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 and hot-pixel spec
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1 Afterglows and Hot pixels

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 that 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 a 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).

Hot pixels are pixels that have an unusually large number of events during an observation. Pixels that are known to be bad, that have bad bias values, and that are in a region associated with the "FEP0" problem are excluded from the search for hot pixels. Pixels associated with bias-parity errors and cosmic-ray afterglows are also excluded, but only during the time interval of the bias-parity error or afterglow. Pixels that are part of a known bad column, that are along the edge of a node, or that were previously identified as being hot are included in the search.

This spec also includes an updated hot-pixel detection algorithm. The difference between this algorithm and the previous one is that this one is designed to try to prevent bright sources in the field of view from reducing the hot-pixel detection sensitivity.

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 after-glows (e.g., 1 sigma = 0.159, 90% = 0.1, 2 sigma = 0.0228, 99% = 0.01 and 3 sigma = 0.00135)"`
8. `cntthresh,i,h,4,2,10,"Minimum number of events in an afterglow"`
9. `regwidth,i,h,7,3,255,"Size of reference region (e.g., 7 pixels × 7 pixels)"`
10. `nfpixreg,i,h,32,16,256,"Size of region used to calculate the fluence"`
11. `nfrepeat,i,h,10,1,30,"Number of iterations during the calculation of the fluence"`
12. `clobber,b,h,"no",,,"Overwrite output file if it exists?"`
13. `verbose,i,h,0,0,5,"Amount of messages produced (0=none, 5=a lot)"`
14. `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, after the bias-parity error file(s) has been searched for bad pixels and the "FEP0" problem, and before the event data is searched for hot pixels. The afterglow and hot-pixel detection algorithms are summarized below.

Verify that the `infile`, `badpixfile`, `maskfile`, and `statfile` exist. If `clobber=no`, then verify that the `outfile` does not exist. Verify that the `infile` has `READMODE=TIMED`. The afterglow and hot-pixel detection algorithms are not appropriate for `READMODE=CONTINUOUS`. Verify that the values of the parameters `expnowindow`, `probthresh`, `cntthresh`, `regwidth`, `nfpixreg`, and `nfrepeat` are in the valid ranges for these parameters. Note that `regwidth` must be an odd number and that the only valid values for the parameter `nfpixreg` are 16, 32, 64, 128, and 256 (i.e. those values for which the width of a node in pixels (256) is an integer multiple of `nfpixreg`).

1.5.1 Afterglows

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

2. 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.

$$\mathtt{CCD\_ID}_i = \mathtt{CCD\_ID}_j, \quad (1)$$
$$\mathtt{CHIPX}_i = \mathtt{CHIPX}_j, \quad (2)$$
$$\mathtt{CHIPY}_i = \mathtt{CHIPY}_j, \text{ and} \quad (3)$$
$$|\mathtt{EXPNO}_i - \mathtt{EXPNO}_j| \leq \mathtt{expnowindow}. \quad (4)$$

3. During a subsequent pass through the data, the ith, $(i+1)$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

$$N_{\rm evt}^{\rm aft} \geq \mathtt{cntthresh}, \quad (5)$$
$$P_{\rm post} < \mathtt{probthresh}, \text{ and} \quad (6)$$
$$P_{\rm ref} \geq \mathtt{probthresh}, \quad (7)$$

where the post-trials probability

$$P_{\rm post} = 1 - (1 - P_{\rm pre})^{\rm N_{trial}}, \quad (8)$$

[1]Here an invalid pixel is one that has `SAMP_CYC` = 0 in the `maskfile` or that has one or more of the following `STATUS` bits set in the `badpixfile`.

Bit	Description	Notes
0	bad pixel	
2	bias-parity error	only for the duration of the error
3	bias = 4095	
4	bias = 4094	
13	FEP0 problem	
15	afterglow	only for the hot-pixel algorithm and only for the duration of the afterglow
16	bad bias value	

Note that the `STATUS` bits are numbered 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.

the pre-trials probability $P_{\rm pre}$ is given by the series[2]

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

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

$$N_{\rm bgd}^{\rm aft} = \frac{F}{\texttt{SAMP\_CYC}_{\rm aft}} \left(\frac{N_{\rm frame}^{\rm aft}}{N_{\rm frame}^{\rm tot}} \right), \tag{11}$$

$\texttt{SAMP\_CYC}_{\rm aft}$ is the sample cycle for the pixel on which the potential afterglow occurred, $N_{\rm frame}^{\rm aft}$ is the number of valid frames[3] in the afterglow, $N_{\rm frame}^{\rm tot}$ is the total number of valid frames for the CCD, the number of trials[4]

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

$N_{{\rm pix},k}^{\rm ccd}$ is the number of valid pixels[1] for the kth CCD (i.e., $= 1024 \times 1024$ less the number of invalid pixels), $N_{{\rm frame},k}^{\rm tot}$ is the total number of valid frames for the kth CCD, the probability[5] $P_{\rm ref}$ that the event fluence in the reference region is consistent with the event fluence on the entire node (i.e., that the potential afterglow or hot pixel is not part of a dithered source) is given by the series[2]

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

$N_{\rm evt}^{\rm ref}$ is the total the number of events in the reference region,[6] $N_{\rm bgd}^{\rm ref}$ is given by[7]

$$N_{\rm bgd}^{\rm ref} = \frac{F}{\texttt{SAMP\_CYC}_{\rm ref}} N_{\rm pix}^{\rm ref}, \tag{15}$$

$\texttt{SAMP\_CYC}_{\rm ref}$ is the sample cycle for the pixels in the reference region, $N_{\rm pix}^{\rm ref}$ is the number of valid pixels[8]

[2]In practice, the series does not extend to infinity. Each term in the sum is of the form $\mu^n \exp(-\mu)/n!$. The last term is the series is given by $n = N$, where N is the smallest integer that satisfies the relation

$$\frac{\mu^N}{N!} < 10^{-15} \left[\frac{1}{2} \frac{\mu^{n_0}}{n_0!} + \frac{\mu^{n_1}}{n_1!} + \ldots + \frac{\mu^{N-1}}{(N-1)!} \right]. \tag{9}$$

[3]Here an invalid frame for a CCD is one that is not listed in the `statfile`. For `TIMED` mode observations, frames with `EXPNO` < 3 are invalid. Note that a frame does not have to include an afterglow event to be included in $N_{\rm frame}^{\rm aft}$. For example, if a pixel has afterglow events in frames 100, 101, 104, 107, 109, 113, and 119, and if all of the frames from 100 to 119 are valid, then $N_{\rm frame}^{\rm aft} = 20$.

[4]The estimate of $N_{\rm trial}$ 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 $N_{\rm trial}$ can be obtained by calculating the number of nonoverlapping windows. This value is smaller than equation 12 by a factor of about ($\texttt{expnowindow} + 1$). Since a precise value for $N_{\rm trial}$ can be difficult to determine, equation 12 is used because it yields the most conservative (i.e., the largest) number of trials.

[5]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.

[6]Do not include in $N_{\rm evt}^{\rm ref}$ the events on the central pixel of the region and, if the region overlaps more than one node, the events that lie on a different node from the central pixel.

[7]Equation 15 is valid only if all of the valid pixels in the reference region have the same sample cycle. If, for example, the reference region contains subsets A and B with $N_{\rm pix,A}^{\rm ref}$ and $N_{\rm pix,B}^{\rm ref}$ valid pixels and sample cycles $\texttt{SAMP\_CYC}_{\rm ref,A}$ and $\texttt{SAMP\_CYC}_{\rm ref,B}$, respectively, then equation 15 becomes

$$N_{\rm bgd}^{\rm ref} = F \left(\frac{N_{\rm pix,A}^{\rm ref}}{\texttt{SAMP\_CYC}_{\rm ref,A}} + \frac{N_{\rm pix,B}^{\rm ref}}{\texttt{SAMP\_CYC}_{\rm ref,B}} \right). \tag{14}$$

[8]For the purposes of calculating $N_{\rm pix}^{\rm ref}$, 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]

in the `regwidth` pixel × `regwidth` pixel reference region surrounding the pixel with the potential afterglow, and the nominal fluence F is computed as follows.

(a) For each `nfpixreg` pixel × `nfpixreg` pixel region l of the node,[9]

$$F_l = \texttt{SAMP\_CYC}_l \frac{N^l_{\rm evt}}{N^l_{\rm pix}}, \tag{17}$$

where $\texttt{SAMP\_CYC}_l$ is the sample cycle for region l, $N^l_{\rm pix}$ 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_ls.

(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 or equal to $F_{\rm med} - 2F_{\rm rms}$, 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 3e–3g an additional `nfrepeat` − 1 times (i.e., a total of `nfrepeat` times).

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

4. Each potential afterglow that satisfies the criteria in equations 1–7 is written to the `outfile` with

$$\texttt{TIME} = \texttt{TIME}_{\rm start} - \texttt{TIMEPIXR} \times \texttt{TIMEDEL} - \texttt{FLSHTIME} \tag{18}$$

and

$$\texttt{TIME\_STOP} = \texttt{TIME}_{\rm stop} + (1 - \texttt{TIMEPIXR}) \times \texttt{TIMEDEL}, \tag{19}$$

where $\texttt{TIME}_{\rm start}$ and $\texttt{TIME}_{\rm stop}$ are the `TIME`s in the `statfile` that are associated with the start and stop `EXPNO`s of the afterglow and `TIMEDEL`, `TIMEPIXR`, and `FLSHTIME` are keywords in the `statfile`. The contents of the `badpixfile` are also copied to the `outfile`. Note that it is possible, albeit unlikely, for more than one afterglow to occur on the same pixel during an observation.

1.5.2 Hot pixels

1. Exclude "invalid" pixels[1]

2. A pixel is identified as hot if

$$\begin{aligned} P_{\rm post} &< \texttt{probthresh} \text{ and} \quad (20)\\ P_{\rm ref} &\geq \texttt{probthresh}, \quad (21) \end{aligned}$$

where the post-trials probability $P_{\rm post}$ is given by equation 8, the pre-trials probability $P_{\rm pre}$ is given by the series[2]

$$P_{\rm pre} = \left[\frac{1}{2} \frac{\left(N^{\rm hot}_{\rm bgd}\right)^{N^{\rm hot}_{\rm evt}}}{N^{\rm hot}_{\rm evt}!} + \left(\sum_{n=N^{\rm hot}_{\rm evt}+1}^{\infty} \frac{\left(N^{\rm hot}_{\rm bgd}\right)^n}{n!} \right) \right] e^{-N^{\rm hot}_{\rm bgd}}, \tag{22}$$

[9] Equation 17 is valid only if all of the valid pixels in the region have the same sample cycle. If, for example, the region contains subsets A and B with $N^l_{\rm evt,A}$ and $N^l_{\rm evt,B}$ events on $N^l_{\rm pix,A}$ and $N^l_{\rm pix,B}$ valid pixels and sample cycles $\texttt{SAMP\_CYC}_{l,\rm A}$ and $\texttt{SAMP\_CYC}_{l,\rm B}$, respectively, then equation 17 becomes

$$F_l = \frac{\texttt{SAMP\_CYC}_{l,\rm A} N^l_{\rm evt,A} + \texttt{SAMP\_CYC}_{l,\rm B} N^l_{\rm evt,B}}{N^l_{\rm pix,A} + N^l_{\rm pix,B}}. \tag{16}$$

$N_{\rm evt}^{\rm hot}$ is the number of events on the potential hot pixel,

$$N_{\rm bgd}^{\rm hot} = \frac{F}{\texttt{SAMP\_CYC}_{\rm hot}}, \quad (23)$$

$\texttt{SAMP\_CYC}_{\rm hot}$ is the sample cycle for the potential hot pixel, the number of trials

$$N_{\rm trial} = \sum_k N_{{\rm pix},k}^{\rm ccd}, \quad (24)$$

$N_{{\rm pix},k}^{\rm ccd}$ is the number of valid pixels[1] for the kth CCD (i.e., $= 1024 \times 1024$ less the number of invalid pixels) and the probability $P_{\rm ref}$ that the event fluence in the reference region is consistent with the event fluence on the entire node is given by equation 13.

3. Each potential hot pixel that satisfies the criteria in equations 20 and 21 is written to the `outfile`. The contents of the `badpixfile` are also copied to the `outfile`.

Once the afterglow and hot-pixel detection algorithms have been used, the tools `acis_build_badpix` and `acis_process_events` are used to mark the pixels adjacent to such pixels as bad and to set the appropriate `STATUS` bit for events associated with afterglows (16 of 0–31) and hot pixels (4 of 0–31), respectively.

1.6 Caveats

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

2. The algorithms are not applied to the data for continuous-clocking mode observations.

3. The choices of default values for the parameters `expnowindow`, `probthresh`, `cntthresh`, `regwidth`, `nfpixreg`, and `nfrepeat` may not be optimum.

4. Add `TIME` and `TIME_STOP` to the last step of the hot-pixel algorithm.