IMAGING ANALYSIS OF THE HARD X-RAY TELESCOPE ProtoEXIST2 AND NEW TECHNIQUES FOR HIGH-RESOLUTION CODED-APERTURE TELESCOPES

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ABSTRACT
Wide-field (≥100 deg²) hard X-ray coded-aperture telescopes with high angular resolution (≤2') will enable a wide range of time domain astrophysics. For instance, transient sources such as gamma-ray bursts can be precisely localized without the assistance of secondary focusing X-ray telescopes to enable rapid followup studies. On the other hand, high angular resolution in coded-aperture imaging introduces a new challenge in handling the systematic uncertainty: the average photon count per pixel is often too small to establish a proper background pattern or model the systematic uncertainty in a timescale where the model remains invariant. We introduce two new techniques to improve detection sensitivity, which are designed for, but not limited to, a high-resolution coded-aperture system: a self-background modeling scheme which utilizes continuous scan or dithering operations, and a Poisson-statistics based probabilistic approach to evaluate the significance of source detection without subtraction in handling the background. We illustrate these new imaging analysis techniques in high resolution coded-aperture telescope using the data acquired by the wide-field hard X-ray telescope ProtoEXIST2 during a high-altitude balloon flight in fall 2012. We review the imaging sensitivity of ProtoEXIST2 during the flight, and demonstrate the performance of the new techniques using our balloon flight data in comparison with a simulated ideal ideal Poisson background.

Key words: balloons – instrumentation: detectors – techniques: image processing – X-rays: binaries

1. INTRODUCTION
Near-arcmin angular resolution for wide-field hard X-ray coded-aperture telescopes is within reach in the near future. The Burst Alert Telescope (BAT) on Swift, which has been operating successfully for more than a decade, covers a 1.4 sr field (50% coding) with 22' angular resolution in the 15–200 keV band (Gehrels et al. 2004). The Imager on Board the INTEGRAL Satellite (IBIS) and the Joint European X-ray Monitor (JEM-X) can observe a ∼19×19 deg² field with the 12' resolution in the 15 keV–10 MeV band and a 7.5' diameter field with the 3' resolution in the 3–35 keV band, respectively (Winkler et al. 2003).

Recently we have achieved 5' angular resolution over a 20×20 deg² field in the 5–200 keV band with the balloon-borne hard X-ray coded-aperture telescope ProtoEXIST2 (Hong et al. 2013) by employing an array of CdZnTe detectors with the Application Specific Integrated Circuits (ASICs) of a high pixel density used in the Nuclear Spectroscopic Telescope Array (NuSTAR) (Harrison et al. 2013). Next-generation ASICs with a higher pixel density will soon enable ≤2' resolution, which will allow source localization within 20'. High-precision source localization from a wide-field hard X-ray telescope can initiate rapid follow-up studies of transient sources with many telescopes around the world without the assistance of secondary focusing X-ray telescopes, and thus open a wide range of discovery space in time domain astrophysics.

High resolution in coded-aperture telescopes introduces a new challenge in handling the systematics, such as non-uniform detector background. Even with a decent exposure, observed photon counts per pixel often remain too low to establish the precise pattern of non-uniformity in the detector plane, which can limit the detection and localization sensitivity. Novel observing schemes such as continuous scan or dithering can reduce the unknown systematic errors (Grindlay & Hong 2004), but as the pixel density increases, additional care in the analysis is required to ensure high sensitivity. Here we introduce two new techniques to alleviate the effects of systematics and improve detection sensitivity even under low count statistics of high-resolution coded-aperture telescopes. We illustrate these new imaging analysis techniques using the data acquired by the wide-field high-resolution hard X-ray telescope ProtoEXIST2 during a high-altitude balloon flight in fall 2012.

In Section 2, we review the basic parameters of the ProtoEXIST2 telescope. In Section 2.1, we describe the boresight calibration and performance of our pointing and aspect system during the high-altitude balloon flight in fall 2012. In Section 2.2, we estimate the sensitivity limit of the ProtoEXIST2 telescope and illustrate the challenge of high-resolution coded-aperture telescopes using the ProtoEXIST2 observations during the flight. In Section 3, we introduce a self-correcting background modeling scheme, which utilizes continuous scan or dithering operations. In Section 4, we introduce a Poisson statistics-based detection significance map, called a “trial map” (Hong et al. 2016) for coded-aperture imaging, which can handle the background without subtraction.

2. ProtoEXIST2

The ProtoEXIST2 payload during the flight in 2012 consisted of two X-ray telescopes, ProtoEXIST1 and 2, and a daytime optical star camera for pointing guidance and aspect correction. The detailed description of the instruments and the flight performance of the detector system are found in Hong et al.
Active Area 220 cm$^2$ depends on the source spectrum and the pointing elevation.

Note. The analysis showed that a relative offset is fl after the telescopes and the star camera. We measured the additional cap, this introduced an additional shift between the X-ray a few degrees. Since the coded masks were mounted on the top the outside of the PV forced the top cap of the PV to bow out by during the flight, the pressure difference between the inside and the outside of the pressure vessel expected between the ground level of Ft. was measured to be ∼140 mCrab/hr$^a$

### Table 1

Telescope Parameters of ProtoEXIST2

| Parameters             | Values                                      |
|------------------------|---------------------------------------------|
| Sensitivity            | ~140 mCrab/hr$^a$                           |
| Energy Range           | 5–200 keV                                   |
| Energy Resolution      | 2–3 keV                                     |
| Field of View          | $20^\circ \times 20^\circ$ (50% Coding)     |
| Angular Resolution     | 4$^\circ$                                    |
| CZT Detector           | 56 crystals × (1.98 × 1.98 cm$^2$)           |
| Active Area            | 220 cm$^2$                                  |
| Pixel, Thickness       | 0.6 mm, 5 mm                                |
| Tungsten Mask          | 4 layers × 0.1 mm thick                     |
| Coding Area            | 33.3 × 33.3 cm$^2$                           |
| Pixel, Grid, Thickness | 1.1 mm, 0.1 mm, 0.4 mm                      |
| Pattern                | Random                                      |
| Mask-Det. Separation   | 90 cm                                       |
| Rear and Side Shields  | Graded Pb/Sn/Cu                             |
| $^{241}$Am Cal. Source | 220 nCi each, ~36 cm above det              |

$^a$ Without atmospheric absorption. The atmospheric absorption at an altitude of 40 km can reduce the signal by a factor of ~3 in the 30–100 keV band, which depends on the source spectrum and the pointing elevation.

(2013). In this paper, we focus on the imaging performance of the ProtoEXIST2 telescope. Table 1 summarizes the telescope parameters of ProtoEXIST2.

The ProtoEXIST2 telescope is a wide-field hard X-ray telescope with an array of CZT detectors and a tungsten mask. High pixel density in the CZT detectors and the tungsten mask enables $S'$ angular resolution over more than a $20^\circ \times 20^\circ$ field of view (FOV) of 50% coding fraction. The combined thickness of 0.4 mm in the tungsten mask can modulate X-rays up to ~200 keV. Low-noise ASICs used in NuSTAR and thick CZT crystals (5 mm) cover a wide energy range from 5 to 200 keV, although at a typical flight altitude (~40 km) X-rays below ~30 keV from celestial sources are undetectable due to absorption in the remaining atmosphere along the lines of sight.

![Figure 1. Pointing history of the ProtoEXIST telescopes during the 2012 flight in azimuth and elevation. The number indicates the sequence of the observations.](image)

2.1. Pointing and Aspect System

A few days before the flight in 2012, we measured the boresight offset between the X-ray telescopes and the optical star camera using an $^{241}$Am radioactive source (Hong et al. 2013). The analysis showed that a relative offset is $(\Delta \text{az}, \Delta \text{el}) = (+5^\prime$, $+39^\prime)$ for ProtoEXIST2 when there is no pressure difference between the inside and the outside of the pressure vessel (PV). During the flight, the pressure difference between the inside and the outside of the PV forced the top cap of the PV to bow out by a few degrees. Since the coded masks were mounted on the top cap, this introduced an additional shift between the X-ray telescopes and the star camera. We measured the additional offset by creating an artificial pressure difference on the ground after the flight. Under about a 12 psi difference, which is expected between the ground level of Ft. Sumner, New Mexico and the air pressure at an altitude of 40 km, the additional offset was measured to be $(\Delta \text{az}, \Delta \text{el}) = (+12/1, +13/9)$, so that the total boresight offset of ProtoEXIST2 relative to the star camera was $(17/2, 52/9)$. The correction for this boresight offset was applied in reconstructing X-ray sky images from the ProtoEXIST2 observations below.

Figure 1 shows the pointing history of the ProtoEXIST telescopes during the 2012 flight in azimuth and elevation. We observed six X-ray sources with eight separate pointings that lasted 15–160 minutes each. While the ProtoEXIST2 telescope performed well during the flight (Hong et al. 2013), the pointing guidance system encountered a few issues that prevented the telescopes from locking on each target. The top panel in Figure 2 shows a scatter plot of the target positions relative to the pointing direction retrieved from the 206 star camera images during the observation of GRS 1915+105. The gray tracks are interpolated points by the onboard gyroscope in between two successive star camera images. While the targets were mostly in the central FOV during the observations as seen in Figure 2, they were constantly drifting beyond the angular resolution of the telescope at various speeds.

We had to rely on the star camera images to recalculate the precise pointing direction and apply the subsequent corrections. Unfortunately, the pointing software was not designed to store all the star camera images, and the number of the usable star camera images saved during the flight was limited to 20 during the observation of Sco X-1, 50 for Swift J1745.1–2624 and 206 for GRS 1915+105. The bottom two panels in Figure 2 show accumulative histograms of the changes in pointing direction between two successive star camera images during the observations of GRS1915+105 (middle) and Swift J1745.1–2624 (bottom). The shortest interval between two star camera images was 20 s and the next 40 s apart. In 20 and 40 s the pointing system drifted more than 3$'$ and 5$'$ for a half of the time, respectively. Although the pointing system became more stable by the second observation of GRS 1915+105, the movement between two successive star camera images is often larger than the angular resolution (4$^\circ$/8).

This indicates that one cannot rely on the aspect information beyond ±10 s within each star camera image. Unfortunately this severely limits the data usable for X-ray imaging. For instance, in the case of GRS 1915+105, the relatively good
time interval (GTI) is about 69 minutes out of the 118 minutes observation. For the rest of the sources, the GTIs range from about 7 to 14 minutes total per source.

2.2. Sensitivity Estimate

We mainly focus on the observation of GRS 1915+105, which was conducted during a relatively stable pointing period and produced the largest number of star camera images. Figure 3 shows the lightcurve of GRS 1915+105 measured by the Swift/BAT pointing and BAT slew survey (BATSS) (Copete 2012) around the ProtoEXIST2 observations of the source. A longer-term lightcurve of the source shows that the 15–50 keV flux of GRS 1915+105 was ∼400 mCrab weeks before our observation but fluctuated down to ∼100–150 mCrab during our observation.

For about a 70 minute observation of a 150 mCrab source, we expect 1400 photons on the detector in 30–100 keV after accounting for the atmospheric attenuation (by a factor of 3 on average). We observed about 1.1 cps per detector unit in 30–100 keV, so the total background is about 270,000 counts. For an ideal system with perfect pointings and pure Poisson-driven background, we expect a signal-to-noise ratio ($S/N$) of 2.7. The finite mask to detector pixel ratio (1.8) introduces an imaging factor of 0.8 (Skinner 2008), causing an additional loss in $S/N$ of 20%. Assuming a relatively moderate aspect blurring of 1′ (likely an underestimate given the performance of the pointing system), we expect another reduction in $S/N$ by ∼20%. We also expect that the non-uniformity in the background reduced the S/N by another ∼10% when untreated (see Section 3). Therefore a more realistic $S/N$ expected from the source is $\lesssim$1.7. The sensitivity limit for a 5σ detection in a 4000 s (GTI) observation (see Section 2.2).

According to Swift, the 15–50 keV X-ray fluxes of Swift J1745.1–2624 and Sco X-1 were about 500 mCrab and 1.5 Crab, respectively, during the time of the ProtoEXIST2 observations. However, for Swift J1745.1–2624, only 50 star
camera images were saved and the pointing system was more unstable during the observation of Swift J1745.1–2624 by about a factor of 2 compared to the GRS 1915+105, as seen in Figure 2. The low elevation of the source would have also increased the atmospheric attenuation (Figure 1). In the case of Sco X-1, only 50 star camera images are available and its X-ray emission is dominantly soft, mostly below 30 keV, which is likely attenuated by the atmospheric absorption at the altitude of our flight.

Figure 4 shows ProtoEXIST2 X-ray images of a $10^\circ \times 10^\circ$ region around GRS 1915+105. We extracted the data in a 20 s interval around each of the 206 star camera images, and combined them with proper boresight and aspect corrections using the world coordinate system of the star camera images. The reconstructed sky image on the left panel is without any background treatment, and on the right is with the background treatment described in the next section. There is no significant source in the FOV as expected from the above S/N estimates. Although the noise distribution in the sky image is well fitted by a Gaussian distribution, the sky image created without any background treatment shows large-scale structures (e.g., diagonal and circular ridges), indicating the effects of the non-uniform background in the detector. In 20 s, the average counts in each pixel of the detector is about 0.02 counts, so the non-uniform pattern of the background is not apparent in each individual detector plane image.
3. SELF-CORRECTING BACKGROUND SCHEME

Figure 5 shows the distribution of X-ray events in the detector during the flight. The gaps between CZT crystals, including the additional space the wirebonds used for control and readout of the NuSTAR ASICs, expose the side of each crystal to background radiation. As a result, edge pixels experience higher background counts than inner pixels. The edge pixel background enhancement is more clearly visible when the event distribution of each unit is stacked together (the right panel in the figure). Since the size of the gaps varies across the detector plane, each unit will have a different enhancement in the edge pixels. Besides the edge pixel background enhancement, there is also a more gradual trend of count increase toward the edges. The overall view of the event distribution in the detector (the left panel) also reveals other background patterns that are not originated from the coding pattern of the mask. These non-uniform background patterns are the source of the large-scale structures in the reconstructed sky images (the left panel in Figure 4).

A common way to handle non-uniform background in coded-aperture telescopes is first to establish a model of the background pattern from measurements and then subtract the properly scaled background model from the data set. For instance, in Swift/BAT, the detector plane image is “cleaned” with a 14-element background model (Krimm et al. 2013).

During the 2012 flight, ProtoEXIST2 recorded about 1 count ks\(^{-1}\) pix\(^{-1}\) in the 30–100 keV band after excluding X-ray events from the onboard \(^{241}\)Am source. Over an hour’s observation, each pixel would accumulate about 3 counts on average, which is too small to build a reliable analytic model for the background. Using a longer interval for background modeling would enable higher count statistics, but this is not favorable since the background pattern often varies with time.

Alternatively, one could try smoothing the event distribution to better identify the background pattern under the assumption that the background pattern does not have high spatial frequencies. However, as seen in the edge pixel enhancement due to detector gaps (Figure 5), it is not unusual to have high-frequency noise fluctuations. Since bright sources will also generate high-frequency fluctuations in the detector plane, it often requires complex multi-component background modeling with proper cleaning of bright sources to properly handle the systematics in the detector plane (e.g., Krimm et al. 2013).

In order to combat non-uniformity in the detector response in general, a continuous scan or slew motion instead of a fixed pointing has been proposed (Grindlay & Hong 2004; Copete 2012). During a scan, the relative position of each detector pixel with respect to a given sky pixel changes continuously, which allows any detector-coordinate-dependent systematic errors to average out to some degree, depending on how thoroughly the scanning operation covers the given FOV. In fact, the scanning operation can be viewed as an extreme version of dithering motions, which are commonly used to reduce the systematics for both focusing and non-focusing telescopes.

In Swift/BAT, the roll angle is varied within \(\pm 1^\circ\) from an orbit to another to prevent the systematic errors from accumulating. The BAT slew survey (BATSS) takes advantage of the self-correcting feature in slew motions (Copete 2012). In BATSS, given the high-speed slews performed by Swift, one sky image is generated every 0.2 s in order to minimize blurring, which is later combined to a single stacked image for source detection. Counts in each pixel of each 0.2 s image are relatively small and the pre-calculated background model may be not suitable for the rapid change of the telescope orientation during the slew. Nonetheless, the images generated by BATSS with no background handling procedure show an improvement relative to the images cleaned by a sophisticated background model from pointed observations of the equivalent duration (Copete 2012). However, similarly to X-ray images generated from the ProtoEXIST2 data, the sky images from BATSS show large-scale fluctuations due to lack of any treatment on the non-uniform background.

Figure 6 illustrates our new approach to auto-correcting non-uniformity in the background under scanning or dithering motions while (unknown) sources of interest are in the FOV. The total duration of the observation is shown in the green interval (T). First we divide the data into multiple segments, where each segment is well separated in terms of either
pointing direction or roll angles more than the angular resolution. The segment as shown in Figure 6.

Figure 6. Illustration of the data selection (Bk) for background modeling for each segment (Sk) (a) sliding window selection (b) anti-segment selection.

Figure 7. Input and measured S/N ratio for various simulated sources with purely Poisson backgrounds (dotted lines with open symbols) and the real ProtoEXIST2 background (solid lines with closed symbols) under a single pointing observations (circles) and 40 point dithering operation (squares and diamonds). The error bars are drawn from 10 cases of single pointing observations with Poisson background for illustration.

(see Section 4 to handle the background without subtraction), and generate a background-subtracted detector image. Then we combine the image of each segment with a proper aspect correction to make a final stacked image for source detection.

If changes in the pointing or roll angles between the segments are equivalent to or smaller than the angular resolution of the telescope, this procedure will eliminate the source signal as well as the background fluctuations since in essence it is a self-subtraction procedure. However, if each segment is different in pointing direction or roll angle larger than the angular resolution, this procedure will eliminate the background pattern tied to the detector coordinates within the limit of the given photon statistics, while allowing the source counts to accumulate at the right sky position.

The right panel in Figure 4 shows an X-sky image generated with the background subtraction following the recipe in Figure 6(b), which clearly shows a drastic reduction in the large-scale variations, compared to the case without any background subtraction (a). In addition, while the overall noise distributions of the sky images in Figures 4(a) and (b) follow Gaussian distributions as seen in Figure 4(c), the noise distributions of the sky images in the raw count unit in Figure 4(d) show that their noise spread is in fact larger than that expected from the pure statistical fluctuation of the observed counts (green). The large-scale variations in Figure 4(a) are also the cause of the offset in the noise distribution (red) in Figure 4(d). These indicate that there is indeed a systematic-driven contribution in Figure 4(a). The self-correcting background scheme reduces the rms of the noise by 5%–7% in addition to largely removing the large-scale variations. Since our data did not have any detectable sources, in order to make sure that the source signal under the self-correction scheme did not get canceled out, we performed the same procedure with simulated sources.

Figure 7 shows the ratio of the input and measured output S/N from simulated sources with a wide range of input signals. For background, we tested both pure Poisson statistics-based backgrounds (dotted lines with open symbols) and the ProtoEXIST2 data (solid lines with solid symbols). Observations with fixed pointings (circles) are compared with the 40 point dithering motions (squares and diamonds). The results of a fixed pointing with pure Poisson noise set an ideal limit of the system, which is bounded by the imaging factor at low S/N (80%) (Skinner 2008) and by the coding noise limit at high S/N. The coding noise is the mask pattern-induced noise (Skinner 2008). The coding noise limit of the output S/N is about 296 for ProtoEXIST2. In observations with fixed pointings, the real background reduces the S/N down to 40%–50% (closed circles) of the input S/N.

Dithering motions (red) alleviate the coding noise limit by mixing different parts of the mask pattern in the detector image, and thus outperform pointed observations at high S/N. To simulate realistic aspect corrections, we allowed about 1′ errors in simulated source positions, so even with pure Poisson noise backgrounds (open squares) the measured S/Ns in the reconstructed images are lower than the input S/Ns by about 60%–70%. With the real background (closed squares), the output S/Ns drop even more but not as much as the pointed observations, which illustrates the benefits of dithering or scanning motions. With the proposed treatment on the non-uniform background (green diamonds), the output S/Ns recover almost up to the pure Poisson noise cases, which
means about 3%–10% improvements relative to the cases of no background handling. The improvements at low input $S/N$s are relatively larger: e.g., the proposed method improves the output $S/N$ from 8.4 to 9.2. The improvement varies with the scale of dithering or scanning motions and the number of segments. If the number of segments is too small (or $B_k/S_k \ll 10$), the treatment will increase the rms of the sky background although it may still reduce the large-scale structures.

### 4. POISSON STATISTICS-BASED DETECTION SIGNIFICANCE MAP

A common method to reconstruct sky images ($s_i$; $i$ represents the sky pixel index) for coded-aperture telescopes is to cross-correlate detector plane images ($d_j$; $j$ represents the detector pixel index) with the mask pattern ($M_{ij} = 1$ for open and 0 for closed pixels). The cross-correlation is often performed through fast Fourier transformations (FFTs). In order to set the baseline value of the sky image at zero and the source counts at the right signal, the mask pattern is balanced by an open fraction ($\rho$), where the balanced pattern $N_{ij}$ is 1 for open pixels, and $\rho/(\rho - 1)$ for closed pixels. The detector plane image ($d_j$) is background ($b_j$) subtracted and masked out for dead pixels or inactive zones, if any, before cross-correlation. For a random mask pattern, detector plane images are “rebalanced” to have a total count of zero using a constant ($c$), which suppresses large-scale structures bigger than the angular resolution. The “rebalancing” procedure is often essential for point source detection, but it suppresses a large-scale variation even if its origin is celestial. In summary, the reconstructed sky image ($s_i$) is given by

$$s_i = N_{ij} \cdot (d_j - b_j - c),$$

(1)

where $\Sigma(d_j - b_j - c) = 0$.

The background subtraction, although it efficiently addresses non-uniformity of the detector, may not be optimal in handling non-negative counts of Poisson statistics, especially for characterizing the detection significance of faint sources near the detection threshold. An alternative approach is to calculate the probability of having more than the observed counts from a random fluctuation of the background counts based on the Poisson statistics. For every sky position in the FOV, one can estimate the total observed counts ($p_j$) by cross-correlating the raw mask pattern and the raw detector plane image: $p_j = M_{ij} \cdot d_j$.

The mask pattern ($M_{ij}$) consists of non-negative numbers representing an open fraction ranging from zero to totally opaque elements to one for fully open elements. The detector plane image also consists of non-negative raw counts. For the estimation of the background counts, we repeat the calculation using the background model.

$$q_i = M_{ij} \cdot b_j,$$

Then for a given pixel ($i$) in the sky, the expected background ($r_i$) is given as

$$r_i = p_i q_i / \bar{q}_i,$$

where

$$\bar{p}_i = M_{ij} \cdot d_j,$$

$$\bar{q}_i = M_{ij} \cdot b_j.$$

Note $\bar{M}_{ij}$ is an inverted mask pattern, which ranges from zero for fully open elements to one for totally opaque elements, but the non-imaging opaque elements remain zero. Then, $\bar{p}_i$ and $\bar{q}_i$ represent the portion of the counts that cannot come from the sky pixel $j$ among the coded detector area for the sky position.

For the total observed counts ($p_i$) and the background estimate ($r_i$) at a given sky position ($i$), the probability that the observed counts are purely due to a random fluctuation of the background counts is given by a normalized incomplete
gamma function (Weisskopf et al. 2007; Kashyap et al. 2010)

\[ P(>p_i) = \gamma(p_i + 1, r_i) \]
\[ = \frac{1}{\Gamma(p_i + 1)} \int_0^{r_i} e^{-t} t^{p_i} dt \]

One can repeat the calculation for every sky position \(i\) to generate the probability map.

In order to make a sky image in a conventional way where bright sources have larger values, one can simply use an inverse of this probability map, which is the number of trials required to generate the observed counts from a random fluctuation. We call this map of required random trial numbers a “trial” map and it represents a significance map of source detection. Hong et al. (2016) first applied this trial map-based approach to point source detection in X-ray images taken from NuSTAR, and in this paper we extend the approach to coded-aperture imaging. Since each pixel in a sky image of a coded-aperture telescope represents one trial of a source search, if the value in a trial map greatly exceeds the total number of the pixels in the image, it indicates a high chance of a real source (or a systematic artifact). Detection threshold setting, therefore, is more straightforward in trial maps generated by coded-aperture imaging than in those by focusing telescopes, where the threshold depends on the (potentially varying) size of the point-spread function relative to the image.

A source in the partially coded FOV in a sky image generated by Equation (1) has less signal than a source of the same strength in the fully coded FOV; thus in order to reflect the source signal properly, the image has to be renormalized by the partial coding fraction. On the other hand, such a normalization enhances the noise fluctuation in the partially coded FOV. When stacking multiple sky images generated by Equation (1), they have to be weighted by the variance in order to account for the proper coding fraction, where the error due to improper handling of Poisson statistics can propagate and amplify. In the case of trial maps, they describe a chance of having a real source in any part of the FOV regardless of the coding fraction. For stacking multiple images, one simply accumulates the sky images of \(p_i\) and \(r_i\), then re-applies Equation (3) to get the stacked new trial map.

Figure 8 shows trial maps of the images in Figure 4. The images are color-coded logarithmically with the trial numbers \((10^3)\). Each image has about 60k independent pixels, and the threshold for 0.1% false detection is about \(X \sim 7.8\). The background treatment described in Section 3 reduces the large-scale structures and lowers the noise fluctuation by about 100 in trial numbers, but the trial map on the right panel indicates there is some residual non-uniformity in the image, which is not apparent in Figure 4.

In terms of computational requirements, the total observed \((p_i)\) and background counts \((q_i)\) can be estimated through FFTs. The latter can be pre-calculated if the background model is known ahead and remains unchanged.

5 In order to “clean” bright sources (i.e., reduce the coding noise associated with the bright sources), the sky images of all four quantities \(p_i\), \(q_i\), \(P_i\) and \(q_i\) have to be tracked. The cleaning procedure simply recalculates \(r_i\) by treating the contribution of the bright sources as a part of the background, and thus it does not involve any subtraction from \(p_i\).

In coded-aperture imaging, source detection often relies on a large number of counts, but for a high-resolution imager aimed at detecting fleeting signals from transient sources, the total number of counts can be relatively small, so the suggested rigorous probabilistic approach of a source search is more appropriate.

5. CONCLUSION AND FUTURE WORK

In future, direct localization of transient sources like gamma-ray bursts without the assistance of secondary instruments will enable a wide range of time domain astrophysics. To achieve this, next-generation wide-field hard X-ray telescopes should be capable of sub-2’ angular resolution. In high-resolution coded-aperture telescopes, new challenges arise in handling non-uniformity in the detector system due to the low count statistics per pixel. During a high-altitude balloon flight in 2012, the ProtoEXIST2 telescope of 4/8 resolution collected about 3 counts hr\(^{-1}\) in each detector pixel on average, which illustrates this new challenge. Dithering or continuous scan as shown in BAT data alleviates the effects of the systematics by automatically averaging out the non-uniformity even without special treatment, but large-scale variations still remain in their sky images, which can limit the detection and localization sensitivity.

We presented a method to improve the sensitivity of high-resolution coded-aperture systems by self-correcting the non-uniform background of low statistics efficiently. Combining simulated sources with the real balloon flight data of the ProtoEXIST2 telescope, which exhibits pixel-dependent background variations, we demonstrated that the proposed techniques can reduce the large-scale variation dramatically and improve the S/N by a few to 10% depending on the input S/N. We also proposed a new method to estimate detection significance using a Poisson statistics-based probabilistic approach without relying on subtraction in background handling. We plan to apply these techniques to the Swift/BAT data to evaluate the improvements in a wide range of operating environments for further optimization.

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