JX-ISAS-SUZAKU-MEMO-2007-04
Title: Empirical Correction of Thermal Wobbling
Category: XIS, XRT
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Date: 2007-05-09

Empirical Correction of Thermal Wobbling

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May 9 2007

Abstract

The *Suzaku* satellite "wobbles" owing to time-dependent thermal distortions of its chassis (most likely, the cross frames attached to side panel #7, exposed to external radiation), being synchronized with orbital motion. This "uncontrolled dithering" causes astrometric error as large as $1'$ in the XIS images and significant distortions of the core of a point-spread function (PSF). We have found an empirical way to compensate for these effects. The wobbling-correction to XIS events will be made, starting from processing V2.0, with FTOOLS `aeattcor`. In this report, we describe the correction functions we found and their applications to XIS events; the accuracy of the derived source coordinates is now largely improved, from $60''$ to $20''$, and crummy distortions of PSF are relieved. In Appendix, we also describe a recent improvement on the attitude determination logic on ground.

1 Characteristic example of thermal wobbling

For the purpose of illustration, in Fig. 1 we show time history of source positions for seven orbits in the case of SS Cyg (Seq# 400006010, processing V1.2). Showing synchronization with orbital motion of *Suzaku* (a period of $\sim$ 90 min), the source positions oscillate with amplitudes of $10''$–$30''$ in both DETX and DETY directions, as a result of thermal distortions of the chassis. Furthermore, the center of oscillation shifts toward a minus DETX direction by $\sim 40''$, which causes a large astrometric error in the *Suzaku* XRT-XIS system.

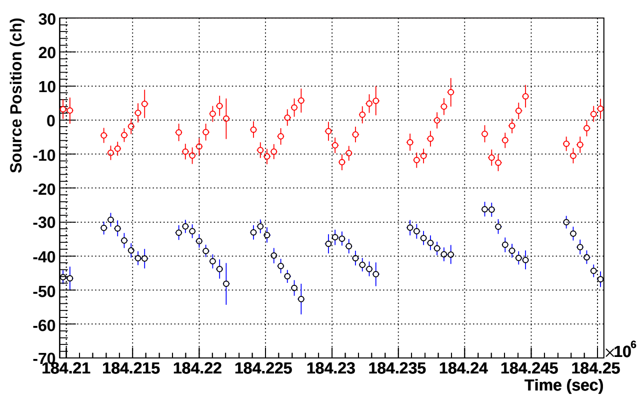

Figure 1: Source centroid in DETX (black) and DETY (red) directions as a function of time: in the case of SS Cyg. One channel corresponds to $\simeq 1.04''$. The origin of the source position is its nominal position, at which a source is expected to fall. Source centroids are derived based on the (X, Y) coordinates assigned to each photon, and therefore the ground attitude determination by using gyro and STT was applied.

2 Correlating for thermal wobbling

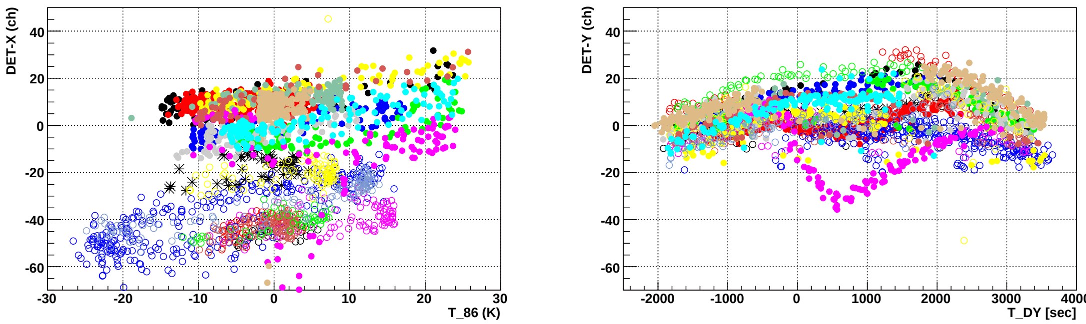

Figure 2: (Left) Correlation between a source centroid in the DETX direction and T_86 defined in Eq. (1). Each symbol is a centroid in one time-bin (500 sec) of each target. The origin of the source position is its expected position. The (X, Y) coordinates of photons are projected onto the DETX axis. (Right) Same as the left panel, but for correlation between a DETY position and T_DY defined in Eq. (2). Filled violet circles obtained with X1630−472 (Seq# 400010010) appear to be outliers. It is found that this observation exhibits an anomalous behavior in wobbling (see §4).

We have found that the following three parameters can describe a source- and time-dependent position of source centroid: (a) $\beta_{\rm ecl}$, ecliptic latitude of the source, (b) T_86 [K], temperature difference between the radiators at panel #8 and at panel #6, as defined in Eq. (1), and (c) T_DY [sec], time after night-day transition, as defined in Eq. (2).

$$\texttt{T\_86} \equiv \texttt{HK\_XIS\_RAD8\_T1\_CAL} - \texttt{HK\_XIS\_RAD6\_T1\_CAL}\ [\text{Kelvin}] \tag{1}$$

$$\texttt{T\_DY} \equiv \begin{cases} \texttt{T\_DY\_NT} & [\text{sec}]\ \text{for day-time,} \\ -\texttt{TN\_DY\_NT} & [\text{sec}]\ \text{for night-time} \end{cases} \tag{2}$$

Both T_86 and T_DY reflect thermal cycling of the orbiting spacecraft and are periodic with an orbital period. The ecliptic latitude $\beta_{\rm ecl}$ represents the spacecraft pointing angle with respect to the ecliptic plane and describes the way of illumination by bright Earth.

The ecliptic latitude $\beta_{\rm ecl}$ well determines the offset position in DETX, namely the center of oscillation, as shown in Figure 3. This implies that the angle between the cross frames at panel #7 and the ecliptic plane somehow controls the way of distorting the frames. Also, periodically-changing T_86(t) describes time-dependent part of the DETX position (see Figure 2). The DETX centroid relative to the nominal position at time t can be best described as follows:

$$\Delta\text{DETX}(t) = -38.5\left(\frac{\beta_{\rm ecl}}{60\ \text{deg}}\right) - 9.25 + \frac{2}{5}\left(\frac{\texttt{T\_86}(t)}{\text{Kelvin}}\right)\quad[\text{ch}]. \tag{3}$$

Based on Figure 2, the DETY centroid relative to the nominal position at time t can be approximated in the following way:

$$\Delta\text{DETY}(t) = \begin{cases} 10.0 + 7.0\left(\frac{\texttt{T\_DY}(t)}{1000\ \text{sec}}\right)\ [\text{ch}] & \text{for } \texttt{T\_DY} < 0\ [\text{sec}], \\ 10.0 + 5.0\left(\frac{\texttt{T\_DY}(t)}{2000\ \text{sec}}\right)\ [\text{ch}] & \text{for } 0 < \texttt{T\_DY} < 2000\ [\text{sec}], \\ 45.0 - 15.0\left(\frac{\texttt{T\_DY}(t)}{1000\ \text{sec}}\right)\ [\text{ch}] & \text{for } 2000 < \texttt{T\_DY}\ [\text{sec}]. \end{cases} \tag{4}$$

3 Wobbling-corrections with aeattcor

A newly developed FTOOLS `aeattcor` (written by Y. Ishisaki) that comes with processing V2.0 will be in charge of correcting for the thermal wobbling. It calculates a position shift at each time in the original

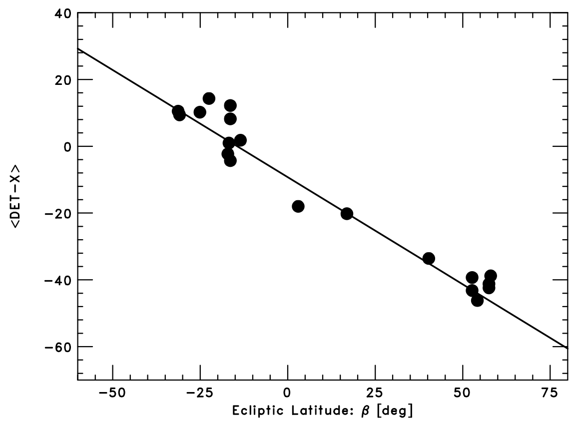

Figure 3: Source offset positions in the DETX direction as a function of the ecliptic latitude $\beta_{\rm ecl}$.

attitude file based on Eqs. (3) and (4), and generates a new attitude file with wobbling-corrected Euler angles. If one simply converts (DETX, DETY) to (X,Y) using the new attitude file, the resultant (X,Y) is automatically wobbling-corrected. In the calculation of the corrected Euler angles, only the 1st and 2nd Euler angles are changed so that it reflects the position shift, and the 3rd Euler angle is kept unchanged. The original Euler angles are stored in a column `EULER_OLD`. If the `EULER_OLD` column already exists in the input attitude file, `aeattcor` reads the Euler angles from this column. Therefore, applying `aeattcor` to the corrected products gives the same output with the input attitude file, except for history in the FITS header.

In the left panels of Figure 4, we demonstrate time-integrated XIS0 images for Her X-1 before and after wobbling-correction. One can realize that a large shift from the nominal position, Δr, in the uncorrected image gets improved in the corrected image. Also, a weird shape of the point-source image is relieved in the corrected image; a butterfly-shaped PSF now appears.

In the right panels of Figure 4, the distributions of Δr are shown for uncorrected (top) and corrected (bottom) cases. Without wobbling-correction, significant deviations from the nominal position, as large as $\Delta r \simeq 50''$, are observed. The wobbling-correction with `aeattcor` is able to restore the pointing accuracy to $\Delta r \leq 20''$, close to the preflight specifications.

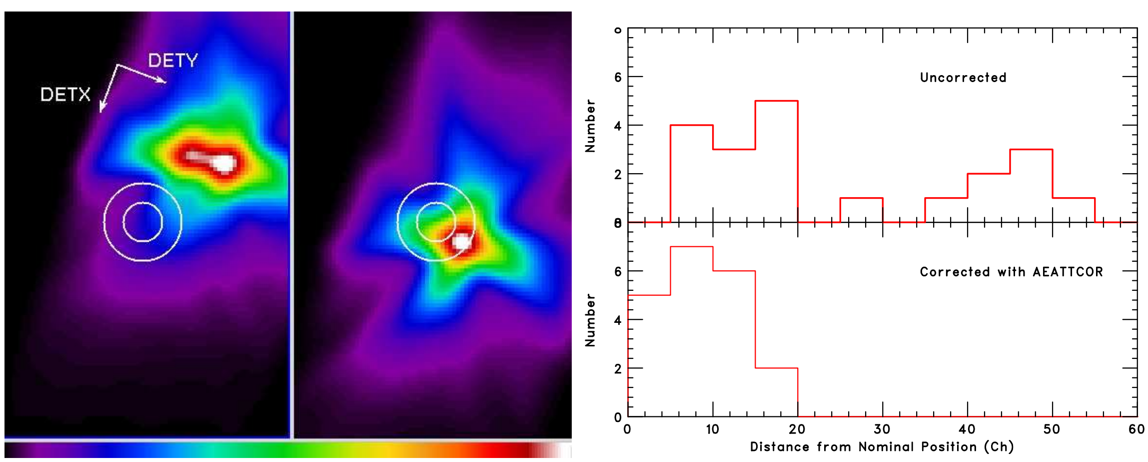

Figure 4: (Left) Wobbling-correction before and after. Time-integrated XIS0 images made with (X, Y) columns for Her X-1 are displayed. North (Y) is up and west (X) is to the right. The double circles with a radius of $10''$ and $20''$ show the nominal (expected) position of the source. The source peak in the wobbling-corrected image (in the right panel) is closer to the nominal position. Furthermore, a wired PSF shape of the original image is clearly improved. (Right) Distributions of source distances Δr from the nominal position. The top panel shows the Δr distribution for 20 observations before wobbling-correction, while the bottom panel shows that after correction.

4 Caveat

We found one peculiar case, out of 20 sample sources, which exhibits an exceptional behavior of wobbling: X1630−472 (Seq# 400010010). For this case, the wobbling-correction described above is not effective. This issue will be pursued by analyzing a larger sample.

Appendix: Update on the ground attitude determination logic

Here we briefly report the recent improvement on the ground attitude determination logic with the data from gyroscopes and star trackers. In some targets, the attitude of the satellite is better reproduced on ground during the first several tens of minutes in the new logic. Figure 5 shows the case of 3C 120 observation as an example. The new logic was already applied to all the attitude files created after March 26th, 2007, i.e., FITS header keyword DATE is later than 2007-04-06. Also, it will be applied to all the observations in the archive as well in upcoming V2.0 processing. Note that the attitude error due to the satellite thermal wobbling described above is not included in the logic and should be corrected with FTOOLS `aeattcor` independently.

The attitude of the *Suzaku* satellite is determined with the combination of the gyro (Inertial Reference Unit: IRU) and the STar Tracker (STT), The direction of the STT field of view can be determined, in principle, with the accuracy of several arcseconds. However, immediate aftermath of maneuver, an estimation of a drift rate with the gyroscopes has large errors depending on the maneuver angles. The lack of STT calibration in this period causes an attitude error of $\sim 1'$. With this update, the accuracy of the ground attitude determination in this period (first ~ 20 minutes after maneuver) has been improved. Specifically, possible attitude errors in the new logic are expected to be:
(a) from the maneuver end to the first star track: $< 0.3'$, and
(b) from the last star track to the observation end: $< 1.5'$.

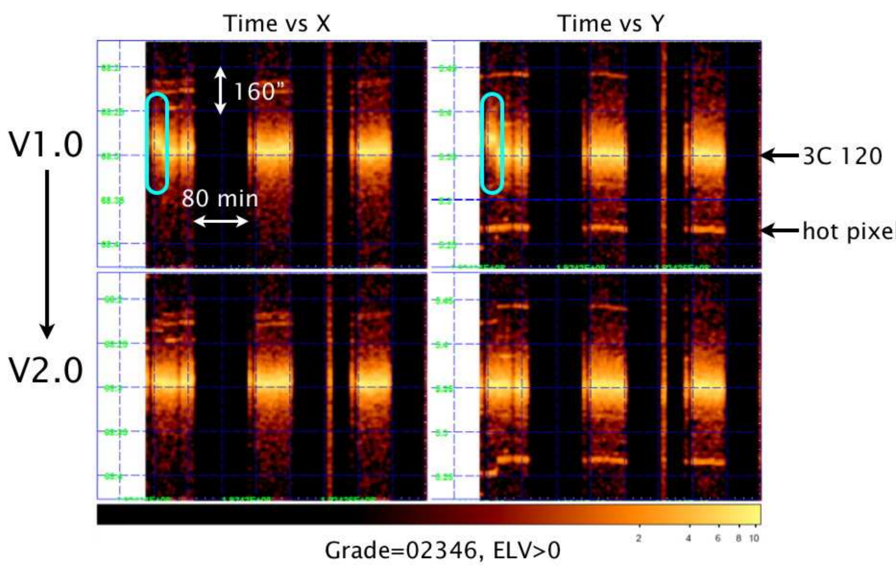

Figure 5: History histograms of source (3C 120) positions. In V1.0 processing, the attitude error is large ($\sim 1'$) due to the lack of STT calibration for the first 20 minutes aftermath of maneuver.