		29	31	33	25	22	21
13	14	15	16	17	18		27	28	35	18	20	19
19	20	21	22	23	24		1	2	0	17	10	9
25	26	27	28	29	30		3	4	7	15	13	11
31	32	33	34	35	36		5	6	8	16	14	12

Figure 29 shows the mapping between the pixels numbers from the calibration spreadsheeet (left) and the PSP channel numbers (right). Both are oriented look-down.

To make the PIXEL_MAP table in the SXS TelDef file, the following steps were taken:

1) Add additional columns to the spreadsheet to indicate PSP channel (Figure) and pixel corner number. To conform to the existing TelDef definition of pixel corners, the numbering is 1= bottom-left, 2=bottom-right, 3=top-right, 4=top-left, viz Figure 30 .

4	3
1	2

Figure 30 shows the pixel corner numbering system used in the TelDef file.

2) The spreadsheet is re-ordered by PSP Channel and then by pixel corner number.

3) The spreadsheet is converted to a five-column intermediate FITS table with scalar columns CHANNEL, CORNER, X, Y, PIXEL. This table has 144 rows (36 channels X 4 corners).

4) The intermediate FITS table is converted into the PIXEL_MAP format, with scalar column PIXEL (1I format) and vector columns PIXELX (4E) and PIXELY (4E). The mapping from the intermediate file to the PIXEL_MAP table is as follows:

Intermediate File Column		PIXEL_MAP Column
CHANNEL		PIXEL
X	CORNER = 1	PIXELX[1]
X	CORNER = 2	PIXELX[2]
X	CORNER = 3	PIXELX[3]
X	CORNER = 4	PIXELX[4]
Y	CORNER = 1	PIXELY[1]

Y	CORNER = 2	PIXELY[2]
Y	CORNER = 3	PIXELY[3]
Y	CORNER = 4	PIXELY[4]

5 HXI Coordinates

The HXI consists of 5 separate detectors (Figure 31), each of which is read out through 8 separate ASIC chips (4 per side). The HXI is a strip detector, so only one dimension of positional information can be obtained from a single hit. It is required for there to be at least two hits (one top side, one bottom side) to reconstruct a full X-Y position. For the HXI, the RAW coordinate is reconstructed from two or more hits with the same time stamp. The ACT coordinate is derived from RAW using a Δ-attitude file based on the CAMS corrections. Then there is a standard translation plus rotation to convert from DET (flipped relative to ACT) to the common FOC coordinates. Thus the HXI has RAW, ACT, DET, FOC and SKY coordinates.

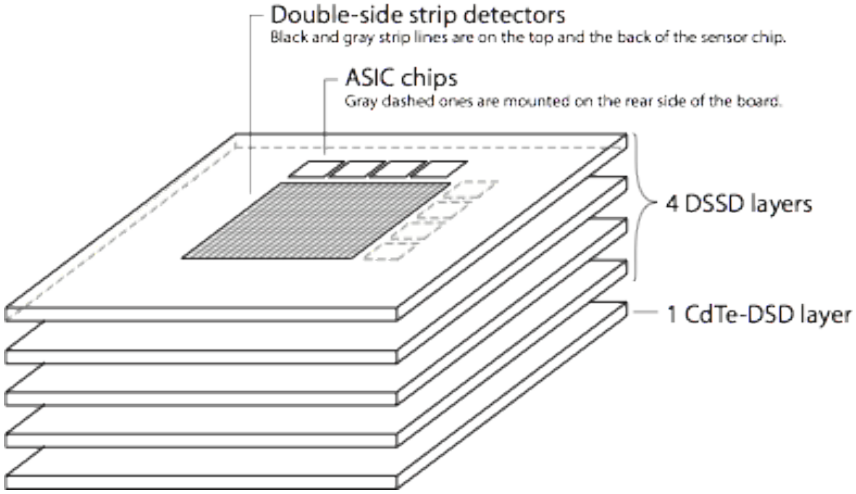


Figure 31. Expanded view of the HXI detectors. Each of the four detectors is double-sided with 4 readout ASIC chips on each side. case,

5.1 HXI Reconstruction of Photon Events

In the simplest case, a photon makes two signals on the top and bottom layers of a single detector. In this case (Figure 32), the position is determined from the intersection of the two strips.

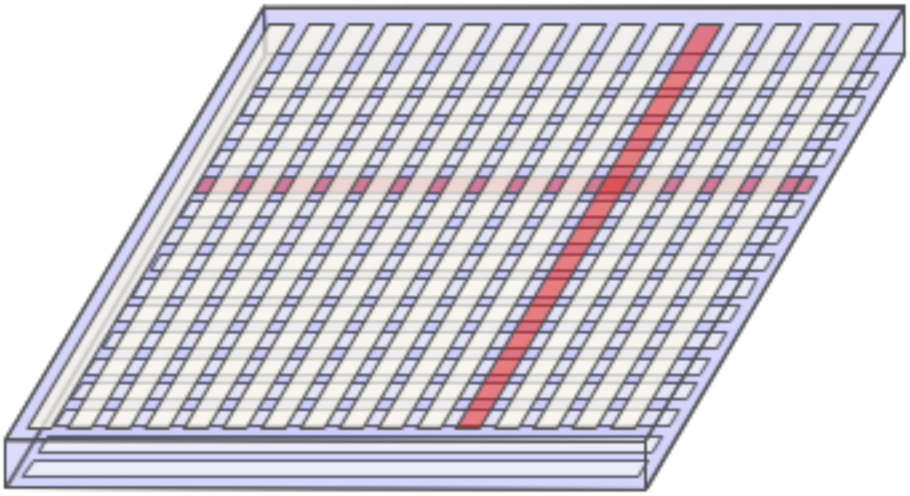


Figure 32 A photon makes a pair of hits on the top and bottom sides of a single HXI detector. The position (X,Y) is derived from the intersection of the two strips.

There are many examples of more complicated situations in which a single photon makes multiple hits in multiple detectors (Figure 33). The reconstruction software must be capable of determining a best (X,Y) RAW position for each situation. It is estimated that ~90% of the events produce only a single pair of hits (top and bottom) in a single detector.

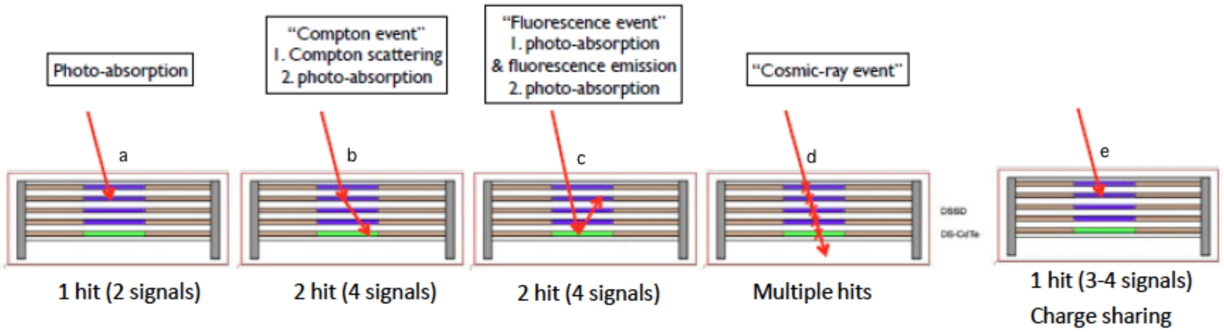


Figure 33. Some possibilities for multiple signals in the HXI detectors. The position must be reconstructed properly in each situation.

The method for calculating RAW X/Y from multiple hits is discussed in the HXI Instrument document. In Figure 33 the arrows are just for illustration. All that is detected is the location of the hit in each detector. The timing resolution is such that one cannot determine the order in which the detectors are hit. Thus it is not possible from the hit positions alone to distinguish between scenarios (b) and (c) since it is not known whether the CdTe or the Si detector was hit first. However, it is possible to distinguish these scenarios by measuring the relative amounts of energy deposited in the two hit detectors. For instance, a fluorescence event would produce a photon at a specific energy (~30 keV) corresponding to the Kα line in the CdTe detector. In reconstructing scenario (a), the photon incident angle is assumed to be 0. In scenario (e), only one detector is hit, but the charge is shared among multiple strips. In this case, it makes sense to make a weighted average (weighted by charge collected) of the strip signals in each dimension. In scenario (d) there are multiple hits that do not line up along the optical axis, so it is not possible to reconstruct a single RAW X/Y and the event must be rejected.

The positional information for a signal consists of two parts, the ASIC ID and the strip channel. Each of the five separate physical detectors consists of two layers of 128 strips each. The strips on top (P-side) are aligned parallel to the RAW-X axis, thus allowing the measurement of the hit position in the Y-direction, and the strips on the bottom (N-side) are aligned parallel to the RAW-Y axis, thus allowing the measurement of the hit position in the X-direction. The readouts are controlled by ASIC chips, where each ASIC provides read-out for 32 strip channels. The remapping of the ASIC number and Channel number is in section 5.5.

5.2 HXI Reconstruction of Photon Events

Unlike the situation for the SXI and SXS, the HXI RAW coordinates are derived coordinates, assigned during event reconstruction, which is described briefly in Section %.% ?. Once reconstructed, the RAW coordinates of an event represent the physical location of the primary photon interaction with the detector. These coordinates are linearized into a pixel grid, and the pixel grid spacing is 250 µm, the same as the HXI strip spacing. Note that the RAW coordinates are only defined for fully reconstructed photon events (not for individual hits.).

The HXI RAW coordinates are parallel to the X and Y strips in the HXI sensors. Therefore they are rotated (by 180° ± 22.5°) from the SXI DET coordinates. Since the two HXI sensors are oriented differently there are separate definitions of RAW and DET coordinates for HXI-1 and HXI-2. They are co-registered in the conversion to FOC coordinates.

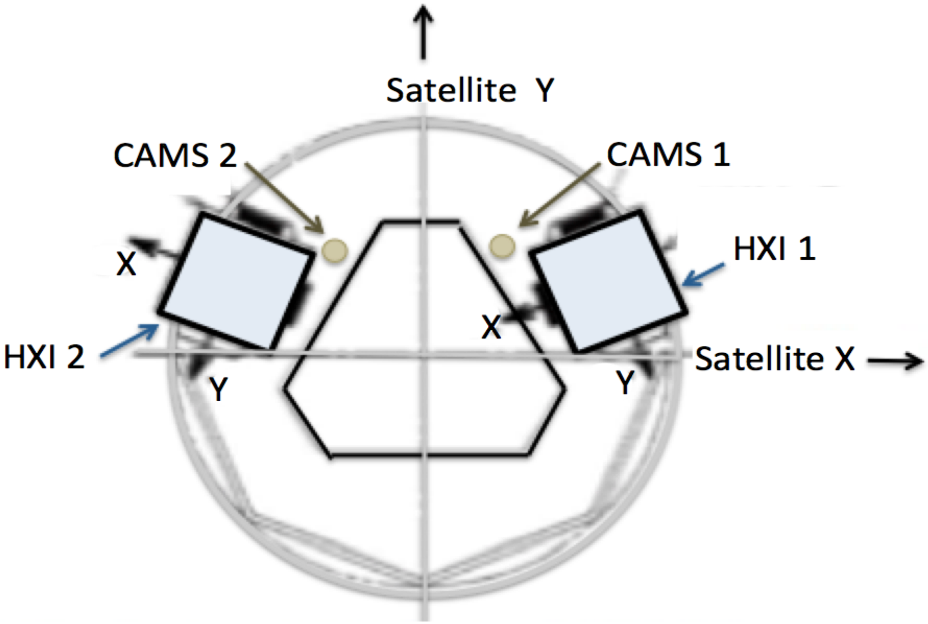


Figure 34. Schematic view (look-down view) showing the orientation and locations of the HXI detectors and the location of the CAMS.

Figure 35 shows how the HXI RAW coordinates are defined relative to the edges of the sensors and to the satellite coordinates. Note that the RAWY strips are on the tops of the sensors and the RAWX strips are on the bottom.

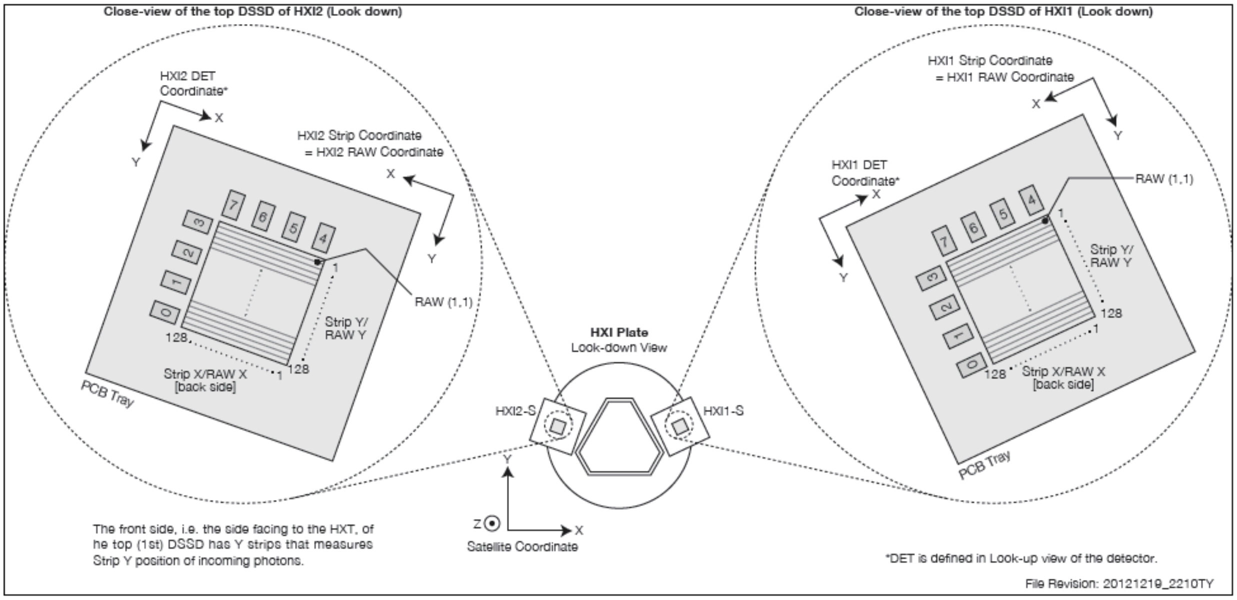


Figure 35. Showing the orientation of the two HXI sensors and the strip read-out for RAWX (back side) and RAWY (top side). .

5.3 HXI ACT and DET coordinates

The full transformation from RAW → ACT → DET → FOC has three components. First (RAW → ACT) is the correction for a time-dependent shift in the position of the EOB based on Δ-attitude transformation parameters (Δx, Δy, γ) derived from the CAMS. The design accuracy of the CAMS is 60 μm, which is smaller than the HXI strip width, 128 μm. The basics of the generation of the Δ-attitude file from the CAMS telemetry is given in the CAMS instrument description document (ast_sct_cams_V20160310).

The details of the transformation from RAW → ACT using the Δ-attitude file are as follows. A transformations in the Δ-attitude file is expressed as a quaternion *q*, where (*q0,q1,q2*) represent the imaginary component (rotation axis) and *q3* represents the real component, the magnitude of the rotation. In the attitude transformation software, the quaternion *q* is converted into a structure of type Xform2d, which consists of a 2 × 2 rotation matrix, R(θ) and a shift in the *x*-direction, and a shift in the *y*-direction which is rendered as the vector **Δs**. This Xform2d structure is derived from the CAMS transformation parameters and the HXI teldef file using the following steps.

Definitions:

$\mathbf{r}_{\mathbf{RAW}}$ is the vector position of a photon event in the HXI RAW system.

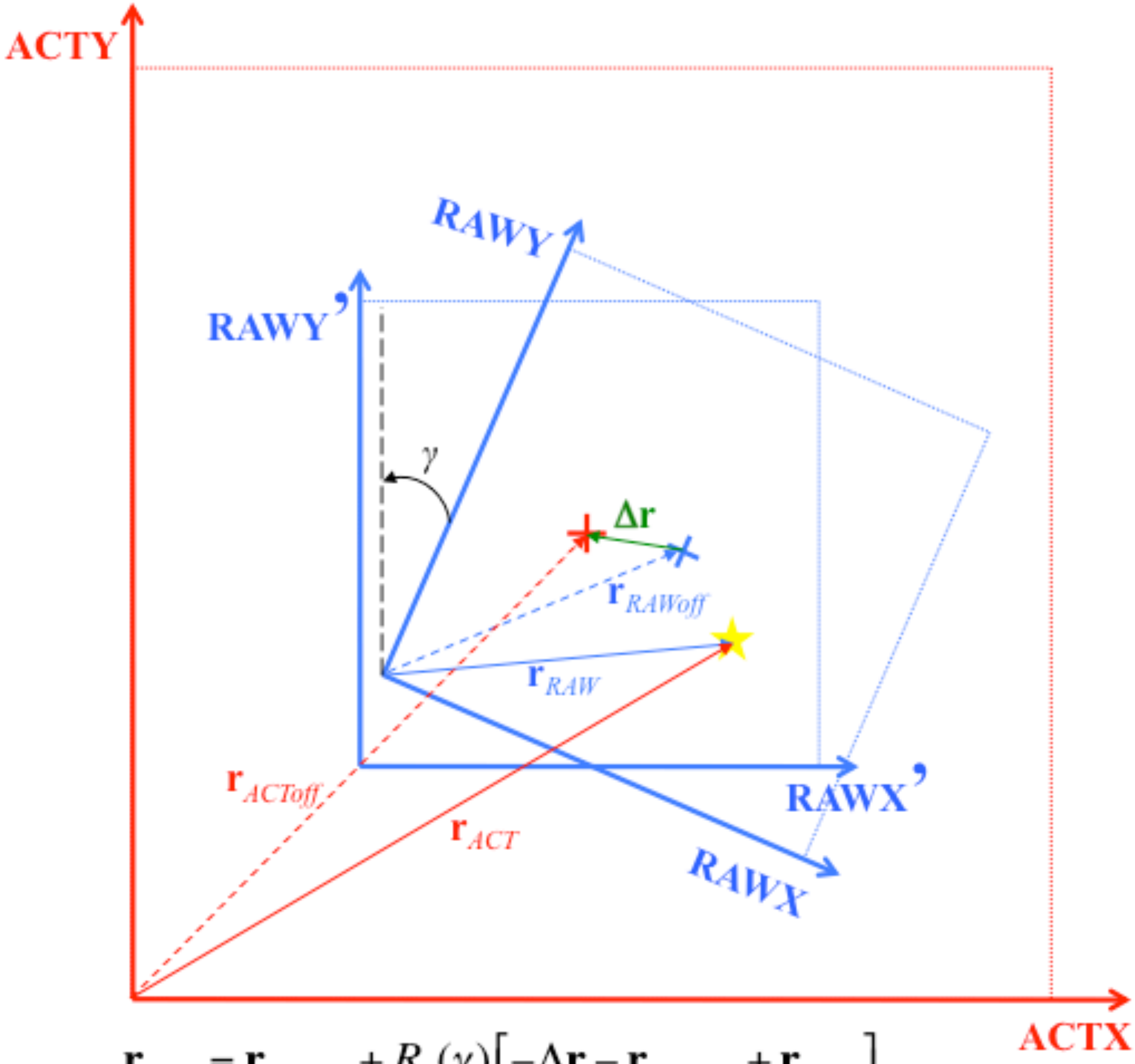
$\mathbf{r}_{\mathbf{ACT}}$ is the vector position of a photon event in the HXI ACT system.

Δr is the translation piece of the transformation derived in the CAMS: **Δr** = (Δx $\hat{\mathbf{\imath}}$, Δy $\hat{\mathbf{\jmath}}$). It is defined in the RAW system and points from the center of the RAW system to the center of the ACT system.

γ is the rotation angle derived from the CAMS. It is defined as a rotation about the z-axis to take the RAW system into the ACT.

R(γ) is the rotation matrix for the angle γ. R(γ) = [cos γ -sin γ]
[sin γ
cos γ]

r$_{\mathbf{RAW,OFF}}$ is a vector from the RAW origin to the RAW coordinate center.
r$_{\mathbf{ACT,OFF}}$ is a vector from the ACT origin to the ACT coordinate center.
All of the vectors are indicated on Figure 36.



$$\mathbf{r}_{ACT} = \mathbf{r}_{ACToff} + R_z(\gamma)\left[-\Delta\mathbf{r} - \mathbf{r}_{RAWoff} + \mathbf{r}_{RAW}\right]$$

Figure 36. This diagram shows the transformation between the HXI RAW and ACT systems. All of the vectors are described in the text above. The initial RAW system (blue, rotated) is centered at the blue cross. The yellow star shows an example photon position. The RAW' system is rotated by the

angle γ and shifted by an amount $\mathbf{\Delta r}$, so that it is aligned with the ACT system shown in red. The center of the ACT system (red cross) coincides with the center of the transformed RAW system. The equation connecting $\mathbf{r_{RAW}}$ and $\mathbf{r_{ACT}}$ can be traced on the figure and is derived below.

Derivation of the Xform2d structure:

1) Translation contribution: $\mathbf{\Delta s}_1 = -\mathbf{\Delta r}$. The negative sign is a convention in the definition of the structure.

$$R_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ (the unity rotation).}$$

2) Rotation contribution: $\mathbf{\Delta s}_2 = \mathbf{r_{RAW,OFF}} - R(\gamma)[\mathbf{r_{RAW,OFF}}]$, $R_2 = R(\gamma)$. The shift is non-zero because the rotation is defined as being about the center of the RAW system. This is the equivalent of translating by - $\mathbf{r_{RAW,OFF}}$, rotating about the origin, then translating by $\mathbf{r_{RAW,OFF}}$.

3) Combine the translation and rotation contributions:

$$\mathbf{\Delta s}_3 = \mathbf{\Delta s}_2 + R_2[\mathbf{\Delta s}_1] = \mathbf{r_{RAW,OFF}} - R(\gamma)[\mathbf{r_{RAW,OFF}}] + R(\gamma)[-\mathbf{\Delta r}]$$

$$R_3 = R_2 \times R_1 = R_2 = R(\gamma).$$

4) The attitude library function has one additional step before the Xform2d structure is converted to a quaternion. This is required because the quaternion is defined as a transformation *within* the RAW system:

$$\begin{aligned}\mathbf{\Delta s}_4 &= \mathbf{\Delta s}_3 - \mathbf{r_{RAW,OFF}} + R_3[\mathbf{r_{RAW,OFF}}] \\ &= \mathbf{r_{RAW,OFF}} - R(\gamma)[\mathbf{r_{RAW,OFF}}] + R(\gamma)[-\mathbf{\Delta r}] - \mathbf{r_{RAW,OFF}} + R(\gamma)[\mathbf{r_{RAW,OFF}}] \\ &= R(\gamma)[-\mathbf{\Delta r}]\end{aligned}$$

$$R_4 = R_3 = R(\gamma).$$

5) The conversion to a quaternion is transparent. Then in the conversion back to an Xform2d structure, there is an additional step. This step arises because, in addition to applying the rotation and shift encoded in the Δ-attitude quaternion, the transformation must also take into account any intrinsic differences in scale, size, offset or rotation between the initial and final coordinate systems. Since there is no intrinsic rotation between HXI RAW and ACT (i.e. no rotation apart from that derived by the CAMS), the rotation component of the structure is not modified.

$$\begin{aligned}\mathbf{\Delta s}_5 &= \mathbf{\Delta s}_4 + \mathbf{r_{ACT,OFF}} - R_4[\mathbf{r_{RAW,OFF}}] \\ &= R(\gamma)[-\mathbf{\Delta r}] + \mathbf{r_{ACT,OFF}} - R(\gamma)[\mathbf{r_{RAW,OFF}}]\end{aligned}$$

$$R_5 = R_4 = R(\gamma).$$

Applying the final transformation to $\mathbf{r_{RAW}}$ gives:

$$\begin{aligned}\mathbf{r_{ACT}} &= R(\gamma)[\mathbf{r_{RAW}}] + R(\gamma)[-\mathbf{\Delta r}] + \mathbf{r_{ACT,OFF}} - R(\gamma)[\mathbf{r_{RAW,OFF}}] \\ &= \mathbf{r_{ACT,OFF}} + R(\gamma)[-\mathbf{\Delta r} - \mathbf{r_{RAW,OFF}} + \mathbf{r_{RAW}}]\end{aligned}$$

This equation can be seen by tracing the four contributing vectors in Figure 36. Note that the rotation $R(\gamma)$ ensures that all of these vectors are rendered in the ACT system.

The second (ACT → DET) transformation flips to a look-up system. The size of the DET space is 256 X 256, which gives adequate space for rotation of the sensors. The third (DET → FOC) is the correction for known time-independent misalignments between the HXI sensors and the FOC plane, given in the teldef file. There is also a resampling in the DET → FOC stage, to a 103 μm, commensurate with the SXI scale.

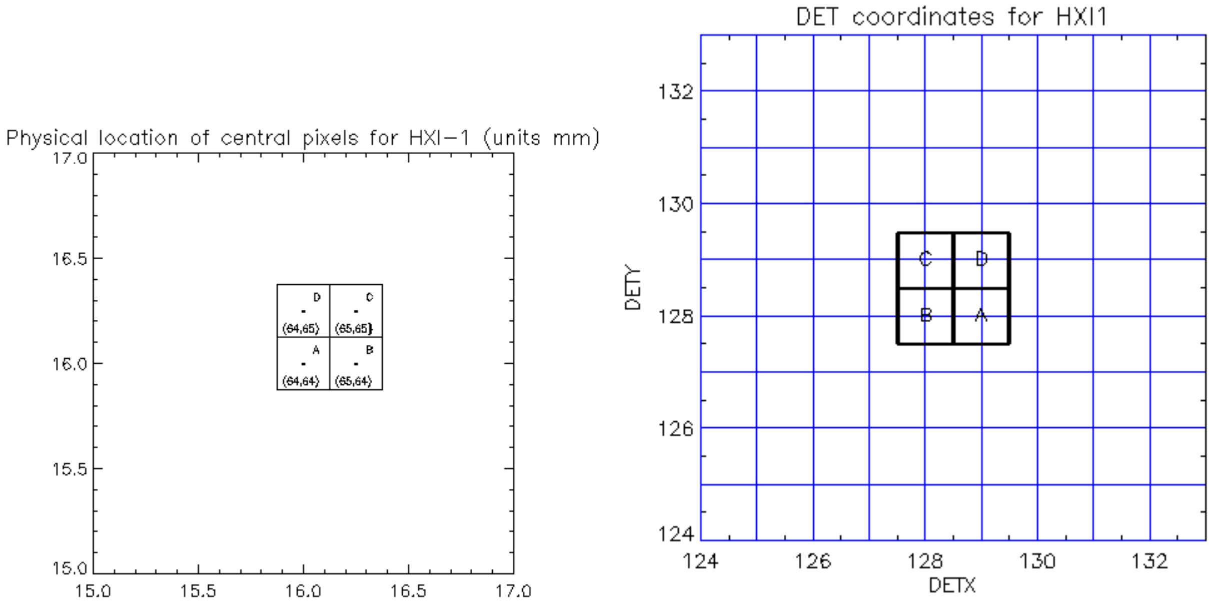
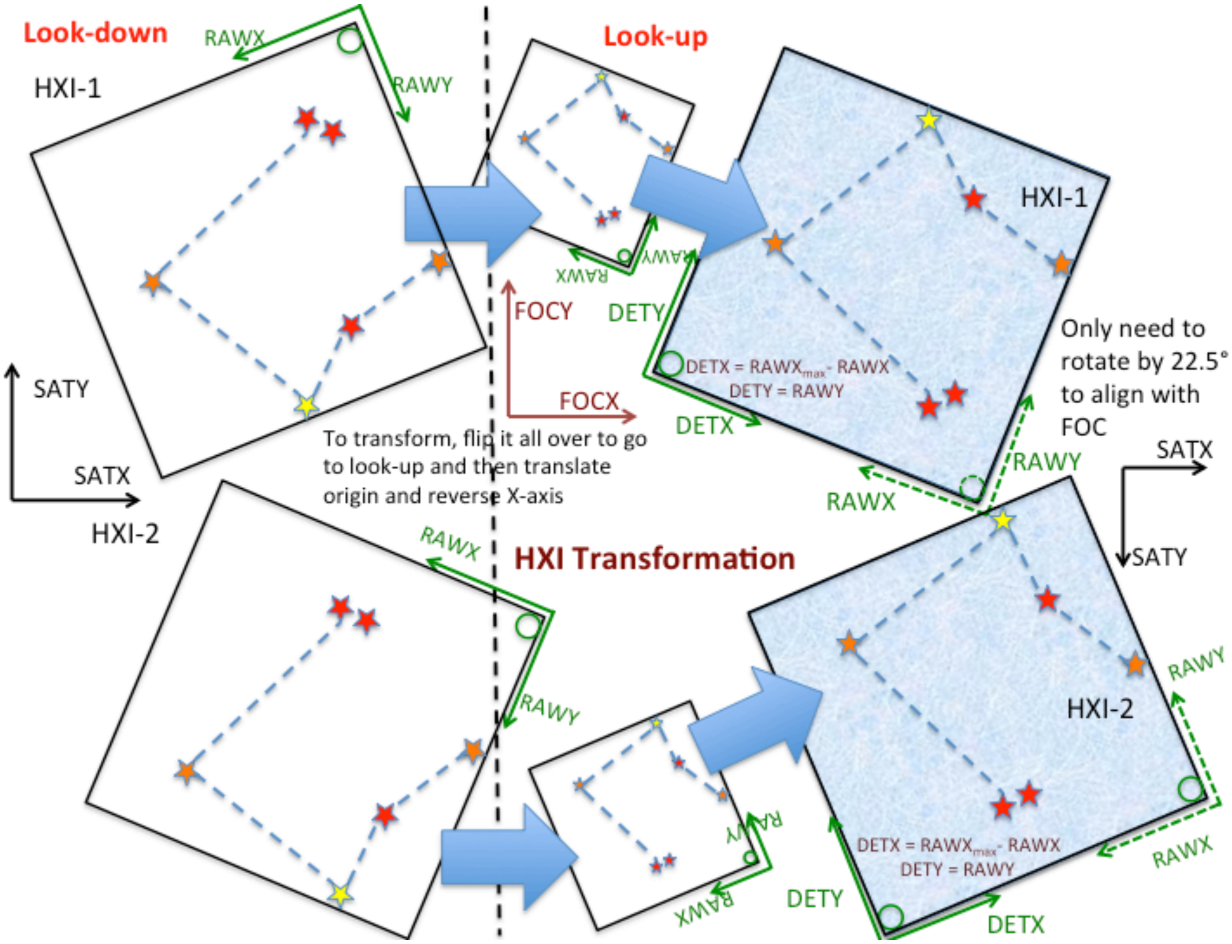


Figure 37. The central four RAW pixels for HXI1 shown in physical location with respect to the corner of the HXI sensor (left) and in HXI DET coordinates (right). The DET system is shown with no CAMS-measured displacement. The transformation from RAW to DET is the same for HXI2.



To transform, flip it all over to go to look-up and then translate origin and reverse X-axis

Only need to rotate by 22.5° to align with FOC

Figure 38. Schematic showing the conversion from RAW → DET for the two HXI instruments. The X-axis is reversed in this transformation (for the SXI/SXS the Y-axis is reversed.)

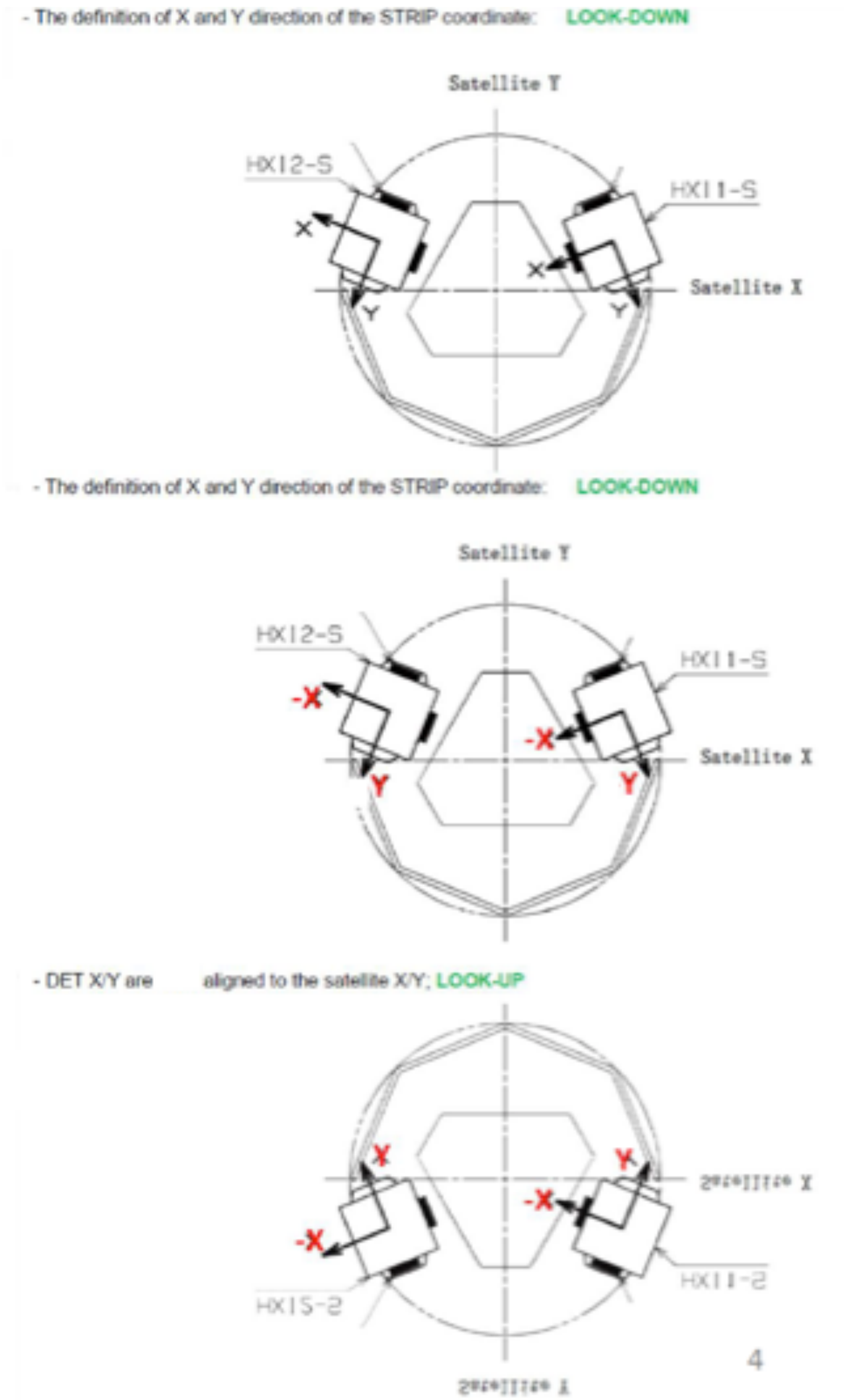


Figure 39. Three views showing, from top to bottom, the progression from HXI RAW to DET coordinates. Top: The axes show the RAW coordinates as defined relative to the HXI strips. Middle: The X-axis is flipped, so that X -> -RAWX. Bottom: Change to a look-up view by flipping about the Satellite X-axis. Now the HXI DET coordinates are in the same sense as the DET coordinates for the other instruments: DET-X in the direction of SAT-X and DET-Y in the direction of –SAT-Y.

rectory

5.4 HXI FOC Coordinates

The FOC coordinates are common to all of the sensors and hence take into account misalignments among the sensors. The scale of HXI FOC is common to all sensors (see Section 2.3 and 2.4)The physical space for HXI FOC and SKY (2430 X 2430) is calculated to allow for full rotation of the fields of the sensors relative to each other. The nominal transformation is straightforward and involves a separate teldef file for each of the HXI sensors.

The HXI DET coordinates are in a look-up orientation and are corrected for time-dependent variations due to movement of the EOB. The transformation from DET → FOC is therefore a straightforward translation and rotation to register the HXI field with the common FOC coordinates. However, calculation of the offsets and rotation angles are somewhat complicated and are different for the two HXI sensors. Using the design specifications, the DET → FOC transformation collapses to a simple case. In reality, though, the as-built instruments will have offsets from the ideal, so the transformation parameters will need to be calculated.

The physical scale of the HXI strips is 0.25 mm pitch (full size of 128 strips is 32 mm). With the HXT focal length of 12 m (12000 mm), this means that the effective pixel size is (0.25 mm / 12000 mm) = $0.07^{/}$ ($4.3^{//}$). However, following the Suzaku example, in order to register all instrument coordinates to the same FOC scale, it is necessary to redefine the pixel scale to match the focal length of the SXT's. The native SXI scale is 0.048 mm. The conversion to the HXI plate scale is:

$$\frac{\text{HXI scale}}{0.048\text{ mm}} = \frac{12000\text{ mm}}{5600\text{ mm}} = 2.143$$

HXI scale = (0.048 mm) (2.143) = 0.1029 mm, which corresponds to an angular scale of $0.03^{/}$ ($1.8^{//}$). This means that the HXI FOC scale is ~2.4 times finer than the native scale of the HXI strips. The rescaling factor is thus FOC_SCAL = (0.1029)/(0.25) = 0.411. Without further manipulation, this leads to a granularity in the HXI FOC (and ultimately SKY plane) since not all FOC pixels correspond to the center of an HXI event pixel. For data selection by regions this is not expected to cause a major problem. However, HXI images must be smoothed to remove this effect. The smoothing algorithm uses a probabilistic approach to place the photon in one of several FOC pixels.

The *coordevt* code and teldef standard is defined so that the coordinate rotation is made around the center of the FOC coordinate system. Therefore offsets must be calculated between the DET coordinates and the FOC coordinate center.

The rotation angles can be derived by reference to Figure 6 and 38. The angle FOC_ROTD is defined as the angle between FOCX and DETX, measured counterclockwise from the FOCX axis. For HXI-1, a rotation of FOC_ROTD = $-\theta$ = 22.5° brings the HXI-1 DETX/DETY in line with the SXI DETX/DETY (which is the same as FOCX/FOCY). For HXI-2, FOC_ROTD = θ = -22.5°.

For the designed instruments, the offsets between HXI DET and FOC are identically zero. The details of the conversion in the case of imperfect alignment are found in Appendix B.

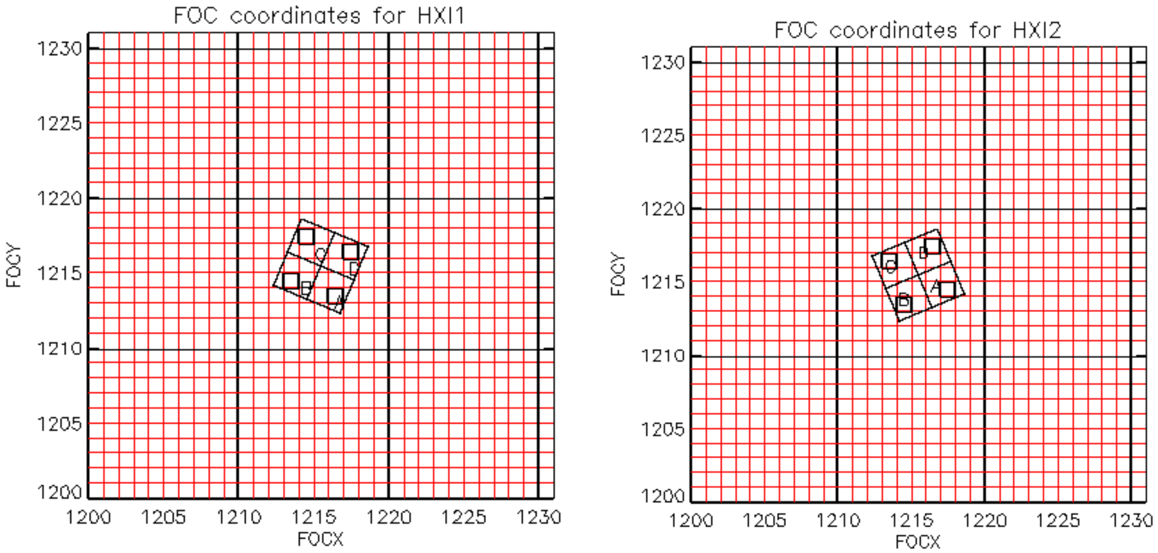


Figure 40. Showing the FOC system for HXI-1 (left) and HXI-2 (right) using the same four raw pixels as in Figure 37. The grid scale is the same as for the HXI DET coordinate system.

5.5 HXI Remapping From ASIC and Channel ID

In the first level telemetry (First FITS File; FFF), the ASIC and channel information is encoded as three numbers: (a) Detector layer (Figure 31) numbered from 0 for the top Si DSSD to 4 for the CdTe DSSD; (b) ASIC for the given layer numbered from 0 to 7; and (c) Channel number for the given ASIC numbered from 0 to 31 (Figure 41). In producing the Second FITS File (SFF) the ASIC and channel number is remapped to provide a Remapped ASIC ID (numbered 1 to 40) and a Remapped Channel ID (RCH) numbered from 1 to 1280. The conversion from FFF ASIC and channel ID to remapped ASIC ID and RCH is given in a look-up table (Table 10) provided by the Instrument Team.

The actual conversion from remapped ASIC and Channel ID is quite complicated and depends on the number and locations of signals in the detector. This conversion is described in detail in the HXI Instrument document, and is run as part of the production of the HXI SFF.

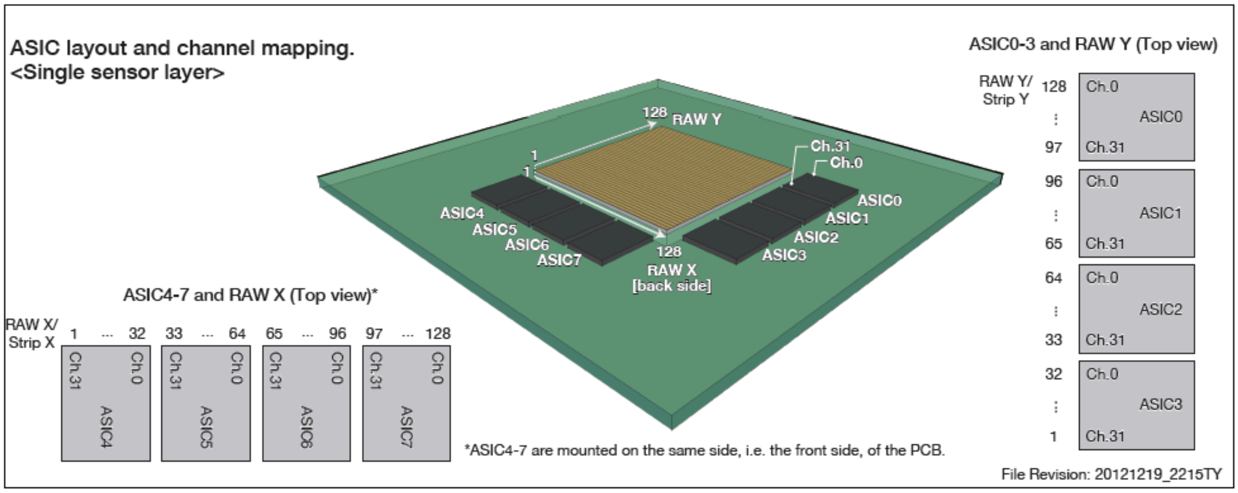


Figure 41. Diagram showing the readouts of the two sides of a single HXI detector. Each of the 8 ASICs reads out 32 strip channels.

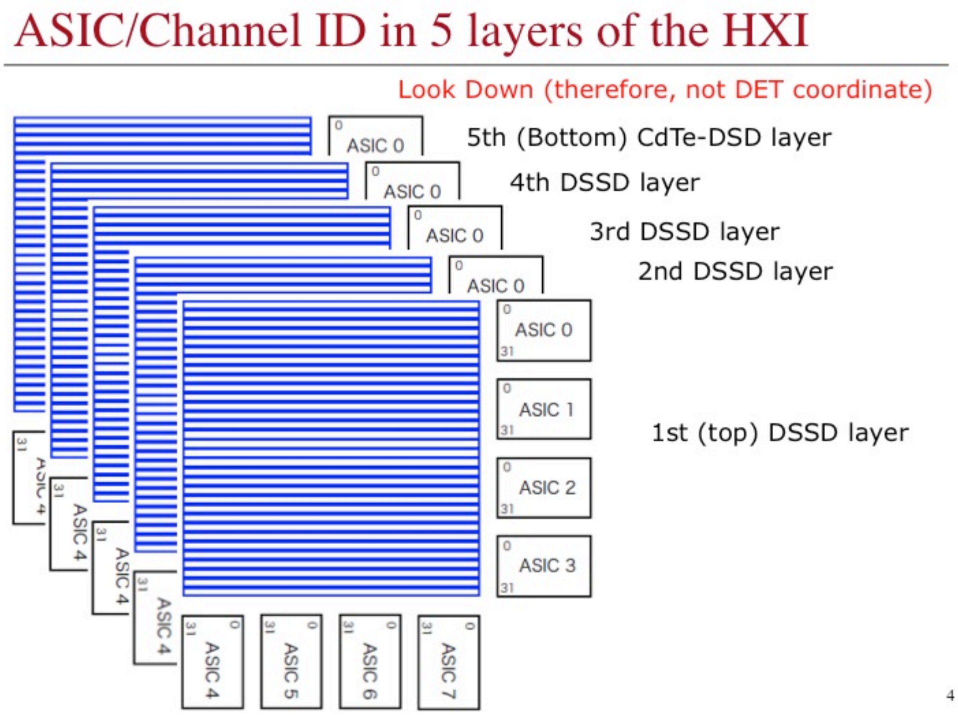


Figure 42. Schematic view of the five HXI detectors showing four Si and one CdTe detector.

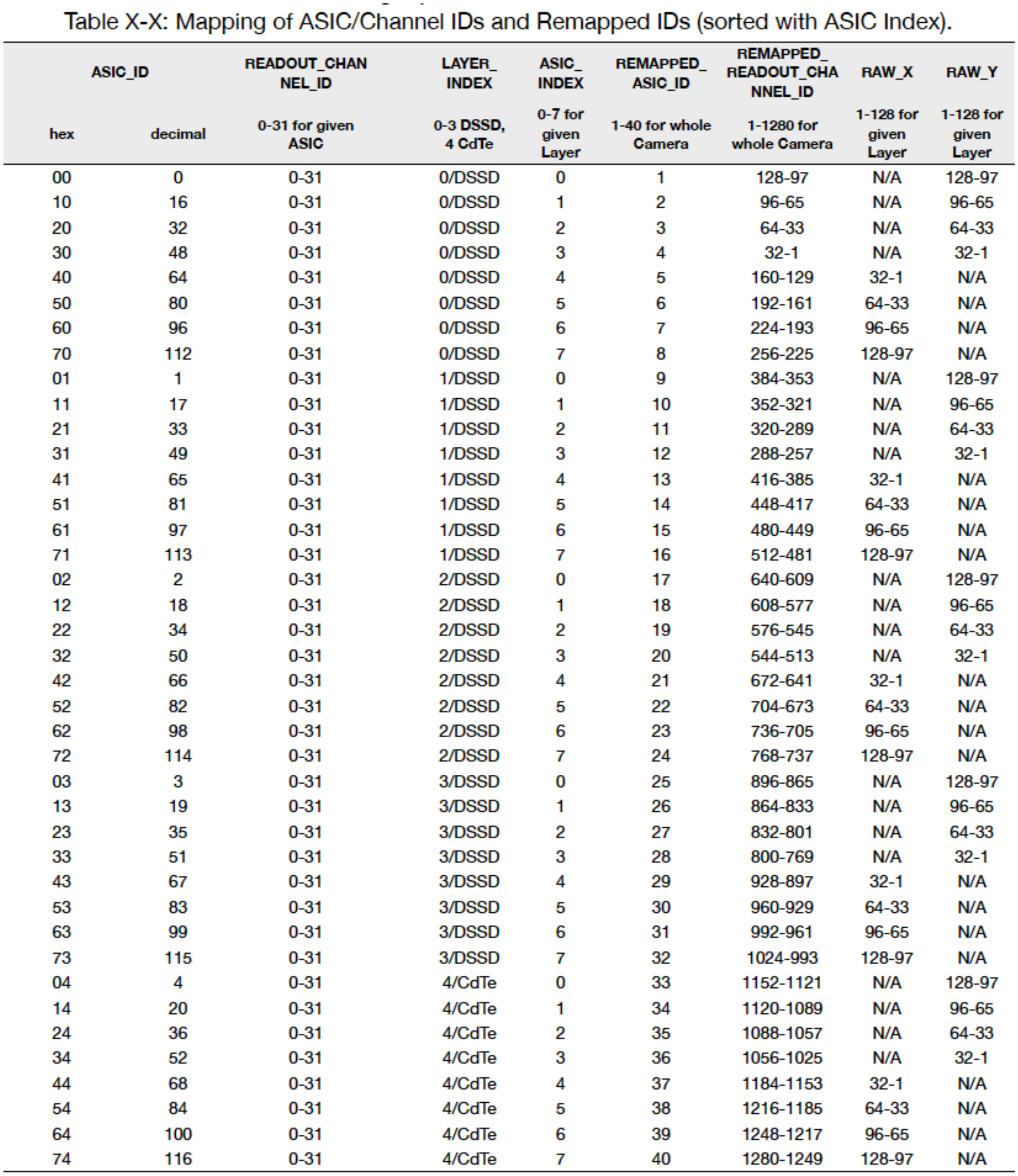


Table X-X: Mapping of ASIC/Channel IDs and Remapped IDs (sorted with ASIC Index).

ASIC_ID		READOUT_CHANNEL_ID	LAYER_INDEX	ASIC_INDEX	REMAPPED_ASIC_ID	REMAPPED_READOUT_CHANNEL_ID	RAW_X	RAW_Y
hex	decimal	0-31 for given ASIC	0-3 DSSD, 4 CdTe	0-7 for given Layer	1-40 for whole Camera	1-1280 for whole Camera	1-128 for given Layer	1-128 for given Layer
00	0	0-31	0/DSSD	0	1	128-97	N/A	128-97
10	16	0-31	0/DSSD	1	2	96-65	N/A	96-65
20	32	0-31	0/DSSD	2	3	64-33	N/A	64-33
30	48	0-31	0/DSSD	3	4	32-1	N/A	32-1
40	64	0-31	0/DSSD	4	5	160-129	32-1	N/A
50	80	0-31	0/DSSD	5	6	192-161	64-33	N/A
60	96	0-31	0/DSSD	6	7	224-193	96-65	N/A
70	112	0-31	0/DSSD	7	8	256-225	128-97	N/A
01	1	0-31	1/DSSD	0	9	384-353	N/A	128-97
11	17	0-31	1/DSSD	1	10	352-321	N/A	96-65
21	33	0-31	1/DSSD	2	11	320-289	N/A	64-33
31	49	0-31	1/DSSD	3	12	288-257	N/A	32-1
41	65	0-31	1/DSSD	4	13	416-385	32-1	N/A
51	81	0-31	1/DSSD	5	14	448-417	64-33	N/A
61	97	0-31	1/DSSD	6	15	480-449	96-65	N/A
71	113	0-31	1/DSSD	7	16	512-481	128-97	N/A
02	2	0-31	2/DSSD	0	17	640-609	N/A	128-97
12	18	0-31	2/DSSD	1	18	608-577	N/A	96-65
22	34	0-31	2/DSSD	2	19	576-545	N/A	64-33
32	50	0-31	2/DSSD	3	20	544-513	N/A	32-1
42	66	0-31	2/DSSD	4	21	672-641	32-1	N/A
52	82	0-31	2/DSSD	5	22	704-673	64-33	N/A
62	98	0-31	2/DSSD	6	23	736-705	96-65	N/A
72	114	0-31	2/DSSD	7	24	768-737	128-97	N/A
03	3	0-31	3/DSSD	0	25	896-865	N/A	128-97
13	19	0-31	3/DSSD	1	26	864-833	N/A	96-65
23	35	0-31	3/DSSD	2	27	832-801	N/A	64-33
33	51	0-31	3/DSSD	3	28	800-769	N/A	32-1
43	67	0-31	3/DSSD	4	29	928-897	32-1	N/A
53	83	0-31	3/DSSD	5	30	960-929	64-33	N/A
63	99	0-31	3/DSSD	6	31	992-961	96-65	N/A
73	115	0-31	3/DSSD	7	32	1024-993	128-97	N/A
04	4	0-31	4/CdTe	0	33	1152-1121	N/A	128-97
14	20	0-31	4/CdTe	1	34	1120-1089	N/A	96-65
24	36	0-31	4/CdTe	2	35	1088-1057	N/A	64-33
34	52	0-31	4/CdTe	3	36	1056-1025	N/A	32-1
44	68	0-31	4/CdTe	4	37	1184-1153	32-1	N/A
54	84	0-31	4/CdTe	5	38	1216-1185	64-33	N/A
64	100	0-31	4/CdTe	6	39	1248-1217	96-65	N/A
74	116	0-31	4/CdTe	7	40	1280-1249	128-97	N/A

Table 10 Mapping of ASIC/Channel IDs and Remapped IDs.

6 Appendix A : Aberration Correction in Astro-H

6.1 ApA: Aberration basic

Aberration is a relativistic effect that was discovered in 1727. As the Earth moves around the Sun, the apparent positions of stars changes slightly (≤ 20.’’5) relative to the mean (catalog) position. The aberration depends on the star position and the direction of the Earth’s velocity vector. The aberration, or apparent shift, is in the direction of the Earth’s velocity.

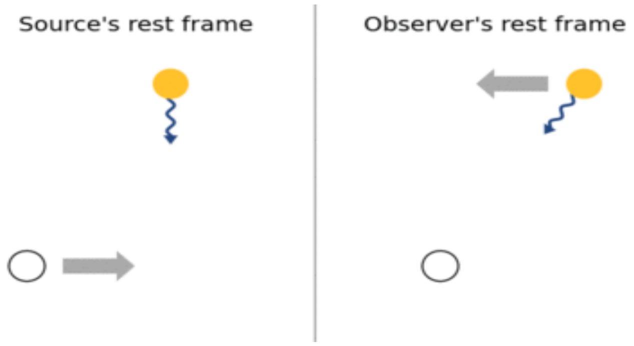


Figure 43 . A simple illustration of aberration. In the observer’s frame (right), the source appears to be moving to the left, so the apparent path of the light ray is offset to the right. (Figure from http://en.wikipedia.org/wiki/Aberration_of_light).

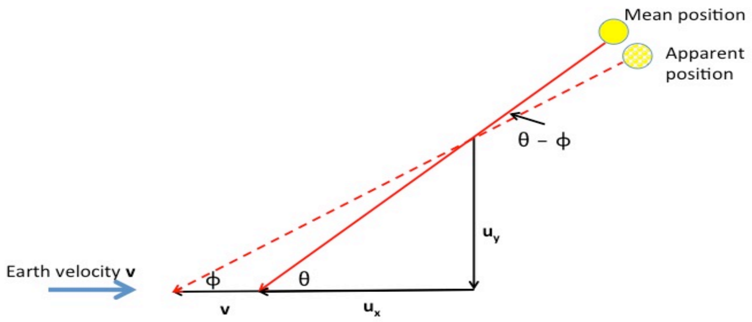


Figure 44 Illustration showing the origin of the aberration. The mean angle of the source is θ (the direction with no earth motion). The vectors u_x and u_y are the components of the speed of light in the directions parallel and perpendicular to the Earth velocity. Since the source has an additional apparent velocity v, the apparent position of the source is Φ. Thus the aberration (mean-apparent: $\theta - \Phi$) is to the right, in the direction of the earth velocity.

The trigonometry allows a calculation of the maximum aberration κ:

$\cos\theta = u_x/c$
$\sin\theta = u_y/c$
$\tan \phi = u_y / (u_x + v) = \sin\theta / (v/c \cos\theta)$.

Since $v/c = 10^{-4} << 1$, when $\theta \approx 90°$, one can approximate

$\tan(\theta - \phi) \approx v/c = 20''.5 \ (= \kappa)$.

The magnitude of **v** is (nearly) constant, so the big effect is on direction of **v**, which changes θ throughout the year.

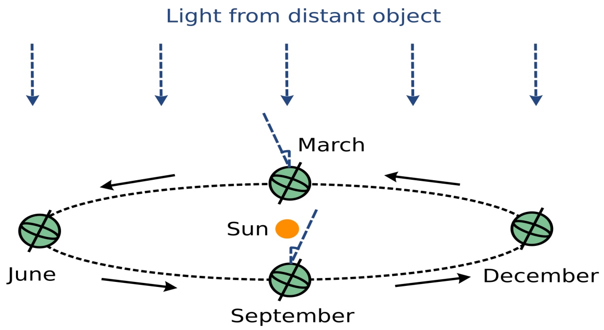


Figure 45. Showing the (exaggerated) aberration for a source near the North Celestial Pole. The aberration in September is to the right and in March it is to the left. There is little aberration in June or December. (Figure from http://en.wikipedia.org/wiki/Aberration_of_light).

For an object near the North Ecliptic Pole (Figure 45), the direction of the aberration changes with time of year. In September the Earth's motion is mostly northward, so the aberration is large and northward in declination. The opposite is true in March. In June and December, the aberration is mostly in Right Ascension.

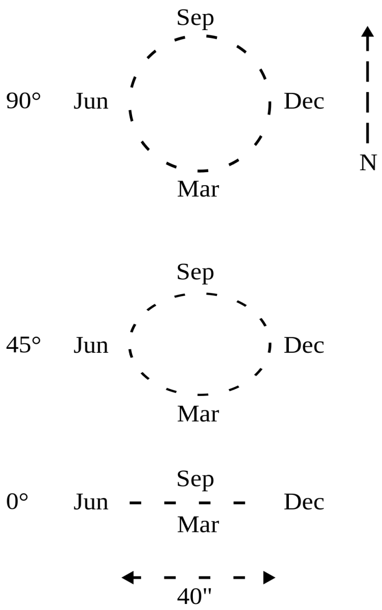


Figure 46. Stars at the ecliptic poles (top) appear to move in circles, stars exactly in the ecliptic plane (bottom) move in lines, and stars at intermediate angles move in ellipses. Shown here are the apparent motions of stars with the ecliptic latitudes corresponding to these cases, and with ecliptic longitude of 270 degrees (From http://en.wikipedia.org/wiki/Aberration_of_light).

The standard (textbook) formula for aberration correction (e.g. Meeus, *Astronomical Algorithms*) determines the aberration in RA (Δα) and dec (Δδ) from two simple formulas involving α, δ, the obliquity of ecliptic ε, and the ecliptic longitude of the Sun Θ. In this formula ε and Θ are time-dependent, but can be readily calculated from time based on further simple formulae. This method is not applicable to the Astro-H coordinate conversion tool, *coordevt*, since the tool transforms coordinate systems, not individual coordinates of a point. This method is confirmed by comparison to the aberration correction calculated by the Voyager 4 Sky Simulator software (http://www.carinasoft.com/voyager.html).

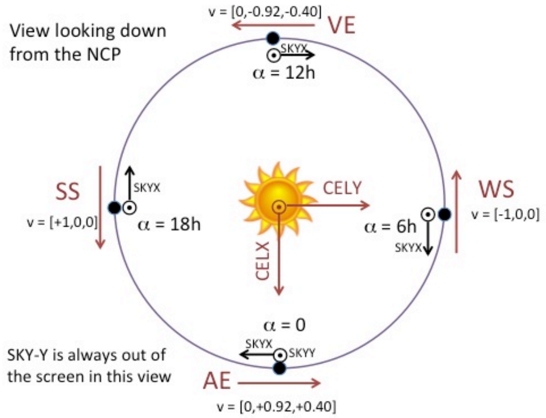


Figure 47 Showing the projection of the Earth velocity vector onto the equatorial plane at four different seasons: Vernal Equinox, Summer Solstice, Autumnal Equinox and Winter Solstice. Also shown are the directions of the SKYX and SKYY coordinates for a source at each of the four cardinal directions on the ecliptic plane.

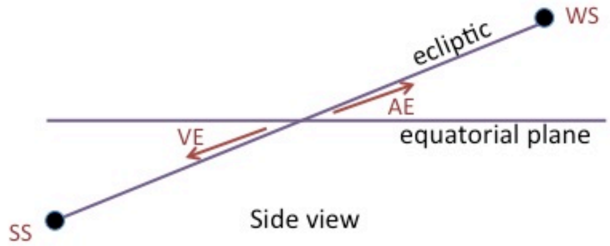
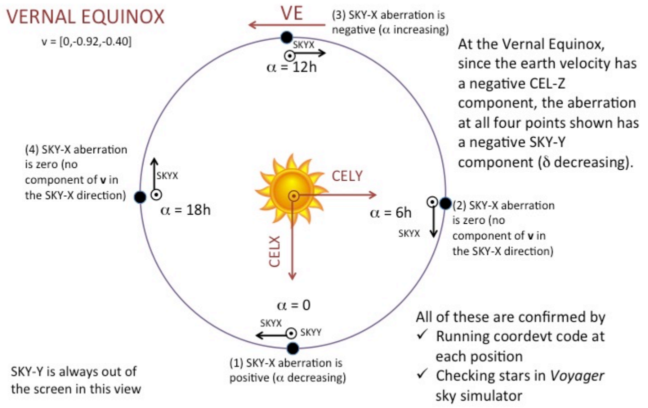


Figure 48. Side view showing the tilt of the ecliptic with respect to the equatorial plane. At Vernal Equinox, the earth is moving downward (to the South), at Autumnal Equinox, it is moving upward. At the Solstices, it has no vertical component of velocity.

Aberration is defined as how much the apparent position of the star differs from the mean (catalog) position. Aberration is always in the direction of the earth's velocity vector. To find the aberration in a given part of the sky project the earth velocity vector onto the tangent plane at that point. The aberration can be expressed in terms of SKY-X and SKY-Y. The following figures show the aberration for stars at various points on the equatorial plane for four different times in the year.



(3) SKY-X aberration is negative (α increasing)

At the Vernal Equinox, since the earth velocity has a negative CEL-Z component, the aberration at all four points shown has a negative SKY-Y component (δ decreasing).

(4) SKY-X aberration is zero (no component of **v** in the SKY-X direction)

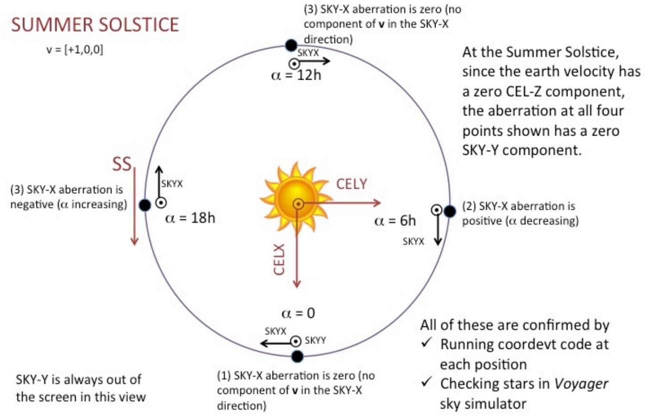
(2) SKY-X aberration is zero (no component of **v** in the SKY-X direction)

All of these are confirmed by
- ✓ Running coordevt code at each position
- ✓ Checking stars in *Voyager* sky simulator

(1) SKY-X aberration is positive (α decreasing)

SKY-Y is always out of the screen in this view

Figure 49 View of the sky at the Vernal Equinox. The Earth velocity vector is shown at the top of the figure as the brown arrow pointing to the left.



(3) SKY-X aberration is zero (no component of **v** in the SKY-X direction)

At the Summer Solstice, since the earth velocity has a zero CEL-Z component, the aberration at all four points shown has a zero SKY-Y component.

(3) SKY-X aberration is negative (α increasing)

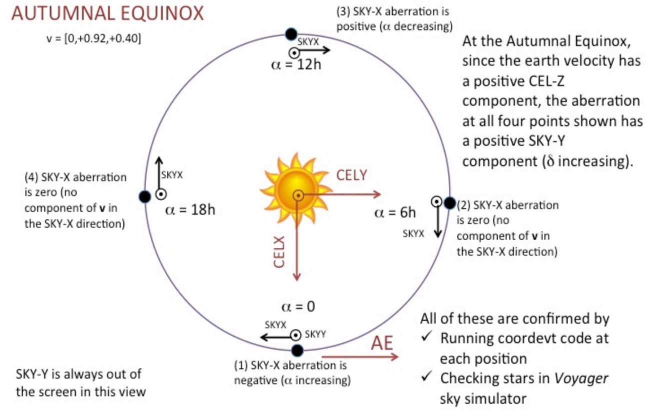
(2) SKY-X aberration is positive (α decreasing)

All of these are confirmed by
- ✓ Running coordevt code at each position
- ✓ Checking stars in *Voyager* sky simulator

(1) SKY-X aberration is zero (no component of **v** in the SKY-X direction)

SKY-Y is always out of the screen in this view

Figure 50. View of the sky at the Summer Solstice. The Earth velocity vector is shown at the left of the figure as the brown arrow pointing downward.



(3) SKY-X aberration is positive (α decreasing)

At the Autumnal Equinox, since the earth velocity has a positive CEL-Z component, the aberration at all four points shown has a positive SKY-Y component (δ increasing).

(4) SKY-X aberration is zero (no component of **v** in the SKY-X direction)

(2) SKY-X aberration is zero (no component of **v** in the SKY-X direction)

All of these are confirmed by
- ✓ Running coordevt code at each position
- ✓ Checking stars in *Voyager* sky simulator

(1) SKY-X aberration is negative (α increasing)

SKY-Y is always out of the screen in this view

Figure 51. View of the sky at the Autumnal Equinox. The Earth velocity vector is shown at the bottom of the figure as the brown arrow pointing to the right.

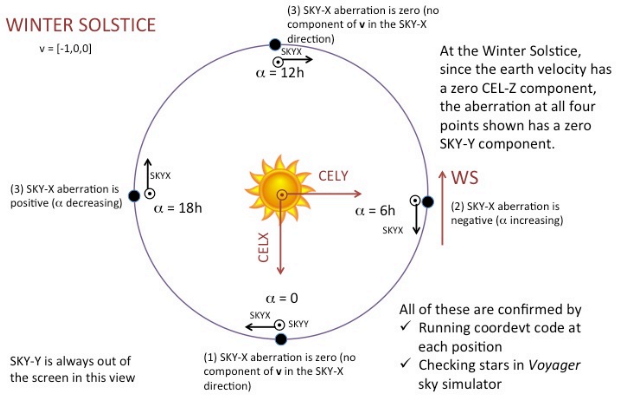


Figure 52. View of the sky at the Winter Solstice. The Earth velocity vector is shown at the right of the figure as the brown arrow pointing upward.

Here are some examples of the calculation of aberration.

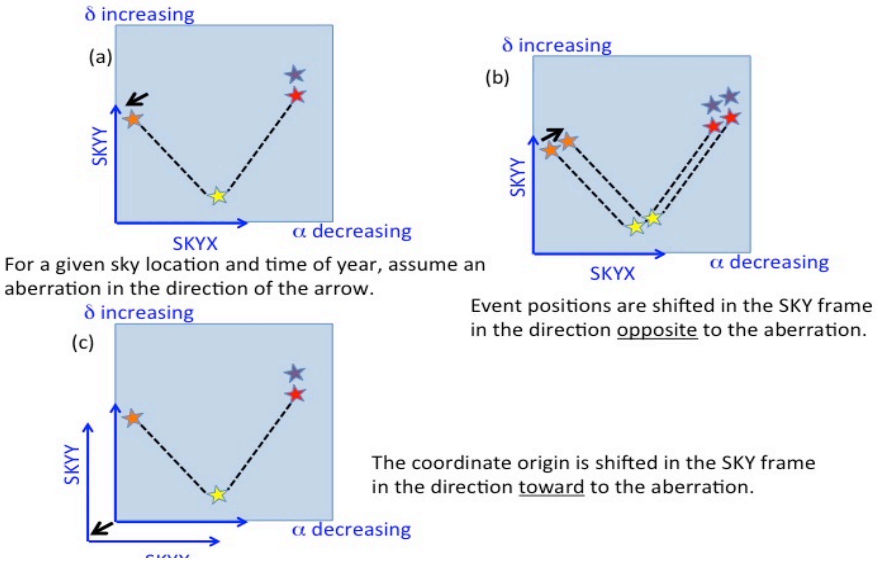
Star HD 224726 is located near α=0, δ=0.
Catalog position is 00 11.621 -00 21 37.64

At the Vernal Equinox (Figure), aberration should decrease both α and δ.
At the Vernal Equinox, its aberrated position is
00 10.36 -00 21 45.8
So both α and δ are decreasing (δ is more negative)

At the Autumnal Equinox (Figure), aberration should increase both α and δ.
At the Autumnal Equinox, its aberrated position is
00 12.87 -00 21 29.5
So both α and δ are increasing (δ is less negative)

At the Summer Solstice (Figure), aberration should be nearly zero.
At the Autumnal Equinox, its aberrated position is
00 00 11.60 -00 21 37.6
Both Δα and Δδ are nearly zero.

In practice, the aberration can be corrected in one of two ways: (a) the origin of the coordinate system is shifted (by correcting the reference pixel values) while keeping the coordinate values for individual events the same (i.e. move the coordinates; Figure 53c), or (b) the event coordinate values are modified within a fixed coordinate system (i.e. move the events; Figure 53b). In ASCA, the coordinate system is shifted (by modifying the reference pixel TCRVL values), while in Suzaku and Astro-H, the events are shifted (figure 54).

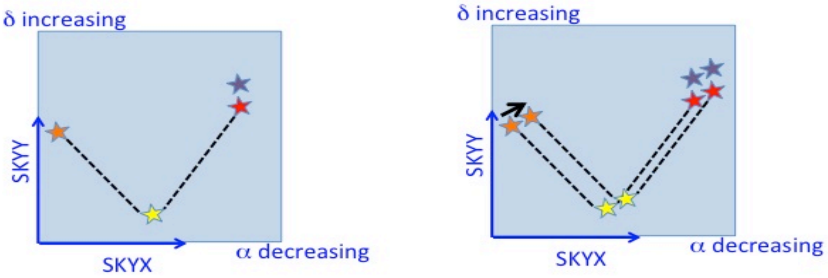


For a given sky location and time of year, assume an aberration in the direction of the arrow.

Event positions are shifted in the SKY frame in the direction opposite to the aberration.

The coordinate origin is shifted in the SKY frame in the direction toward to the aberration.

Figure 53 Diagram showing the two methods for correcting aberration. In panel (a), the aberration is in the direction of the black arrow. In other words, the apparent position of this star field is down and to the left of the mean position. To correct, one can either (b) shift the star field up and to the right by adding to the SKYX and SKYY pixel values (correction opposite the direction of the aberration), or (c) shift the origin of the coordinate system down and to the left (correction in the direction of the aberration).



Event positions are shifted in the SKY frame based on the calculated aberration

Figure 54. In coordevt, the aberration correction is done by shifting the values of the sky coordinates X, Y for each event. The correction is in the direction opposite the aberration.

While aberration (on the order of 20″) is the largest term in correcting star positions, there are two other effects which are smaller, but within an order of magnitude. Aberration is also caused by variations in the orbital motion of the satellite. The satellite velocity around the earth is roughly 7.7 km/s, leading to an orbital aberration of ~5.3″. The orbital aberration is also applied for Astro-H. Nutation is a small wobble superimposed on stellar precession from wobbles in the precession of the Earth's axis due to the gravitational effects of the Moon and the other planets. The principal term of nutation is due to the regression of the moon's nodal line and has the same period of 6798 days (18.61 years). It reaches plus or minus 17″ in longitude and 9″ in obliquity. Nutation is corrected in the spacecraft attitude. There are also two other terms, which can be safely ignored, due to their very slow variation (on the time scale of centuries). The ecliptic obliquity, or the inclination of Earth's equator to the ecliptic varies by ~46″, and the eccentricity of the Earth's orbit by 0.2%.

6.2 ApA: Aberration correction : Astro-H

In *coordevt*, the aberration correction is handled at the very last stage. The correction is projected onto the SKY tangent plane as a pair of translations in the SKY-X and SKY-Y directions and added to the translation part of the xform2d structure:

$$\begin{bmatrix}\text{SKY-X}\\ \text{SKY-Y}\end{bmatrix} = \begin{bmatrix}ROT_{00} & ROT_{01}\\ ROT_{10} & ROT_{11}\end{bmatrix}\begin{bmatrix}\text{FOC-X}\\ \text{FOC-Y}\end{bmatrix} + \begin{bmatrix}\Delta X\\ \Delta Y\end{bmatrix} + \begin{bmatrix}\Delta X_{aberr}\\ \Delta Y_{aberr}\end{bmatrix}$$

The corrections ΔX_{aberr} and Δy_{aberr} are calculated by projecting the inverse of the earth velocity unit direction vector û onto the tangent plane at the nominal pointing position:

$$\begin{bmatrix}\Delta X_{aberr}\\ \Delta Y_{aberr}\end{bmatrix} \begin{matrix} = \; - \\ \end{matrix} \begin{bmatrix}B_{00} & B_{01} & B_{02}\\ B_{10} & B_{11} & B_{12}\end{bmatrix} \times \begin{bmatrix}-u_x\\ -u_y\\ -u_z\end{bmatrix} \times (S)$$

In this equation, B_{ij} is the first two rows of the 3-dimensional rotation matrix corresponding to the pointing quaternion Q_B, and the scaling factor S converts to the appropriate pixel scale. The negative sign on the top row corrects for the fact that the CEL system is look-down and the SKY system is look-up. The negative sign in the velocity vector terms means that what is projected is the inverse of V (actually û, the unit direction vector) to get the correction, rather than the aberration itself. The earth velocity vector is itself derived in a straightforward way in code from the attitude library. First the earth position vectors are calculated in units of A.U., $\mathbf{p}_1$, $\mathbf{p}_2$ (using the atPlanet routine) at times ± 30 seconds from the event epoch. The earth velocity vector (Figure 55) is derived as $\mathbf{V}$ (km/s) = ($\mathbf{p}1$-$\mathbf{p}2$)*(1.5×10^8 km/AU)/60 sec.

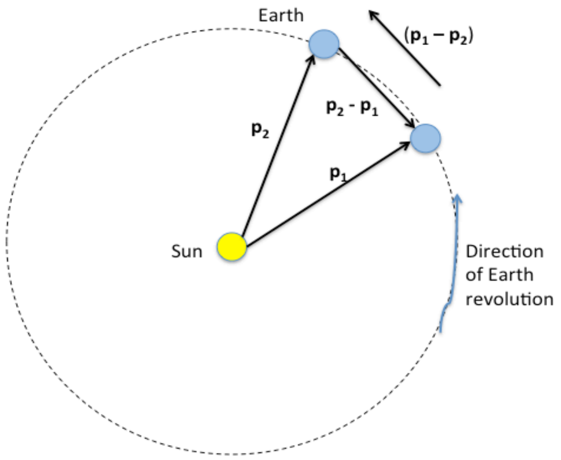


Figure 55 The Earth position vectors are calculated at two successive times. The difference $p_1 - p_2$ is in the direction of the Earth's motion around the Sun. It is divided by the time differential to derive the Earth velocity vector.

The velocity vector is then converted to units of the speed of light: $\mathbf{V}(c) = \mathbf{V}$ (km/s) / (3×10^5 km/s). Then the unit direction vector is found as $\hat{\mathbf{u}} = \mathbf{V}(c)/\sqrt{(V_x^2 + V_y^2 + V_z^2)}$ and the magnitude $|v_c|$ is the normalization factor $|v_c| = \sqrt{(V_x^2 + V_y^2 + V_z^2)}$.

The scaling factor, S, in the above equation consist of |v| (dimensionless velocity magnitude as a fraction of the speed of light) divided by the pixel to radian conversion factor, C. The average earth velocity magnitude |V| is 29.78 km/s, so

$|v_c| = |V|/c = (29.78 \text{ km/s})/(3 \times 10^5 \text{ km/s}) = 9.9 \times 10^{-5}$ radians

($= 5.68 \times 10^{-3}$ degrees = 20.47 arc seconds).

For the Astro-H FOC and SKY systems C is:

$C = (0.048 \text{ mm/pixel})/(5600 \text{ mm F.L.})$ [For SXS and SXI]
$C = (0.103 \text{ mm/pixel})/(12000 \text{ mm F.L.})$ [For HXI]
$C = 8.57 \times 10^{-6}$ radian/pixel

The combination $S = |v_c| \div C = (9.9 \times 10^{-6} \text{ radians}) \div (8.57 \times 10^{-6} \text{ radian/pixel})$
$S = 11.6$ pixels

The magnitude and direction of the correction calculated with this method is consistent with (a) the aberration calculated using the formulae of Meeus, *Astronomical Algorithms,* 2nd Edition, Whitman-Bell, 1999) and (b) the aberration calculated in the Voyager 4 Sky Simulator software (http://www.carinasoft.com/voyager.html).

7 Appendix B : Calculation of the TelDef Keywors value

7.1 ApB : SXI

The physical size of a CCD chip is 640 x 640 pixels, but since each chip has two read outs, the actual size of a readout segment is 320 x 640. Nevertheless, the RAW coordinate system for a segment is still defined to be 640 x 640.

```
RAW_XSIZ=          640 /RAW address space Xsize (pixel) actual size 320
RAWXPIX1=            0 /RAW address space x first pixel number (pixel)
RAW_YSIZ=          640 /RAW address space Ysize (pixel) actual size 640
RAWYPIX1=            0 /RAW address space y first pixel number (pixel)
```

The RAW scale is based on the actual physical size of a SXI CCD pixel.

```
RAW_XSCL=        0.048 /RAW X scale (mm/pixel)
RAW_YSCL=        0.048 /RAW Y scale (mm/pixel)
RAW_UNIT= 'mm      '           /physical unit of RAW
```

The conversion from RAW to ACT uses the values in the look-up table `MULTISEG0_COEFF` (First extension of the SXI TelDef file). There is a full discussion of the derivation of these values in Section 3.1.2.

The following are from the defintion of the ACT coordinate system, which is defined to be the same size as the RAW system. The ACT system is defined per chip, while the RAW system is defined per segment.

```
ACT_XSIZ=          640 /ACT address space Xsize (pixel) actual size 640
ACTXPIX1=            1 /ACT address space x first pixel number (pixel)
ACT_YSIZ=          640 /ACT address space Ysize (pixel) actual size 640
ACTYPIX1=            1 /ACT address space y first pixel number (pixel)
```

The scale and orientation of the SXI ACT system are defined to be the same as that of the RAW system.

```
ACT_XSCL=        0.048 /ACT X scale (mm/pixel)
ACT_YSCL=        0.048 /ACT Y scale (mm/pixel)
ACT_UNIT= 'mm      '           /physical unit of ACT
ACTXFLIP=            1 /ACT coords are look down, so no flipping
ACTYFLIP=           1 /
```

Coefficients for the transformation from ACT to DET. Whereas ACT system is defined per CCD, the DET system is defined for the entire SXI.

```
ACT_SCOL= 'CCD_ID  '           /column name of a chip in event files
ACT_NSEG=              4 /number of segments, one for each of 4 chips
CO1_X0_A=              254.217 /SXI CCD_ID=0
CO1_X0_B=             -0.00227 /DETX = 0 + ACTY
CO1_X0_C=                1.000 /
CO1_Y0_A=              917.762 /DETY = OFFSET + ACTX
CO1_Y0_B=                1.000 /
CO1_Y0_C=              0.00227 /
CO1_X1_A=              251.920 /SXI CCD_ID=1
CO1_X1_B=              0.00279 /DETX = 0 + ACTY
CO1_X1_C=                1.000 /
CO1_Y1_A=              255.481 /DETY = 0 + ACTX
CO1_Y1_B=                1.000 /
CO1_Y1_C=             -0.00279 /
CO1_X2_A=             1558.604 /SXI CCD_ID=2
CO1_X2_B=               -0.000 /DETX = OFFSET - ACTY
CO1_X2_C=               -1.000 /
CO1_Y2_A=             1555.173 /DETY = OFFSET - ACTX
CO1_Y2_B=               -1.000 /
CO1_Y2_C=                0.000 /
CO1_X3_A=             1556.310 /SXI CCD_ID=3
CO1_X3_B=              0.00244 /DETX = OFFSET - ACTY
CO1_X3_C=               -1.000 /
CO1_Y3_A=              894.536 /DETY = OFFSET - ACTX
CO1_Y3_B=               -1.000 /
CO1_Y3_C=             -0.00244 /
IN1_XCEN=          905.5 /x center of ACT pixel measurement coordinates
IN1_YCEN=          905.5 /y center of ACT pixel measurement coordinates
```

The transformation from ACT to DET involves a translation plus rotation:

DET = TRN + ROT * ACT,
where DET, TRN and ACT are vectors, e.g. ACT = [ACTX ACTY] and ROT is a two-dimensional rotation matrix:
ROT = [ROT00 ROT01]
        [ROT10 ROT11]

The components of TRN and ROT are given in the TelDef as six keywords for each CCD chip, indexed by *n*=0,1,2,3:

`CO`*n*`_X0_A=`	`TRNX:  X translation coefficient`
`CO`*n*`_X0_B=`	`Rotation Matrix element ROT00`
`CO`*n*`_X0_C=`	`Rotation Matrix element ROT01`
`CO`*n*`_Y0_A=`	`TRNY:  Y translation coefficient`
`CO`*n*`_Y0_B=`	`Rotation Matrix element ROT10`
`CO`*n*`_Y0_C=`	`Rotation Matrix element ROT11`

These coefficients are derived in the following manner.

Set up arrays that contain the coordinates of the corners of each CCD chip in "GAP" coordinates with the origin at the origin of the CCD3 ACT system (opposite the origin of the DET system). These are the numbers provided by the Instrument Team. Note that not all corner values are specified. The place holders listed are not used in the calculation of the coefficients.

```
ccd1_gap[0,0:1]=[635.41,1302.39] ; Upper left corner   0 1
ccd1_gap[1,0:1]=[633.96,663.39]  ; Upper right corner  3 2
ccd1_gap[2,0:1]=[-5.04,664.84]   ; Lower right corner
ccd1_gap[3,0:1]=[9999.0,9999.0]  ; Placeholder

ccd2_gap[0,0:1]=[9999.0,9999.0]  ; Placeholder
ccd2_gap[1,0:1]=[1299.48,665.68]  ; Upper right corner  0 1
ccd2_gap[2,0:1]=[660.48,663.90]   ; Lower right corner  3 2
ccd2_gap[3,0:1]=[658.70,1302.90]  ; Lower left corner

ccd3_gap[0,0:1]=[0.0,0.0]
ccd3_gap[1,0:1]=[0.0,639.0]
ccd3_gap[2,0:1]=[639.0,639.0]
ccd3_gap[3,0:1]=[639.0,0.0]

ccd4_gap[0,0:1]=[660.64,2.29]
ccd4_gap[1,0:1]=[662.20,641.29]
ccd4_gap[2,0:1]=[1301.20,639.73]
ccd4_gap[3,0:1]=[9999.0,9999.0]  ; Placeholder
```

The origin of the DET system in GAP coordinates is detorigin = 1310.0

For each corner, offset by detorigin, and note the reversal of coordinates between GAP and DET (i.e. DETX = -GAPY; DETY = -GAPX)

```
for i=0,3 do begin  (Loop over the four corners)
   ccd1_det[i,0] = detorigin - ccd1_gap[i,1]
   ccd1_det[i,1] = detorigin - ccd1_gap[i,0]
   ccd2_det[i,0] = detorigin - ccd2_gap[i,1]
   ccd2_det[i,1] = detorigin - ccd2_gap[i,0]
   ccd3_det[i,0] = detorigin - ccd3_gap[i,1]
   ccd3_det[i,1] = detorigin - ccd3_gap[i,0]
   ccd4_det[i,0] = detorigin - ccd4_gap[i,1]
   ccd4_det[i,1] = detorigin - ccd4_gap[i,0]
endfor
```

Set the corner positions in ACT coordinates

```
act_corner[0,0:1]=[1,1]        ; Upper left corner
act_corner[1,0:1]=[1,640]      ; Upper right corner
act_corner[2,0:1]=[640,640]  ; Lower right corner
act_corner[3,0:1]=[640,1]      ; Lower left corner
```

The Instrument Team also provided the rotation angle for each CCD chip relative to CCD3.

```
ccd1_angle = -0.13
ccd2_angle = 0.16
ccd3_angle = 0.0
ccd4_angle = -0.14
```

The task is to use these numbers to derive the rotation plus translation coefficients to take ACT -> DET coordinates.

For each of *n* CCDs, set up a rotation matrix based on the rotation angle

```
Rotn = [ cos(ccdn_angle)   -sin(ccdn_angle)]
         [ sin(ccdn_angle)    cos(ccdn_angle)]
         n = 0,1,2,3
```

For each corner of each CCD chip, the translation constant can be found as the difference between the DET coordinate and the rotated ACT coordinate. For each CCD, only three corner positions are given in DET, these are indicated by a, b and c in the equations below (e.g. for CCD1, there are coordinates given for corners 0,1,2, so a=0, b=1, c=2, where corner 3 is not used)

```
consta = ccdn_det[a,0:1] – rot # (act_corner[a,0:1])
constb = ccdn_det[b,0:1] – rot # (act_corner[b,0:1])
constc = ccdn_det[c,0:1] – rot # (act_corner[c,0:1])
```

Take the average of the three derived constants to determine the translation coefficients to be written to the TelDef:

const*n* = mean(consta, constb, constc) for a given CCD*n* (*n* = 0,1,2,3)
We thus have two constants (x,y) for each CCD chip:

act_x*n*_a = const*n*[0]
act_y*n*_a = const*n*[1]
n = 0,1,2,3

One further correction is needed to put the center of the CCDs at the center of the DET system. The DET_XSIZ and DET_YSIZ keywords have value 1810, so the center is at DETCEN=[905.5, 905.5]. The correction is the difference beween DETCEN and the center of the gap among the four CCDs, which is the same as the mean position of the centers of the four CCD chips.

For each of the four CCDs , find the mean x and mean y by averaging the x/y positions of the four corners.

mean1x=mean(ccd1_det[*,0])
mean2x=mean(ccd2_det[*,0])
mean3x=mean(ccd3_det[*,0])
mean4x=mean(ccd4_det[*,0])
meanx=mean([mean1x,mean2x,mean3x,mean4x])

mean1y=mean(ccd1_det[*,0])
mean2y=mean(ccd2_det[*,0])
mean3y=mean(ccd3_det[*,0])
mean4y=mean(ccd4_det[*,0])
meany=mean([mean1y,mean2y,mean3y,mean4y])

Now derive the offset:
detoffx = meanx - DETCENx
detoffy = meany - DETCENy

and calculate the `COn_X0_A` (translation) keyword values:
`CO1_X0_A =` act_x*n*_a - detoffx
`CO1_Y0_A =` act_y*n*_a - detoffy
n = 0,1,2,3

The “B” and “C” (rotation) keywords are simply sines and cosines of the rotation angles:
`COn_X0_B =` sin(ccd*n*_angle)
`COn_X0_C =` cos(ccd*n*_angle)
`COn_Y0_B =` cos(ccd*n*_angle)
`COn_Y0_C =` -sin(ccd*n*_angle)

The following are from the defintion of the DET coordinate system:

```
DET_XSIZ=          1810 /DET address space x size (pixels)
DETXPIX1=             1 /DET address space x first pixel number (pixel)
```

```
DET_YSIZ=          1810 /DET address space y size (pixels)
DETYPIX1=             1 /DET address space y first pixel number (pixel)
```

The scale of the SXI DET system is defined to be the same as that of the RAW and ACT systems.

```
DET_XSCL=         0.048 /DET address space mm per x det unit (mm/pixel)
DET_YSCL=         0.048 /DET address space mm per y det unit (mm/pixel)
DET_UNIT= 'mm      '           /physical unit of DET
```

The actual transformation from ACT to DET uses the coefficients derived above, so there is no flip or rotation.

```
DETXFLIP=                    1 /All transformations to DET are
DETYFLIP=                    1 /carried out using coefficients
DET_ROTD=                    0 /where the flip is taken care of
```

The following are from the defintion of the FOC coordinate system, which is common to all Hitomi instruments:

```
FOC_XSIZ=                 2430 / FOC address space x size (pixels)
FOCXPIX1=            1 / FOC address space x first pixel number (pixel)
FOC_YSIZ=                 2430 / FOC address space y size (pixels)
FOCYPIX1=            1 / FOC address space y first pixel number (pixel)
```

The SXI FOC scale is the same as the DET scale.

```
FOC_XSCL=                0.048 /FOC X scale (mm/pixel)
FOC_YSCL=                0.048 /FOC Y scale (mm/pixel)
FOC_UNIT= 'mm      '           /physical unit of FOC
```

The offsets are derived from the flight data to place the centroid of the image of G21.5 at the same place for all detectors. The details of this process are given in Section 2.2.2.

```
FOC_XOFF=      -122.646 /DETX offset (pixel) to the FOC center position
FOC_YOFF=      -113.663 /DETY offset (pixel) to the FOC center position
FOC_ROTD=           0.0 /DET rotation angle (deg) in FOC coordinates
```

The SKY system is defined to be on the same scaled as the FOC system.

```
SKY_XSIZ=                 2430 / SKY address space x size (pixels)
SKYXPIX1=            1 / SKY address space x first pixel number (pixel)
SKY_XSCL=                0.103 / SKY X scale (mm/pixel)
SKY_YSIZ=                 2430 / SKY address space y size (pixels)
SKYYPIX1=            1 / SKY address space y first pixel number (pixel)
SKY_YSCL=                0.103 / SKY Y scale (mm/pixel)
SKY_UNIT= 'deg      '          / physical unit of SKY
```

The focal length of the SXT is 5600 mm.

```
FOCALLEN=              5600.0 / SXT focal length (mm)
```

The rotation matrix between the FOC system and the spacecraft (SAT) system is an identity matrix.

```
FOC_M11 =             1.0 / SAT -> FOC coordinates alignment matrix Mij
FOC_M12 =                  0.0 / (look-down) (look-up)
FOC_M13 =                  0.0
FOC_M21 =            0.0 / [3x3 rotation matrix, common to all sensors]
FOC_M22 =                  1.0
FOC_M23 =             0.0 / FOCX =    M11*SATX + M12*SATY + M13*SATZ
FOC_M31 =             0.0 / FOCY =    M21*SATX + M22*SATY + M23*SATZ
FOC_M32 =             0.0 / FOCZ =    M31*SATX + M32*SATY + M33*SATZ
FOC_M33 =                  1.0
```

The ALIGNMxx matrix is redundant to the FOC_Mxx matrix above. However the keywords must be present since the *aspect* tool requires these keywords. If there is a non-identity alignment matrix, then the corresponding FOC_Mxx and ALIGNMxx keywords must be identical.

```
ALIGNM11=        1.0 / This matrix is redundant to the FOC_MXX matrix
ALIGNM12=        0.0 / above, but both are required.  The FOC_MXX
ALIGNM13=        0.0 / matrix is used by the teldef2 code (and ALIGNMX
ALIGNM21=        0.0 / is obsolete).
ALIGNM22=        1.0 / However, the aspect tool requires the ALIGNMXX
ALIGNM23=        0.0 / keywords.
ALIGNM31=                 0.0
ALIGNM32=                 0.0
ALIGNM33=                 1.0
```

The optical axis location is defined in the DET system. The derivation of the HXI optical axis is given in Section 2.2.1.

```
OPTCOORD= 'DET     '       /optical axis is defined in DET coordinates
OPTAXISX=         783.464 /optical axis x in DET coordinates (pixel)
OPTAXISY=         794.180 /optical axis y in DET coordinates (pixel)
OPT_ROTD=         0.00000 /rotation of telescope output system wrt DET
OPTXFLIP=              1 /flip of telescope axes relative to DETX/Y
OPTYFLIP=             -1 /flip from (look-down) to (look-up)
```

7.2 ApB: SXS

For the SXS, the RAW system is a PIXEL system in one dimension instead of a two-dimensional system. However, both X and Y keywords are required and must be defined.

```
RAW_SCOL= 'PIXEL   '           /Each SXS pixel is a segment
```

```
RAW_NSEG=                  36 /number of segments, 36 pixels for SXS
RAW_XSIZ=                   1 /only one pixel per segment
RAWXPIX1=                   1 /arbitrary coordinate of single pixel
RAW_YSIZ=                   1 /only one pixel per segment
RAWYPIX1=                   1 /arbitrary coordinate of single pixel
RAW_UNIT= 'mm      '          /physical unit of RAW
```

The following are from the defintion of the ACT coordinate system, which is a two-dimensional map of the SXS pixels.

```
ACT_XSIZ=            8 /ACT address space x size (pixels)
ACTXPIX1=            1 /ACT address space x first pixel number (pixel)
ACT_YSIZ=            8 /ACT address space y size (pixels)
ACTYPIX1=            1 /ACT address space y first pixel number (pixel)
```

The SXS ACT scale is the size of the SXS pixels with gaps.

```
ACT_YSCL=               0.832 /ACT Y scale (mm/pixel)
ACT_XSCL=               0.832 /ACT X scale (mm/pixel)
ACT_UNIT= 'mm      '          /physical unit of ACT
ACT_SCAL=         0.832 /pixel measurement unit (mm) per one ACT pixel
```

The following keywords are used in the conversion from PIXEL to ACT and are based on the definition of ACT and the PIXEL_MAP (see below) and the SXS scale.

```
IN0_XCEN=             0.0 /x center of RAW pixel measurement coordinates
IN0_YCEN=             0.0 /y center of RAW pixel measurement coordinates
ACT_XOFF=          0.832 /RAWX offset (mm) to the ACT center position
ACT_YOFF=          0.832 /RAWY offset (mm) to the ACT center position
ACTXFLIP=                   1 /do not flip x-axis in RAW -> ACT
ACTYFLIP=                   1 /do not flip y-axis in RAW -> ACT
```

The following are from the definition of the DET coordinate system:

```
DET_XSIZ=            8 /DET address space x size (pixels)
DETXPIX1=            1 /DET address space x first pixel number (pixel)
DET_YSIZ=            8 /DET address space y size (pixels)
DETYPIX1=            1 /DET address space y first pixel number (pixel)
```

The scale of the SXS DET system is defined to be the same as that of the ACT system.

```
DET_XSCL=         0.832 /DET address space mm per x det unit (mm/pixel)
DET_YSCL=         0.832 /DET address space mm per y det unit (mm/pixel)
DET_UNIT= 'mm      '          /physical unit of DET
DET_SCAL=               1.000 /Conversion between ACT and DET scales
```

The definition of the DET system is that the Y-axis is flipped with respect to the ACT system. There is also a 180° rotation between ACT and DET.

```
DETXFLIP=                    1 /do not flip x-axis in RAW -> DET
DETYFLIP=           -1 /flip y-axis in RAW (look-down) -> DET (look-up)
DET_ROTD=               180 /Rotate by 180 degrees between ACT and DET
```

There is an additional offset that moves the SXS array in DET coordinates to place the calibration pixel at DET = (6,8)

```
DET_XOFF=                   -2 /Correct to put the cal pixel at (6,8)
DET_YOFF=                    0 /No correction for Y
```

The following are from the definition of the FOC coordinate system, which is common to all Hitomi instruments:

```
FOC_XSIZ=                 2430 /FOC address space x size (pixels)
FOCXPIX1=             1 /FOC address space x first pixel number (pixel)
FOC_YSIZ=                 2430 /FOC address space y size (pixels)
FOCYPIX1=             1 /FOC address space y first pixel number (pixel)
```

The FOC scale is the SXI scale, which is common to all instruments

```
FOC_XSCL=                0.048 /FOC X scale (mm/pixel)
FOC_YSCL=                0.048 /FOC Y scale (mm/pixel)
FOC_UNIT= 'mm      '           /physical unit of FOC
```

The FOC_SCAL keyword is the ratio FOC_XSCL/DET_XSCL

```
FOC_SCAL=               0.0577 /Conversion between DET and FOC scales
```

The offsets are derived from the flight data to place the centroid of the image of G21.5 at the same place for all detectors. The details of this process are given in Section 2.2.2.

```
FOC_XOFF=      -0.8637 / DETX offset (pixel) to the FOC center position
FOC_YOFF=      -0.8582 / DETY offset (pixel) to the FOC center position
FOC_ROTD=        0.000 / DET rotation angle (deg) in FOC coordinates
```

The SKY system is defined to be on the same scaled as the FOC system.

```
SKY_XSIZ=                 2430 / SKY address space x size (pixels)
SKYXPIX1=            1 / SKY address space x first pixel number (pixel)
SKY_XSCL=                0.103 / SKY X scale (mm/pixel)
SKY_YSIZ=                 2430 / SKY address space y size (pixels)
SKYYPIX1=            1 / SKY address space y first pixel number (pixel)
SKY_YSCL=                0.103 / SKY Y scale (mm/pixel)
```

```
SKY_UNIT= 'deg      '          / physical unit of SKY
```

The focal length of the SXT is 5600 mm.

```
FOCALLEN=              5600.0 / SXT focal length (mm)
```

The rotation matrix between the FOC system and the spacecraft (SAT) system is an identity matrix.

```
FOC_M11 =             1.0 / SAT -> FOC coordinates alignment matrix Mij
FOC_M12 =                  0.0 / (look-down) (look-up)
FOC_M13 =                  0.0
FOC_M21 =            0.0 / [3x3 rotation matrix, common to all sensors]
FOC_M22 =                  1.0
FOC_M23 =             0.0 / FOCX =    M11*SATX + M12*SATY + M13*SATZ
FOC_M31 =             0.0 / FOCY =    M21*SATX + M22*SATY + M23*SATZ
FOC_M32 =             0.0 / FOCZ =    M31*SATX + M32*SATY + M33*SATZ
FOC_M33 =                  1.0
```

The ALIGNMxx matrix is redundant to the FOC_Mxx matrix above. However the keywords must be present since the *aspect* tool requires these keywords. If there is a non-identity alignment matrix, then the corresponding FOC_Mxx and ALIGNMxx keywords must be identical.

```
ALIGNM11=         1.0 / This matrix is redundant to the FOC_MXX matrix
ALIGNM12=         0.0 / above, but both are required.  The FOC_MXX
ALIGNM13=         0.0 / matrix is used by the teldef2 code (and ALIGNMX
ALIGNM21=         0.0 / is obsolete).
ALIGNM22=         1.0 / However, the aspect tool requires the ALIGNMXX
ALIGNM23=         0.0 / keywords.
ALIGNM31=                  0.0
ALIGNM32=                  0.0
ALIGNM33=                  1.0
```

The optical axis location is defined in the DET system. The derivation of the HXI optical axis is given in Section 2.2.1.

```
OPTCOORD= 'DET     '       /optical axis is defined in DET coordinates
OPTAXISX=             3.716 / optical axis x in DET coordinates (pixel)
OPTAXISY=             3.343 / optical axis y in DET coordinates (pixel)
OPT_ROTD=          0.00000 /rotation of telescope output system wrt DET
OPTXFLIP=                1 /flip of telescope axes relative to DETX/Y
OPTYFLIP=                  -1 /flip from (look-down) to (look-up)
```

How to calculate the values in the look-up table PIXEL_MAP for conversion from PIXEL to ACT.

The physical locations of each pixel are provided by the Instrument Team, but must be converted to the system consistent with the TelDef.

The numbers provided by the Instrument Team are in a spreadsheet with the following format:

SXS FM array
down-looking
array oriented with cal pixel in +x, -y quadrant, units in mm
pixel numbers (named PIXEL) are left-right, top-bottom, and are **NOT** PSP channel numbers
pixel 36 is not read out (that channel is used for the cal pixel instead)

```
            ^  +X
            |
            |
            |
 1   2   3   4   5   6
 7   8   9  10  11  12
13  14  15  16  17 18   _______>  +Y
19  20  21  22  22  24
25  26  27  28  29  30
31  32  33  34  35  36
```

Thus in this system, PIXELs 15, 16, 21, 22 have values close to zero. The numbers in this orientation are called PIXEL.

Within the spreadsheet Corner and PSP channel are added.
Corner is mapping to corners as defined in the SXS TelDef
Look down, lower-left, lower-right, upper-right, upper-left

```
4  3
1  2
```

These numbers are called CORNER.

PSP Channel is the mapping from physical to read-out channel

30	32	34	26	24	23
29	31	33	25	22	21
27	28	35	18	20	19
1	2	0	17	10	9
3	4	7	15	13	11
5	6	8	16	14	12

All look-down

Channel 12 is the cal pixel is this version. The numbers in this orientation are called CHANNEL.

The values originally associated with PIXEL (upper map) are re-ordered by CHANNEL and CORNER into a FITS table with 144 (= 36 X 4) row and the following columns:

Col	Name	Format[Units](Range)	Comment
1	CHANNEL	I (0:35)	Oriented as in lower table
2	CORNER	I (0:4)	
3	X	E [mm]	Original X position value from Instrument Team
4	Y	E [mm]	Original Y position value from Instrument Team
5	PIXEL	I (1:36)	Oriented in upper table

None of the values are changed, they are simply re-ordered by CHANNEL.

This table must be re-organized once more to put it in a form compatible with the coordinate transformation code. The CHANNEL column is renamed to PIXEL and the four rows for each channel are packed into vector arrays. The original CORNER and PIXEL columns are deleted:

Col	Name	Format[Units](Range)	Comment
1	PIXEL	1I	ID number of pixel (0-35)
2	PIXELX	4E [mm]	coordinate of pixel corners
3	PIXELY	4E [mm]	coordinate of pixel corners

7.3 ApB: HXI

The following are from the definition of the RAW coordinate system:

```
RAW_XSIZ=                  128 / RAW address space Xsize (pixel)
RAWXPIX1=            1 / RAW address space x first pixel number (pixel)
RAW_YSIZ=                  128 / RAW address space Ysize (pixel)
RAWYPIX1=            1 / RAW address space y first pixel number (pixel)
```

These are derived from the scale of the reconstructed HXI images.

```
RAW_XSCL=                0.250 / RAW X scale (mm/pixel)
RAW_YSCL=                0.250 / RAW Y scale (mm/pixel)
RAW_UNIT= 'mm      '           / physical unit of RAW
```

There is no rotation defined between the HXI RAW and ACT systems. Since the transformation from RAW to ACT involves an attitude quaternion, an alignment matrix must be defined and this is it:

```
RAW_M11 =             1.0 / ACT -> RAW coordinates alignment matrix Mij
RAW_M12 =               0.0 / (look-down) (look-down)
RAW_M13 =               0.0
RAW_M21 =            0.0 / [3x3 rotation matrix, common to all sensors]
```

```
RAW_M22 =               1.0
RAW_M23 =               0.0 / RAWX =    M11*ACTX + M12*ACTY + M13*ACTZ
RAW_M31 =               0.0 / RAWY = - (M21*ACTX + M22*ACTY + M23*ACTZ)
RAW_M32 =               0.0 / RAWZ =    M31*ACTX + M32*ACTY + M33*ACTZ
RAW_M33 =               1.0
```

The following are from the defintion of the ACT coordinate system. The ACT space is larger than the RAW space to account for translation and rotation between the two systems.

```
ACT_XSIZ=                  256 / ACT address space x size (pixels)
ACTXPIX1=            1 / ACT address space x first pixel number (pixel)
ACT_YSIZ=                  256 / ACT address space y size (pixels)
ACTYPIX1=            1 / ACT address space y first pixel number (pixel)
```

The scale of the HXI ACT system is defined to be the same as that of the RAW system.

```
ACT_XSCL=        0.250 / ACT address space mm per x det unit (mm/pixel)
ACT_YSCL=        0.250 / ACT address space mm per y det unit (mm/pixel)
ACT_UNIT= 'mm      '           / physical unit of ACT
```

The following are from the defintion of the DET coordinate system:

```
DET_XSIZ=                  256 / DET address space x size (pixels)
DETXPIX1=            1 / DET address space x first pixel number (pixel)
DET_YSIZ=                  256 / DET address space y size (pixels)
DETYPIX1=            1 / DET address space y first pixel number (pixel)
```

The scale of the HXI DET system is defined to be the same as that of the RAW and ACT systems.

```
DET_XSCL=        0.250 / DET address space mm per x det unit (mm/pixel)
DET_YSCL=        0.250 / DET address space mm per y det unit (mm/pixel)
DET_UNIT= 'mm      '           / physical unit of DET
```

The definition of the DET system is that the X-axis is flipped with respect to the RAW and ACT systems. There is no rotation between ACT and DET.

```
DETXFLIP=           -1 / X axis flipped when going from RAW (look-down)
DETYFLIP=                    1 / to DET (look-up)
DET_ROTD=                    0
```

The following are from the defintion of the FOC coordinate system, which is common to all Hitomi instruments:

```
FOC_XSIZ=                 2430 / FOC address space x size (pixels)
FOCXPIX1=            1 / FOC address space x first pixel number (pixel)
FOC_YSIZ=                 2430 / FOC address space y size (pixels)
FOCYPIX1=            1 / FOC address space y first pixel number (pixel)
```

To calculate the scaling factors between the RAW/ACT/DET (HXI scale) and the FOC (SXI scale) one uses the following equation:

```
sxi_scl = 0.048           ; SXI scale mm/pixel
hxt_focal = 12000.0    ; HXT focal length (mm)
sxt_focal = 5600.0       ; SXT focal length (mm)
scaling = hxt_focal/sxt_focal   ; Focal length ratio (= 2.1428571)
foc_scl = sxi_scal * scaling      ; mm/pixel Scale in the SXI focal plane (= 0.10285714 mm)
```

```
FOC_XSCL=                0.103 / FOC X scale (mm/pixel)
FOC_YSCL=                0.103 / FOC Y scale (mm/pixel)
FOC_UNIT= 'mm      '           / physical unit of FOC
```

The conversion factor between the DET and FOC scales is the ratio of the HXI FOC scale (FOC_XSCL) and RAW scale (RAW_XSCL):

```
raw_scl = 0.25     ; HXI scale mm/pixel
foc_scal=foc_scl/raw_scl  ; (unitless) conversion between DET and FOC (rescaling)  (=0.41142858)
```

```
FOC_SCAL=             0.411429 / Conversion between DET and FOC scales
```

The offsets are derived from the flight data to place the centroid of the image of G21.5 at the same place for all detectors. The details of this process are given in Section 2.2.2.

```
FOC_XOFF= -3.088 / HXI 1 DETX offset (pixel) to the FOC center position
FOC_YOFF= -0.112 / HXI 1 DETY offset (pixel) to the FOC center position
FOC_XOFF= -1.063 / HXI 2 DETX offset (pixel) to the FOC center position
FOC_YOFF= 5.744  / HXI 2 DETY offset (pixel) to the FOC center position
```

The design rotation between the HXI detector and the Spacecraft coordinates.

```
FOC_ROTD=    22.500 / HXI 1 DET rotation angle (deg) in FOC coordinates
FOC_ROTD=   -22.500 / HXI 2 DET rotation angle (deg) in FOC coordinates
```

The SKY system is defined to be on the same scaled as the FOC system.

```
SKY_XSIZ=                 2430 / SKY address space x size (pixels)
SKYXPIX1=            1 / SKY address space x first pixel number (pixel)
SKY_XSCL=                0.103 / SKY X scale (mm/pixel)
SKY_YSIZ=                 2430 / SKY address space y size (pixels)
SKYYPIX1=            1 / SKY address space y first pixel number (pixel)
SKY_YSCL=                0.103 / SKY Y scale (mm/pixel)
SKY_UNIT= 'deg     '           / physical unit of SKY
```

The focal length of the HXT is 12000 mm.

```
FOCALLEN=              12000.0 / SXT focal length (mm)
```

The rotation matrix between the FOC system and the spacecraft (SAT) system is an identity matrix.

```
FOC_M11 =             1.0 / SAT -> FOC coordinates alignment matrix Mij
FOC_M12 =                  0.0 / (look-down) (look-up)
FOC_M13 =                  0.0
FOC_M21 =            0.0 / [3x3 rotation matrix, common to all sensors]
FOC_M22 =                  1.0
FOC_M23 =             0.0 / FOCX =    M11*SATX + M12*SATY + M13*SATZ
FOC_M31 =             0.0 / FOCY =    M21*SATX + M22*SATY + M23*SATZ
FOC_M32 =             0.0 / FOCZ =    M31*SATX + M32*SATY + M33*SATZ
FOC_M33 =                  1.0
```

The ALIGNMxx matrix is redundant to the FOC_Mxx matrix above. However the keywords must be present since the *aspect* tool requires these keywords. If there is a non-identity alignment matrix, then the corresponding FOC_Mxx and ALIGNMxx keywords must be identical.

```
ALIGNM11=         1.0 / This matrix is redundant to the FOC_MXX matrix
ALIGNM12=         0.0 / above, but both are required.  The FOC_MXX
ALIGNM13=         0.0 / matrix is used by the teldef2 code (and ALIGNMX
ALIGNM21=         0.0 / is obsolete).
ALIGNM22=         1.0 / However, the aspect tool requires the ALIGNMXX
ALIGNM23=         0.0 / keywords.
ALIGNM31=                  0.0
ALIGNM32=                  0.0
ALIGNM33=                  1.0
```

The optical axis location is defined in the DET system. The derivation of the HXI optical axis is given in Section 2.2.1.

```
OPTCOORD= 'DET     '       / optical axis is defined in DET coordinates
OPTAXISX=     128.470 / HXI 1 optical axis x in DET coordinates (pixel)
OPTAXISY=     127.010 / HXI 1 optical axis y in DET coordinates (pixel)
OPTAXISX=     126.663 / HXI 2 optical axis x in DET coordinates (pixel)
OPTAXISY=     123.746 / HXI 2 optical axis y in DET coordinates (pixel)
OPT_ROTD=         0.00000 / rotation of telescope output system wrt DET
OPTXFLIP=               1 / flip of telescope axes relative to DETX/Y
OPTYFLIP=              -1 / flip from (look-down) to (look-up)
```

Some tools require the optical axis as defined in the ACT coordinate system. The *coordpnt* tool is used to convert the axis from DET to ACT.

```
OPTACTX =     128.530 / HXI 1 optical axis x in ACT coordinates (pixel)
OPTACTY =     127.010 / HXI 1 optical axis y in ACT coordinates (pixel)
```

```
OPTACTX =     130.337 / HXI 2 optical axis x in ACT coordinates (pixel)
OPTACTY =     123.746 / HXI 2 optical axis y in ACT coordinates (pixel)
```

The following ten keywords are used by the *cams2det* tool. The location of the HXI in spacecraft coordinates is taken from the CAMS document, Table 6.

```
HXI_XLOC=           465.000 / HXI-1 X location (mm) in S/C coordinates
HXI_YLOC=           195.000 / HXI-1 Y location (mm)  in S/C coordinates
HXI_ZLOC=          -5491.00 / HXI-1 Z location (mm)  in S/C coordinates
HXI_XLOC=          -465.000 / HXI-2 X location (mm) in S/C coordinates
HXI_YLOC=           195.000 / HXI-2 Y location (mm)  in S/C coordinates
HXI_ZLOC=          -5491.00 / HXI-2 Z location (mm)  in S/C coordinates
```

The rotation angle is the same as `FOC_ROTD`, but defined in the spacecraft system. Thus HXI_ROTD = 180.0 – FOC_ROTD

```
HXI_ROTD=          157.500  / HXI-1 rotation (deg) in S/C coordinates
HXI_ROTD  =       202.500  / HXI-2 rotation (deg) in S/C coordinates
```

The physical size of the HXI sensors.

```
HXI_XPHY=          32.0000  / Physical size of HX sensor (mm)
HXI_YPHY=          32.0000  / Physical size of HX sensor (mm)
```

7.4 ApB: CAMS

CAMS keywords are derived from two sources: the CAMS document "ASTRO-H ALIGNMENT MEASUREMENT SYSTEM (CAMS) Instruments and Data Processing," version 0.92, 15 September 2016 (asth_sct_cams_v20160915) and from post-launch measurements.

The CAMS locations are found in the CAMS document, Table 6, rows 1 and 4:

```
CAM_XLOC=                300.000 /CAMS-1 X location (mm) in S/C system
CAM_YLOC=                480.000 /CAMS-1 Y location (mm) in S/C system
CAM_ZLOC=               -5723.00 /CAMS-1 Z location (mm) in S/C system
CAM_XLOC=               -300.000 /CAMS-2 X location (mm) in S/C system
CAM_YLOC=                480.000 /CAMS-2 Y location (mm) in S/C system
CAM_ZLOC=               -5723.00 /CAMS-2 Z location (mm) in S/C system
```

The CAMS rotations are derived from the CAMS document, Equation 5 and Table 6, rows 2 and 5. The CAMS document equation 5 is:

$$R_{CAMS1}^{SAT} = R_z(-\frac{\pi}{2} + \beta_{C1})$$

$$R_{CAMS2}^{SAT} = R_z(\beta_{C2})$$

The *cams2det* tool requires the rotation angles to be defined as the arguments of the R_z rotation matrix above. Therefore the values in the TelDef are derived from the Table 6 values (β_{C1} and β_{C2}) as follows. For CAMS1, the rotation angle is $-\frac{\pi}{2} + \beta_{C1}$, where β_{C1} is found in Table 6, row 2. For CAMS2, the rotation angle is simply β_{C2}, which is found in Table 6, row 5.

```
CAM_ROTD=     -90.6740 /Rotation of the CAMS-1 unit with respect to S/C
CAM_ROTD=    0.155000 /Rotation of the CAMS-2 unit with respect to S/C
```

Figure 12 in the CAMS document shows that there is no flip between the CAMS axes and the spacecraft axes. These keywords have the same value for both CAMS-1 and CAMS-2 units.

```
CAMXFLIP=                    1 /X-axis flipped between CAMS and S/C
CAMYFLIP=                    1 /Y-axis not flipped
```

The CAMS scaling is defined in the CAMS document in the paragraph just above Table 4.

```
CAM_SCAL=          0.000977000 /mm per one CAMS readout unit
```

The CAMS offsets are not taken from the CAMS document, but instead were measured from in-flight data.

```
CAM_XOFF=    -525.282 /Measured X offset for CAMS-1 (unit CAM_SCAL mm)
CAM_YOFF=     2944.20 /Measured Y offset for CAMS-1 (unit CAM_SCAL mm)

CAM_XOFF=    2137.81 /Measured X offset for CAMS-2 (unit CAM_SCAL mm)
CAM_YOFF=   -38.4677 /Measured Y offset for CAMS-2 (unit CAM_SCAL mm)
```

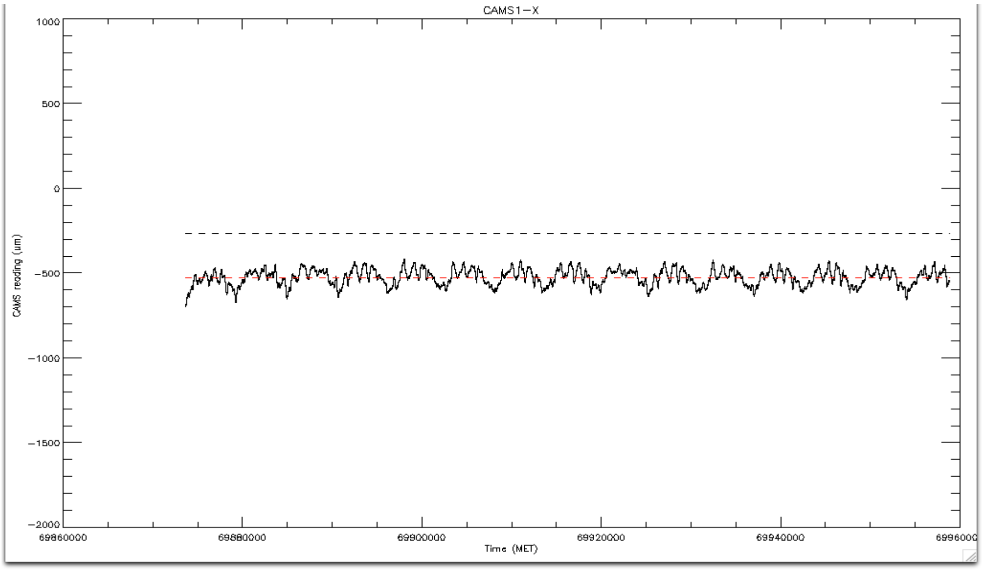
The data used is from the G21.5 observation sequence 100050010, from a run made on April 15. The file is `ah100050010hx1_cms.fits,` which has been corrected for the CAMS temperature. It was also filtered using a GTI created from the attitude for that sequence using the expression ABS(RA_DIFF)<0.25&&ABS(DEC_DIFF)<0.25&&ABS(ROLL_DIFF)<0.25
Here RA_DIFF, DEC_DIFF and ROLL_DIFF are, respectively, the differences between the instantaneous RA, Dec, Roll and the nominal values, listed in the attitude file `ah100050010.att.`

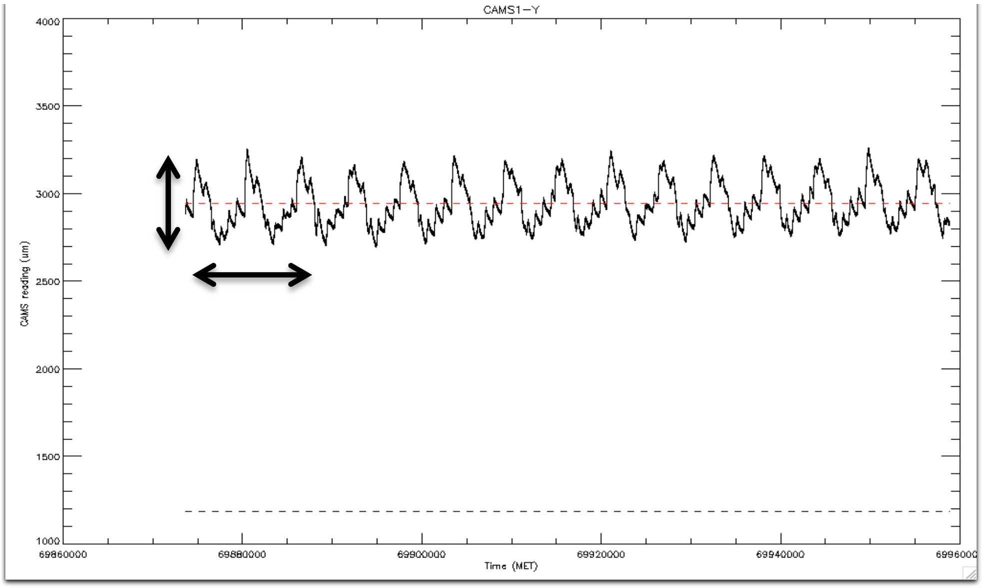
The columns examined were

```
    6 X1       1J                   X direction motion in CAMS1 system
    7 Y1       1J                   Y direction motion in CAMS1 system
    8 X2       1J                   X direction motion in CAMS2 system
    9 Y2       1J                   Y direction motion in CAMS2 system
```

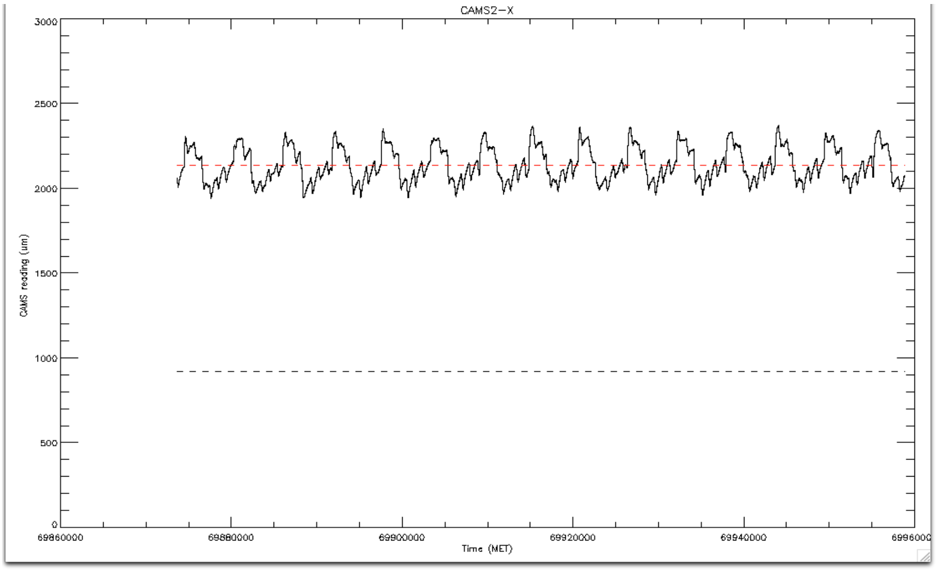
Although the file was derived for HXI1, the values in these columns do not depend on the HXI unit selected.

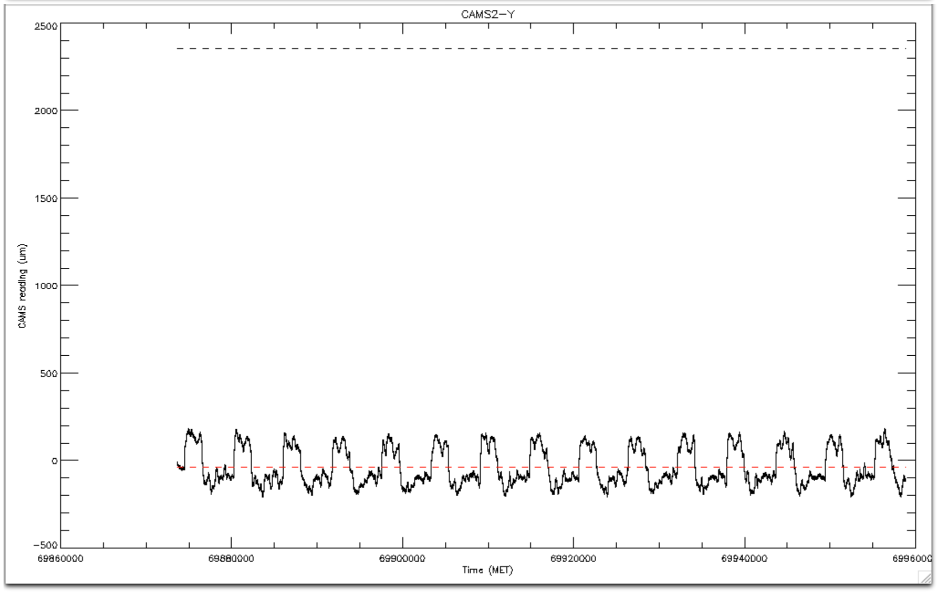
Below is shown each of the CAMS motions values plotted with respect to TIME. These are shown in order from top to bottom, CAMS1-X, CAMS1-Y, CAMS2-X, CAMS2-Y.



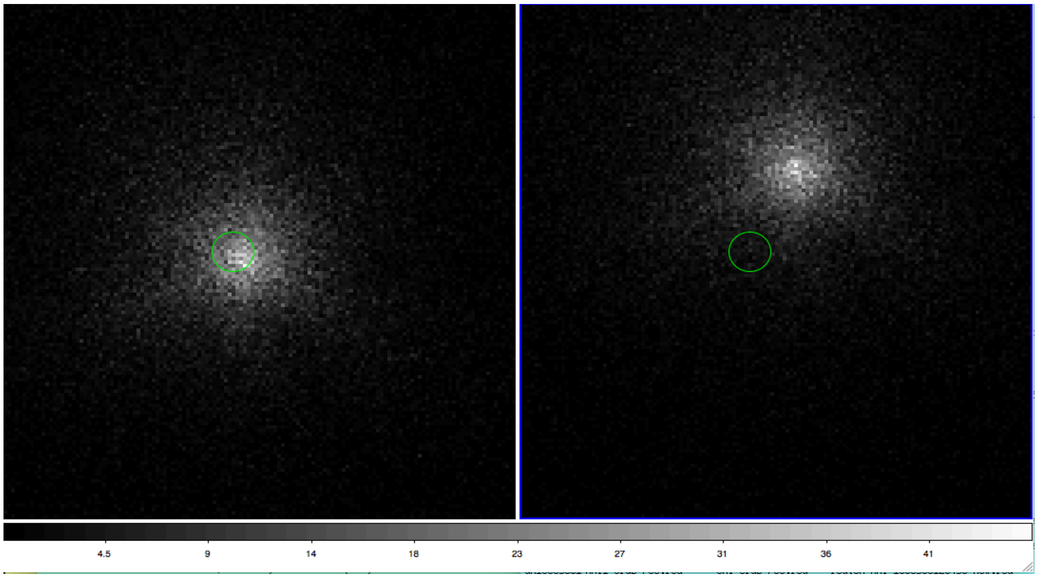


The vertical arrow indicates approximately 0.5 mm, the horizontal arrow indicates approximately 10,000 seconds.





In each figure, the black line indicates the corresponding offset from the CAMS document, Table 6, row 3 or 6 and the red line shows the mean of the data. The data mean (red line) is assumed to be the CAMS reading at zero EOB displacement. This is the value that is given in the TelDef as `CAM_XOFF` and `CAM_YOFF` keywords, which are subtracted from each CAMS measurement in the *cams2det* tool.
It is clear that for all CAMS units, the ground-derived offset (black line) is far from the flight-derived offset (red line). The figure below shows the effect of using the flight-derived offsets.



This is an image of G21.5 in HXI1 in SKY coordinates. The region circle shows the source catalog location. The left-hand panel shows the result when using the flight-derived offsets (currently in the TelDef). The right-hand panel shows the result when using the ground-derived offsets from the CAMS document.

8 Appendix A : Coordinates transformation in Suzaku

8.1 ApC : Coordinate transformation

The coordinate transformation tools used for Suzaku/XIS (the only imaging instrument on Suzaku) and Astro-H (all instruments) are named *xiscoord* and *coordevt*, respectively. Both *xiscoord* and *coordevt* use the same set of transformations. They are represented differently, as Euler angles and 3-d rotation matrices in *xiscoord* and as quaternions and xform2d structures in *coordevt* (the xform2d structure contains a two-dimensional rotation matrix and a translation with *x* and *y* components. The rotation is applied first and then the translation), however transformation steps are the same. Here the transformations matrices are called **M**, **A**, **B**.

1) Apply alignment **M** to transform from FOC to SAT. For Suzaku and Astro-H this is an identity matrix meaning that the FOC system is defined to be parallel to the SAT system.
2) Apply attitude **A** to transform from SAT to ECS. The **A** is derived directly from the attitude file Euler angles for Suzaku. It is the same as the attitude quaternion for Astro-H.
3) Apply pointing **B** to transform from ECS to SKY. The **B** is derived from the pointing reference RA and dec (which should be the same as the RA_NOM and DEC_NOM) and normally has roll=0.

The other difference between *xiscoord* and *coordevt* is that in *xiscoord* the transformations are all done in a look-down orientation, while in *coordevt*, they are done in look-up. So there are extra steps in *xiscoord* to go between look-up and look-down.

There are three steps for the FOC to SKY coordinates conversion, which includes the aberration correction. In terms of subroutines:

```
 aste_foc2ecs(com.teldef, &ea, focx, focy, &alpha, &delta);
         FOC->ECS conversion
if ( com.aberration ) {
         aste_cor_aberration(aetime, mjdrefi, mjdreff, &alpha, &delta);
         Aberration correction
 }
aste_ecs2sky(com.teldef, &com.skyref, alpha, delta, &skyx, &skyy);
ECS->SKY conversion
```

This is shown in the following steps. For reference, the coordinate systems used are

ACTX/Y: look down
DETX/Y: look up
FOCX/Y: look up
VFOCX/Y: look down
SATX/Y: look down
ECSX/Y: look down
VSKYX/Y: look down
SKYX/Y (X/Y): look up

Step 1. Transform from FOC to VFOC.

In code this is

```
/* convert to a pointing vector in FOC coordinate, flipping x-axis to make it look-down */
        vec_foc[0] = - (focx_ch - p->foc.xcen) * p->foc.xscl;
        vec_foc[1] =   (focy_ch - p->foc.ycen) * p->foc.yscl;
        vec_foc[2] =    p->focallen;
```

The transformation is shown graphically in Figure 56 and 57.

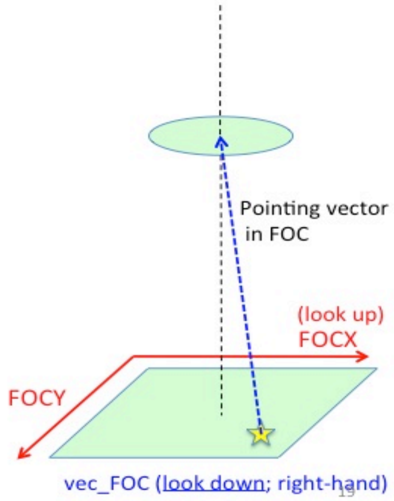


Figure 56. The transformations in *xiscoord* are all carried out in a look-down configuration (named vec_FOC, or VFOC).

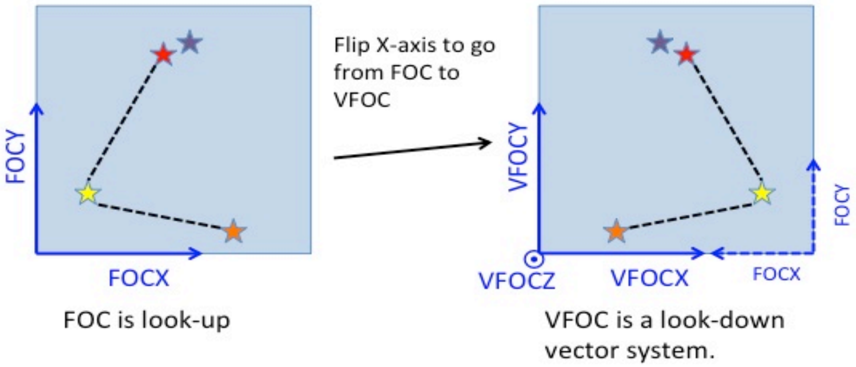


Figure 57. Normal look-up FOC system is transformed to look-down VFOC system by flipping the direction of the X-axis.

Step 2. Transform from VFOC to SAT.

In code this, applies the inverse of the Mij alignment matrix.

```
/* convert to the pointing vector in SAT coordinate, taking account of instrument offsets */
        atRotVect(p->invMij, vec_foc, vec_sat);
```

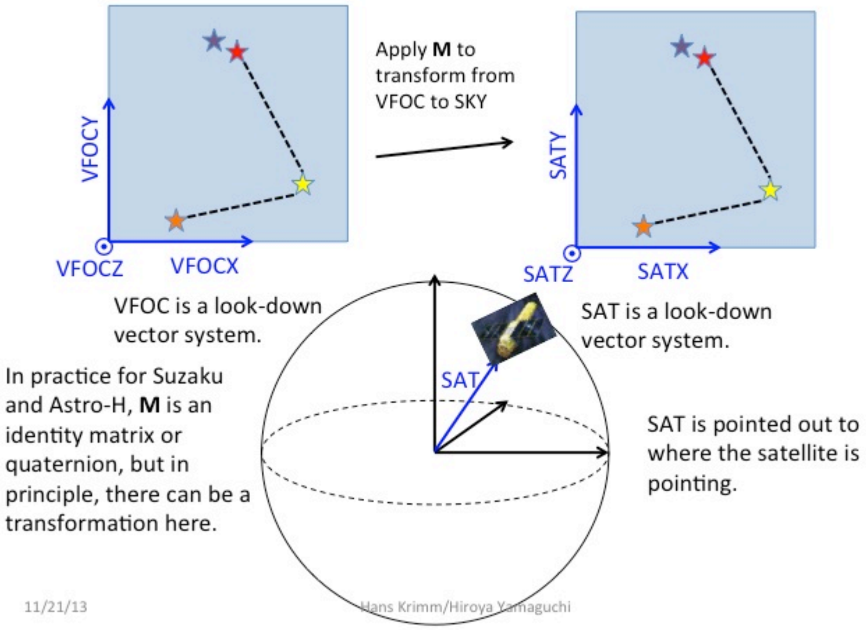


Figure 58 The alignment matrix M is applied to transform to the coordinate system fixed with respect to the satellite axes. The SAT Z-axis is pointing in the direction the spacecraft is pointing.

Step 3. Transform from SAT to ECS using the Euler angles.

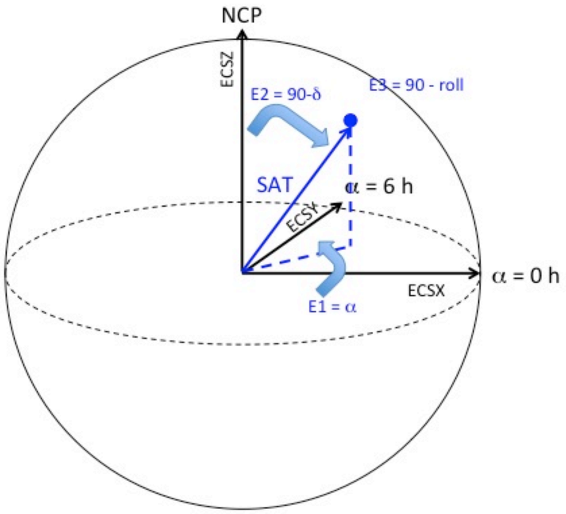


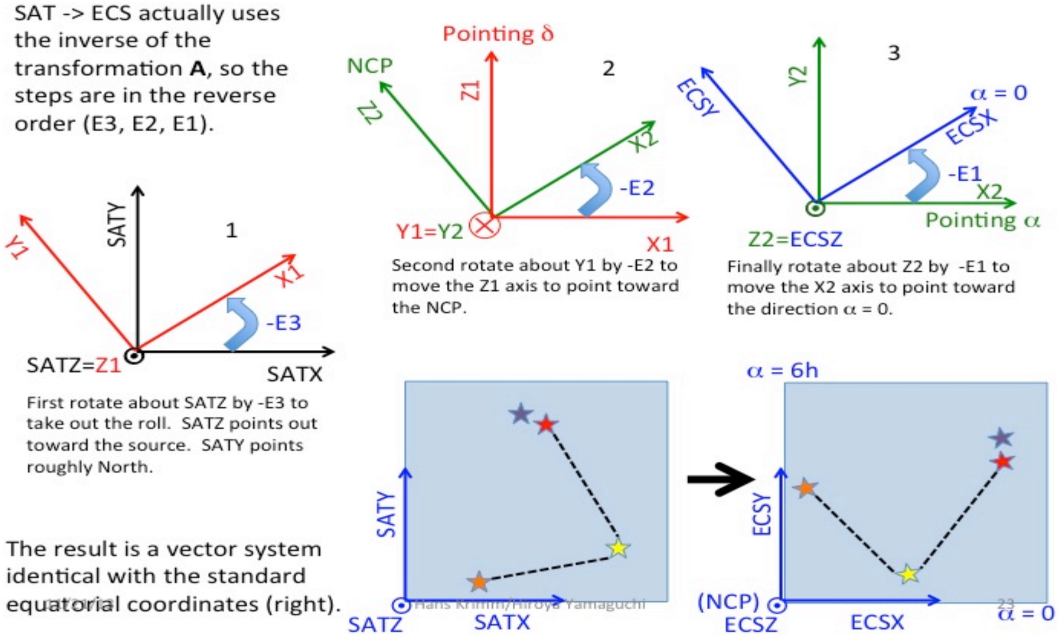
Figure 59 Definition of the Euler angles, which are defined as the orientation of the satellite (SAT system) with respect to the fixed earth-centered equatorial (ECS) system.

Euler angles E_1 and E2 are defined relative to the actual pointing direction of the satellite. Specifically, $E_1 = \alpha$, angle from the line to α=0h, and $E_2 = 90° - \delta$, angle from the line to the North Celestial Pole. E_3 is relative to the roll, which is arbitrary (chosen based on Sun angle, detector orientation or other constraints). Here $E_3 = 90° - \rho$, where ρ is the roll defined as the angle between the local FOC system and the local vector pointing toward the NCP. Note that since the Euler angles define the SAT relative to ECS, in the transformation SAT -> ECS, one needs the inverse transformation.

The Euler angles are transformed to a rotation matrix:

```
/* convert Euler angles to a rotation matrix, then obtain its inverse matrix */
        atEulerToRM(ea, Aij);
        atInvRotMat(Aij, invAij);
/* convert to the pointing vector in celestial coordinates,
  taking account of satellite attitudes */
        atRotVect(invAij, vec_sat, vec_ecs);

/* convert to the RA and DEC */
        atVectToPolDeg(vec_ecs, &norm, alpha, delta);
```



SAT -> ECS actually uses the inverse of the transformation **A**, so the steps are in the reverse order (E3, E2, E1).

First rotate about SATZ by -E3 to take out the roll. SATZ points out toward the source. SATY points roughly North.

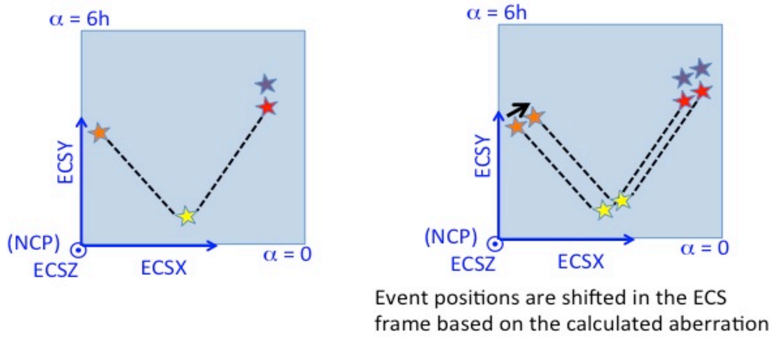
Second rotate about Y1 by -E2 to move the Z1 axis to point toward the NCP.

Finally rotate about Z2 by -E1 to move the X2 axis to point toward the direction α = 0.

The result is a vector system identical with the standard equatorial coordinates (right).

Figure 60 The three steps to transform from SAT to ECS using the Euler angles. The actual transformation is a single three-dimensional rotation matrix.

After this transformation, the field aligned with the equatorial coordinate system. Also at this stage, the field is represented by angles α and δ, and not by their tangent-plane projections. In *xiscoord*, the aberration correction is applied to α and δ in the ECS system. This is shown schematically in Figure 61 and discussed in detail in Section 3.

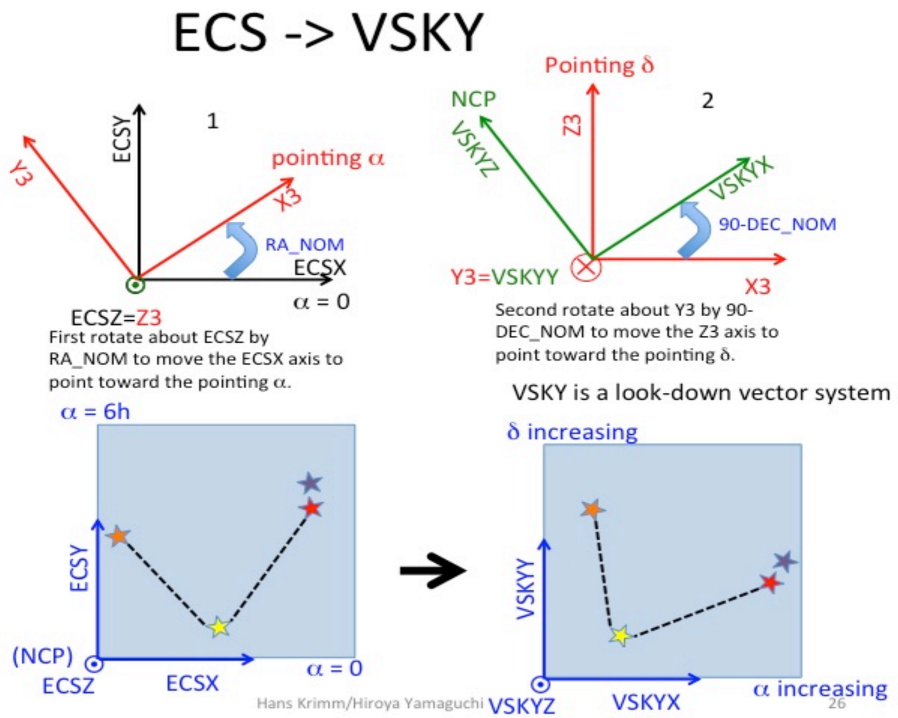


Event positions are shifted in the ECS frame based on the calculated aberration

Figure 61. Schematic showing the aberration correction in xiscoord, which is applied by correcting the α and δ values.

Step 4. Transform from ECS to VSKY using the pointing matrix.

This step transforms back from the ECS system to a tangent plane system VSKY. It basically undoes the E_1 and E_2 transformations. Note that VSKY differs from VFOC only by a (roll) rotation. There can in principle also be a translation, but since the FOC and SKY systems have the same size and origin in Suzaku and Astro-H, this translation is zero.



First rotate about ECSZ by RA_NOM to move the ECSX axis to point toward the pointing α.

Second rotate about Y3 by 90-DEC_NOM to move the Z3 axis to point toward the pointing δ.

VSKY is a look-down vector system

Figure 62. Transformation from ECS to vector VSKY tangent plane system (still look-down). Since by definition and convention, there is no roll in the B transformation, there are only two operations.

Step 5. Transform from VSKY to SKY.

This step transforms the vector, look-down VSKY system to the look-up final sky system. The transformation is simply to reverse the X-axis (the inverse of the transformation from FOC to VFOC.

Since the initial FOC system and final SKY systems are both tangent plane projections centered on the aim point, they are related by a simple rotation plus translation. For Suzaku and Astro-H, the rotation is the roll and there is no translation.

8.2 ApC : Aberration correction in Suzaku

In *xiscoord*, the aberration correction is made at the ECS stage. In other words the angular α and δ values are corrected and then transformed to the SKY system. The code *xiscoord* makes the following calls in the routine aste_cor_aberration() in aste_coord_core.c. It calls these routines for each event:

> mjd_tt = aste2mjdtt(astetime, mjdrefi, mjdreff);
> (calculate the MJD at the current time)
> atPolDegToVect(1.0, *alphaInOut, *deltaInOut, v0);
> (convert *alpha, delta* for the current event to the 3-vector v_0 in equatorial coordinates)
> atAberration(mjd_tt, v0, v1);
> (calculates aberration at time *mjd_tt* and transforms v_0 to the aberrated position v_1)
> atVectToPolDeg(v1, &r, alphaInOut, deltaInOut);
> (converts 3-vector v_1 back to *alpha* and *delta*)

The correction itself is carried out in atAbberation (in the atFunctions). The process is somewhat more complicated than that used in *coordevt*, but apart from the sign error (see below), the mathematics looks sound.

- Calculate the uncorrected J2000 α, δ (RA, declination) for the event by converting from FOC to ECS.
- Precess from J2000 to current epoch.
- Calculate the position vector **S** for the event in equatorial rectangular coordinates.
- Calculate the position of the Sun in equatorial coordinates.
- Transform the Sun vector to earth-centered ecliptic coordinates.
- From this, calculate the earth velocity vector **E** in equatorial coordinates.
- Derive $\mathbf{R_A}$, which is a rotation matrix built from the components of **S**.
- Calculate an aberration vector $\mathbf{A} = \mathbf{R_A} * \mathbf{E}$, which is the transformation of the earth velocity vector **E** into the frame defined by the position vector **S**.
- Add the aberration vector to the position vector $\mathbf{S'} = \mathbf{S} + \mathbf{A}$.
- Transform **S'** back to J2000.
- Calculated corrected α, δ from **S'**.
- Transform ECS (α, δ) to SKY.

The magnitude of the aberration correction is correct (matches that from *coordevt*). However, a sign error is found in the step $\mathbf{A} = \mathbf{R_A} * \mathbf{E}$, which projects the Earth velocity vector into the event frame. This was correct for ASCA, the source of the legacy code, but not for Suzaku. The correct equation should be $\mathbf{A} = \mathbf{R_A} * (-\mathbf{E})$, since one should project the inverse of **E**, as is done in *coordevt*.

Despite this error in *xiscoord*, the Suzaku positions are still corrected to close to the mean positions. The short answer is that the misapplied aberration correction is taken out by another correction, which operates directly on the attitude Euler angles. Early in the Suzaku mission, it was noticed that source positions had an absolute error on the scale of tens of arc seconds, and also showed variations on time scales less than an orbit. The short timescale variations were correctly attributed to thermal distortion of the Suzaku side panel where the attitude control system is mounted and a correction was developed. However, the absolute error was also attributed to the thermal distortions and not to an incorrect calculation of aberration. A paper was written (Uchiyama et al., 2008 PASJ 60, S35: http://adsabs.harvard.edu/abs/2008PASJ...60S..35U) which presented the conclusions and corrections in detail, and a software tool *aeattcor* was written to correct the Euler angles based on the empirical formulae Uchiyama et al derived. All of the Suzaku data were corrected using *aeattcor*. The reason that the aberration correction was not suspected appears to be that a relationship was discovered between the error in the DETX coordinate, ΔDETX, and the ecliptic latitude of the source. This relationship is shown in Figure 4 of Uchiyama et al, reproduced below in Figure 63. The authors fit this relationship to the formula:

$$\Delta\text{DETX} = -38.5\ (\beta/60°) - 9.25 \text{ pixels},$$

where β is the ecliptic latitude. This formula is used in *aeattcor* as part of the overall correction.

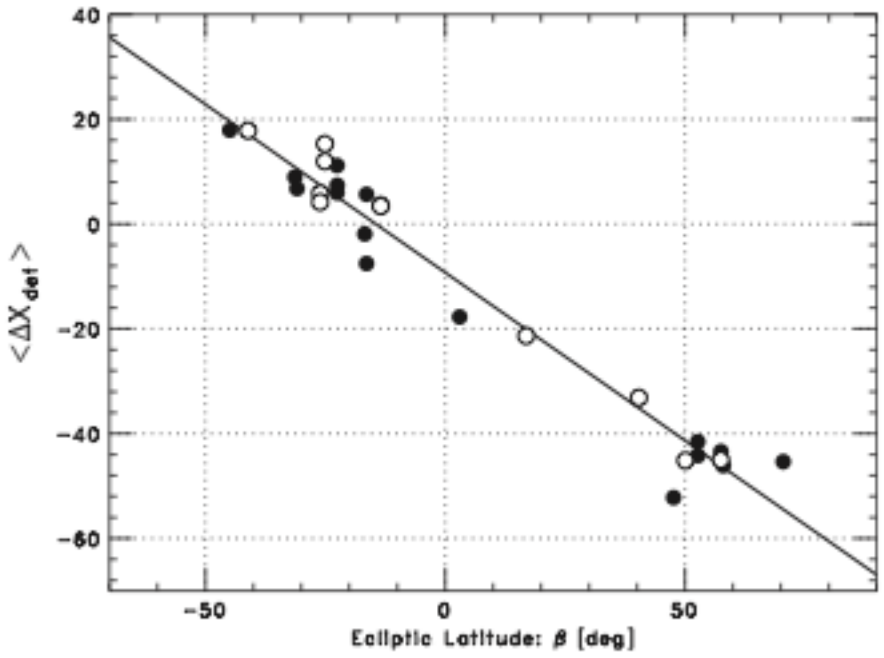


Fig. 4. Correlation between $\langle \Delta X_{\rm det} \rangle$ and the ecliptic latitude $\beta_{\rm ecl}$ of the sources.

Figure 63. Original figure from Uchiyama et al.

The reason that this relationship holds is that, to properly orient the solar panels, the roll angle of Suzaku depends on the angle between the pointing direction to the source (at a given ecliptic latitude β) and the Sun (always at zero ecliptic latitude). Likewise the aberration is also directly related to the relative positions of the Sun and the source. The aberration varies in both α and δ, which are parallel to coordinates –X and +Y, respectively, so there is no clear relationship between ΔX or ΔY and β. However, since the relationship between DETX and X/Y depends on roll ρ:

$\Delta DETX = \Delta X \cos\rho + \Delta Y \sin\rho$

and ρ in turn is directly related to β, it is not surprising that there is a linear relationship between ΔDETX and β. Deriving the relationship between β and ρ is complicated, but this can be checked empirically by calculating the equivalent of Figure 63 using only the independently calculated aberration and the roll angle for each of the observations used in Uchiyama et al, and given in their Table 1.

The method is

1) Calculate for each source in Uchiyama Table 1 the aberration for the particular date of the observation.
2) Derive the error in the X,Y positions of the source due to aberration. Since the aberration correction is in the wrong direction, this comes to twice the aberration: $\Delta X = -2\,(\alpha_{aberr} - \alpha_{mean})$ and $\Delta Y = 2\,(\delta_{aberr} - \delta_{mean})$.
3) Calculate ΔDETX from the equation above using the roll values from Uchiyama Table 1.

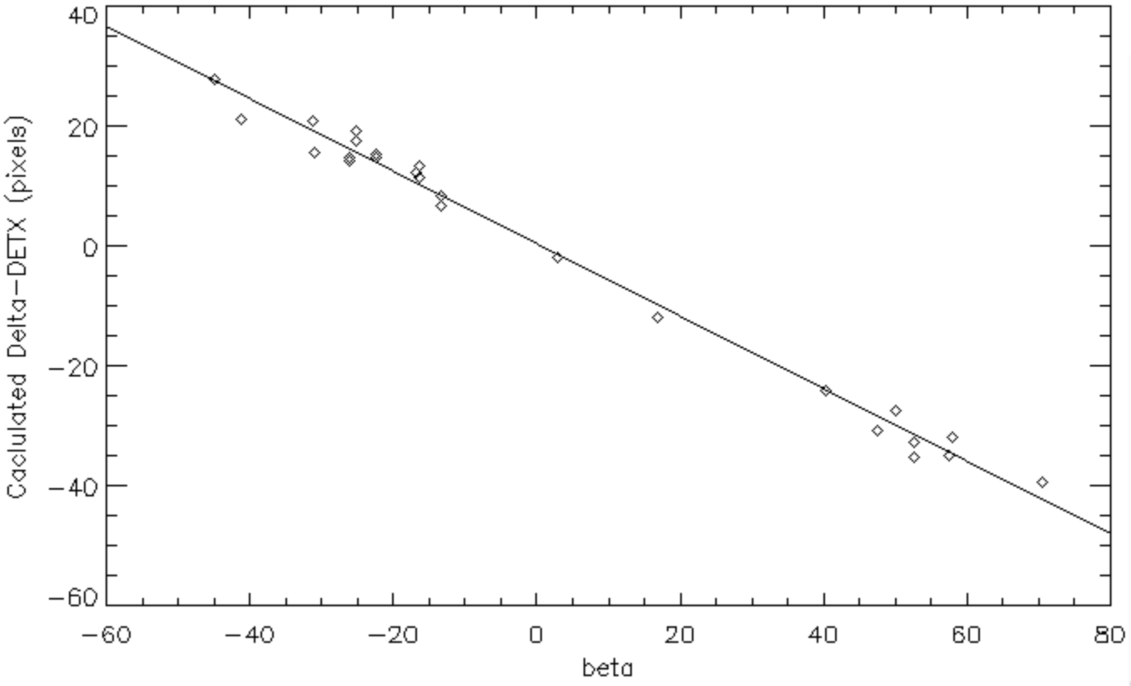


Figure 64 . Calculations of ΔDETX (see text above) plotted relative to the source ecliptic latitude.

In Figure 64 , calculation of ΔDETX are plotted versus β taken from Uchiyama et al. Based entirely on aberration (without looking at any of the images), it is possible to recapitulate their Figure 4. The derived slope is even consistent, although the offset is not:

$\Delta DETX = -0.6\,\beta + 0.36$ pixels.

Thus there is an empirical verification that the basic form of the long-timescale correction term to ΔDETX in *aeattcor*. By examining a celestial sphere, one can see heuristically how this relationship arises. In Suzaku, the SAT system (figure 65) is oriented such that the solar panels point in the +SATY direction. The Suzaku/XIS DET system is oriented parallel to SAT, with the X-axis reversed. Thus the DETY coordinate always point basically toward the Sun and the DETX axis is perpendicular to this direction.

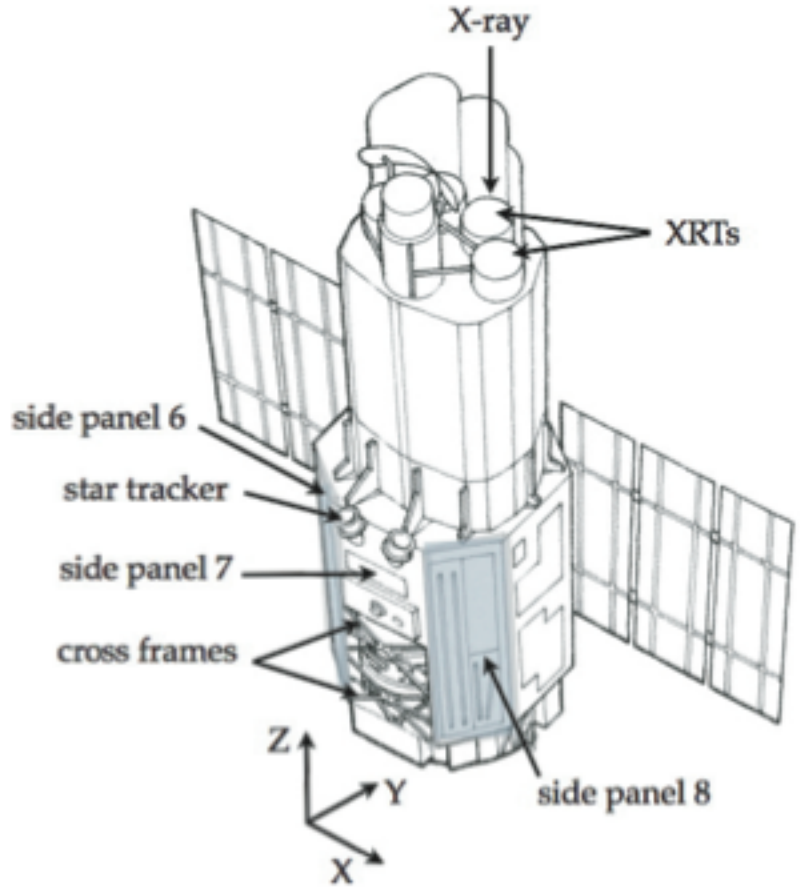


Figure 65 Drawing of the Suzaku satellite (from Uchiyama et al, 2008). The coordinate system shown is the SAT system. The solar panels are oriented in the +SATY direction. The Suzaku/XIS DET system is oriented parallel to the SAT system, but with DETX = -SATX, DETY = +SATY.

In Figure 66 shows the Ecliptic Sphere where two pointing positions are shown as orange stars at two different ecliptic latitudes. The Sun, which is always on the ecliptic equator is shown at an arbitrary longitude. The dark blue lines are along the great circles connecting the star positions with the Sun position, and point along the SATY=DETY direction. The light blue arrows show the DETX direction, which is, of course, perpendicular to DETY. Now since the Earth always moves along the ecliptic and the direction of stellar aberration is in the direction of the Earth velocity, aberration is always parallel to the Ecliptic Equator. The basic direction of the aberration is shown by the magenta arrows. Although the exact angle between the blue great circle and the magenta aberration depends on the relative ecliptic longitudes of the Sun and star, one can see from Figure 66 that the dark blue and magenta lines are closer to parallel at low ecliptic latitude than at high ecliptic latitude. The angle between these two directions is ~β, the ecliptic latitude. One can see this in Figure 67 where the DET system from each of the two points in Figure are shown in the normal orientation. In the low β case (left), the component of the aberration in the direction of DETX is relatively small compared to the high β case (right).

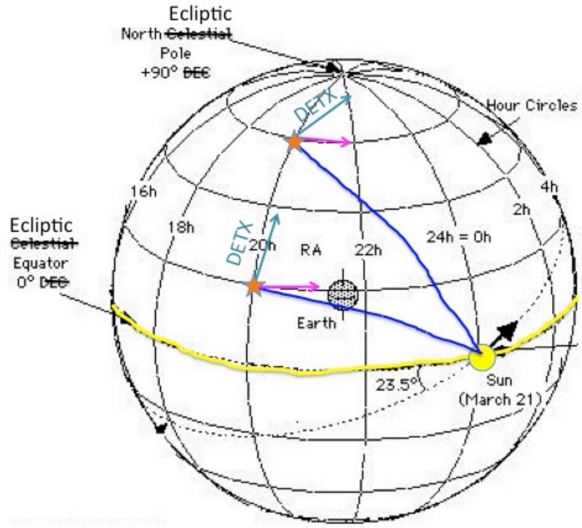
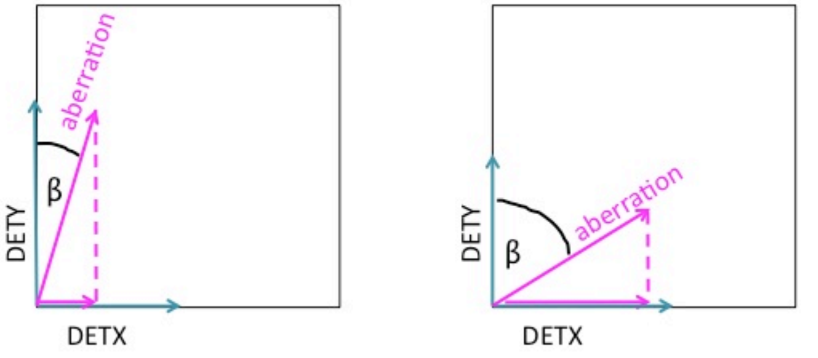


Figure 66. Celestial sphere to illustrate the relationship between ecliptic latitude and ΔDETX. The equator of the sphere is the Ecliptic Equator. See text for discussion.



Source at low ecliptic latitude

Source at high ecliptic latitude

Figure 67. The relationship between DETX and aberration direction at two ecliptic latitudes. In the left case at low β, the component of aberration in the direction of DETX is smaller than in the right case, which is at higher β.

Since the error in DETX, ΔDETX is roughly twice the aberration, and in the same direction, one can see from these illustrations that ΔDETX ~ sinβ. The relationship found in Uchiyama et al (2008) is between ΔDETX and β, but one can see by comparing Figure 64 and 68 that the relationship between ΔDETX and sinβ has less scatter (and has a lower χ^2) than that between ΔDETX and β, although the former is still a good fit.

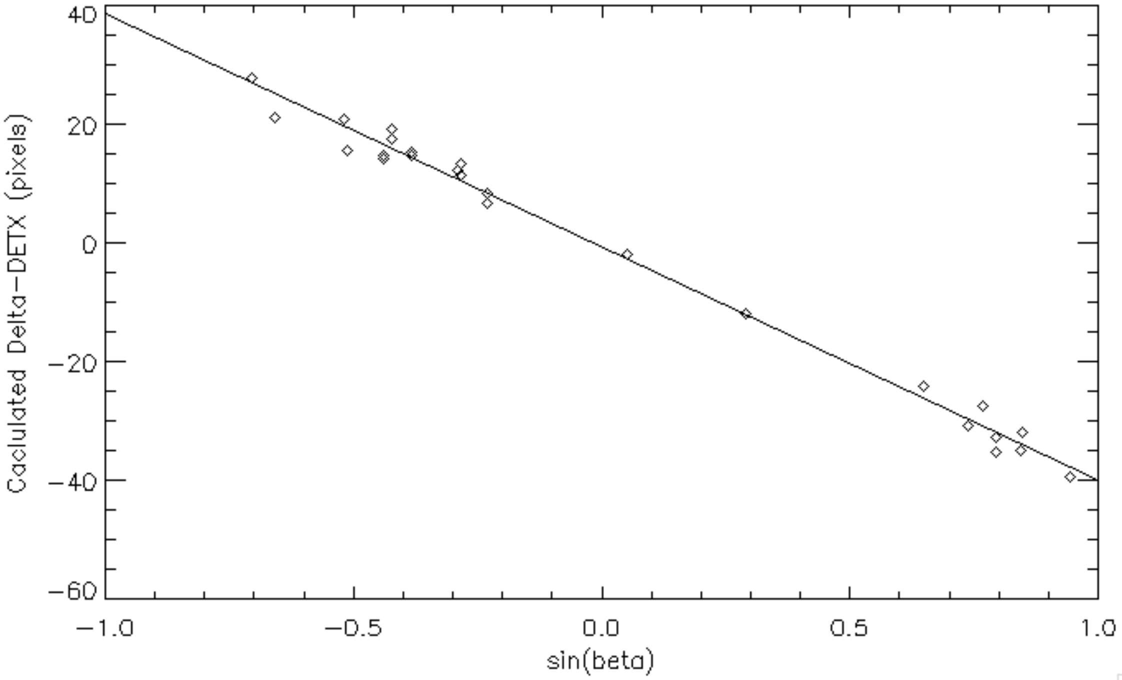
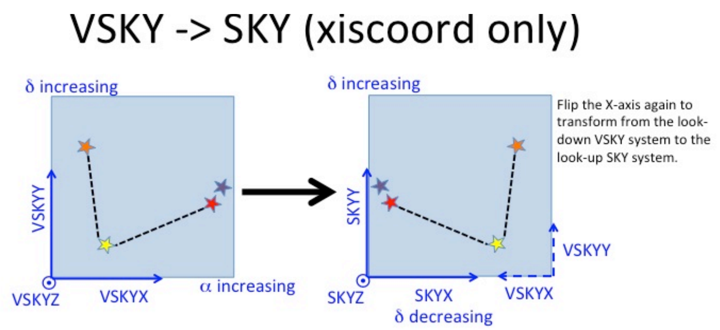


Figure 68. My calculations of ΔDETX (see text above) plotted relative to the sine of the source ecliptic latitude (compare to Figure).

Although this empirical discussion is not a formal (mathematically) derivation of the empirical relationship between ΔDETX and β, it has shown by graphical arguments that the relationship arises from the interplay between the Suzaku sun pointing, the aberration and the ecliptic latitude.



Flip the X-axis again to transform from the look-down VSKY system to the look-up SKY system.

Figure 69 The transformation from VSKY to SKY is a flip of the X-axis to go from look-down (left) to look-up (right).

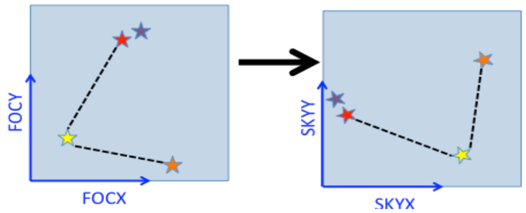


Figure 70. In the final configurations, the FOC and SKY systems are related by a simple 2-d rotation plus translation.

9 Appendix D : Teldef Files

9.1 ApD : SXI Teldef

```
COMMENT -----------------------------------------------------------------------
COMMENT -----------------------------------------------------------------------
COMMENT  Generic coordinate and transformation keywords
COMMENT  -----------------------------------------------------------------------
NCOORDS =                    5 /number of coordinates defined in this file
COORD0  = 'RAW     '           / 0th coordinate system (RAWX,RAWY)
COORD1  = 'ACT     '           / 1st coordinate system (ACTX,ACTY)
COORD2  = 'DET     '           / 2nd coordinate system (DETX,DETY)
COORD3  = 'FOC     '           / 3rd coordinate system (FOCX,FOCY)
COORD4  = 'SKY     '           / 4th coordinate system (X,Y)
TRTYPE0 = 'MULTISEG'           / RAW to ACT transformation
TRTYPE1 = 'RAWTODET'           / ACT to DET
TRTYPE2 = 'BASIC   '           / DET to FOC
TRTYPE3 = 'SKYATT  '           / FOC to SKY
RANCOORD= 'FOC     '           /Origin coordinate for randomization
RAN_SCAL= 'FOC     '           /System to set scale for randomization
COMMENT -----------------------------------------------------------------------
COMMENT RAW coordinate keywords
COMMENT RAW coordinates defines the direct telemetry values
COMMENT RAW coords are defined in the same way for each of the four SXI sensors
COMMENT
COMMENT RAW coordinates are converted to ACT coordinates by the MULTISEG
COMMENT transformation.
COMMENT Description below.
COMMENT -----------------------------------------------------------------------
COMMENT Keywords describing RAW coordinates
RAW_XSIZ=                  640 /RAW address space Xsize (pixel) actual size 320
RAWXPIX1=                    0 /RAW address space x first pixel number (pixel)
```

```
RAW_XSCL=                0.048 /RAW X scale (mm/pixel)
RAW_YSIZ=                  640 /RAW address space Ysize (pixel) actual size 640
RAWYPIX1=                    0 /RAW address space y first pixel number (pixel)
RAW_YSCL=                0.048 /RAW Y scale (mm/pixel)
RAW_UNIT= 'mm      '           /physical unit of RAW
COMMENT  -----------------------------------------------------------------------
COMMENT  Translation from RAWX (pixel) of SEGMENT 'n' to ACTX (pixel)
COMMENT  proceeds in a single step using the coefficients in the MULTISEG0_COEFF
COMMENT
COMMENT  The conversion depends on three properties:
COMMENT  PROPERTY0: SEGMENT (0:1) = (AB:CD)
COMMENT  PROPERTY1: READNODE (0:1) = (A/D,B/C)
COMMENT  PROPERTY2: WINOPT (0:1) = (off,on)
COMMENT  PROPERTY2: WIN_SIZE () = (40,80,160,640)
COMMENT
COMMENT  The generic transformation is
COMMENT ACTX = COEFF_X_A + WINOFFX + COEFF_X_B * (RAWX % COEFF_X_D) +
COMMENT        COEFF_X_C * (RAWY % COEFF_Y_D)
COMMENT ACTY = COEFF_Y_A + WINOFFY + COEFF_Y_B * (RAWX % COEFF_X_D) +
COMMENT        COEFF_Y_C * (RAWY % COEFF_Y_D)
COMMENT  where the coefficients are based on the three properties and provided
COMMENT  in the MULTISEG0_COEFF and the WINOFFX keyword
COMMENT  Note that since there is no "mixing" between RAWX and RAWY,
COMMENT  the COEFF_X_C and COEFF_Y_B are all zero.
COMMENT
COMMENT  The segments and readout nodes are described in the figure below
COMMENT
COMMENT              <------ 640 Active Pixels ------>
COMMENT        ^     +-------+-------+-------+-------+
COMMENT        |     |               |               |
COMMENT        |     |               |               |
COMMENT        |     |               |               |
COMMENT        |     |               |               |
COMMENT              |               |               |
COMMENT       640    |               |               |
COMMENT              |   Segment     |    Segment    | Imaging region
COMMENT      Active  |      AB       |      CD       |
COMMENT              |               |               |
COMMENT      Pixels  |               |               |
COMMENT              |               |               |
COMMENT        |     |RAWY       RAWY|RAWY       RAWY|
COMMENT        |     |^             ^|^             ^|
COMMENT        |     ||  RAWX RAWX  |||  RAWX RAWX  ||
COMMENT   ACTY |     |+--->     <---+|+--->     <---+|
COMMENT   ^    v     +-------+-------+-------+-------+
COMMENT   |           \      |      / \      |      /
COMMENT   |    ACTX    \     |     /   \     |     /
COMMENT   +------->     |    |    |     |    |    |
COMMENT                 |    |    |     |    |    |
COMMENT  (look-down)    |    |    |     |    |    |    Frame-store region
COMMENT                 |    |    |     |    |    |
COMMENT                 |    |    |     |    |    |
COMMENT                 |    |    |     |    |    |
COMMENT                 ===========     ===========    Serial readout register
COMMENT                 |         |     |         |
```

```
COMMENT                 v         v     v         v
COMMENT               Node.A   Node.B Node.C   Node.D
COMMENT
COMMENT  Schematic diagram showing the readout nodes and the relationship
COMMENT  between RAW and ACT coordinates.
COMMENT
COMMENT  In normal operations, the chip is read out from
COMMENT  Node A (Segment AB) and Node C (Segment CD)
COMMENT  However, Nodes B and D are available for redundancy.
COMMENT
COMMENT  The readout can also be done in one of four window modes.
COMMENT  In windowing, a smaller section of a chip is read out at a higher
COMMENT  data rate
COMMENT
COMMENT  Nominally, the centers of the 1/4, 1/8 and 1/16 windows are at the
COMMENT    Y-position of the SXT focus (Chip 2), although this is commandable
COMMENT     and is specified in the WIN_ST keyword in the event file
COMMENT
COMMENT  For all cases,
COMMENT  AB Node A:  ACTX = 1 + RAWX     ACTY = 0 + WIN_ST + (RAWY % WIN_SIZ)
COMMENT  AB Node B:  ACTX = 320 - RAWX   ACTY = 0 + WIN_ST + (RAWY % WIN_SIZ)
COMMENT  CD Node C:  ACTX = 321 + RAWX   ACTY = 0 + WIN_ST + (RAWY % WIN_SIZ)
COMMENT  CD Node D:  ACTX = 640 - RAWX   ACTY = 0 + WIN_ST + (RAWY % WIN_SIZ)
COMMENT
COMMENT  Where the WIN_ST parameters (keywords in the event file) and
COMMENT  WIN_SIZE parameters (corresponding to the COEFF_X_D value in the
COMMENT  MULTISEG0_COEFF table) are
COMMENT  Window:0 (off)   WIN_ST=1     WIN_SIZE=640
COMMENT  Window:1 (1/4)   WIN_ST=415   WIN_SIZE=160
COMMENT  Window:2 (1/8)   WIN_ST=455   WIN_SIZE=80
COMMENT  Window:3 (1/16)  WIN_ST=475   WIN_SIZE=40
COMMENT
COMMENT -----------------------------------------------------------------------
COMMENT Keywords describing ACT coordinates
COMMENT -----------------------------------------------------------------------
ACT_SCOL= 'CCD_ID  '           /column name of a chip in event files
ACT_NSEG=                    4 /number of segments, one for each of 4 chips
ACT_XSIZ=                  640 /ACT address space Xsize (pixel) actual size 640
ACTXPIX1=                    1 /ACT address space x first pixel number (pixel)
ACT_XSCL=                0.048 /ACT X scale (mm/pixel)
ACT_YSIZ=                  640 /ACT address space Ysize (pixel) actual size 640
ACTYPIX1=                    1 /ACT address space y first pixel number (pixel)
ACT_YSCL=                0.048 /ACT Y scale (mm/pixel)
ACT_UNIT= 'mm      '           /physical unit of ACT
ACTXFLIP=                    1 /ACT coords are look down, so no flipping
ACTYFLIP=                    1 /
COMMENT -----------------------------------------------------------------------
COMMENT
COMMENT  Translation from ACTX/Y (pixel) to DETX/Y (pixel)
COMMENT  The formula is different for each SXI chip,
COMMENT  based on orientation:
COMMENT
COMMENT   SATY            +----->DETX
COMMENT    ^              |
COMMENT    |              |
```

```
COMMENT    |              v
COMMENT    +----->SATX   DETY
COMMENT
COMMENT        CCD-1           CCD-3
COMMENT     +----->               ACTX
COMMENT     |    ACTY               ^
COMMENT     |                       |
COMMENT     v                ACTY   |
COMMENT     ACTX              <-----+
COMMENT
COMMENT        CCD-0           CCD-2
COMMENT     +----->               ACTX
COMMENT     |    ACTY               ^
COMMENT     |                       |
COMMENT     v                ACTY   |
COMMENT     ACTX              <-----+
COMMENT
COMMENT  Thus the transformation coefficients
COMMENT  are unique to the individual SXI chip.
COMMENT
COMMENT  The generic transformation is:
COMMENT
COMMENT  DETX = AXN_a + (AXN_b * ACTX) + (AXN_c * ACTY)
COMMENT  DETY = AYN_a + (AYN_b * ACTX) + (AYN_c * ACTY)
COMMENT
COMMENT   The AXN and AYN values are determined by the geometry of the
COMMENT   SXI sensors, taking into account the gaps between detectors and
COMMENT   the relative orientations of the four CCDs,
COMMENT   and setting the DET center to be (905.5, 905.5)
COMMENT
COMMENT  Thus:
COMMENT  AX0_a =  254.217    AX0_b = -0.00227      AX0_c =  1.0
COMMENT  AY0_a =  917.762    AY0_b =  1.0          AY0_c =  0.00227
COMMENT  AX1_a =  251.920    AX1_b =  0.00279      AX1_c =  1.0
COMMENT  AY1_a =  255.481    AY1_b =  1.0          AY1_c = -0.00279
COMMENT  AX2_a = 1558.604    AX2_b = -0.0          AX2_c = -1.0
COMMENT  AY2_a = 1555.173    AY2_b = -1.0          AY2_c =  0.0
COMMENT  AX3_a = 1556.310    AX3_b =  0.00244      AX3_c = -1.0
COMMENT  AY3_a =  894.536    AY3_b = -1.0          AY3_c = -0.00244
COMMENT
COMMENT  -----------------------------------------------------------------------
CO1_X0_A=              254.217 /SXI CCD_ID=0
CO1_X0_B=             -0.00227 /DETX = 0 + ACTY
CO1_X0_C=                1.000 /
CO1_Y0_A=              917.762 /DETY = OFFSET + ACTX
CO1_Y0_B=                1.000 /
CO1_Y0_C=              0.00227 /
CO1_X1_A=              251.920 /SXI CCD_ID=1
CO1_X1_B=              0.00279 /DETX = 0 + ACTY
CO1_X1_C=                1.000 /
CO1_Y1_A=              255.481 /DETY = 0 + ACTX
CO1_Y1_B=                1.000 /
CO1_Y1_C=             -0.00279 /
CO1_X2_A=             1558.604 /SXI CCD_ID=2
CO1_X2_B=               -0.000 /DETX = OFFSET - ACTY
```

```
CO1_X2_C=               -1.000 /
CO1_Y2_A=             1555.173 /DETY = OFFSET - ACTX
CO1_Y2_B=               -1.000 /
CO1_Y2_C=                0.000 /
CO1_X3_A=             1556.310 /SXI CCD_ID=3
CO1_X3_B=              0.00244 /DETX = OFFSET - ACTY
CO1_X3_C=               -1.000 /
CO1_Y3_A=              894.536 /DETY = OFFSET - ACTX
CO1_Y3_B=               -1.000 /
CO1_Y3_C=             -0.00244 /
IN1_XCEN=                905.5 /x center of ACT pixel measurement coordinates
IN1_YCEN=                905.5 /y center of ACT pixel measurement coordinates
COMMENT  -----------------------------------------------------------------------
COMMENT  DET coordinate keywords
COMMENT      DET coordinates are fixed to the detector, look-up
COMMENT  -----------------------------------------------------------------------
DET_XSIZ=                 1810 /DET address space x size (pixels)
DETXPIX1=                    1 /DET address space x first pixel number (pixel)
DET_XSCL=                0.048 /DET address space mm per x det unit (mm/pixel)
DET_YSIZ=                 1810 /DET address space y size (pixels)
DETYPIX1=                    1 /DET address space y first pixel number (pixel)
DET_YSCL=                0.048 /DET address space mm per y det unit (mm/pixel)
DET_UNIT= 'mm      '           /physical unit of DET
DETXFLIP=                    1 /All transformations to DET are
DETYFLIP=                    1 /carried out using coefficients
DET_ROTD=                    0 /where the flip is taken care of
COMMENT  -----------------------------------------------------------------------
COMMENT  FOC coordinate keywords
COMMENT      FOC coordinates are aligned with SXS and HXI
COMMENT  -----------------------------------------------------------------------
FOC_XSIZ=                 2430 /FOC address space x size (pixels)
FOCXPIX1=                    1 /FOC address space x first pixel number (pixel)
FOC_XSCL=                0.048 /FOC X scale (mm/pixel)
FOC_YSIZ=                 2430 /FOC address space y size (pixels)
FOCYPIX1=                    1 /FOC address space y first pixel number (pixel)
FOC_YSCL=                0.048 /FOC Y scale (mm/pixel)
FOC_UNIT= 'mm      '           /physical unit of FOC
COMMENT  -----------------------------------------------------------------------
COMMENT
COMMENT  Translation from DECX/Y (pixel) to FOCX/Y (pixel)
COMMENT
COMMENT    TMPX = DETX - DET_XCEN - FOC_XOFF
COMMENT    TMPY = DETY - DET_YCEN - FOC_YOFF
COMMENT
COMMENT    FOCX = FOC_XCEN + cos(FOC_ROTD)*TMPX - sin(FOC_ROTD)*TMPY
COMMENT    FOCY = FOC_YCEN + sin(FOC_ROTD)*TMPX + cos(FOC_ROTD)*TMPY
COMMENT
COMMENT          DET_XCEN = DETXPIX1 + (DET_XSIZ - 1) / 2.0 = 905.5
COMMENT          DET_YCEN = DETYPIX1 + (DET_YSIZ - 1) / 2.0 = 905.5
COMMENT
COMMENT          FOC_XCEN = FOCXPIX1 + (FOC_XSIZ - 1) / 2.0 = 905.5
COMMENT          FOC_YCEN = FOCYPIX1 + (FOC_YSIZ - 1) / 2.0 = 905.5
COMMENT
COMMENT           DETY (pixel)
COMMENT             ^
```

```
COMMENT             |
COMMENT             |  x (DET_XCEN+FOC_XOFF, DET_YCEN+FOC_YOFF)
COMMENT             |
COMMENT             +-------> DETX (pixel)
COMMENT
COMMENT           _ DETX
COMMENT           /|
COMMENT          /
COMMENT         / FOC_ROTD gives the angle (deg) between the DETX and FOCX
COMMENT        /  axes measured counter-clockwise from FOCX axis
COMMENT       +---------> FOCX
COMMENT
COMMENT  -----------------------------------------------------------------------
FOC_XOFF=              -122.646 /DETX offset (pixel) to the FOC center position
FOC_YOFF=              -113.663 /DETY offset (pixel) to the FOC center position
FOC_ROTD=                   0.0 /DET rotation angle (deg) in FOC coordinates
COMMENT  -----------------------------------------------------------------------
COMMENT  SKY coordinate keywords
COMMENT      unique sky direction (RA, DEC) corresponds to each SKYX/Y pixel
COMMENT  -----------------------------------------------------------------------
SKY_XSIZ=                  2430 /SKY address space x size (pixels)
SKYXPIX1=                     1 /SKY address space x first pixel number (pixel)
SKY_XSCL=                 0.048 /SKY X scale (mm/pixel)
SKY_YSIZ=                  2430 /SKY address space y size (pixels)
SKYYPIX1=                     1 /SKY address space y first pixel number (pixel)
SKY_YSCL=                 0.048 /SKY Y scale (mm/pixel)
SKY_UNIT= 'deg      '           /physical unit of SKY
COMMENT  -----------------------------------------------------------------------
COMMENT
COMMENT  Translation from FOCX/Y (pixel) to SKYX/Y (pixel)
COMMENT
COMMENT  The transformation from FOC to SKY is defined as the product of
COMMENT  three quaternions.
COMMENT
COMMENT  The first is the alignment quaternion Q_M, which is the equivalent
COMMENT  of the 3x3 alignment rotation matrix Mij, specified in this teldef
COMMENT
COMMENT  The second is the attitude quaternion Q_A, which contains the
COMMENT  attitude information of the satellite
COMMENT
COMMENT  The third is the nominal pointing quaternion Q_B, which is
COMMENT  calculated from the reference angles.
COMMENT      The reference angle is found from one of the following places
COMMENT  in order:
COMMENT  First:  Look at the input ra, dec, roll parameters
COMMENT  Second: If dec is outside the range -90 < dec < +90 (degrees)
COMMENT          then look for the DEC_NOM keyword in the event file.
COMMENT          If ra is outside the range 0 < ra < +360 (degrees)
COMMENT          then look for the RA_NOM keyword in the event file.
COMMENT  Third: If the DEC_NOM keyword is not found, then look for the
COMMENT         DEC_PNT keyword. If DEC_PNT is not found exit with an error.
COMMENT         If the RA_NOM keyword is not found, then look for the
COMMENT         RA_PNT keyword. If RA_PNT is not found exit with an error.
COMMENT
COMMENT  Note that the coordevt tool does not read the PA_NOM or PA_PNT
```

```
COMMENT  keywords.  The roll must be specified as a parameter.
COMMENT  The default roll value is 0.
COMMENT  Roll represents an angle of SKYY measured counter-clockwise
COMMENT  from the north direction, and is usually set to zero.
COMMENT
COMMENT  The final transformation is derived as
COMMENT               -1             -1
COMMENT       Q = (Q_B   x Q_A x Q_M  ).  Thus SKY = Q x FOC
COMMENT
COMMENT  Since both FOC and SKY are look-up tangent plane coordinates, the
COMMENT  quaternion is rendered as a combination of a 2-d rotation and a
COMMENT  translation contained in a structure of type XFORM2D.
COMMENT
COMMENT  In component form, this is
COMMENT              [SKY_X] = [ROT00  ROT01] [FOC_X] + [DX]
COMMENT              [SKY_Y]   [ROT10  ROT11] [FOC_Y]   [DY]
COMMENT
COMMENT  The aberration correction is also carried out at this stage, with
COMMENT  the correction added to the translation part of the XFORM2D:
COMMENT              [SKY-X] = [ROT00  ROT01] [FOC-X] + [DX] + [DXaberr]
COMMENT              [SKY-Y]   [ROT10  ROT11] [FOC-Y]   [DY]   [DYaberr]
COMMENT
COMMENT  The aberration correction is derived by projecting the inverse of the
COMMENT  earth velocity unit direction vector u onto the tangent plane:
COMMENT              [DXaberr]  =  - [B00  B01  B02] x [-ux] x [S]
COMMENT              [DYaberr]       [B10  B11  B12]   [-uy]
COMMENT                                                [-uz]
COMMENT  The Bij are the first two rows of the 3x3 rotation matrix corresponding
COMMENT  to Q_B.  The minus sign in the first row of the Bij term is there
COMMENT  because SKYX is by convention opposite to increasing RA.  The minus
COMMENT  sign on the velocity unit vector is because the SKY pixel values are
COMMENT  corrected (i.e. rather than the coordinates); thus there is a
COMMENT  correction in the opposite direction to the aberration.
COMMENT  The scale factor S is derived as
COMMENT               S = (v/c)/(SKY_XSCL/FOCALLEN)
COMMENT  Here v=29.78 km/s is the mean Earth velocity, c is the speed of light,
COMMENT  SKY_XSCL = 0.048 mm/pixel and FOCALLEN = 5600.0 mm
COMMENT  Thus         S = 11.6 pixels
COMMENT
COMMENT        In SKY coordinates, 1 mm roughly corresponds to
COMMENT        atan(1/FOCALLEN) radian on the sky.
COMMENT
COMMENT  -----------------------------------------------------------------------
FOCALLEN=               5600.0 /SXT focal length (mm)
FOC_M11 =                  1.0 /SAT -> FOC coordinates alignment matrix Mij
FOC_M12 =                  0.0 /
FOC_M13 =                  0.0 /
FOC_M21 =                  0.0 /[3x3 rotation matrix, common to all sensors]
FOC_M22 =                  1.0 /
FOC_M23 =                  0.0 /FOCX =    M11*SATX + M12*SATY + M13*SATZ
FOC_M31 =                  0.0 /FOCY =    M21*SATX + M22*SATY + M23*SATZ
FOC_M32 =                  0.0 /FOCZ =    M31*SATX + M32*SATY + M33*SATZ
FOC_M33 =                  1.0 /
COMMENT  -----------------------------------------------------------------------
ALIGNM11=                  1.0 / This matrix is redundant to the FOC_MXX matrix
```

```
ALIGNM12=                  0.0 / above, but both are required.  The FOC_MXX
ALIGNM13=                  0.0 / matrix is used by the teldef2 code (and ALIGNMX
ALIGNM21=                  0.0 / is obsolete).
ALIGNM22=                  1.0 / However, the aspect tool requires the ALIGNMXX
ALIGNM23=                  0.0 / keywords.
ALIGNM31=                  0.0 /
ALIGNM32=                  0.0 /
ALIGNM33=                  1.0 /
COMMENT  ----------------------------------------------------------------------
COMMENT  miscellaneous keywords
COMMENT  ----------------------------------------------------------------------
COMMENT   Optical axis position is not used in coordinates transformation,
COMMENT   but needed for generating ARFs. Optical axis position is determined
COMMENT   from the counting rate maximum.
OPTCOORD= 'DET     '           /optical axis is defined in DET coordinates
OPTAXISX=              783.464 /optical axis x in DET coordinates (pixel)
OPTAXISY=              794.180 /optical axis y in DET coordinates (pixel)
OPT_ROTD=              0.00000 /rotation of telescope output system wrt DET
OPTXFLIP=                    1 /flip of telescope axes relative to DETX/Y
OPTYFLIP=                   -1 /flip from (look-down) to (look-up)
COMMENT
COMMENT  All the values above are tentative without in-orbit calibrations
COMMENT  (basically ideal values).
COMMENT
ROLLSIGN=                 -1.0 /Roll sign convention
ROLLOFF =                  0.0 /Roll offset (degrees)

-----------------------------------------------------------------------

COMMENT
COMMENT  The coefficients in this table are used to convert coordinates as
COMMENT  follows, where CRD1 is the lower-level system and CRD2 the higher:
COMMENT
COMMENT CRD2X = COEFF_X_A+WINOFFX + COEFF_X_B * ((CRD1X-COEFF_X_E) % COEFF_X_D)+
COMMENT         COEFF_X_C * ((CRD1Y-COEFF_Y_E) % COEFF_Y_D)
COMMENT CRD2Y = COEFF_Y_A+WINOFFY + COEFF_Y_B * ((CRD1X-COEFF_X_E) % COEFF_X_D)+
COMMENT         COEFF_Y_C * ((CRD1Y-COEFF_Y_E) % COEFF_Y_D)
COMMENT
NPROP   =                    4 /Number of segment property columns
PROP0   = 'SEGMENT '           /The segment ID number within a chip (0:1)
PROP1   = 'READNODE'           /The read-out node (0:1)
PROP2   = 'WINOPT  '           /The windowing mode (0:1)
PROP3   = 'WIN_SIZE'           /The window size (640,160,80,40)
WINOFFX = 'NONE    '           /Windowing X offset keyword name
WINPROPX= 'NONE    '           /Windowing X offset property name
WINOFFY = 'WIN_ST  '           /Windowing Y offset keyword name
WINPROPY= 'NONE    '           /Windowing Y offset property name
```

9.2 ApD : SXS Teldef

The content of the teldef file header is the following, excluding the mandatory keywords.

```
COMMENT ----------------------------------------------------------------------
```

```
COMMENT  Generic coordinate keywords
COMMENT  -----------------------------------------------------------------------
NCOORDS =                    5 /number of coordinates defined in this file
COORD0  = 'RAW     '           /0th coordinate system (RAWX,RAWY)
COORD1  = 'ACT     '           /1st coordinate system (ACTX,ACTY)
COORD2  = 'DET     '           /2nd coordinate system (DETX,DETY)
COORD3  = 'FOC     '           /3rd coordinate system (FOCX,FOCY)
COORD4  = 'SKY     '           /4th coordinate system (X,Y)
TRTYPE0 = 'RAWTODET'           / RAW to ACT transformation
TRTYPE1 = 'BASIC   '           / ACT to DET
TRTYPE2 = 'BASIC   '           / DET to FOC
TRTYPE3 = 'SKYATT  '           / FOC to SKY
RANCOORD= 'DET     '           /Origin coordinate for randomization
RAN_SCAL= 'DET     '           /System to set scale for randomization
COMMENT -----------------------------------------------------------------------
COMMENT RAW coordinate keywords
COMMENT RAW coordinates are defined using pixel corners
COMMENT in the 'PIXEL_MAP' extension
COMMENT -----------------------------------------------------------------------
RAW_SCOL= 'PIXEL   '           /Each XRS pixel is a segment
RAW_NSEG=                   36 /number of segments, 36 pixels for SXS
RAW_XSIZ=                    1 /only one pixel per segment
RAWXPIX1=                    1 /arbitrary coordinate of single pixel
RAW_YSIZ=                    1 /only one pixel per segment
RAWYPIX1=                    1 /arbitrary coordinate of single pixel
RAW_UNIT= 'mm      '           /physical unit of RAW
COMMENT  -----------------------------------------------------------------------
COMMENT  ACT coordinate keywords
COMMENT      ACT coordinates are fixed to the detector, look-down
COMMENT      and are linearized to the physical positions of the detector pixels
COMMENT
COMMENT      Note that the scale of the ACT coordinates is matched to the
COMMENT      pitch scale of the SXS, which is slightly larger than the physical
COMMENT      the SXS detectors.
COMMENT  -----------------------------------------------------------------------
COMMENT  -----------------------------------------------------------------------
COMMENT
COMMENT  Translation from pixel measurement PIXELX/Y (mm) to ACTX/Y (pixel)
COMMENT
COMMENT   ACTX = ACT_XCEN + ACTXFLIP * (PIXELX - ACT_XSIZ - ACT_XOFF) / ACT_SCAL
COMMENT   ACTY = ACT_YCEN + ACTYFLIP * (PIXELY - INT_YCEN - ACT_YOFF) / ACT_SCAL
COMMENT
COMMENT   The offsets ACT_XOFF,ACT_YOFF are set so that when PIXELX/PIXELY = 0,0
COMMENT   ACTX = 3.5, ACTY = 3.5, which is the nominal location of
COMMENT   the center of the SXS field in ACT coordinates.
COMMENT
COMMENT   3.5 = 4.5 + 1*(0 - 0 - ACT_XOFF)/0.832
COMMENT   1.0 = ACT_XOFF/0.832
COMMENT   ACT_XOFF = 0.832
COMMENT
COMMENT   3.5 = 4.5 - 1*(0 - 0 - ACT_YOFF)/0.832
COMMENT   -1.0 = ACT_YOFF/0.832
COMMENT   ACT_YOFF = -0.832
COMMENT
COMMENT          ACT_XCEN = ACTXPIX1 + (ACT_XSIZ - 1) / 2.0 = 4.5
```

```
COMMENT          ACT_YCEN = ACTYPIX1 + (ACT_YSIZ - 1) / 2.0 = 4.5
COMMENT
COMMENT           PIXELY
COMMENT             ^
COMMENT             |
COMMENT             |  x (ACT_XOFF,ACT_YOFF)
COMMENT             |
COMMENT             +--------> PIXELX
COMMENT
COMMENT    (ACT_XOFF,ACT_YOFF) is origin of the ACT coordinates
COMMENT
COMMENT  -----------------------------------------------------------------------
ACT_XSIZ=                    8 /ACT address space x size (pixels)
ACTXPIX1=                    1 /ACT address space x first pixel number (pixel)
ACT_XSCL=                0.832 /ACT X scale (mm/pixel)
ACT_YSIZ=                    8 /ACT address space y size (pixels)
ACTYPIX1=                    1 /ACT address space y first pixel number (pixel)
ACT_YSCL=                0.832 /ACT Y scale (mm/pixel)
ACT_UNIT= 'mm      '           /physical unit of ACT
ACT_SCAL=                0.832 /pixel measurement unit (mm) per one ACT pixel
IN0_XCEN=                  0.0 /x center of RAW pixel measurement coordinates
IN0_YCEN=                  0.0 /y center of RAW pixel measurement coordinates
ACT_XOFF=                0.832 /RAWX offset (mm) to the ACT center position
ACT_YOFF=                0.832 /RAWY offset (mm) to the ACT center position
ACTXFLIP=                    1 /do not flip x-axis in RAW -> ACT
ACTYFLIP=                    1 /do not flip y-axis in RAW -> ACT
COMMENT  -----------------------------------------------------------------------
COMMENT  DET coordinate keywords
COMMENT      DET coordinates are fixed to the detector, look-up
COMMENT      and are linearized to the physical positions of the detector pixels
COMMENT
COMMENT      Note that the scale of the DET coordinates is matched to the
COMMENT      pitch scale of the SXS, which is slightly larger than the physical
COMMENT      the SXS detectors.
COMMENT  -----------------------------------------------------------------------
DET_XSIZ=                    8 /DET address space x size (pixels)
DETXPIX1=                    1 /DET address space x first pixel number (pixel)
DET_XSCL=                0.832 /DET address space mm per x det unit (mm/pixel)
DET_YSIZ=                    8 /DET address space y size (pixels)
DETYPIX1=                    1 /DET address space y first pixel number (pixel)
DET_YSCL=                0.832 /DET address space mm per y det unit (mm/pixel)
DET_UNIT= 'mm      '           /physical unit of DET
DET_SCAL=                1.000 /Conversion between ACT and DET scales
DETXFLIP=                    1 /do not flip x-axis in RAW -> DET
DETYFLIP=                   -1 /flip y-axis in RAW (look-down) -> DET (look-up)
DET_ROTD=                  180 /Rotate by 180 degrees between ACT and DET
DET_XOFF=                   -2 /Correct to put the cal pixel at (1,1)
DET_YOFF=                    0 /No correction for Y
COMMENT  -----------------------------------------------------------------------
COMMENT  FOC coordinate keywords
COMMENT      FOC coordinates are aligned with SXI and HXI
COMMENT  -----------------------------------------------------------------------
FOC_XSIZ=                 2430 /FOC address space x size (pixels)
FOCXPIX1=                    1 /FOC address space x first pixel number (pixel)
FOC_XSCL=                0.048 /FOC X scale (mm/pixel)
```

```
FOC_YSIZ=                 2430 /FOC address space y size (pixels)
FOCYPIX1=                    1 /FOC address space y first pixel number (pixel)
FOC_YSCL=                0.048 /FOC Y scale (mm/pixel)
FOC_UNIT= 'mm      '           /physical unit of FOC
FOC_SCAL=               0.0577 /Conversion between DET and FOC scales
COMMENT  -----------------------------------------------------------------------
COMMENT By definition, the center of the FOC system is at spacecraft Z-axis
COMMENT This is near the center of the SXS instrument.
COMMENT The physical center is offset by ~1 from the SXS DET system center.
COMMENT  -----------------------------------------------------------------------
FOC_XOFF=              -0.8637 / DETX offset (pixel) to the FOC center position
FOC_YOFF=              -0.8582 / DETY offset (pixel) to the FOC center position
FOC_ROTD=                0.000 /DET rotation angle (deg) in FOC coordinates
COMMENT  -----------------------------------------------------------------------
COMMENT  SKY coordinate keywords
COMMENT      unique sky direction (RA, DEC) corresponds to each SKYX/Y pixel
COMMENT  -----------------------------------------------------------------------
SKY_XSIZ=                 2430 /SKY address space x size (pixels)
SKYXPIX1=                    1 /SKY address space x first pixel number (pixel)
SKY_XSCL=                0.048 /SKY X scale (mm/pixel)
SKY_YSIZ=                 2430 /SKY address space y size (pixels)
SKYYPIX1=                    1 /SKY address space y first pixel number (pixel)
SKY_YSCL=                0.048 /SKY Y scale (mm/pixel)
SKY_UNIT= 'deg     '           /physical unit of SKY
COMMENT  -----------------------------------------------------------------------
COMMENT
COMMENT  Translation from FOCX/Y (pixel) to SKYX/Y (pixel)
COMMENT
COMMENT  The transformation from FOC to SKY is defined as the product of
COMMENT  three quaternions.
COMMENT
COMMENT  The first is the alignment quaternion Q_M, which is the equivalent
COMMENT  of the 3x3 alignment rotation matrix Mij, specified in this teldef
COMMENT
COMMENT  The second is the attitude quaternion Q_A, which contains the
COMMENT  attitude information of the satellite
COMMENT
COMMENT  The third is the nominal pointing quaternion Q_B, which is
COMMENT  calculated from the reference angles.
COMMENT      The reference angle is found from one of the following places
COMMENT  in order:
COMMENT  First:  Look at the input ra, dec, roll parameters
COMMENT  Second: If dec is outside the range -90 < dec < +90 (degrees)
COMMENT          then look for the DEC_NOM keyword in the event file.
COMMENT          If ra is outside the range 0 < ra < +360 (degrees)
COMMENT          then look for the RA_NOM keyword in the event file.
COMMENT  Third: If the DEC_NOM keyword is not found, then look for the
COMMENT         DEC_PNT keyword. If DEC_PNT is not found exit with an error.
COMMENT         If the RA_NOM keyword is not found, then look for the
COMMENT         RA_PNT keyword. If RA_PNT is not found exit with an error.
COMMENT
COMMENT  Note that the coordevt tool does not read the PA_NOM or PA_PNT
COMMENT  keywords.  The roll must be specified as a parameter.
COMMENT  The default roll value is 0.
COMMENT  Roll represents an angle of SKYY measured counter-clockwise
```

```
COMMENT  from the north direction, and is usually set to zero.
COMMENT
COMMENT  The final transformation is derived as
COMMENT               -1            -1
COMMENT       Q = (Q_B   x Q_A x Q_M  ).  Thus SKY = Q x FOC
COMMENT
COMMENT  Since both FOC and SKY are look-up tangent plane coordinates, the
COMMENT  quaternion is rendered as a combination of a 2-d rotation and a
COMMENT  translation contained in a structure of type XFORM2D.
COMMENT
COMMENT  In component form, this is
COMMENT              [SKY_X] = [ROT00  ROT01] [FOC_X] + [DX]
COMMENT              [SKY_Y]   [ROT10  ROT11] [FOC_Y]   [DY]
COMMENT
COMMENT  The aberration correction is also carried out at this stage, with
COMMENT  the correction added to the translation part of the XFORM2D:
COMMENT              [SKY-X] = [ROT00  ROT01] [FOC-X] + [DX] + [DXaberr]
COMMENT              [SKY-Y]   [ROT10  ROT11] [FOC-Y]   [DY]   [DYaberr]
COMMENT
COMMENT  The aberration correction is derived by projecting the inverse of the
COMMENT  earth velocity unit direction vector u onto the tangent plane:
COMMENT              [DXaberr]  =  - [B00  B01  B02] x [-ux] x (S)
COMMENT              [DYaberr]       [B10  B11  B12]   [-uy]
COMMENT                                                [-uz]
COMMENT  The Bij are the first two rows of the 3x3 rotation matrix corresponding
COMMENT  to Q_B.  The minus sign in the first row of the Bij term is there
COMMENT  because SKYX is by convention opposite to increasing RA.  The minus
COMMENT  sign on the velocity unit vector is because the SKY pixel values are
COMMENT  corrected (i.e. rather than the coordinates); thus there is a
COMMENT  correction in the opposite direction to the aberration.
COMMENT  The scale factor S is derived as
COMMENT               S = (v/c)/(SKY_XSCL/FOCALLEN)
COMMENT  Here v=29.78 km/s is the mean Earth velocity, c is the speed of light,
COMMENT  SKY_XSCL = 0.048 mm/pixel and FOCALLEN = 5600.0 mm
COMMENT  Thus         S = 11.6 pixels
COMMENT
COMMENT        In SKY coordinates, 1 mm roughly corresponds to
COMMENT        atan(1/FOCALLEN) radian on the sky.
COMMENT
COMMENT  -----------------------------------------------------------------------
FOCALLEN=               5600.0 /SXT focal length (mm)
FOC_M11 =                  1.0 /SAT -> FOC coordinates alignment matrix Mij
FOC_M12 =                  0.0 /(look-down) (look-up)
FOC_M13 =                  0.0 /
FOC_M21 =                  0.0 /[3x3 rotation matrix, common to all sensors]
FOC_M22 =                  1.0 /
FOC_M23 =                  0.0 /FOCX =    M11*SATX + M12*SATY + M13*SATZ
FOC_M31 =                  0.0 /FOCY =    M21*SATX + M22*SATY + M23*SATZ
FOC_M32 =                  0.0 /FOCZ =    M31*SATX + M32*SATY + M33*SATZ
FOC_M33 =                  1.0 /
COMMENT  -----------------------------------------------------------------------
ALIGNM11=                  1.0 / This matrix is redundant to the FOC_MXX matrix
ALIGNM12=                  0.0 / above, but both are required.  The FOC_MXX
ALIGNM13=                  0.0 / matrix is used by the teldef2 code (and ALIGNMX
ALIGNM21=                  0.0 / is obsolete).
```

```
ALIGNM22=                  1.0 / However, the aspect tool requires the ALIGNMXX
ALIGNM23=                  0.0 / keywords.
ALIGNM31=                  0.0 /
ALIGNM32=                  0.0 /
ALIGNM33=                  1.0 /
COMMENT  --------------------------------------------------------------------
COMMENT  miscellaneous keywords
COMMENT  --------------------------------------------------------------------
COMMENT   Optical axis position is not used in coordinates transformation,
COMMENT   but needed for generating ARFs. Optical axis position is determined
COMMENT   from the counting rate maximum.
OPTCOORD= 'DET     '           /optical axis is defined in DET coordinates
OPTAXISX=                3.716 / optical axis x in DET coordinates (pixel)
OPTAXISY=                3.343 / optical axis y in DET coordinates (pixel)
OPT_ROTD=              0.00000 /rotation of telescope output system wrt DET
OPTXFLIP=                    1 /flip of telescope axes relative to DETX/Y
OPTYFLIP=                   -1 /flip from (look-down) to (look-up)
COMMENT -------------------------------------------------------------------
COMMENT SXS specific keywords
COMMENT -------------------------------------------------------------------
CALPIXEL=                   12 /ID number of the calibration pixel
CAL_DETX=                    0 /DET X value for the cal pixel
CAL_DETY=                    0 /DET Y value for the cal pixel
CAL_FOCX=                    0 /FOC X value for the cal pixel
CAL_FOCY=                    0 /FOC Y value for the cal pixel
CAL_X   =                    0 /SKY X value for the cal pixel
CAL_Y   =                    0 /SKY Y value for the cal pixel
CAL_ROLL=                  0.0 /ROLL  value for the cal pixel
COMMENT
COMMENT  All the values above are based on ground calibration
COMMENT  and are subject to modification after on-orbit calibration
COMMENT
ROLLSIGN=                 -1.0 /Roll sign convention
ROLLOFF =                  0.0 /Roll offset (degrees)

-----------------------------------------------------------------------

COMMENT
COMMENT  This extension contains the planar positions of the four corners of
COMMENT  each pixel
COMMENT  Each pixel has a square shape made of HgTe crystal and the nominal
COMMENT  size/pitch/gap of the pixels are 814/832/18 um, respectively.
COMMENT  To a very good approximation the x and y axes correspond to
COMMENT  the Astro-E2 spacecraft axes, and the origin of the coordinate is
COMMENT  placed at the geometric center of the array between the inner most
COMMENT  corners of pixels 0, 17, 18, 35 (indicated by the "@").
COMMENT
COMMENT  Pixel identification numbers are explained in the diagram below,
COMMENT  when looking down the pixels from the telescope side.
COMMENT  The pixel No.12 is the "CAL" pixel,
COMMENT  The actual location of the calibration pixel is around upper left,
COMMENT  outside the array
COMMENT  The corners 1, 2, 3 and 4 of each pixel correspond to the lower-left,
COMMENT  lower-right, upper-right and upper-left, respectively.  An average of
COMMENT  the four corners represents the pixel position of (DETX, DETY).
```

```
COMMENT
COMMENT
COMMENT  +---+---+                 4+---+3
COMMENT  |   |   |                  |   |
COMMENT  +---+---+                 1+---+2
COMMENT
COMMENT
COMMENT              Physical dimension 4.974 mm square
COMMENT        Corner    +---+---+---+---+---+---+
COMMENT   (-2.487,2.487) |   | 14| 16|  8|  6|  5|
COMMENT                  +---+---+---+---+---+---+
COMMENT                  | 11| 13| 15|  7|  4|  3|
COMMENT                  +---+---+---+---+---+---+
COMMENT                  |  9| 10| 17|  0|  2|  1|
COMMENT                  +---+---+---@---+---+---+
COMMENT                  | 19| 20| 18| 35| 28| 27|
COMMENT                  +---+---+---+---+---+---+
COMMENT                  | 21| 22| 25| 33| 31| 29|
COMMENT                  +---+---+---+---+---+---+
COMMENT                  | 23| 24| 26| 34| 32| 30|      Corner
COMMENT                  +---+---+---+---+---+---+ (2.487,-2.487)
COMMENT
COMMENT
COMMENT    PIXELY (mm)
COMMENT    ^
COMMENT    |    Space Craft Coordinates
COMMENT    |   (viewing from the +Z axis, +Y is toward the solar panel)
COMMENT    |
COMMENT    +--------> PIXELX (mm)
COMMENT
COMMENT  Relation to DET-coordinates
COMMENT    DETX [pixel] = DETXFLIP * (PIXELX - DET_XOFF) / DET_SCAL + DET_XCEN
COMMENT    DETY [pixel] = DETYFLIP * (PIXELY - DET_YOFF) / DET_SCAL + DET_YCEN
COMMENT
COMMENT  The values in the table are from calibrations performed
COMMENT  by Dr. Caroline Kilbourne (NASA GSFC) on Sep. 26, 2012
```

9.3 ApD : HXI1 and HXI2 Teldef

The content of the teldef file header is the following, excluding the mandatory keywords.

```
COMMENT ------------------------------------------------------------------------
COMMENT  Generic coordinate keywords
COMMENT  ------------------------------------------------------------------------
NCOORDS =                    5 / number of coordinates defined in this file
COORD0  = 'RAW     '           / 0th coordinate system (RAWX,RAWY)
COORD1  = 'ACT     '           / 1st coordinate system (ACTX,ACTY)
COORD2  = 'DET     '           / 2nd coordinate system (DETX,DETY)
COORD3  = 'FOC     '           / 3rd coordinate system (FOCX,FOCY)
COORD4  = 'SKY     '           / 4th coordinate system (X,Y)
TRTYPE0 = 'SKYATT  '           / RAW to ACT transformation
TRTYPE1 = 'BASIC   '           / ACT to DET
```

```
TRTYPE2 = 'BASIC   '           / DET to FOC
TRTYPE3 = 'SKYATT  '           / FOC to SKY
RANCOORD= 'DET     '           / Origin coordinate for randomization
RAN_SCAL= 'ACT     '           / System to set scale for randomization
COMMENT ------------------------------------------------------------------------
COMMENT RAW coordinate keywords
COMMENT RAW coordinates defines the direct telemetry values
COMMENT      Note that the RAW coordinates are the lowest level for HXI
COMMENT      since the conversion from the RAW channel numbers is done
COMMENT      as part of the basic event analysis code.
COMMENT
COMMENT ------------------------------------------------------------------------
RAW_XSIZ=                  128 / RAW address space Xsize (pixel)
RAWXPIX1=                    1 / RAW address space x first pixel number (pixel)
RAW_XSCL=                0.250 / RAW X scale (mm/pixel)
RAW_YSIZ=                  128 / RAW address space Ysize (pixel)
RAWYPIX1=                    1 / RAW address space y first pixel number (pixel)
RAW_YSCL=                0.250 / RAW Y scale (mm/pixel)
RAW_UNIT= 'mm      '           / physical unit of RAW
RAW_M11 =                  1.0 / ACT -> RAW coordinates alignment matrix Mij
RAW_M12 =                  0.0 / (look-down) (look-down)
RAW_M13 =                  0.0
RAW_M21 =                  0.0 / [3x3 rotation matrix, common to all sensors]
RAW_M22 =                  1.0
RAW_M23 =                  0.0 / RAWX =    M11*ACTX + M12*ACTY + M13*ACTZ
RAW_M31 =                  0.0 / RAWY = - (M21*ACTX + M22*ACTY + M23*ACTZ)
RAW_M32 =                  0.0 / RAWZ =    M31*ACTX + M32*ACTY + M33*ACTZ
RAW_M33 =                  1.0
COMMENT  ------------------------------------------------------------------------
COMMENT  ACT coordinate keywords
COMMENT      ACT coordinates are fixed to the detector, look-up
COMMENT
COMMENT  Transformation from RAW to ACT coordinates uses
COMMENT  a rotation matrix Aij determined from a "delta-attitude"
COMMENT  file giving the offset (Delta-X, Delta-Y, rotation)
COMMENT  between the nominal HXI sensor location and the actual
COMMENT  time-dependent location as derived from the CAMS telemetry.
COMMENT
COMMENT  The ACT coordinates are thus correctly registered to
COMMENT  the HXT boresight
COMMENT  ------------------------------------------------------------------------
ACT_XSIZ=                  256 / ACT address space x size (pixels)
ACTXPIX1=                    1 / ACT address space x first pixel number (pixel)
ACT_XSCL=                0.250 / ACT address space mm per x det unit (mm/pixel)
ACT_YSIZ=                  256 / ACT address space y size (pixels)
ACTYPIX1=                    1 / ACT address space y first pixel number (pixel)
ACT_YSCL=                0.250 / ACT address space mm per y det unit (mm/pixel)
ACT_UNIT= 'mm      '           / physical unit of ACT
COMMENT  ------------------------------------------------------------------------
COMMENT  DET coordinate keywords
COMMENT      DET coordinates are fixed to the detector, look-up
COMMENT
COMMENT  The DET coordinates are transformed to the FOC system
COMMENT  by a simple rotation and translation as described below.
COMMENT  ------------------------------------------------------------------------
```

```
DET_XSIZ=                  256 / DET address space x size (pixels)
DETXPIX1=                    1 / DET address space x first pixel number (pixel)
DET_XSCL=                0.250 / DET address space mm per x det unit (mm/pixel)
DET_YSIZ=                  256 / DET address space y size (pixels)
DETYPIX1=                    1 / DET address space y first pixel number (pixel)
DET_YSCL=                0.250 / DET address space mm per y det unit (mm/pixel)
DET_UNIT= 'mm      '           / physical unit of DET
COMMENT  -----------------------------------------------------------------------
DETXFLIP=                   -1 / X axis flipped when going from RAW (look-down)
DETYFLIP=                    1 / to DET (look-up)
DET_ROTD=                    0
COMMENT  -----------------------------------------------------------------------
COMMENT  FOC coordinate keywords
COMMENT      FOC coordinates are aligned with SXS and SXI
COMMENT
COMMENT    The scale for HXI ACT/DET/FOC coordinates is derived from the SXI
COMMENT    scale as follows:
COMMENT    HXI_SCALE/SXI_SCALE = HXI_FOCALLEN/SXI_FOCALLEN
COMMENT    HXI_SCALE = SXI_SCALE * (HXI_FOCALLEN/SXI_FOCALLEN)
COMMENT    HXI_SCALE = 0.048 * (12000/5600
COMMENT    HXI_SCALE = 0.102857 mm/pixel
COMMENT         in the teldef, this is written as
COMMENT    [ACT,DET,FOC]_[XY]SCL = 0.102857 mm/pixel
COMMENT
COMMENT    and the ACT_SCAL between RAW and ACT is given by
COMMENT    ACT_SCALE = ACT_[XY]SCL/DET_[XY]SCL = 0.103/0.25 = 1.000
COMMENT    ACT_SCAL = 1.00000 (pixel/pixel)
COMMENT
COMMENT  -----------------------------------------------------------------------
FOC_XSIZ=                 2430 / FOC address space x size (pixels)
FOCXPIX1=                    1 / FOC address space x first pixel number (pixel)
FOC_XSCL=                0.103 / FOC X scale (mm/pixel)
FOC_YSIZ=                 2430 / FOC address space y size (pixels)
FOCYPIX1=                    1 / FOC address space y first pixel number (pixel)
FOC_YSCL=                0.103 / FOC Y scale (mm/pixel)
FOC_UNIT= 'mm      '           / physical unit of FOC
FOC_SCAL=             0.411429 / Conversion between DET and FOC scales
COMMENT  -----------------------------------------------------------------------
COMMENT In the design alignment, there is no offset between
COMMENT    HXI DET and FOC
COMMENT  -----------------------------------------------------------------------
FOC_XOFF=               -3.088 / DETX offset (pixel) to the FOC center position
FOC_YOFF=               -0.112 / DETY offset (pixel) to the FOC center position
```

----------------------------------- Specific to HXI1 -----------------------------------

```
FOC_ROTD=               22.500 /DET rotation angle (deg) in FOC coordinates
```

----------------------------------- Specific to HXI2 -----------------------------------

```
FOC_ROTD=              -22.500 /DET rotation angle (deg) in FOC coordinates
```

```
COMMENT  -----------------------------------------------------------------------
COMMENT  SKY coordinate keywords
COMMENT      unique sky direction (RA, DEC) corresponds to each SKYX/Y pixel
COMMENT  -----------------------------------------------------------------------
```

```
SKY_XSIZ=                 2430 /SKY address space x size (pixels)
SKYXPIX1=                    1 /SKY address space x first pixel number (pixel)
SKY_XSCL=                0.103 /SKY X scale (mm/pixel)
SKY_YSIZ=                 2430 /SKY address space y size (pixels)
SKYYPIX1=                    1 /SKY address space y first pixel number (pixel)
SKY_YSCL=                0.103 /SKY Y scale (mm/pixel)
SKY_UNIT= 'deg      '          /physical unit of SKY
COMMENT  --------------------------------------------------------------------
COMMENT
COMMENT  Translation from FOCX/Y (pixel) to SKYX/Y (pixel)
COMMENT
COMMENT  The transformation from FOC to SKY is defined as the product of
COMMENT  three quaternions.
COMMENT
COMMENT  The first is the alignment quaternion Q_M, which is the equivalent
COMMENT  of the 3x3 alignment rotation matrix Mij, specified in this teldef
COMMENT
COMMENT  The second is the attitude quaternion Q_A, which contains the
COMMENT  attitude information of the satellite
COMMENT
COMMENT  The third is the nominal pointing quaternion Q_B, which is
COMMENT  calculated from the reference angles.
COMMENT      The reference angle is found from one of the following places
COMMENT  in order:
COMMENT  First:  Look at the input ra, dec, roll parameters
COMMENT  Second: If dec is outside the range -90 < dec < +90 (degrees)
COMMENT          then look for the DEC_NOM keyword in the event file.
COMMENT          If ra is outside the range 0 < ra < +360 (degrees)
COMMENT          then look for the RA_NOM keyword in the event file.
COMMENT  Third: If the DEC_NOM keyword is not found, then look for the
COMMENT         DEC_PNT keyword. If DEC_PNT is not found exit with an error.
COMMENT         If the RA_NOM keyword is not found, then look for the
COMMENT         RA_PNT keyword. If RA_PNT is not found exit with an error.
COMMENT
COMMENT  Note that the coordevt tool does not read the PA_NOM or PA_PNT
COMMENT  keywords.  The roll must be specified as a parameter.
COMMENT  The default roll value is 0.
COMMENT  Roll represents an angle of SKYY measured counter-clockwise
COMMENT  from the north direction, and is usually set to zero.
COMMENT
COMMENT  The final transformation is derived as
COMMENT             -1            -1
COMMENT       Q = (Q_B   x Q_A x Q_M  ).  Thus SKY = Q x FOC
COMMENT
COMMENT  Since both FOC and SKY are look-up tangent plane coordinates, the
COMMENT  quaternion is rendered as a combination of a 2-d rotation and a
COMMENT  translation contained in a structure of type XFORM2D.
COMMENT
COMMENT  In component form, this is
COMMENT           [SKY_X] = [ROT00  ROT01] [FOC_X] + [DX]
COMMENT           [SKY_Y]   [ROT10  ROT11] [FOC_Y]   [DY]
COMMENT
COMMENT  The aberration correction is also carried out at this stage, with
COMMENT  the correction added to the translation part of the XFORM2D:
COMMENT           [SKY-X] = [ROT00  ROT01] [FOC-X] + [DX] + [DXaberr]
```

```
COMMENT           [SKY-Y]   [ROT10  ROT11] [FOC-Y]   [DY]   [DYaberr]
COMMENT
COMMENT  The aberration correction is derived by projecting the inverse of the
COMMENT  earth velocity unit direction vector u onto the tangent plane:
COMMENT           [DXaberr]  =  - [B00  B01  B02] × [-ux] × (S)
COMMENT           [DYaberr]       [B10  B11  B12]   [-uy]
COMMENT                                   [-uz]
COMMENT  The Bij are the first two rows of the 3x3 rotation matrix corresponding
COMMENT  to Q_B.  The minus sign in the first row of the Bij term is there
COMMENT  because SKYX is by convention opposite to increasing RA.  The minus
COMMENT  sign on the velocity unit vector is because the SKY pixel values are
COMMENT  corrected (i.e. rather than the coordinates); thus there is a
COMMENT  correction in the opposite direction to the aberration.
COMMENT  The scale factor S is derived as
COMMENT               S = (v/c)/(SKY_XSCL/FOCALLEN)
COMMENT  Here v=29.78 km/s is the mean Earth velocity, c is the speed of light,
COMMENT  SKY_XSCL = 0.048 mm/pixel and FOCALLEN = 5600.0 mm
COMMENT  Thus         S = 11.6 pixels
COMMENT
COMMENT        In SKY coordinates, 1 mm roughly corresponds to
COMMENT        atan(1/FOCALLEN) radian on the sky.
COMMENT
COMMENT  -----------------------------------------------------------------------
COMMENT  -----------------------------------------------------------------------
COMMENT  miscellaneous keywords
COMMENT  -----------------------------------------------------------------------
COMMENT   Optical axis position is not used in coordinates transformation,
COMMENT   but needed for generating ARFs. Optical axis position is determined
COMMENT   from the counting rate maximum.
FOCALLEN=              12000.0 /SXT focal length (mm)
FOC_M11 =                  1.0 /SAT -> FOC coordinates alignment matrix Mij
FOC_M12 =                  0.0 /(look-down) (look-up)
FOC_M13 =                  0.0 /
FOC_M21 =                  0.0 /[3x3 rotation matrix, common to all sensors]
FOC_M22 =                  1.0 /
FOC_M23 =                  0.0 /FOCX =    M11*SATX + M12*SATY + M13*SATZ
FOC_M31 =                  0.0 /FOCY =    M21*SATX + M22*SATY + M23*SATZ
FOC_M32 =                  0.0 /FOCZ =    M31*SATX + M32*SATY + M33*SATZ
FOC_M33 =                  1.0 /
COMMENT  -----------------------------------------------------------------------
ALIGNM11=                  1.0 / This matrix is redundant to the FOC_MXX matrix
ALIGNM12=                  0.0 / above, but both are required.  The FOC_MXX
ALIGNM13=                  0.0 / matrix is used by the teldef2 code (and ALIGNMX
ALIGNM21=                  0.0 / is obsolete).
ALIGNM22=                  1.0 / However, the aspect tool requires the ALIGNMXX
ALIGNM23=                  0.0 / keywords.
ALIGNM31=                  0.0 /
ALIGNM32=                  0.0 /
ALIGNM33=                  1.0 /
COMMENT  -----------------------------------------------------------------------
COMMENT  miscellaneous keywords
COMMENT  -----------------------------------------------------------------------
COMMENT   Optical axis position is not used in coordinates transformation,
COMMENT   but needed for generating ARFs. Optical axis position is determined
COMMENT   from the counting rate maximum.
```

```
OPTCOORD= 'DET     '           /optical axis is defined in DET coordinates
```

-------------------------------- **Specific to HXI1** --------------------------------

```
OPTAXISX=              128.470 / optical axis x in DET coordinates (pixel)
OPTAXISY=              127.010 / optical axis y in DET coordinates (pixel)
OPT_ROTD=              0.00000 / rotation of telescope output system wrt DET
OPTXFLIP=                    1 / flip of telescope axes relative to DETX/Y
OPTYFLIP=                   -1 / flip from (look-down) to (look-up)
OPTACTX =              128.530 / optical axis x in ACT coordinates (pixel)
OPTACTY =              127.010 / optical axis y in ACT coordinates (pixel)
COMMENT
COMMENT  The below keywords HXI_XXXX are used by det2att and not coordevt
HXI_XLOC=              465.000 /HXI-1 X location (mm) in S/C coordinates
HXI_YLOC=              195.000 /HXI-1 Y location (mm)  in S/C coordinates
HXI_ROTD=              157.500 /HXI-1 rotation (deg) in S/C coordinates
HXI_XPHY=              32.0000 /Physical size of HX sensor (mm)
HXI_YPHY=              32.0000 /Physical size of HX sensor (mm)
```

-------------------------------- **Specific to HXI2** --------------------------------

```
OPTAXISX=              126.663 / optical axis x in DET coordinates (pixel)
OPTAXISY=              123.746 / optical axis y in DET coordinates (pixel)
OPT_ROTD=              0.00000 / rotation of telescope output system wrt DET
OPTXFLIP=                    1 / flip of telescope axes relative to DETX/Y
OPTYFLIP=                   -1 / flip from (look-down) to (look-up)
OPTACTX =              130.337 / optical axis x in ACT coordinates (pixel)
OPTACTY =              123.746 / optical axis y in ACT coordinates (pixel)
COMMENT
COMMENT  The below keywords HXI_XXXX are used by det2att and not coordevt
HXI_XLOC=             -465.000 /HXI-2 X location (mm) in S/C coordinates
HXI_YLOC=              195.000 /HXI-2 Y location (mm)  in S/C coordinates
HXI_ROTD=              202.500 /HXI-2 rotation (deg) in S/C coordinates
HXI_XPHY=              32.0000 /Physical size of HX sensor (mm)
HXI_YPHY=              32.0000 /Physical size of HX sensor (mm)
```

```
COMMENT
COMMENT  All the values above are tentative without in-orbit calibrations
COMMENT  (basically ideal values).
COMMENT
ROLLSIGN=                 -1.0 /Roll sign convention
ROLLOFF =                  0.0 /Roll offset (degrees)
```

9.4 ApD : CAMS1 and CAMS2 Teldef

The content of the teldef file header is the following, excluding the mandatory keywords.

-------------------------------- **Specific to CAMS1** --------------------------------

```
CAM_XLOC=              300.000 /CAMS-1 X location (mm) in S/C system
```

```
CAM_YLOC=              480.000 /CAMS-1 Y location (mm) in S/C system
CAM_ZLOC=             -5723.00 /CAMS-1 Z location (mm) in S/C system
CAM_ROTD=             -90.6740 /Rotation of the CAMS-1 unit with respect to S/C
CAMXFLIP=                    1 /X-axis flipped between CAMS and S/C
CAMYFLIP=                    1 /Y-axis not flipped
CAM_SCAL=          0.000977000 /mm per one CAMS readout unit
CAM_XOFF=             -525.282 /Measured X offset for CAMS-1 (unit CAM_SCAL mm)
CAM_YOFF=              2944.20 /Measured Y offset for CAMS-1 (unit CAM_SCAL mm)
```

-------------------------------- Specific to CAMS2 --------------------------------

```
CAM_XLOC=             -300.000 /CAMS-2 X location (mm) in S/C system
CAM_YLOC=              480.000 /CAMS-2 Y location (mm) in S/C system
CAM_ZLOC=             -5723.00 /CAMS-2 Z location (mm) in S/C system
CAM_ROTD=             0.155000 /Rotation of the CAMS-2 unit with respect to S/C
CAMXFLIP=                    1 /X-axis flipped between CAMS and S/C
CAMYFLIP=                    1 /Y-axis not flipped
CAM_SCAL=          0.000977000 /mm per one CAMS readout unit
CAM_XOFF=              2137.81 /Measured X offset for CAMS-2 (unit CAM_SCAL mm)
CAM_YOFF=             -38.4677 /Measured Y offset for CAMS-2 (unit CAM_SCAL mm)
```