

axiscorrect: Off-Axis Angle Correction Tool

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2019 Jul 11 (v1.4)

This memo specifies a new tool to update Chandra aspect solution files to reflect our new understanding of the boresight correction, and a procedure to use it to update already-processed data.

Note that the work discussed here - getting more accurate off-axis angles - is completely independent of the recent operational/mission-planning discussion on how to ensure a suitable aimpoint in future observations.

This specification defines a correction to the ASOL files. The corrected ASOL files, when used in `acis_process_events`, will generate event files with corrected DETX, DETY values, i.e. corrected off-axis angles, for each photon. Other CXC software (e.g. `dmcoords`) will be unchanged and simply make use of the corrected ASOL files.

I acknowledge Kenny Glotfelty's help in this analysis; most of the figures are his. Tom Aldcroft, Jean Connelly, Mark Cresitello-Dittmar, Joe Miller, Ian Evans and Janet Evans also contributed significantly to the overall plan, especially in its revisions.

1 Background to the issue

1.1 The problem

The aspect camera measures an offset versus time between the ACA frame and the focal plane instrument (ACIS or HRC) using the instrument fiducial lights. This offset is transformed into columns DY, DZ giving offsets in mm (whose zero point we'll discuss below).

Our initial assumption was that the ACA and HRMA were firmly attached and that the observed time variation was between ACA/HRMA assembly and the SIM. In processing, we currently apply the DY, DZ to offset the SIM from the HRMA frame accordingly. However, analysis by Ping Zhao and Tom Aldcroft has shown that in fact the ACA and HRMA frames are moving with respect to each other but the HRMA and SIM frames are not (to within the measurement error).

What does this mean? If you point Chandra/ACA at a particular RA and Dec, then as the ACA moves wrt the rest of Chandra, both the off-axis angle of a given celestial pointing

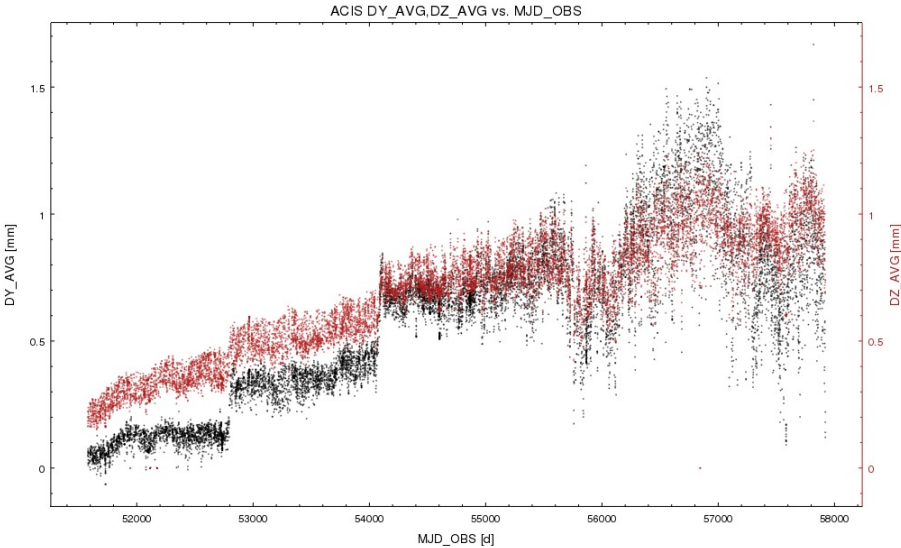


Figure 1: DY and DZ boresight offsets versus time for all ACIS data

direction and the place where the photons land on the (e.g.) ACIS chip will change. In the past we have observed the latter effect and noted the short and long term drifts in target CHIP position over time. We incorrectly interpreted this as the HRMA optical axis also moving in CHIP position to follow, but it turns out we were wrong. However, we can retrospectively correct the data.

The magnitude of the effect is up to 30" in recent data (much less for early phases of the mission). Does this affect science? The only real problem is in PSF fitting of pointlike sources; a simulated PSF generated by specifying an incorrect off axis angle may be slightly broader or narrower than it should be. This effect will certainly be negligible except for high count sources within 1' of the optical axis; we carried out simulations and Sherpa fitting to determine that TBD counts are needed to be affected by the issue for an on-axis source.

1.2 Consequences for the current data products

CHIP and SKY coordinates - and celestial RA and Dec - are correct, but our inferred off-axis angles are wrong. These inferred angles are encoded in event file columns DETX and DETY, in which a fixed position (e.g. (4096.5, 4096.5) for ACIS) is the implied HRMA optical axis.

The magnitude of the effect in typical recent data has grown to about 20 to 30 arcseconds. This is starting to affect PSF simulations for HRC; it's too small right now to mess up ACIS analysis, but that could change. If a user follows our threads and determines the off-axis angle of a not-too-far-off-axis source from the DETX,DETY coordinates of its photons (via e.g. dmcoords or dmstat) and then plug that off-axis angle into a PSF simulator, they will

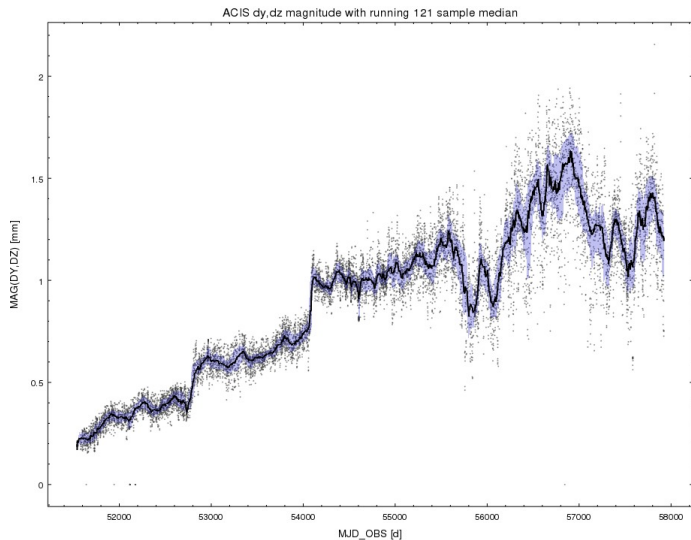


Figure 2: Magnitude of boresight offset vs time with running median

get the a simulated PSF which is too narrow or too broad, depending on the location. There are not a large number of science programs which will be affected by this but it's important Chandra science.

1.3 New approach

We create a new ASOL file in which the boresight offsets are zero, and the pointing data RA DEC ROLL is converted to be relative to the new optical axis.

When this new aspect solution is used as input to `acis_process_events` the resulting event file DETX, DETY columns reflect our new assumption about the position of the optical axis. The output SKY(X,Y) columns should be almost unchanged - there will be a small shift of up to 0.1 arcsec at the edges of the field, which results from an implicit reprojection of the tangent point from the old to the new optical axis.

We have tested the prototype code on all public ACIS data and confirmed that the sky coordinates remain within this tolerance in all cases.

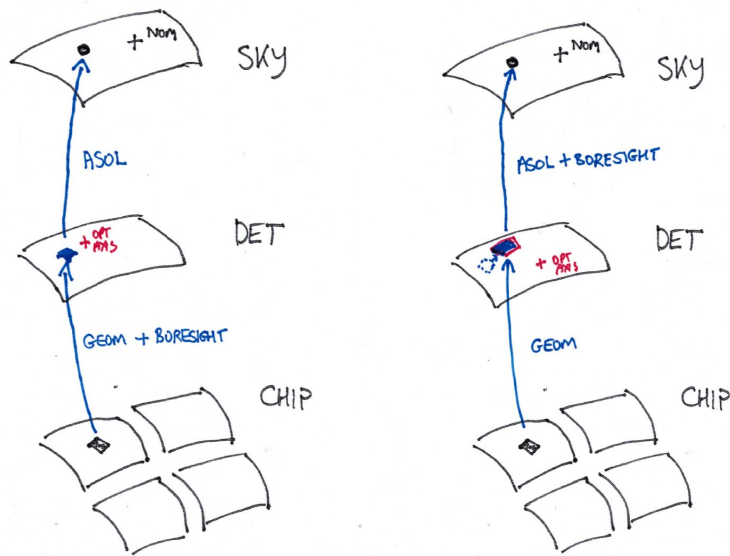


Figure 3: Comparison of old (left) and new (right) approaches. The boresight correction is now to be applied between the mirror (DET) plane and the sky plane instead of between the chip and mirror planes. As a result, DETX/DETY coordinates (and the corresponding off-axis angle) are changed, but the X/Y sky coordinates do not change.

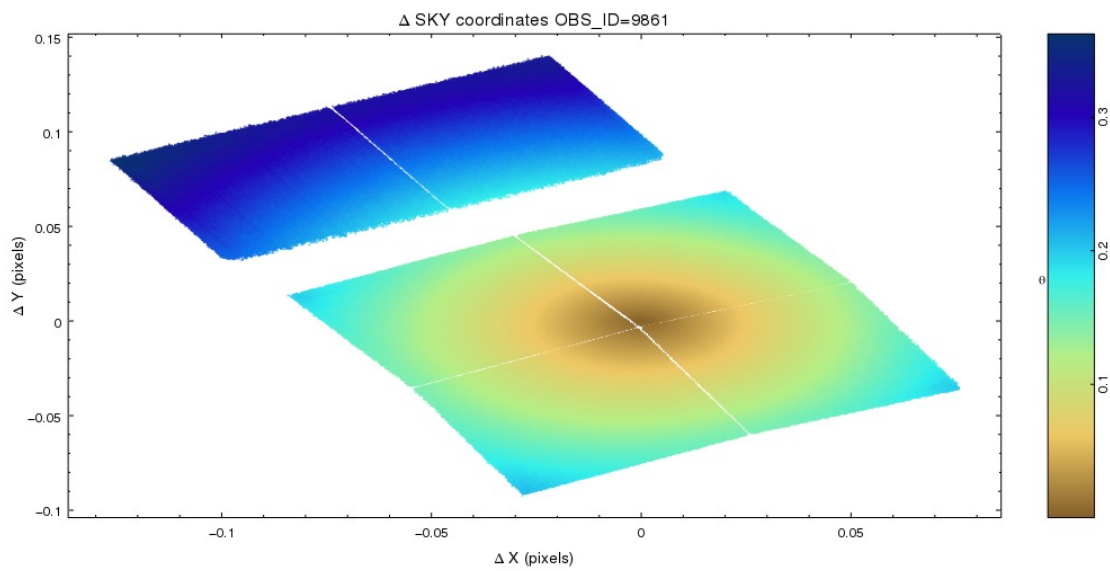


Figure 4: Example of an obsid with relatively large changes to the sky coordinates. This is a scatter plot of the change in sky X,Y between the old boresight method and the new one. The changes are larger further off axis which results in the chip pattern being reflected in the form of the image.

2 axiscorrect Tool spec

We will modify the current Level 1 ASOL file to generate a 'Corrected Level 1 ASOL file'.
The parameters to the tool are:

- **infile:** input ASOL file
- **obsfile:** input observation header (evt file for users, obs.par for pipeline?)
- **outfile:** output modified ASOL file
- First, check the value of header key BOREVER. If BOREVER is absent or is equal to 1 we may proceed. If BOREVER is equal to 2, the file has already been corrected; issue a warning message and exit successfully without creating a new file. (This latter case should not occur in the pipeline, but is provided for the case of CIAO users running the tool).
- (A) Copying the current DY, DZ, DTHETA values to new columns ADY, ADZ, ADTHETA; copy current RA, DEC, ROLL values to new columns RA_RAW, DEC_RAW, ROLL_RAW; Copy current Q_ATT[4] values to new column Q_RAW.
- (B) Keeping the DY, DZ, DTHETA columns but setting their values to be all 0.0
- (C) Applying the ADY, ADZ, ADTHETA values to the RA, DEC, ROLL to generate updated RA', DEC', ROLL' values using the algorithm described below.
- (D) Accumulate the average values of RA', DEC', ROLL'; write them out as the new aspect solution RA_PNT, DEC_PNT, ROLL_PNT keywords defining the optical axis estimate for this file. OMIT any NOM keywords.
- (E) Add new keyword BOREVER = 2 to indicate that the new boresight method is used.

(This is implemented as prototype code in /data/jcm/sds/specs/aim/code/aim.c)

Note that we assume the error values RA_ERR, DEC_ERR, ROLL_ERR, DY_ERR, DZ_ERR, DTHETA_ERR are unchanged, as are the three bias and three bias_err columns.
The algorithm (C) is:

- C.1 Determine SKY WCS crpix, cdelt.
 - CRPIX and CDELTA can be found in the SKY WCS of the event file header.
 - Or, if an obs.par is being used, they can be determined from pixlib based on the instrument in obs.par.

- Note that the original CRVAL and the original RA_NOM DEC_NOM of the obs0a.par are not in fact used.

For each ASPECT SOLUTION entry:

- C.2 - Read the RA, DEC ROLL values into the triple 'asp' = (RA,DEC,ROLL)
- C.3 - Read DY DZ DTHETA values into the triple 'bore' = (ADY, ADZ, ADTHETA) (the old boresight corrections)
- C.4 Determine the DETX DETY coords of the old optical axis by dmTanWorldToPix(asp, asp, crpix, cdelt, det); These values should be DETX, DETY = 4096.5 4096.5 for ACIS.
- C.5 Correct these entries with the bore values as follows The new (and closer to true) nominal optical axis is NDET = (NDETX, NDETY) where

$$\begin{aligned} \text{NDETX} &= \text{DETX} + \text{SCALE} * \text{ADY} \\ \text{NDETY} &= \text{DETY} - \text{SCALE} * \text{ADZ} \end{aligned}$$

where SCALE is the pixel scale in mm/pixel. For ACIS this is 0.0240 We can either hardcode the ACIS and HRC values, or calculate them from CDELTA and the telescope focal length FOC_LEN (keyword in the evt file)

$$\text{SCALE} = |\text{CDELTA}| * (\text{PI} / 180.0) * \text{FOCLEN}$$

- C.6 Calculate the RA and Dec of the new optical axis, NASP = (RA',DEC') from its detector coordinates by

$$\text{dmTanPixToWorld}(\text{NDET}, \text{asp}, \text{crpix}, \text{cdelt}, \text{NASP})$$

- C.7 Correct the roll angle by adding -ADTHETA

$$\text{ROLL}' = \text{ROLL} - \text{ADTHETA}$$

- C.8 Write out the new values RA', DEC', ROLL' to the aspect solution
- C.9 Write out the new DY, DZ, DTHETA values - these are 0.0, 0.0, 0.0 (Save the old values in other columns ADY, ADZ, ADTHETA for aspect analysis use)
- C.10 Use RA',DEC',ROLL' to calculate new q_att quaternion values (these are needed by SAOTrace) and write them out.

The corrected ASOL file will then be used for all downstream SDP and CIAO software requiring ASOL file updates.

3 Implementation in pipeline and CIAO

The changes are to the Level 1 Aspect Pipeline, as follows:

- At the end of the current ASP L1 STD aspect pipeline, run `axiscorrect` to create an corrected ASOL file.
- Remove pipeline step which adds NOM keys to output products. The output ASOL files are referred to as the CAI ASOL files and are archived (i.e. the archived files have the additional RAW asol columns and the modified keywords; the pre-axiscorrect ASOL file is not archived.)
- Define a new pipeline L1 OBIDET, run per OBI. It combines the CAI ASOL files into a single OBI ASOL file using a new aspect pipeline tool `asp_combine`, as follows:
 - All (corrected) CAI ASOL files for the OBI are input to the pipeline, together with a set of NOM parameters (perhaps via an `obs.par`)
 - Calculate OBI NOM and OBI PNT (i.e RA,DEC,ROLL NOM and PNT for the OBI) as the average of the data (not the header keywords) in the concatenated corrected CAI ASOL files. This could presumably be done with `dmstat` rather than requiring a new tool. NOM is constant for the OBSID, PNT is different for each OBI.
 - If there is only one CAI ASOL for the OBI, NOM is calculated as the average of that CAI ASOL (should just be the input CAI PNT in that case yes?). Otherwise use input NOM parameters.
- Define new pipeline L1 OBSPAR, run per OBI. The `obspar0.5` file shall be copied to a new data product, `obs1.par` (the ‘Level 1 obspar file’).
- Input OBI ASOL if needed to modify the `obs1.par` to reflect the revised RA,DEC,ROLL NOM and RA,DEC,ROLL PNT, and archive it; also update the archive databases to reflect these revised values.

In downstream pipelines:

- Running `acis_process_events` or `hrc_process_events` in the Level 1 event pipeline will use the new ASOL files instead of the old ones, causing correct DETX/DETY values to be generated.
- The `mean_simoffset` script should be changed to ensure the evt1 `DY_AVG`, `DZ_AVG`, `DTH_AVG` keywords in the evt1 file are set to 0.0.

- References in downstream pipelines to the obs0a.par file should be changed to obs1a.par.
- References in the V&V pipe to RA, DEC, ROLL, DY, DZ, DTHETA and Q_ATT should be changed to the raw values RA_RAW, DEC_RAW, ROLL_RAW, ADY, ADZ, ADTHETA and Q_RAW.
- Also, the Aspect Team may need to modify internal scripts that make use of these files and values.

If running outside the pipeline (e.g. by a user on an existing old evt1 file, you will now need to update event file keywords: (in the pipeline, they should be OK already, if obs.par has been updated):

- Ensure the DY_AVG, DZ_AVG, DTH_AVG keywords in the evt1 file are set to 0.0.
- Ensure the evt1 RA_NOM, DEC_NOM, ROLL_NOM, RA_PNT, DEC_PNT, ROLL_PNT keywords have the correct values. For the single obi case the NOM and PNT should be the same and be equal to the revised asol NOM values.

This should be sufficient to make correct DET coordinates for newly processed data, and to reprocess existing event files manually or in chandra_repro.

The following sections provide methods to calculate off-axis angles for sources with current data files and CIAO in the absence of the correction tool.

4 Manual calculation of off-axis angle using dmcoords

You can calculate a corrected off axis angle of a source using dmcoords simply by setting the SIM/DISPLACE parameters to all zeroes. This will give incorrect RA and Dec, but better off-axis angles.

```
dmcoords acisf16092\_repro\_evt2.fits pcadf515260906N001\_asol1.fits celfmt=deg
set sim/displace (enter all zeroes)
chip 190 495
```

This will give you the off axis angle for those chip coordinates corresponding to the average aspect. You probably want the (time-)average aspect for figuring out the off-axis angle of a source. Note that you have to go from chip coords, NOT from sky coords. Once we've set the sim/displace to zero we've broken the sky coordinates, so you can either find out the mean chip coords of the source by using dmstat on the event file filtered by a region, or you can use dmcoords without zeroing out the sim/displace to go from sky to chip first, and then zero out sim/displace before going from chip to det.

We can do a more precise calculation of a photon using the aspect record for the photon arrival time, to illustrate that we can recover the photon sky coordinates precisely. As an example I picked OBSID 16092 and selected a photon that is nearly on axis:

```
TIME 515262418.5546540022 (2175s after observation start)
CCD 7
CHIPX/CHIPY 190, 495
```

By typing

```
dmclist "acisf16092_repro_evt2.fits[cols time,chip,
      det,sky,msc,eqpos][detx=4100:4110,dety=4090:4110]" data rows=1
```

you can isolate this photon and find:

```
DETX,DETY      4016.58 4096.50
SKY X,Y        4083.42 4106.39
PHI,THETA     359.99, 0.001377
RA,DEC        233.7371189 23.5027326
```

The THETA value is the inferred off-axis angle of the photon in degrees (which corresponds to 5.0 arcseconds). The above values were those calculated by `acis_process_events`. We can reproduce them in interactive `dmcoords`. First, we find the corresponding aspect solution record:

```
dmclist "pcadf515260906N001_asol1.fits[cols time,ra,
      dec,roll,dy,dz,dtheta][time=515262418.5:]" data rows=2
```

This gives us both the aspect

```
TIME = 515262418.52599
RA, DEC, ROLL = 233.735744887 23.5032882401 156.19889
```

(this RA and Dec are those of the ASSUMED axis of the HRMA at that time) and the fiducial light correction

```
DY, DZ = 0.9787 0.890144
```

These values allow us to reproduce the `acis_process_events` coordinates for the photon as follows:

```
dmcoords acisf16092_repro_evt2.fits pcadf515260906N001_asol1.fits celfmt=deg
dmcoords>:
```

(right now, `dmcoords` has loaded the time-averaged aspect and offsets, and set the SIM position correctly from the header info. We now load up the aspect for this particular photon:)

```
dmcoords>: set aspect
Aspect RA (deg): 233.735744887
Aspect Dec (deg): 23.5032882401
Roll (deg): 156.19889
```

(now we set the DY DZ values, with an annoying minus sign, sorry about that, all my fault:)

```
dmcoords>: set sim/displace
SIM DISPLACE X: 0.0
SIM DISPLACE Y: -0.9787
SIM DISPLACE Z: -0.890144
SIM DISPLACE THETA X: 0
SIM DISPLACE THETA Y: 0
SIM DISPLACE THETA Z: 0
```

(let's check these got loaded correctly:)

```
dmcoords>: status
```

Now we can let dmcoords figure out the coordinates of the photon given its chip coords:

```
dmcoords>: chip 190 415
```

```
(RA,Dec):      15:34:56.908      +23:30:09.83
(RA,Dec):      233.73712         23.50273 deg
THETA,PHI      5.0"             359.99 deg
(Logical):     4083.42           4106.40
SKY(X,Y):     4083.42           4106.40
DETX,DETY     4106.57           4096.50
CHIP ACIS-S3   190.00           495.00
TDET          4107.00           2197.00
```

Note the good agreement with the ACIS process events values, including the INCORRECT values of THETA,PHI, DETX,DETY.

Now do

```
dmcoords>: set sim/displace
SIM DISPLACE X: 0
SIM DISPLACE Y: 0
SIM DISPLACE Z: 0
SIM DISPLACE THETA X: 0
SIM DISPLACE THETA Y: 0
SIM DISPLACE THETA Z: 0
```

and repeat

```

dmcoords>: chip 190 415
(RA,Dec):      15:34:55.040    +23:30:01.24
(RA,Dec):      233.72933      23.50035 deg
THETA,PHI      23.7"          129.62 deg
(Logical):      4135.66        4088.93
SKY(X,Y):      4135.66        4088.93
DETX,DETY      4065.83        4133.56
CHIP ACIS-S3    190.00         495.00
TDET           4107.00        2197.00

```

We see that we have new values of THETA, PHI, DETX, DETY which corresponds to assuming that the HRMA axis is still at its 1999 initially-calibrated location - not perfect but not as bad as a half-arcmin offset.

We also have new values of SKY and RA,Dec. These values are INCORRECT and should be ignored; the previous calculation (and the event files) have the correct values.

5 Other notes

- Possible interim script

If you make a copy of the aspect solution (asol) file and use dmtcalc to zero out the DY, DZ columns, then rerun acis_process_events, you can make an event file with good DETX,DETY but bad X,Y. By suitable dmcopyp/dmpaste magic you could combine this with the original event file (with bad DETX DETY but good X,Y) to make a file where all the columns are good. We could script this and add it to chandra_repro.

- Deferred option: fix earlier on

A purist approach would be to change the CALALIGN coefficients so that the aspect solution would be relative to the new optical axis in the first place. This is a more invasive change to the pipeline and wouldn't allow you to correct old data without full reprocessing.

- Rejected option: keep current ASOL and fix downstream

For the record, I investigated what we would need to do if we kept ASOL as is and altered the the rest of the software to use the new interpretation. This would require changes to a moderately large number of tools, so it's not a good idea. Also, the proposed approach has the advantage that it can support *both* a HRMA-ACA *and* a HRMA-SIM displacement if later analysis shows that is needed.

- PSF modelling

No changes are needed to MARX, SAOTRACE except perhaps in nominal position of instruments relative to optical axis.