**MIT Kavli Institute** **Chandra X-Ray Center**

**MEMORANDUM**
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| **To:** | Jonathan McDowell, SDS Group Leader |
| **From:** | Glenn E. Allen, SDS |
| **Subject:** | Afterglow spec |
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# 1 Afterglows

## 1.1 Description

A cosmic-ray "afterglow" is produced when a large amount of charge is deposited on a CCD by a cosmic ray. Most of the charge is clocked off of the CCD in a single frame. However, a small amount can be captured in charge traps, which release the charge relatively slowly. As a result, a sequence of events can appear in a single detector pixel over a few frames as the trapped charge is released.

To date, two algorithms have been used by the CXC to identify cosmic-ray afterglows. The first algorithm was implemented in the CIAO tool `acis_detect_afterglow` and used for pipeline processing from the summer of 2000 to the fall of 2004. This algorithm searches for occasions when events are detected in two or more consecutive frames on the same CCD pixel. While the events are flagged as potential cosmic-ray afterglows and excluded from Level 2 event-data files, the corresponding pixels are not included in the observation-specific bad-pixel file. This algorithm finds many afterglow events, but at the expense of discarding X-ray events associated with real astrophysical sources. The fraction of the source events that are discarded depends on the brightness and variability of the source.

In an attempt to minimize the loss of source events, another algorithm was developed and implemented in the CIAO tool `acis_run_hotpix`, which is a wrapper around the tools `acis_find_hotpix`, `acis_classify_hotpix` and `acis_build_badpix`. The second algorithm searches for detector pixels that have an unusually large number of events that occur over a short period of time. Suspicious pixels are added to the observation-specific bad-pixel file only if the neighboring pixels do not have a significant excess of events. This condition helps insure that events associated with dithered sources are not discarded. Events associated with afterglows are flagged and excluded from Level 2 event-data files. The newer algorithm has been used for pipeline processing (and reprocessing) since the fall of 2004. While it is relatively gentle on astrophysical sources, it does let some afterglows "slip through the cracks." The afterglow detection efficiency depends on the number of events in the afterglow. The efficiency declines quickly as the number of events in an afterglow drops below about eight.

This spec describes a third afterglow-detection algorithm. Like the second algorithm, it is designed to avoid discarding events associated with real astrophysical sources. It is also designed to enhance the detection efficiency for afterglows that have as few as four events. The principal change between the second and third afterglow-detection algorithms is that the third algorithm searches for afterglows using the events in a short,

sliding time window instead of using the events from the entire duration of an observation (i.e., the algorithm searches in three dimensions instead of two).

## 1.2 Input

1. A Level 1 event-data file (acis*evt1.fits)
2. A Level 1 observation-specific bad-pixel file (acis*bpix1.fits)
3. A Level 1 mask file (acis*msk1.fits)
4. A Level 1 exposure statistics file (acis*stat1.fits)

## 1.3 Output

1. An updated observation-specific bad-pixel file

## 1.4 Parameters

1. infile,s,a,“”,,,“Name of input event-data file”
2. outfile,s,a“”,,,“Name of output bad-pixel file”
3. badpixfile,s,a,“”,,,“Name of input bad-pixel file”
4. maskfile,s,a,“”,,,“Name of input mask file”
5. statfile,s,a,“”,,,“Name of input exposure-statistics file”
6. expnowindow,i,h,10,1,100,“Number of frames in the sliding time window”
7. probthresh,r,h,0.001,1.0e-10,0.1,“Minimum post-trials significance of potential afterglows (1 sigma = 0.159, 90% = 0.1, 2 sigma = 0.0228, 99% = 0.01 and 3 sigma = 0.00135)”
8. cntthresh,i,h,2,4,10,“Minimum number of events in an afterglow”
9. clobber,b,h,“no”,,,“Overwrite output file if it exists?”
10. verbose,i,h,0,0,5,“Amount of messages produced (0=none, 5=a lot)”
11. mode,s,h,“ql”,,,

## 1.5 Processing

In the standard ACIS pipeline, the afterglow-detection algorithm is used after the bias(es) has been searched for bad bias values and before the event data is searched for hot pixels. The afterglow-detection algorithm is summarized below.

1. Verify that the input files exist. If clobber=no, then verify that the output files do not exist. Verify that the input event-data file has READMODE=TIMED. The afterglow-detection algorithm is not appropriate for continuous-clocking mode event data. Verify that the values of the parameters `expnowindow`, `probthresh` and `cntthresh` are in the valid ranges for these parameters.

2. Exclude "invalid" pixels[1] from the search.

3. To improve the performance of the algorithm, perform more than one pass through the data. In the first pass, potential afterglow events are identified as suspicious using a minimum set of criteria. Events $i$ and $j$ may be part of an afterglow if the following four conditions are satisfied.

$$\begin{aligned} \mathrm{CCD_ID}_i &= \mathrm{CCD_ID}_j, && (1)\\ \mathrm{CHIPX}_i &= \mathrm{CHIPX}_j, && (2)\\ \mathrm{CHIPY}_i &= \mathrm{CHIPY}_j, \text{ and} && (3)\\ |\mathrm{EXPNO}_i - \mathrm{EXPNO}_j| &\leq \texttt{expnowindow}. && (4) \end{aligned}$$

4. During a subsequent pass through the data, the $i$th, $(i+1)$th, ..., $(i+n)$th set of events on a pixel is identified as an afterglow if each consecutive pair of events in the set satisfies equations 1–4 and if

$$\begin{aligned} N_{\mathrm{evt}}^{\mathrm{aft}} &\geq \texttt{cntthresh}, && (5)\\ P_{\mathrm{post}} &< \texttt{probthresh}, \text{ and} && (6)\\ P_{\mathrm{ref}} &\geq \texttt{probthresh}, && (7)\\ & && (8) \end{aligned}$$

where the post-trials probability

$$P_{\mathrm{post}} = 1 - (1 - P_{\mathrm{pre}})^{\mathrm{N_{trial}}}, \tag{9}$$

the pre-trials probability

$$P_{\mathrm{pre}} = 1 - \left[ \left( \sum_{i=0}^{N_{\mathrm{evt}}^{\mathrm{aft}}-1} \frac{\left(N_{\mathrm{bgd}}^{\mathrm{aft}}\right)^i}{i!} \right) + \frac{1}{2} \frac{\left(N_{\mathrm{bgd}}^{\mathrm{aft}}\right)^{N_{\mathrm{evt}}^{\mathrm{aft}}}}{N_{\mathrm{evt}}^{\mathrm{aft}}!} \right] e^{-N_{\mathrm{bgd}}^{\mathrm{aft}}}, \tag{10}$$

$N_{\mathrm{evt}}^{\mathrm{aft}}$ is the number of events in the potential afterglow, the number of background events for the potential afterglow

$$N_{\mathrm{bgd}}^{\mathrm{aft}} = F\left(\frac{N_{\mathrm{frame}}^{\mathrm{aft}}}{N_{\mathrm{frame}}^{\mathrm{tot}}}\right), \tag{11}$$

$N_{\mathrm{frame}}^{\mathrm{aft}}$ is the number of valid frames[2] in the afterglow, $N_{\mathrm{frame}}^{\mathrm{tot}}$ is the total number of valid frames, the number of trials[3]

$$N_{\mathrm{trial}} = \sum_k N_{\mathrm{pix},k}^{\mathrm{ccd}} \left(N_{\mathrm{frame},k}^{\mathrm{tot}} - \texttt{expnowindow} - 1\right), \tag{12}$$

[1]Here an invalid pixel is one that has one or more of the following STATUS bits set in the observation-specific bad-pixel file or that has SAMP_CYC = 0 in the mask file.

| Bit | Description |
|---|---|
| 0 | bad pixel |
| 2 | bias-parity error |
| 3 | bias = 4095 |
| 4 | bias = 4094 |
| 13 | FEP0 problem |
| 16 | bad bias value |

Note that the STATUS bits are number from 0 to 31. It is not necessary to ignore pixels that have bias values of 4096 (i.e., are missing data) because biases with such problems are adjusted on the ground. If they are not adjusted, then all events on pixels with a bias = 4096 are discarded.

[2]Here an invalid frame for a CCD is one that is not listed in the exposure statistics file. Also note that for TIMED mode observations, frames with EXPNO < 3 are invalid.

[3]The estimate of $N_{\mathrm{trial}}$ is an upper limit on the number of trials. The actual number of trials includes only the number of "independent" searches. Since adjacent windows in the sliding EXPNO window overlap, they are not independent. A lower limit on $N_{\mathrm{trial}}$ can be obtained by calculating the number of nonoverlapping windows. This value is smaller than equation 12 by a factor of (`expnowindow` + 1). Since a precise value for $N_{\mathrm{trial}}$ can be difficult to determine, equation 12 is used because it yields the most conservative (i.e., the largest) value.

$N^{\rm ccd}_{{\rm pix},k}$ is the number of valid pixels[1] for the $k$th CCD (i.e., $= 1024 \times 1024$ less the number of invalid pixels), $N^{\rm tot}_{{\rm frame},k}$ is the total number of valid frames for the $k$th CCD, the probability[4] that the event fluence in the reference region is consistent with the event fluence on the entire node (i.e., that the potential afterglow is not part of a dithered source)

$$P_{\rm ref} = \begin{cases} 1 - \left[ \left( \sum_{i=0}^{N^{\rm ref}_{\rm evt}-1} \frac{\left(N^{\rm ref}_{\rm bgd}\right)^i}{i!} \right) + \frac{1}{2} \frac{\left(N^{\rm ref}_{\rm bgd}\right)^{N^{\rm ref}_{\rm evt}}}{N^{\rm ref}_{\rm evt}!} \right] e^{-N^{\rm ref}_{\rm bgd}} & (N^{ref}_{\rm evt} > 0) \\ 1 & (N^{\rm ref}_{\rm evt} = 0) \end{cases} \tag{13}$$

the number of background events for the reference region

$$N^{\rm ref}_{\rm bgd} = F N^{\rm ref}_{\rm pix}, \tag{14}$$

$N^{\rm ref}_{\rm pix}$ is the number of valid pixels[5] in the 7 pixel $\times$ 7 pixel reference region surrounding the pixel with the potential afterglow, and the nominal fluence $F$ is computed as follows.

(a) For each 32 pixel $\times$ 32 pixel region $l$ of the node

$$F_l = \frac{N^l_{\rm evt}}{N^l_{\rm pix}}, \tag{15}$$

where $N^l_{\rm pix}$ is the total number of valid pixels[1] in the region, and $N^l_{\rm evt}$ is the total number of events on these pixels during the entire observation.

(b) Select the regions where $F_l$ is greater than zero and less than two times the mean value of the set of $F_l$s.

(c) Calculate the median value, $F_{\rm med}$, of the selected values of $F_l$.

(d) Calculate the root-mean-square, $F_{\rm rms}$, of the selected values.

(e) Select the regions where $F_l$ is greater than zero, is greater than $F_{\rm med} - 2F_{\rm rms}$, and is less than $F_{\rm med} + 2F_{\rm rms}$.

(f) Calculate the median of the selected values.

(g) Calculate the root-mean-square of the selected values.

(h) Repeat steps 4e–4g ten times.

(i) Set $F$ equal to the value of $F_{\rm med}$ from the last iteration.

5. Each potential afterglow that satisfies criteria 1–7 is written to the outfile with

$$\text{TIME} = \text{TIME}_{\rm start} - \text{TIMEPIXR} \times \text{TIMEDEL} - \text{FLSHTIME} \tag{16}$$

and

$$\text{TIME_STOP} = \text{TIME}_{\rm stop} + (1 - \text{TIMEPIXR}) \times \text{TIMEDEL}, \tag{17}$$

where $\text{TIME}_{\rm start}$ and $\text{TIME}_{\rm stop}$ are the TIMEs in the exposure statistics file that are associated with the start and stop EXPNOs of the afterglow and TIMEDEL, TIMEPIXR and FLSHTIME are keywords in the exposure statistics file. Note that it is possible, albeit unlikely, for more than one afterglow to occur on the same pixel during an observation.

Once the afterglow-detection algorithm has been used, the tools `acis_build_badpix` and `acis_process_events` are used to mark the pixels adjacent to afterglows as bad and to set the appropriate STATUS bit (16 of 0–31) for events associated with afterglows.

[4]Unlike the previous afterglow-detection algorithm, the probability $P_{\rm ref}$ is a pre-trials probability instead of a post-trials probability. In this case, it is more difficult for events associated with real astrophysical sources to be identified as afterglows.

[5]For the purposes of calculating $N^{\rm ref}_{\rm pix}$, the central pixel of the region (i.e., the pixel on which the potential afterglow occurred) is invalid as are pixels that lie on a different node from the central pixel. Other pixels are considered invalid if they satisfy the usual conditions.[1]

## 1.6 Caveats

1. Although it may not be optimum to do so, the afterglow-detection algorithm is applied separately to the primary and secondary data for interleaved mode observations.

2. The algorithm is not applied to the data for continuous-clocking mode observations.

3. The choices of default values for the parameters `expnowindow` and `cntthresh` may not be optimum.

4. The algorithm, as described, is appropriate only for mask files that have one nonzero value for SAMP_CYC.

5. Unlike the afterglow-detection algorithm in `acis_run_hotpix`, it is not possible for a user to change the size of the reference region (7 pixels $\times$ 7 pixels).