AXAF Science Center

Harvard–Smithsonian
Center for Astrophysics

MEMORANDUM

October 2, 1997

File:

To: ACIS team

From: B.R. McNamara

Subject: An Analytic ACIS Pileup Model

1.0 Definition of Pileup

Pileup with the ACIS camera can be defined as the coincidence of two or more photon events in a detect cell per ACIS frame. The signatures of pileup appear in the spatial and spectral information extracted from ACIS with properties that depend on the illumination pattern. We consider here illumination by an on-axis point source modulated by the HRMA point spread function (PSF).

2.0 Signatures of Pileup in ACIS Data

The two most apparent signatures of pileup in the spatial domain are a depression of the PSF's core amplitude, and event grade "migration." Pileup occurs preferentially in regions of high event density, so the core of the PSF suffers a higher rate of coincident events than the wings, resulting in a deficit in the number of detected events in the core relative to the wings. Because two or more coincident events are counted by the instrument as a single, higher energy event, the number density of counts in the core is reduced with respect to the wings. As the count rate per frame increases, a second more serious type of depression can occur in the PSF. At the point where the illuminated pixels accumulate enough charge to saturate the 12 bit analog to digital converter, the event information is lost completely, and no local event maximum can be found by the event finding software. Therefore, no events are detected in the core of the PSF.

In the limit of no pileup, the fraction of events occupying a given split event morphology, its so-called "grade", tends to be constant for a given energy. (The grade ratios change with photon energy and depend on whether we are considering a front or back illuminated device.) As the degree of pileup increases, the fraction of the total number of events occupying a particular grade can change as the events "migrate" to other grades. For example, this effect is apparent for front illuminated devices as events migrate between ASCA grades 1 and 7. Thus, grade migration could have a significant effect on the data analysis, such as flux measurements of point sources when using standard grade sets. The benchmark grade set being used to calibrate ACIS is ASCA G02346. We have found that as pileup increases, G0 events tend to migrate to G7, the grade occupied predominantly by background events. G7 events will not be telemetered to the ground during standard operations to avoid telemetry saturation by background events. Therefore photon events that migrate to G7 may be lost.

In the spectral domain, pileup takes low energy photons and registers them as higher energy, higher pulse height events. The total amount of charge (or pulse height) accumulated in a particular detect cell in a particular ACIS frame is proportional to the energy of the incident photon and the number of photons detected. Therefore, the event recognition software cannot distinguish between a single, large pulse height (energy) event and two or more lower energy events. As coincident events accumulate, the spectrum becomes harder as the detected count rate is depleted with respect to the true incident ACIS count rate.

The detected spectrum can be complex. For the simple case of a monochromatic source, pileup removes counts from the spectral feature at the true incident energy (E_0) and distributes the power primarily into spectral peaks of decreasing amplitude at $E_n = n \times E_0$, $n = 1, 2, ..$ (e.g. Fig 1.17). The spectrum of a polychromatic source, for example an emission feature superposed on a continuum of unknown intrinsic shape, can become difficult to interpret as photons from the line and continuum interact, distorting the detected spectral energy distribution, making it difficult to determine the true incident spectrum.

3.0 Analytic Pileup Model

Although pileup cannot be avoided entirely, there are steps that the user can take to reduce pileup to tolerable levels. In order to do so we need a model to estimate the amount of pileup expected for a given source flux, size, and axial location. Pileup is most problematic for a point source observed on or near the optical axis, so we present a simple analytic model for this case.

Model Definitions:

1) The rate of monoenergetic photons, $(N(E))$, is the number of photons detected by ACIS per unit time per unit energy,

$$N(E)_{\rm ACIS} \simeq I(E)_{\rm source} \times EA(E)_{\rm HRMA} \times QE(E)_{\rm ACIS} \quad ({\rm cts\ s^{-1}}),$$

where I is the source flux at the entrance of the HRMA in units of photons per sec per square cm per unit energy, EA is the HRMA effective area, and QE is the quantum efficiency of ACIS.

2) The ACIS frametime, t_f, is the effective integration time per ACIS readout frame. A full 1024×1024 frame can be read out in about 3.3 sec; whereas, the readout time decreases for smaller frame sizes (see Section TBD).

3) The expected number of counts per frame, or the expectation value, is defined as

$$< m >= N(E) \times t_f.$$

4) The probability, f, of detecting n photons per ACIS frame with expectation value $< m >$ is

$$f(n, < m >) = \frac{< m >^n \;\; e^{-<m>}}{n!}.$$

5) The pileup fraction, P, is defined here as the ratio of the number of frames with two or more events to the number of frames with one or more events

$$P(< m >) = \frac{1 - [f(0, < m >) + f(1, < m >)]}{1 - f(0, < m >)}.$$

Note that this definition excludes frames with zero events.

6) The detect cell is the effective region of the CCD occupied by a single event, taken to be the standard 3×3 pixel island with $24\mu m$ pixels.

7) The encircled energy fraction, $\epsilon(R)$, is the fraction of the total power detected by the HRMA + ACIS within a specified radius in the focal plane.

The AXAF PSF is similar in size to to an ACIS detect cell. Fig. XX in the ACIS section of the Proposers Guide shows a plot of the encircled energy radius in ACIS pixels vs the fraction of the total on-axis encircled power for the Al-K target focused with the HRMA at the XRCF. Since each detect cell has an effective radius of $\simeq \sqrt{2}/2 \times 3 = 2.1$ pix, one detect cell encircles between 60-70% of the power at the XRCF. Roughly 90% of the power will lie within the central detect cell in flight, and nearly all of the power lies within a radius of two times the size of the central detect cell. Therefore, our pileup model assumes a central detect region one detect cell in size, surrounded by an annular region composed of eight detect cells which we refer to as the second detect region. A schematic diagram of this model is shown in Fig. 1. The central detect cell is hatched, and the area surrounding is the outer detect region composed of eight detect cells. The circle shows roughly the 70% encircled energy radius for ACIS measured at the XRCF.

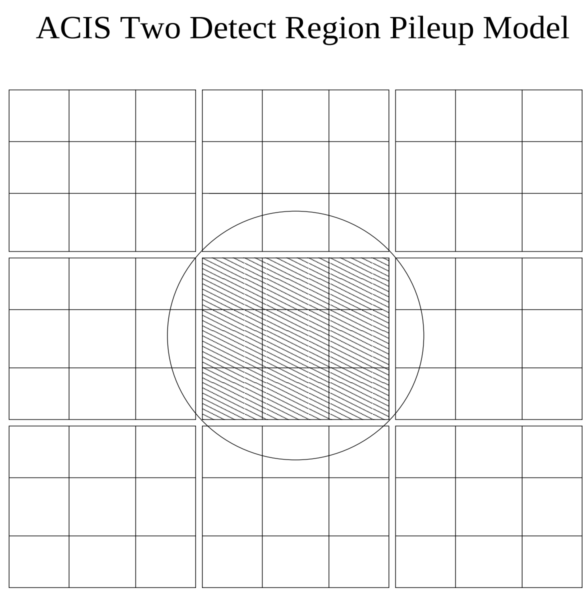

Figure 1. The two detect regions for the model are shown with the $\simeq 70\%$ encircled energy (circle) shown relative to the inner detect region (hatched) and the surrounding eight detect cells comprising the outer detect region. The small squares represent an ACIS pixel.

The count rate of interest for calculating pileup is the mean detection rate per frame per 3×3 pixel detect cell in each detect region. The central detect region is composed of one detect cell (the hatched region in Fig. 1), so the count rate of interest there, $< m >_1'$, is simply the total expected count rate per frame $< m >$ times the encircled energy fraction within the inner detect region $\epsilon(R_1)$,

$$< m >'_1 = < m > \times \epsilon(R_1).$$

The outer detect region covering the wings of the PSF is composed of eight detect cells. The photon flux there is spread over a larger area, which greatly decreases the pileup fraction there. We estimate the detection rate per frame per detect cell in the outer detect region similarly to the inner detect cell as

$$< m >'_2 = < m > \times \epsilon(R_2) \times \frac{A(R_1)}{A(R_2)},$$

where $A(R_1)/A(R_2)$ is the ratio of the areas of the two detect regions, which is $\simeq 1/8$.

We then calculate the pileup fraction as the sum of the pileup fractions in each detect region weighted by the fraction of the total number of events in each region

$$P_T = P(< m >'_1) \times \epsilon(R_1) + P(< m >'_2) \times \epsilon(R_2).$$

Most of the pileup occurs in the central detect region; the photon flux per detect cell per frame in the outer detect region is only $< m >'_2 \sim \frac{3}{10} \times \frac{1}{8} \times < m >'_1 = 4\%$ of the flux in the inner detect region. In fact this treatment will underestimate somewhat the degree of pileup in the outer detect region because the photon density increases rapidly at the inner edge of the outer detect region, effectively decreasing the active area of the outer detect region. In addition, $\epsilon(R_1)$ will be somewhat larger on orbit than the value 0.6 derived from the XRCF data because in flight the mirrors will not be distorted by gravity. But these approximations should be reasonable for purposes of proposal planning and for comparison to PIMMS and MARX simulations.

In Fig. 2 we plot the total pileup fraction, P_T, as a function of the detected count rate per ACIS frame. The solid line shows the nominal case assuming a 70% encircled energy fraction within the inner detect cell derived from the XRCF data. The remaining curves are for the 90% encircled energy fraction (predicted in flight), and the limiting and unrealistic case of all photons landing in the inner detect cell. So for example, if the user calculates an

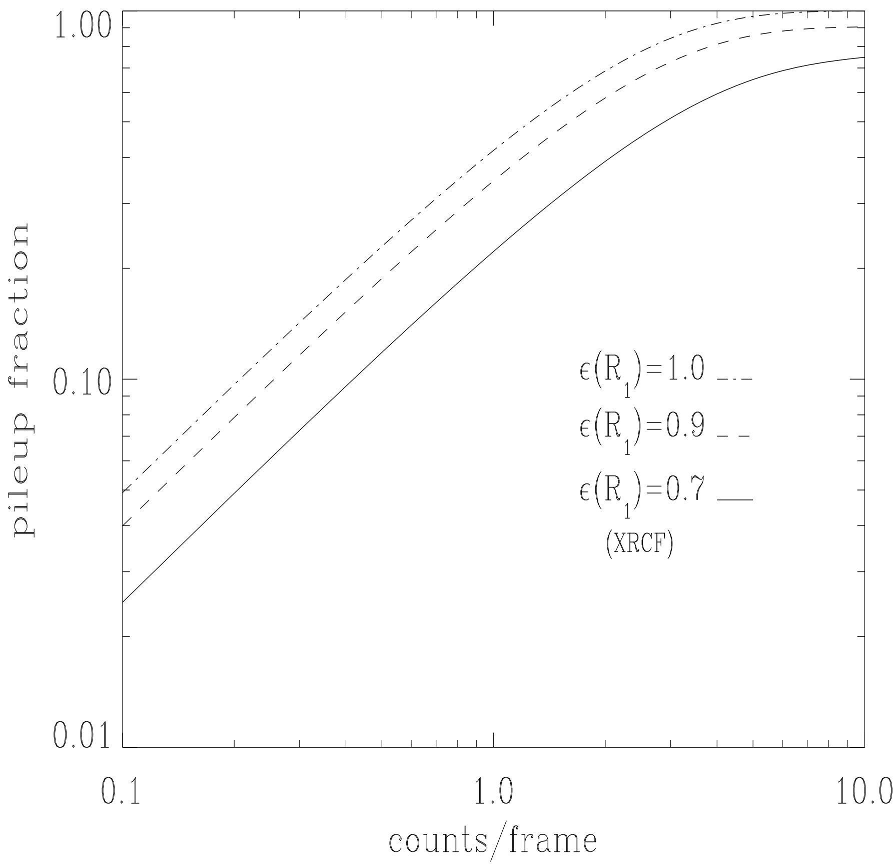

Figure 2. Pileup fraction as defined in the text plotted against the number of incident counts per ACIS frame for three encircled energy radii: $\epsilon = 0.7$, roughly the value at the XRCF, $\epsilon = 0.9$, the predicted in-flight value, and the limiting and unrealistic case of $\epsilon = 1$, which places all of the incident flux in one detect cell.

expectation value of 1 count per frame using a full 3.3 sec frame or a subarray, the model predicts that about 22% of the detected photons will pile up for $\epsilon(R_1) = 0.7$, 35% pileup for $\epsilon(R_1) = 0.9$, and in the limiting case we get 42% pileup.

4.0 Conclusions

The pileup fraction for astronomical point sources with the in-flight HRMA + ACIS ($\epsilon(R_1) \sim 0.9$) is expected to be roughly 35% for the case above, based on our model. The degree of pileup that is acceptable for a particular observation will depend on the scientific goals of the measurement being made, and there is no clear-cut tolerance level. If the science goal demands high precision flux calibration in a spectral line, the degree of pileup within the line should be kept below the level of precision desired when possible. We urge the user to do a detailed pileup analysis using MARX prior to writing their proposal.

I thank Joel Kastner and Paul Plucinsky for their comments.