Thoughts on Filtering Flares in L3 Background Files

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In what follows, I am going to make the implicit assumption that we can *characterize* the background, and therefore whether or not one filters a flare merely becomes an issue of whether the signal-to-noise for a source of interest improves by the filtering. If background flares simultaneously decrease our ability to characterize the background, then more stringent filtering criteria are required. I will also exclusively deal with sources at the margin of detectability. Brighter sources will either see less increase in their signal-to-noise, or possibly even see S/N decrease. (For example– for a 1" point source, filtering out 10% of the lightcurve is almost never a good idea, as 1" hardly has any background to remove – you are more likely to be removing solely signal photons.)

Let's start by assuming that there is an observation with length T_o, over which time we accumulate S source counts and B background counts from the *steady* component of the background. Assume that over a flare time T_f an *additional* B_f background photons are accumulated. (B and B_f will depend upon observation lengths and source extraction region areas.) The signal-to-noise for the whole observation is then:

$$\mathcal{S}_o/\mathcal{N}_o \equiv \frac{S}{\sqrt{S+2B}} \tag{1}$$

while the signal-to-noise for the part of the observation outside of the flare is:

$$\mathcal{S}_{noflare}/\mathcal{N}_{noflare} \equiv \frac{S\left(\frac{T_o-T_f}{T_f}\right)}{\sqrt{S\left(\frac{T_o-T_f}{T_f}\right)+2(B-B_f)\left(\frac{T_o-T_f}{T_f}\right)}} \tag{2}$$

We can then take the difference between the two and ask the question: for what background flare rate and flare duration does removing the flare increase the $\mathcal{S}/\mathcal{N}$? This can be shown to be:

$$1+\frac{B_f/T_f}{B/T_o} \geq 1+\frac{(S/B+2)}{2\,(1-T_f/T_o)} \tag{3}$$

For marginal detection cases (S/B small) as the flare duration goes to 0 only flares that double the background rate are worth excising. (Again, we are assuming that we have a good *characterization* of the background.) As signal-to-noise increases, it becomes increasingly unworthwhile to remove flares.

The interesting case comes when removing the flare just increases the signal-to-noise to 3 (which we will take as our detectability limit). Setting eq. (2) equal to 3, this happens for total source counts of

$$S=\frac{9}{2}\mathcal{F}^{-1}\left(1+\sqrt{1+\frac{8}{9}\mathcal{F}B}\right) \tag{4}$$

where $\mathcal{F}\equiv(T_o-T_f)/T_o$. For this marginally detected source, the fractional increase in the background flare rate required to increase the signal-to-noise is:

$$1+\frac{B_f/T_f}{B/T_o} \geq 1+\mathcal{F}^{-1}\left[1+\frac{9}{4\mathcal{F}B}\left(1+\sqrt{1+\frac{8}{9}\mathcal{F}B}\right)\right] \tag{5}$$

There is an implicit dependence upon the duration of the observation and the size of the detection region by the fact that B depends upon both those quantities.

To translate this into realistic numbers for *Chandra* we take 50 ksec as a fiducial observation length, and choose $3\times10^{-7}\ \mathrm{counts/s/arcsec^2}$ as a typical background rate. (For the detection bands of interest for Level 3, background rates can differ from this by a factor of three in either direction. Observation lengths likewise can differ from this by about a factor of three in either direction.) Using those numbers, we can then translate

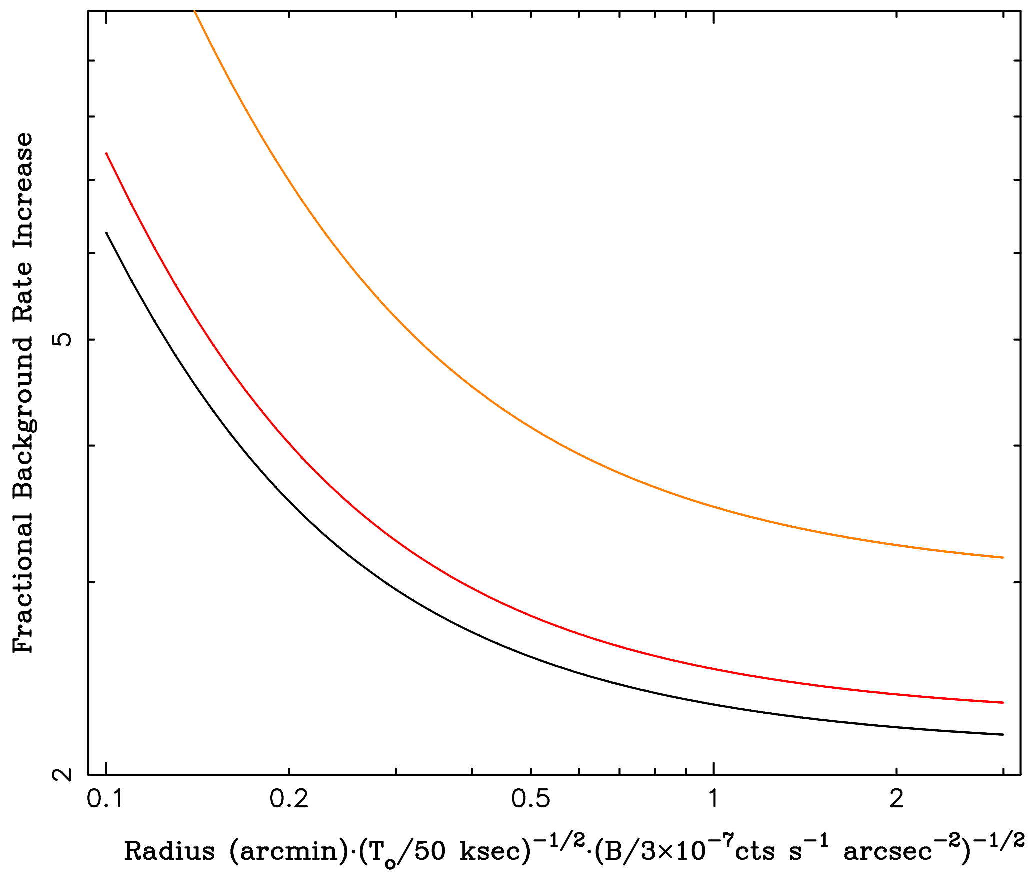

Figure 1: Minimum fractional increase in the background count rate (over a given integrated source region) for which removing the "flare" causes the source signal-to-noise to *improve* to $S/N \geq 3$ (i.e., the above is geared towards marginally detectable sources). This also entails a total counts for the source - see Fig. 2. Black line assumes the flare covers 10% of the observation, red line 20% of the observation, and orange line 50% of the observation. X-axis is the source region size, presuming a fiducial observation length and steady (i.e., non-flare) background rate. For typical *Chandra* observations, either could differ by a factor of three in either direction.

a source detection radius into a value for B, and thereby into a fractional increase in background rate required to make it worthwhile excising a flare, and likewise a total source region counts value for a source at the margin of detectability. Note that I am looking at cases where we are removing 10% or more of the lightcurve (for lower fractions of the lightcurve being removed, we are getting into the regime of removing less than one background photon from the smaller source regions.)

These results suggest that so long as we can do a good job of characterizing the background, we should only worry about flares that more than double the background count rate. We also see that the catalog criterion of rejecting outright observations that have background rates 5 times the instrumental average is also quite reasonable, as such rates severely affect source with radii $\gtrsim 6$". The catalog requirements document (at least version 0.5, which I have sitting on my desk) is a little confusing as regards source extent. It quotes 1' as the upper limit. Is that diameter or radius??? The former, as we can see in Fig. 2, is a problem, as the desire to go as faint as 50 counts is not likely feasible for most observations. If, on the other hand, one means radius, then 50 counts might be plausible.

In terms of filtering an observation, we can define the magnitude of the flare, in terms of a statistical deviation, that we are excising in order to improve the S/N to 3. Here there are various ways one can define this statistical deviation. I am taking the estimate of the mean rate to be $(B + B_f)/T_o$, and using that as a baseline by which the σ of a deviation will be judged (despite the fact that the B_f counts come in shorter

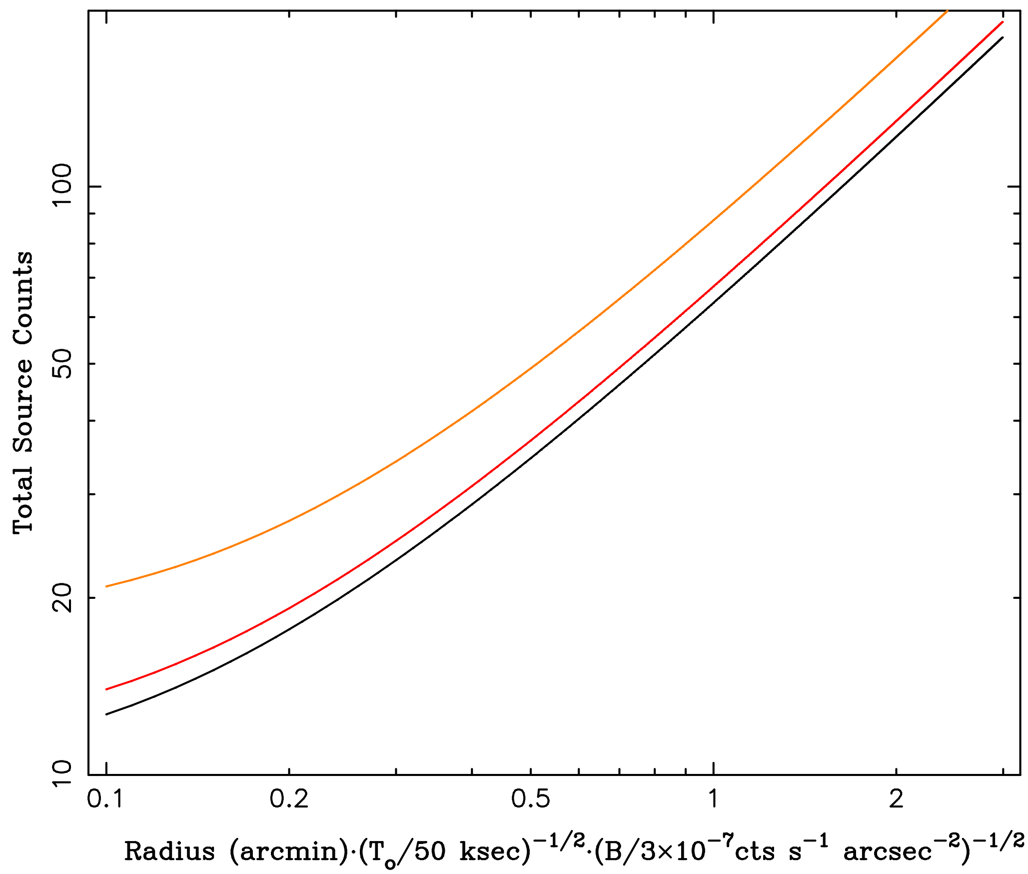

Figure 2: Total source counts – for 100% of the observation – at which removing the background "flare" improves the S/N to 3, under the same assumptions as Fig. 1. Color-coded lines again refer to 10%, 20%, and 50% of the observation being compromised by a flare. Again, the X-axis is the source region size, presuming a fiducial observation length and steady (i.e., non-flare) background rate. As before, for typical *Chandra* observations, either could differ by a factor of three in either direction.

duration, T_f. The σ deviation of the excised flare then becomes:

$$\sigma \equiv \frac{B_f \mathcal{F}}{\sqrt{(B+B_F)(1-\mathcal{F})(2-\mathcal{F})}} \ , \tag{6}$$

where B and B_F implicitly depend upon source detection region size and length of observation. We plot this value, for the same conditions as in the previous figures, in Fig. 3.

Note that the above flare amplitude is referenced to signal-to-noise in the source detection region. Realistically, one would use a much larger region of the chip to assess background flares. We can calculate the signal-to-noise of the flare in this larger region by multiplying the above expression by $\sqrt{B_q/B}$, where B_q is the background in the larger region. This is plotted in Fig. 4, using one quarter of the chip (for a 50 ksec observation) as the fiducial size. At first blush, this seems a rather high signal-to-noise, except when you stop to consider that 1/4 of the chip has approximately 900 counts, we are considering flares that occur over 10% or more of the observation (yielding 90 counts as our baseline for the background), and are more than doubling the background rate during the flare. I.e., signal-to-noise over a large background region is almost an irrelevant concern in practical situations.

So what does this all mean in terms of recommendations? I have read through Arnold Rots's specifications, and a few things immediately struck me. First, it ignores the fact that we (or, more specifically, Mike McCullough) have gone through some amount of effort to create a background region to input to the source detection process. This leads to the first major question:

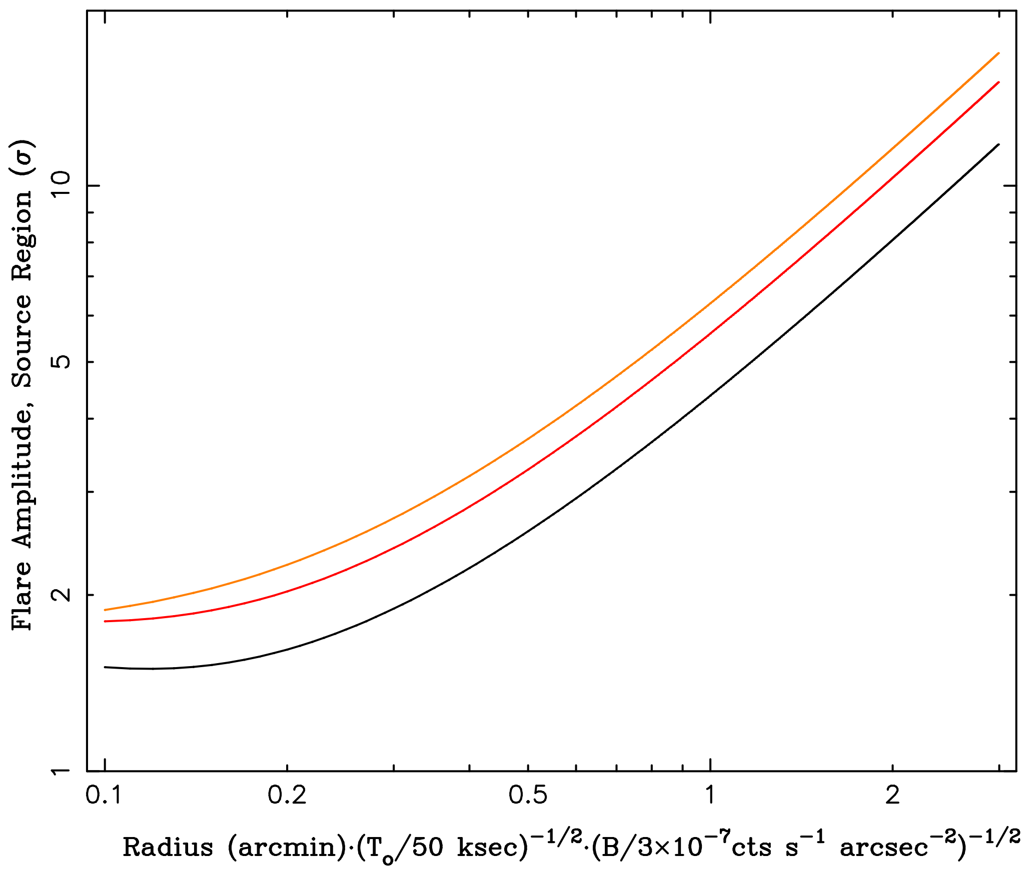

Figure 3: Flare signal-to-noise, *in the source detection region*, for which removing the flare times improves the S/N to 3, under the same assumptions as Fig. 1. Color-coded lines again refer to 10%, 20%, and 50% of the observation being compromised by a flare. Again, the X-axis is the source region size, presuming a fiducial observation length and steady (i.e., non-flare) background rate. As before, for typical *Chandra* observations, either could differ by a factor of three in either direction.

- *Do we want an iterative procedure for source detection and determination of background flares?* That is, do we want to create a background, detect the sources, remove the sources, use the source free regions to filter the background for flares, and then redo the background estimate/source detection algorithms?

Arnold's method, which sounds at least somewhat plausible, is very much in the camp of: identify and remove flares, then create backgrounds, then perform the source detection algorithm once. Given the results shown in Fig. 1, which tends to indicate that only removing very large flares improves detection signal-to-noise, I believe we probably can get away with an algorithm that filters times of background flares first and once, followed by a single round of background estimation and source detection. Clearly, however, more accurate results would be achieved by an iterative scheme. Furthermore, I believe we have a chance of being more rigorously quantitative with our criteria if we adopt an iterative scheme. The background mean and variance will be better defined if point sources are first removed.

The second aspect of Arnold's specifications that struck me is the lack of quantitative assessment of the effects of background flare removal on the signal-to-noise of the source. This leads to the second major question:

- *What are the goals of background flare removal?* Are we trying to increase the detectability of extended sources? Are we trying to improve the characterization of point sources? To some extent, those goals are at odds with one another.

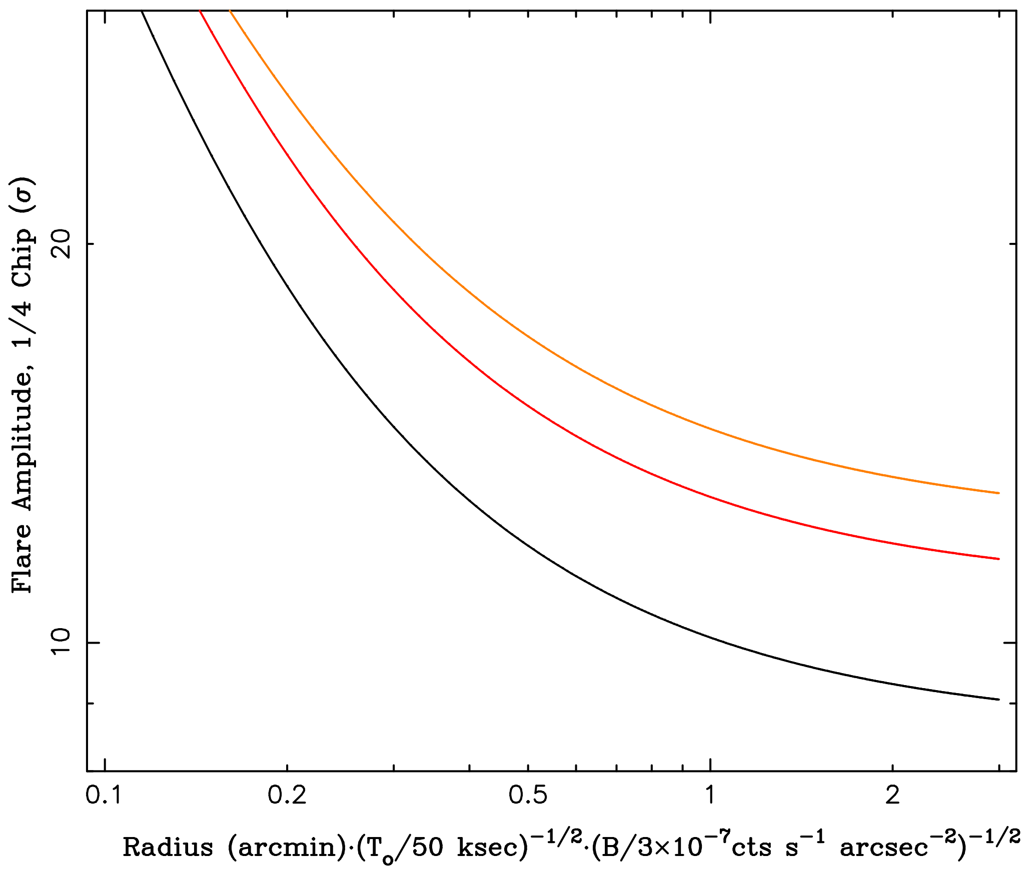

Figure 4: Flare signal-to-noise, *over 1/4 of an ACIS chip*, for which removing the flare times improves the S/N to 3, under the same assumptions as Fig. 1. Color-coded lines again refer to 10%, 20%, and 50% of the observation being compromised by a flare. Again, the X-axis is the source region size, presuming a fiducial observation length and steady (i.e., non-flare) background rate. As before, for typical *Chandra* observations, either could differ by a factor of three in either direction.

I am presuming that the goal is to improve the *detectability* of extended sources (whether the extent is physical, or due to being far off-axis from the aimpoint). It has to be realized, however, that whatever flare criteria that are adopted will likely decrease the signal-to-noise of point sources. Improving the *detectability* of extended sources, as opposed to merely improving their *characterization*, implies that either background flare specification occurs first, or an iterative scheme is adopted (or both).

The third aspect of Arnold's specifications that struck me was the lack of quantitative recommendations, coupled with references to human intervention. I.e., phrases such as "If it is a significant fraction of the total exposure time, the observation is a lost cause; if it is a negligible amount of time, something else is going on . . . review is recommended . . .", and, ". . . compare its total duration to that of the intersection. If close, use the union to excise bad time intervals; if significantly different, review is recommended." What constitutes 'significant'? What constitutes 'negligible'? What constitutes 'close'? How does the 'review' proceed? This leads to the third major question:

- *What are the quantitative criteria for excising times of high background?* And should these criteria apply to individual energy bands? Should all energy bands be excised in a given time period if any are excised during that interval?

I am of the opinion that for uniformity and simplicity, all energy bands should cover the same good time intervals. If any energy band leads to excising of an interval, it should be excised for all.

My own recommendations would be to adopt a scheme along the following lines.

1. Characterize the background via the methods being developed and described by Mike McCullough.

2. If the background in any detection energy band exceeds 5 times the average background for the instrument, throw the observation out.

3. Run the source detect algorithm, and remove the detected sources by removing the union of source regions from all detection energy bands.

4. Run a to-be-determined variability search algorithm on the remaining background regions that adopts at least some of Arnold's suggested criteria, namely the presence of peaks near zero lag of the cross-correlation across multiple chips and/or nodes.

5. Excise the union of times when the background rate exceeds the mean rate by a factor of three or more in *any* of the detection energy bands. Don't worry so much about signal-to-noise, realizing that for any reasonable scheme a signal-to-noise criterion is more likely to oversubtract good time intervals. Note: the 5 times threshold for throwing an observation out is a global criterion, referenced to *mission-averaged* properties of the detectors. The factor of three rate increase is a *local* criterion, referenced to the mean of the observation in question. So long as the background can be *characterized*, we only want to remove times where it flares relative to that mean. One could in principle make this relative threshold depend upon the mean (in general, *decreasing* with the mean rate), but further work would be required to establish a quantitative, reasonable method for scaling this threshold.

6. If the remaining good time intervals are shorter than 5 ksec, throw the observation out. (This number could be played with a bit; however, as far as point sources on axis are concerned, often one can get very reasonable information in very short observations. Therefore I would choose a fairly short lower threshold for throwing an observation out. Whatever that criterion, I would choose it by total remaining time in the good intervals, not by percentage excised.)

7. If the background flare times were none-zero, re-characterize the background for the remaining good times via the standard methods, and re-run the source detection algorithm.

8. Do not adopt any criteria that are not rigorously quantitative, or that require 'review' as part of the standard process. So long as the methods are rigorously quantitative we can at least *characterize* their effect, even if the scheme is less than "optimal" in some sense.

The above suggestions are themselves at this point not fully-formed and thought out. However, it is clear to me that Arnold's specifications do not yet fully meet reasonable requirements for development, do not account for the development work as regards background characterization, and have not accounted for a quantitative assessment of the effect of background removal on source signal-to-noise.