A Probabilistic Method of NXB Removal for X-ray Astronomy

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Take Home Message

This is not a talk about how to estimate non x-ray background events - it is a talk about how to better remove them from your event list. The calculations and images were designed for ART-XC data, but can be applied to any high energy event list data. It is especially well suited to diffuse, low signal-to-noise regions of the sky or moving telescopes.
The Key Challenge

X-ray astronomy is almost always photon starved, and in many instances we only observe a few sky + NXB counts in a region of interest. We want to separate the sky from the background.
The simple calculation

- Observe $k$ counts in a detector/sky region
- Expect $\mu_N$ NXB events in this region
- Interested in the expected number of sky events, $\mu_S$
- Naively, $\mu_S = k - \mu_N$
Limitations

Simple subtraction has limitations for X-ray data at low counts

- Subtraction can go negative - not physical
- Fluctuations can make spurious signals appear “real” and vice-versa
- Difference of two Poisson RV’s is not a Poisson
- Cannot ID any specific event as sky/NXB.
Assumptions

- We will assume that $\mu_N$ and $\mu_S$ are Poisson processes.
- We observe $k_N$ NXB counts and $k_S$ sky photons, but only know that $k_N + k_S = k$.

We consider each possible count state individually and take the weighted average over all states. What are the values of $\mu_S$ that are consistent with $k$ observed counts given $\mu_N$?
The Poisson distribution is at the center of all of these calculations.

\[
P(k|\mu) = \frac{e^{-\mu} \times \mu^k}{k!}
\]
The Math II

Per-state net counts estimated as the maximum of a simple Poisson

\[ \frac{\partial P(k_S | \mu_S)}{\partial \mu_S} = 0 \rightarrow \bar{\mu}_S(k_N) = k_S = k - k_N \]

Weights for each state are the background probabilities

\[ w(k_N | \mu_N, \bar{\mu}_S, k) = P(k_N | \mu_N) \]
The Math III

Final result is weighted average over all states

$$\mu_s^* = \frac{1}{\sqrt{1}} \sum_{k_{N}=0}^{k} \bar{\mu}_S(k_{N}) \times w(k_{N}|\mu_N, \bar{\mu}_S, k)$$
Examples

$\mu_N = 0.5, \ k = 2$
Examples

$\mu_N = 5.0, \ k = 3$
Examples

$\mu_N = 5.0, k = 10$
Uncertainties

We can calculate a central $c \times 100\%$ confidence interval $(x_L, x_U)$ analytically

\[
\frac{\gamma_L(k+1, x_L + \mu_N) - \gamma_L(k+1, \mu_N)}{\Gamma_U(k + 1, \mu_N)} = \frac{1 - c}{2}
\]

\[
\frac{\gamma_L(k+1, x_U + \mu_N) - \gamma_L(k+1, \mu_N)}{\Gamma_U(k + 1, \mu_N)} = \frac{1 + c}{2}
\]
Old Versus New Calculation

The graph shows the relationship between $\mu^*_S$ and $\mu_N$ for $k = 25$. The shaded areas represent different regions of interest, possibly indicating thresholds or critical points for the calculation.
Advantages of this New Method

- Always non-negative. Only get zero net counts when zero counts observed.
- Net counts converge to zero as $\mu_N >> k$.
- Monte Carlo simulations show small bias ($\sim 0.5$ counts high using ground truth inputs) that otherwise does not vary with input parameters.
- Can construct event specific probabilities $p_S = \frac{\mu_S^*}{\mu_S^* + \mu_N}$. 
Event Specific Probabilities

Here are three ways to use event specific probabilities ($p_S$) to clean images of NXB for X-ray telescopes, depending on your interests and needs:

- **Random Removal**: select a random number between 0 and 1 for each event. If that random number is less than $p_S$ keep it.
- **Fractional Photons**: Instead of projecting 1 whole event onto the sky, only project $p_S$ events.
- **False Probability**: Project $p_N = 1 - p_S$ onto the sky. As you add telescopes take the product in order to reduce noise.
Simulated Cluster Images
Simulated Cluster Profiles

![Graph showing simulated cluster profiles with different subtraction methods: Cluster + BG, Simple Subtraction, Random Removal, Fractional Photons, and Cluster. The graph plots surface brightness against distance in arcseconds.](image)
Next Steps

• Paper coming to MNRAS soon - just got first referee report
• A version of this calculation for Chandra data will be integrated into CIAO, with development and science testing underway
• Develop use with other observatories
• Investigate use with other modes beyond imaging