CHANDRA ACIS SUBPIXEL EVENT REPOSITIONING: FURTHER REFINEMENTS AND COMPARISON BETWEEN BACKSIDE- AND FRONTSIDE-ILLUMINATED X-RAY CCDs

JINGQIANG LI,1 JOEL H. KASTNER,1 GREGORY Y. PRIGOZHIN,2 NORBERT S. SCHULZ,2 ERIC D. FEIGELSON,3 AND KONSTANTIN V. GETMAN3

Received 2003 December 19; accepted 2004 April 13

ABSTRACT

We further investigate subpixel event repositioning (SER) algorithms in application to Chandra X-Ray Observatory (Chandra) CCD imaging. SER algorithms have been applied to backside-illuminated (BI) Advanced CCD Imaging Spectrometer (ACIS) devices and demonstrate spatial resolution improvements in Chandra ACIS observations. Here a new SER algorithm that is charge split–dependent is added to the SER family. We describe the application of SER algorithms to frontside-illuminated (FI) ACIS devices. The results of SER for FI CCDs are compared with those obtained from SER techniques applied to BI CCD event data. Both simulated data and Chandra ACIS observations of the Orion Nebular Cluster were used to test and evaluate the achievement of the various SER techniques.

Subject headings: instrumentation: detectors — methods: data analysis — techniques: image processing — X-rays: general

On-line material: color figures

1. INTRODUCTION

Subpixel event repositioning (SER) algorithms can be used to improve the spatial resolution of Chandra X-ray imaging with the Advanced CCD Imaging Spectrometer (ACIS) by reducing photon impact position (PIP) uncertainties to subpixel accuracy. Utilizing the extra information provided by the observation, in particular, event charge-split morphologies and the telescope pointing history, SER techniques essentially change the shape and decrease the size of the detector pixel. Therefore, the image quality degradation due to pixelization is reduced. Tsunemi et al. (2001) first introduced SER methods for ACIS imaging, describing a technique to reposition corner split events. In Li et al. (2003, hereafter Paper I), SER algorithms for backside-illuminated (BI) devices were modified by including single-pixel events and 2 pixel split events to increase the statistical accuracy as well as to improve detection efficiency (from using ~25% of events to ~95% of events). In this formulation (static SER [SSER]), the repositioned event landing locations do not depend on energy.

Employing a high-fidelity BI CCD model (Prigozhin et al. 2003), we further modified SER by determining event PIPs according to photon energies (energy-dependent SER [EDSER]). Both CCD simulations and real Chandra observations demonstrate the improved performance for SSER and EDSER compared to the Tsunemi et al. (2001) model (TSER), with EDSER displaying the best performance (Paper I).

In Paper I, SER algorithms were discussed only for the BI devices, two of which are located in the ACIS-S (spectroscopy) CCD array and four of the six ACIS-S array positions. The details of the implementation for BI and FI devices, however, are not the same. The reason is that photon absorption and charge-spreading mechanisms differ significantly for the two types of CCDs, especially at low X-ray energies.

The collection of signal charge occurs near the front surface, the same one that is illuminated by the incoming photons in the FI CCD. A much larger fraction of photons interact close to the surface of the device, where electric potentials are influenced by the grounded channel-stop layer, resulting in a very different charge-splitting pattern from the one in the BI devices. On average, charge clouds are formed closer to the collecting potential wells and travel shorter distances, therefore having less time to expand. Smaller charge clouds reduce the possibility of forming split events.

A thicker dead layer covering vertical charge-splitting pixel boundaries of the FI CCD is another factor contributing to the reduction of the proportion of split events. As a result, the TSER technique for FI devices suffers seriously from low detection efficiency.

Mori et al. (2001) effectively modified TSER to SSER by adding single-pixel and 2 pixel split events. However, they assume that 2 pixel events land on the center of the split boundary, for both BI and FI devices. In Paper I, we showed that this assumption for the impact position of 2 pixel split events can be refined significantly for BI CCDs, and it follows that there is significant room for improvement in the case of FI devices as well.

Here we describe modifications to SSER and EDSER algorithms for FI devices. These modifications are based on a physical model of FI CCDs (Prigozhin et al. 1998b), as well as Chandra observations with FI ACIS CCDs. In addition, we describe a new SER technique that is dependent on charge-split proportion, and we apply this method to both CCD types.

2. STATIC SER FOR FI CCDs

In the FI SSER method, as for BI SSER, single-pixel events and 2 pixel split events were added to corner split events, in...
order to improve photon counting statistics. FI devices generate far fewer corner split events than BI devices (see Table 1). Because the charge cloud has a relatively small size, only photons that interact with silicon close to boundaries result in split events in the case of FI devices. Using a detailed CCD model (Prigozhin et al. 1998b), we simulated a distribution of events across the pixel and found that for FI devices, single-pixel events can occur almost everywhere within a pixel except for areas very close to corners and boundaries, i.e., such events are constrained within an area only slightly smaller than a CCD pixel. Two-pixel split events are generated by photons that are absorbed in areas restricted to the pixel boundaries, while the impact positions of corner split events are limited to diamond-shaped areas that are diagonally oriented and heavily populated toward pixel corners. Because the charge cloud size is very small compared with the ACIS pixel size, single-pixel events will have the biggest position uncertainty in both dimensions, and corner split events will have the smallest uncertainty among all the events in both dimensions. Two-pixel split events have relatively small landing position uncertainties in the direction perpendicular to the split boundary and have uncertainties similar to those of single-pixel events in the direction parallel to the split boundary. Thus, properly repositioning both corner and 2 pixel split events will essentially decrease the ACIS pixel size.

In our initial FI SER implementation, we assume that corner split events take place at the split corners instead of event pixel centers, and 2 pixel split events occur at the centers of split boundaries, 0.47 pixels away from the pixel centers. Single-pixel event PIPs remain at the event pixel centers. Note that the 0.47 pixel offset for 2 pixel split events here is different from BI SSER, in which the shift is 0.366 pixels. These 2 pixel split-event shifts for FI and BI SSER were determined from FI and BI CCD model simulations, respectively. As in Paper I, we refer to this modified algorithm as SSER (static [energy-dependent] SER). The algorithm’s schematics can be found in Figure 1 of Paper I.

Simulations for BI CCDs show that a given type of event can be formed in a fairly large area, and the mean offset of this event type from pixel center is determined by the charge cloud size, which is energy dependent. The same principles hold for FI devices too, but differences exist; in particular, split events are much less probable and occur closer to split boundaries, as shown in Figure 1 for 1740 eV photons.

The first three panels in the bottom row in Figure 2 show the improvement in the determination of PIPs enabled by SSER, using FI CCD simulated data at an energy of 1740 eV. For comparison, the simulated BI data for photons of the same energy (shown in Paper I) are also included in Figure 2. In each panel we show the differences between actual PIPs and repositioned PIPs from various models in chip coordinates, for all three subgroups of events. The plot axes are in ACIS pixel units, i.e., a 0.5 difference represents 12 μm and indicates photons that interacted near the pixel boundaries. The first panel from the left shows the difference between actual PIPs for a random spatial distribution of events and unrandomized, standard-processed PIPs that are assumed to lie at the event pixel centers; one can see the expected uniform random distribution within the pixel. The second panel is the difference after applying TSER, in which only corner split events were repositioned. A big improvement for the small fraction of events that occur near corners can be seen. However, because of the small proportion of corner split events, there is no correction for most events. This fact is more obvious for the FI simulations. The third panel shows the difference after the SSER correction, in which the 2 pixel split events also were repositioned. For FI devices, SSER results in a cross-shaped structure, because the position uncertainties of 2 pixel events can only be minimized in one direction. However, the smaller PIP differences of the SSER method relative to the Tsunemi et al. (2001) method are apparent, with the improvement more obvious for BI devices. The other two panels in the figure are discussed later in the paper.

Essentially, the PIP differences plotted in Figure 2 represent the corrected PIP uncertainty (or probability distribution) within a pixel, and therefore can be considered as representing the ACIS pixel shape and size after SER correction. Adopting this concept, one sees that the far left panel reflects the ACIS pixel after standard Chandra ACIS processing, i.e., a square pixel with 24 μm width. After TSER and SSER correction, the effective ACIS pixel becomes smaller in size and no longer has a uniform spatial response.

### 3. FURTHER MODIFICATIONS TO SER BASED ON ACIS CCD SIMULATIONS

#### 3.1. Energy-dependent SER for FI CCDs

In Paper I, an EDSER method was proposed for BI devices, based on simulations for a BI CCD model. The advantages of this method were demonstrated from both simulated data and real observations. Figures 3 and 4 show the motivation for EDSER from the simulation, i.e., the branching ratio and the mean offset of the split-event position indicate that the mean shifts for each subgroup of split events are strongly energy dependent. Therefore, adjusting the assumed PIPs according to energy should significantly improve SER performance.

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### TABLE 1

| ACIS CCD Type | Corner Split Events (%), 2 Pixel Split Events (%), Single-Pixel Events (%), Total Split Events (%) |
|---------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| BF            | 20.8–38.8                                       | 38.4–50.3                                       | 10.9–25.2                                       | 69.6–83.8                                       |
| FP            | 1.0–5.7                                         | 15.0–23.3                                       | 70.5–83.3                                       | 16.5–29.0                                       |

*Note.—Table values are calculated from 20 and 32 individual bright sources with Gaussian shapes for the BI and FI observations, respectively.

a Chandra ObsID 4.

b COUP data (see § 5).
Figure 3 shows the percentage of events of a given split morphology as a function of photon energy, while Figure 4 shows the mean shift in position for different split-event types, for FI devices. For comparison, we include the same plots for BI CCDs that were published in Paper I. Note the differences between BI and FI devices. For BI CCDs, both subgroup event percentage and mean PIP shift depend sensitively on energy at low energy \((E < 2 \text{ keV})\); however, the three subgroups of split-event percentages and PIP shifts are insensitive to energy for \(E > 6 \text{ keV}\). This reflects the fact that, for photons with energy exceeding 6 keV, the characteristic penetration depth becomes comparable to or larger than the thickness of the ACIS BI CCD, which is only 45 \(\mu\text{m}\). In contrast, ACIS FI CCDs are much thicker, with larger depletion depth \((\sim 70 \mu\text{m}; \text{Prigozhin et al. 1998a})\). Therefore, the branching ratios and PIP shifts depend sensitively on energy over most of the Chandra ACIS bandwidth.

EDSER consists of repositioning the split-event PIPs by event grade, using the mean PIP offset look-up table as a function of photon energy derived from the data shown in Figure 4. PIP determination benefits from applying the mean energy-dependent shifts for different split-event groups. The fourth panels (from the left) of Figure 2 demonstrate the PIP differences after EDSER for BI and FI devices. Compared with SSER, the EDSER BI data display a more concentrated structure in the center, indicating that the split events were relocated more accurately, and the EDSER method will improve SER performance, via better PIP determination. However, because of the narrower confinement of split events to pixel boundaries, there is a substantially smaller improvement for FI data from the third to the fourth panel of Figure 2.

3.2. Charge Split–dependent SER

Simulations show that, for a split event, the proximity to the split boundary of a PIP is related to the proportion of the charge deposited in split pixels relative to the total charge generated by the photon. This fact provides motivation for an SER algorithm that is both energy- and charge-split proportion–dependent (we hereafter refer to this SER technique as charge split–dependent SER [CSDSER]). Figure 5 shows distances of PIPs (relative to split boundaries) as a function of the charge-split proportion, for three types of split events. ACIS CCD models were used for these simulations, at a photon energy of 1740 eV. The simulation results are shown in the left and right columns for BI and FI devices, respectively. The measured fraction is the proportion of charge within a split pixel relative to the total charge generated by the event, including all split charge that exceeds the split threshold. For 3 and 4 pixel corner split events, the charge fraction in both horizontal and vertical split pixels was measured independently. The charge fraction in the diagonal split pixel of the 4 pixel corner split events was not measured, since the fractions from the other two split pixels already provide information about photon landing locations.

The plot shows that, with only energy information, the PIP uncertainty is relatively large since it includes all “local” uncertainties. By including charge-split proportion information, one can divide the uncertainty into local uncertainties, i.e., the uncertainty at each split fraction. For example, for a 3 pixel corner split in a BI device (Fig. 5, left middle), the total uncertainty is about 0.4 pixels, while the local uncertainty for a 0.4 split fraction is only about 0.03 pixels. Therefore, including charge-split information will greatly reduce PIP uncertainties. The function describing PIP offset in terms of charge-split–fraction for horizontal and vertical directions is assumed to be indistinguishable, \(5\) for a given split-event subgroup, at the same energy.

The rightmost panels in Figure 2 show the simulated PIP uncertainties after CSDSER correction for BI and FI devices, at an energy of 1740 eV. The improvement in PIP determination

\[\text{Fig. 1.—PIPs for three subgroups of 13 “viable” event grades for BI (top) and FI (bottom) devices. Each panel shows 4000 photons uniformly distributed within an ACIS CCD pixel. Plus signs stand for the PIPs of 2 pixel events within a pixel, while triangles represent the PIPs of corner (3 or 4 pixel) split events. The crosses show the PIPs of single-pixel events. All the photons have an energy of 1.74 keV. [See the electronic edition of the Journal for a color version of this figure.]}\]
for those panels can be seen, especially for BI devices, compared with the EDSER correction. Figure 2 suggests that an increasing degree of image quality can be achieved by using SSER, EDSER, and CSDSER.

4. TESTING SER: END-TO-END SIMULATIONS

MARX (Model of AXAF Response to X-rays) is a program suite that can run in sequence to simulate Chandra on-orbit performance, with FITS file and image output. The built-in instrument models, including HRMA (High Resolution Mirror Assembly) and focal plane detectors, enable MARX to perform a ray trace and thereby simulate Chandra CCD imaging spectroscopy of a variety of astrophysical sources. Postprocessing routines can simulate aspect movement and ACIS photon pileup. However, ACIS simulations within the versions of MARX available to date do not include a high-fidelity CCD model. Therefore, SER-related simulations must rely on CCD models (such as those described in §2 and 3) to analyze the CCD charge distribution, event grade formation, and, therefore, SER implementation.

Fig. 2.—Differences between actual PIPs and event locations assumed in standard processing for 1.74 keV events, in chip coordinates. First panel (from left), ACIS-assumed PIPs; second panel, correction using corner events only (Tsunemi et al. 2001); third panel, SSER correction; fourth panel, EDSER correction; fifth panel, CSDSER correction. The panels are in units of pixels. The top panels are for BI devices, while the bottom panels are for FI devices, for 4000 (BI) and 5000 (FI) photons with uniformly random landing positions. [See the electronic edition of the Journal for a color version of this figure.]

6 See http://space.mit.edu/CXC/MARX.

Fig. 3.—Fraction of different event grades versus photon energy, from simulations of FI (solid line) and BI (dotted line) CCD models. The X-ray attenuation length in silicon is overplotted, in units of 50 μm. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 4.—Mean shifts from pixel centers for the three subgroups of split events, according to the photon energy. FI CCD model simulations are plotted with solid lines, and BI simulations with dotted lines. [See the electronic edition of the Journal for a color version of this figure.]
To test the extent to which various SER techniques should improve image performance for BI and FI CCDs, we have carried out simulations combining MARX with MIT BI/FI CCD models. We performed simulations of 50 point sources with realistic spectral distributions at positions ranging from on-axis to 160° off-axis, in steps of 3'. The MARX telescope “internal dither” model was used, with an 8' dither amplitude in both right ascension and declination. The simulations were run until \( \frac{C24}{1200} \) and \( \frac{C24}{1500} \) photons were detected per source for the BI and FI devices, respectively. The spectra used in the simulations were based on the averaged spectra of BI and FI Orion Nebular Cluster (ONC) observations, respectively. The BI simulation spectrum was calculated by averaging the normalized spectra of 20 pointlike sources\(^7\) observed using the BI chip during an observation of the ONC (observation ID [obsID] 4), while the FI simulation spectrum was calculated by averaging the normalized spectra of 32 well-shaped X-ray sources from a deep Chandra ACIS-I observation (see § 5). The resulting average BI and FI spectra used in the simulations are plotted in Figures 6 and 7, respectively.

The degree of improvement due to the SER algorithms was evaluated numerically by calculating the source FWHM before and after applying SER. Tsunemi et al. (2001) and Paper I give the definition of improvement used here; i.e., assuming that \( F_B \) and \( F_A \) are the FWHMs of a source before and after applying SER, respectively, then the improvement \( \Delta \) is defined as

\[
\Delta = \sqrt{\frac{F_B^2 - F_A^2}{F_B^2}}.
\]

The results of the simulations are shown in Figures 6 and 7 for BI and FI models, respectively. The progressively better performance of SSER, EDSER, and CSDSER is apparent.

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\(^7\) The sources were listed in Table 1 of Paper I, excluding sources 5 and 6, which may have been affected by pileup.
in BI simulations, as expected (see Table 2). However, the performances of SSER, EDSER, and CSDSER are very comparable in the cases of FI devices, even though we might theoretically expect to see an improvement (e.g., of CSDSER relative to SSER). In comparison to BI devices, the lack of improvement in imaging performance under the refined SER approaches for FI CCDs is most likely due to the following factors:

1. FI devices generate fewer split events than BI devices, especially corner split events. Therefore, single-pixel events dominate over the better repositioned split events.

2. For soft sources, such as those simulated here, the charge cloud size is relatively small. Therefore, most split events in FI CCDs are very close to the split boundaries, not widespread as in BI devices. As a result, the positional uncertainties of 2 pixel split events form a long-arm cross structure after applying SER.

3. Because of the small charge cloud, the PIP determinations of EDSER and CSDSER do not provide significant advantages over the static method, as for BI devices.

4. The slight potential improvement offered by CSDSER is degraded by the telescope point-spread function (PSF), which includes contributions from both the HRMA PSF and aspect blurring.

Figures 6 and 7 show that SER algorithms are highly source location dependent, i.e., all SERs have better performance for on-axis sources, and the improvement decreases when the off-axis angle increases. This is because the telescope PSF...
increases in size with off-axis angle, and therefore, the influence of the event repositioning decreases.

5. APPLICATION OF THE SER ALGORITHMS TO X-RAY SOURCES IN ORION

The steps involved in implementing SER on real Chandra observations were discussed in Paper I, and BI SER algorithms (TSER, SSER, and EDSER) were evaluated from data obtained for the ONC (Schulz et al. 2001). Here we compare CSDSER with other SER algorithms for BI data (Figs. 8 and 9, top panels). The same implementation steps hold for FI CCDs, except that the chip orientations differ for the eight FI chips. Similar plots for applications of SER methods to FI Chandra Orion Ultradeep Project (COUP) data are also shown (Figs. 8 and 9, bottom panels). The COUP data consist of six consecutive

\[ 
\text{TABLE 2} 
\]

| NUMBER OF SOURCES | OFF-AXIS RANGE (arcsec) | CCD TYPE | CSDSER vs. EDSER | CSDSER vs. SSER | EDSER vs. SSER |
|------------------|------------------------|----------|-----------------|-----------------|----------------|
|                  |                        |          | \( P^a \)        | \( \text{Percentage}^b \) | \( P^a \)        | \( \text{Percentage}^c \) | \( P^a \)        | \( \text{Percentage}^d \) |
| 50               | 0–158.7 BI             | 0.996    | 68              | 0.367           | 86             | 0.551           | 80             |
|                  | 0–158.7 FI             | 0.954    | 56              | 0.954           | 52             | 0.996           | 56             |
| 25               | 0–78.5 BI              | 0.990    | 64              | 0.059           | 96             | 0.877           | 64             |
|                  | 0–78.5 FI              | 0.990    | 56              | 0.990           | 60             | 0.124           | 88             |

\(^a\) Probability that the distributions of FWHM improvement will be identical under the two SER methods, as determined from a Kolmogorov-Smirnov test.

\(^b\) Percentage of sources for which CSDSER FWHM improvement is larger than that of EDSER.

\(^c\) As for footnote b but for CSDSER compared to SSER.

\(^d\) As for footnote b but for EDSER compared to SSER.

Fig. 8.—FWHM of BI (top) and FI (bottom) ONC pointlike sources before and after applying the various SER algorithms described in this paper. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 9.—Comparison of image FWHM improvements using TSER (Tsunemi et al. 2001), SSER, EDSER, and CSDSER on BI (top) and FI (bottom) Chandra ONC data.
observations of the ONC taken in 2003 January with the ACIS-I. The total exposure time was 0.84 Ms, and over 1600 sources were detected. COUP data reduction started with the Level 1 event files provided by the Chandra X-Ray Center. Only events on the four CCDs of the ACIS-I array were considered. Event energies and grades were corrected for charge transfer inefficiency (CTI) using the procedures developed by Townsley et al. (2002). The data were cleaned to remove a variety of potential problem events with the procedures developed by Townsley et al. (2002). The data grades were corrected for charge transfer inefficiency (CTI) using the procedures developed by Townsley et al. (2002). The total exposure time was 0.84 Ms, and over 1600 sources were identified but not removed from the data set at this time. The data were then searched for hot columns or hot pixels that were not removed by the standard processing (e.g., events below 700 eV were removed from column 3 of CCD 10), and a very coarse energy filter (eliminating events with $E > 10.5$ keV) was applied to remove background events.

Event positions were adjusted slightly in three ways. First, individual corrections to the absolute astrometry of each of the six COUP exposures were applied based on several hundred matches between a preliminary catalog of Chandra sources and near-infrared sources in a forthcoming catalog from the ESO Very Large Telescope. Second, the subarcsecond broadening of the PSF produced by the Chandra X-Ray Center’s pipeline randomization of positions was removed. Third, the tangent planes of five COUP exposures were reprojected to match the tangent plane of the first observation (ObsID 4395). The six exposures were then merged into the single data event file used in this paper. These position corrections do not affect the results of SER, as demonstrated by the comparison between the FWHMs for the simulated and real data sets (Figs. 7 and 9).

5.1. Results

As in Paper I, we have calculated the FWHM of 22 bright pointlike sources in BI ONC data, obtained by Chandra using ACIS-S3 for various SER methods. The sources were selected to represent a range in off-axis angle from 2772 to 13678 and in count rate from 0.0052 to 0.2791 s$^{-1}$. Figure 8 (top) shows that after applying the SER technique to these data, all SER algorithms (3) improved the FWHM for every source (except that source 1, which displays evidence for pileup, has

| Source | $\alpha$ | $\delta$ | CSNb | $\theta^c$ | $R^d$ | $F_0^e$ | Improvement (%) |
|--------|----------|----------|------|-----------|-------|--------|----------------|
| 1       | 17.06    | 23 39.78 | 856  | 0.35      | 0.0057 | 0.628  | 7.8            |
| 2       | 17.06    | 23 33.88 | 855  | 6.15      | 0.0489 | 0.670  | 18.5           |
| 3       | 15.68    | 23 38.80 | 725  | 20.45     | 0.0054 | 0.641  | 19.7           |
| 4       | 15.45    | 23 45.19 | 708  | 24.41     | 0.0051 | 0.642  | 13.3           |
| 5       | 16.37    | 24 03.40 | 801  | 25.45     | 0.0488 | 0.667  | 15.9           |
| 6       | 15.38    | 23 33.38 | 700  | 25.72     | 0.0031 | 0.656  | 11.3           |
| 7       | 14.72    | 23 23.05 | 658  | 38.62     | 0.0035 | 0.696  | 5.5            |
| 8       | 14.39    | 23 33.38 | 631  | 40.16     | 0.0050 | 0.660  | 17.1           |
| 9       | 17.56    | 22 56.98 | 899  | 43.72     | 0.0027 | 0.695  | 14.1           |
| 10      | 14.95    | 24 12.74 | 673  | 45.24     | 0.0049 | 0.717  | 13.5           |
| 11      | 18.71    | 22 56.98 | 993  | 49.71     | 0.0066 | 0.690  | 14.5           |
| 12      | 14.33    | 23 08.29 | 624  | 51.52     | 0.0051 | 0.686  | 12.6           |
| 13      | 14.69    | 23 01.90 | 649  | 51.88     | 0.0070 | 0.685  | 14.4           |
| 14      | 20.46    | 23 29.94 | 1101 | 51.91     | 0.0114 | 0.722  | 1.8            |
| 15      | 13.47    | 24 40.27 | 545  | 53.38     | 0.0073 | 0.653  | ...            |
| 16      | 15.48    | 22 48.61 | 707  | 56.48     | 0.0100 | 0.679  | 13.2           |
| 17      | 19.20    | 22 50.58 | 1023 | 59.02     | 0.0066 | 0.734  | 10.2           |
| 18      | 21.05    | 23 49.13 | 1130 | 60.47     | 0.0079 | 0.729  | 13.5           |
| 19      | 19.67    | 24 26.52 | 1045 | 60.76     | 0.0059 | 0.693  | 7.0            |
| 20      | 21.38    | 23 45.19 | 1149 | 64.90     | 0.0083 | 0.746  | 6.4            |
| 21      | 16.73    | 23 31.39 | 825  | 68.79     | 0.0050 | 0.729  | 11.1           |
| 22      | 14.72    | 22 29.92 | 655  | 78.22     | 0.0087 | 0.814  | 18.4           |
| 23      | 20.62    | 24 46.20 | 1112 | 85.02     | 0.0039 | 0.772  | 11.9           |
| 24      | 15.35    | 22 15.65 | 697  | 88.10     | 0.0081 | 0.766  | 9.8            |
| 25      | 22.20    | 24 25.04 | 1193 | 89.19     | 0.0053 | 0.774  | 12.3           |
| 26      | 16.37    | 25 09.82 | 803  | 90.35     | 0.0049 | 0.806  | 2.7            |
| 27      | 10.74    | 23 34.37 | 394  | 94.33     | 0.0710 | 0.733  | 10.5           |
| 28      | 23.82    | 23 34.37 | 1268 | 101.26    | 0.0065 | 0.807  | 11.6           |
| 29      | 11.56    | 24 48.17 | 427  | 106.56    | 0.0050 | 0.858  | 18.1           |
| 30      | 09.68    | 23 56.01 | 338  | 111.12    | 0.0048 | 0.827  | 13.2           |
| 31      | 10.97    | 24 48.66 | 404  | 113.80    | 0.0033 | 0.872  | 7.8            |
| 32      | 23.69    | 24 57.51 | 1261 | 125.83    | 0.0079 | 0.933  | 10.1           |

Notes:

- a Right ascension for all sources is at 5h35m, and values in the table are in units of seconds; declination for all sources is at $-5^\circ$, and values in table are in units of arcminutes and arcseconds.
- b COUP data catalog source number (K. Getman et al. 2004, in preparation).
- c Source count rate in counts s$^{-1}$.
- d Source FWHM (in arcseconds) after removing randomization but before applying SER.
- e TSER: SSR: EDSER: CSDSER.
no improvement after applying the Tsunemi et al. [2001] method). Figure 8 (bottom) displays 32 pointlike sources chosen from Chandra ACIS-I COUP observations, with count rate ranging from 0.0027 to 0.0799 s\(^{-1}\) and off-axis angle from 0\(^{\circ}\)35 to 125\(^{\circ}\). Results for FWHM and improvement percentage for these 32 sources are listed in Table 3. Both abscissa axes are source number, sorted with the FWHMs of the original point sources, before applying SER but after removing randomization.

The source size, represented by the FWHM, was apparently smaller after applying SER approaches to BI devices, from TSER to SSER, EDSER, and finally CSDSER (Fig. 8), demonstrating the capability of improving the spatial resolution of BI Chandra ACIS imaging. The degree of improvement observed (Fig. 9, top) agrees very well with the predictions of the simulations (Fig. 6, bottom). At the same time, FI devices illustrate more modest improvements after application of SER techniques (Fig. 9). The improved performance of SSER over TSER is evident, but from SSER to EDSER and CSDSER, the improvement is less clear, for the reasons discussed in § 4. However, a small improvement in the effective FI Chandra ACIS PSF can still be seen after application of SER techniques.

Using the definition of improvement given in § 4, we quantitatively evaluate the performance of different SER methods on ONC data. The top and bottom panels of Figure 9 show this metric of the improvement for all SER algorithms for BI and FI Chandra ACIS sources, respectively. As expected from MARX simulations, BI data show superior improvement for CSDSER and EDSER, while FI data only show improvement for modified SERs, and there is no favorite among the three modified methods. Improvement for most sources in the FWHM range is from 40% to 70% and from 20% to 50% for BI and FI CCDs, respectively, with the improvement statistically dependent on off-axis angle.

6. SUMMARY

A study of potential improvements to subpixel event repositioning (SER) for Chandra ACIS data was conducted here, for BI and FI devices. We formulate modified SER algorithms at three levels of improvement for both CCD types: (1) inclusion of single-pixel events and 2 pixel split events (static SER); (2) in addition to event grade/split morphology, accounting for the mean energy dependence of differences between apparent and actual photon impact positions, based on the results of CCD simulations (energy-dependent SER); (3) adjusting PIPs according to the charge-split proportion in the split pixel(s), event type, and event energy, based on CCD model simulation results (charge split–dependent SER).

All three modified SER methods produce improvements in spatial resolution over those possible using an SSER algorithm employing only corner split events (Tsunemi et al. 2001), for both BI and FI devices. BI and FI CCDs exhibit different performance, and, overall, BI applications benefit more from angular resolution improvement after applying SER techniques. In addition, BI data demonstrate the superiority of energy- and/or charge split–dependent SER methods, while FI data show only marginal differences between the various modified SER methods. The improvements in image quality measured for actual BI and FI CCD observations agree well with the predictions of simulations.

This research was supported by NASA/Chandra grants G02-3009X and G04-5169X to R. I. T.

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