ACIS Pileup: Analysis of XRCF Phase H Data

Joel Kastner, Kester Allen, & Kenny Glotfelty (AXAF Science Center)

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Summary

Results of analysis of XRCF ACIS pileup tests H-IAI-CR-1.001, 1.003 and 1.005 are presented. In this series of tests with monotically increasing Al Kα source flux (ranging from ~ 0.3 to ~ 3.0 ACIS counts/frame in the absence of pileup) incident on a frontside-illuminated CCD, various symptoms of pileup — image degradation, grade migration, count rate non-linearity, and event pulse height confusion — are observed and quantified. As the fraction of events consisting of two or more photons increases (from 3% to 26% over this suite of tests) the image core broadens slightly while the proportion of events occupying multiple pixels increases markedly. A large fraction of events ($\sim 23\%$) are "lost" from the "standard" ASCA grade set (02346) at the highest flux. We tabulate the rates of single- and multiple-photon events, and the event pileup fraction, as functions of the ACIS count rate in the absence of pileup (as inferred from beam normalization detector data). Non-linearity of the single-photon count rate is evident, as is the loss of photons both to "non-standard" grades and (possibly) to off-line event amplitudes.

1 Data

Data for this analysis were collected at the AXAF X-ray Calibration Facility (XRCF) in April, 1997, during XRCF Phase H (ACIS plus the High Resolution Mirror Assembly [HRMA]). The TRW test identifiers are H-IAI-CR-1.001, H-IAI-CR-1.003, and H-IAI-CR-1.005. Source parameters were set to produce a monochromatic beam of Al Kα photons (energy 1.487 keV). Source flux was essentially constant during each test, and monotonically increased from test 1.001 to test 1.005. The Five Axis Mount was positioned such that the HRMA beam appeared on the front-illuminated CCD I3 (w215c2r); the beam was well focused (§2.1). ACIS was placed in 38-row "staggered" readout mode, wherein 38-row blocks are clocked down the CCD at a rate governed by the (~ 0.12 s) readout time of the block (this mode is essentially a hybrid of Timed Exposure and Continuous Clocking modes). Events were recorded into telemetry in "faint with bias" mode.

Data were obtained from two different sources: the ACIS telemetry stream and the ACIS high-speed tap (HST). Processing of the telemetry stream dataset consisted of decommutation (by the ASC ACIS Data Extractor; event extraction was performed by the ACIS flight software), and event bias subtraction, grading, and pulse height summation (by the ASC XRCF Level 1 pipeline). Processing of the raw HST data — which consist of CCD image frames — consisted of bias frame subtraction followed by event extraction, grading and pulse height summation. Hence, the starting points for analysis described herein were two "Level 1" event lists for each test — one produced from ACIS telemetry and one produced from ACIS HST data — each event list consisting of event records containing event locations, grades, and pulse heights. Comparison of results obtained from analysis of these "parallel" datasets were used to verify the analysis (§2.2.1, 2.2.3).

2 Analysis and Results

2.1 Images

Figure 1 shows images (in the CCD coordinate system) constructed from the telemetry event list for each test. The beam is well collimated for these tests, as evidenced by the compact image resulting from tests 1.001 and 1.003, for which we measure FWHM=2.1 pix. However, the effect of pileup is marginally evident at the higher count rate in test 1.005; the FWHM of the image increases to 2.4 pix. This effect is likely due to depression of the event count rate in the central pixel(s) of the PSF relative to the rest of the PSF core, as multiple-photon events in the center pixel become more common.

Note that the source position on CCD I3 changes from test to test, and that the source position was shifted during test 1.003 (to re-center the source within the window). These secular position shifts do not affect the count rate analysis described below, since this analysis was conducted in the event grade and energy regimes after appropriate source region event screening.

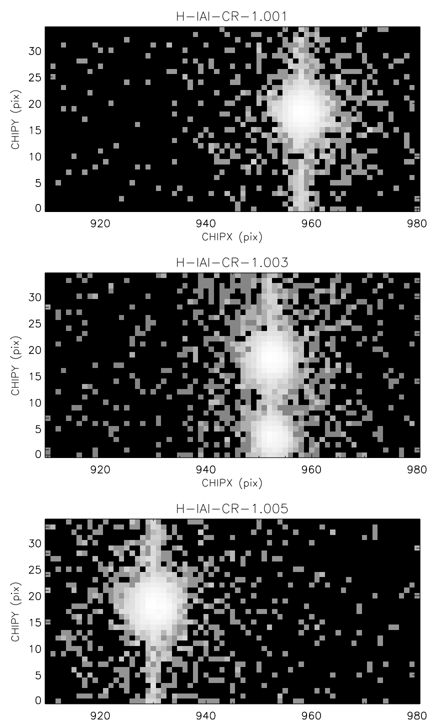

Figure 1: Images constructed from telemetry event lists for XRCF tests H-IAI-CR-1.001, 1.003, and 1.005 (top to bottom). From the top to the bottom panel, source flux increases by about an order of magnitude.

Table 1: Start/stop times and grade split ratios, for telemetry and HST datasets

TEST ID	data source	ONTIME	% of events in ASCA grade							
		(s)	0	1	2	3	4	5	6	7
H-IAI-CR-1.001	telemetry	7524	75.1	2.1	11.7	3.8	3.6	1.3	1.6	0.7
	HST	6410	69.0	1.9	12.5	4.1	3.7	1.4	2.4	4.9
H-IAI-CR-1.003	telemetry	3356	63.9	6.2	13.1	4.6	4.4	3.9	2.3	1.5
	HST	2166	60.2	6.0	13.8	4.7	4.2	4.2	3.0	3.9
H-IAI-CR-1.005	telemetry	790	43.9	10.5	13.0	5.4	5.1	8.5	5.9	7.7
	HST	675	42.3	10.0	12.9	5.3	5.1	8.7	6.6	9.1

2.2 ACIS event statistics

2.2.1 Grade split ratios

For each XRCF test, Table 1 lists the total integration times (ONTIME) and the percentage of events in each (ASCA system) grade for both telemetry and HST datasets. The agreement between the datasets is quite good, considering the different test time interval definitions (reflected in the different values of ONTIME) and the somewhat different event filtering criteria (e.g. source region definitions) applied. The larger proportion of G7 events in the HST data is likely due to the inclusion of spurious events due to certain detector artifacts, such as readout window boundary markers; most of these events are screened out during the ASC Level 1 event processing. Since grade 7 events were excluded in the following analysis, the discrepancy between the grade 7 percentages for telemetry and HST data should not effect our results, though it serves as a caveat that different data reduction procedures were used to produce the event lists under analysis here.

It is apparent from Table 1 that as source flux increases, the fraction of G0 events decreases sharply, and the fraction of events in G1,5,7 increases sharply (the fraction in G6 also increases somewhat with source flux). This reflects the "grade migration" resulting from photon pileup; i.e., events that consist of two or more G0,2,3,4 photons in diagonally adjacent pixels in a given CCD exposure are treated by the event detection and classification software as single-photon events that have deposited charge into a corner pixel (and hence are assigned grades of G1, G5 or G7).

For the following analysis, we restrict the events to those in G02346, to provide a comparison with calibration results derived from this "standard" ASCA gradeset. However, Table 1 shows that caution must be applied when evaluating the G02346 ACIS count rate as a function of source flux. At low count rate (test 1.001), the proportion of events in these grades is $\sim 96\%$, but falls to $\sim 73\%$ at high count rate (test 1.005). Thus, for test 1.005, we throw away $\sim 23\%$ of the source counts by restricting events to grades G02346.

2.2.2 BND count rates and fluxes; predicted ACIS count rates

To estimate the ACIS count rate that would have been measured for each test in the absence of pileup (i.e., given infinite time resolution), we analyzed beam normalization detector (BND) data obtained for the same three XRCF tests.[1] Average BND count rates and fluxes are listed in Table 2. The last column of the Table lists the predicted "no-pileup" count rate (in counts per ACIS frame)

[1]BND analysis techniques will be described in detail in the forthcoming ASC memo "HRMA+ACIS Effective Area Measurements from XRCF Data," by Kester Allen.

Table 2: BND analysis

Test ID	BND count rate ($cts\ s^{-1}$)	BND flux (photons $cm^{-2}\ s^{-1}$)	predicted ACIS count rate (cts $frame^{-1}$)
1.001	0.133 (0.006)	0.0043 (0.0002)	0.302 (0.015)
1.003	0.49 (0.01)	0.0145 (0.0003)	1.03 (0.03)
1.005	1.42 (0.04)	0.044 (0.002)	3.25 (0.09)

for each test. For this estimate, we assumed an effective area at Al Kα (HRMA plus ACIS-I3) of 600 cm^2 (source: ACIS Calibration Report) and a frame time of 0.122 s. The former quantity is probably uncertain by $\sim 5-10\%$ as of this writing, and hence dominates over photon counting error in contributing to the overall uncertainty in the estimated ACIS count rate in the absence of pileup. However, for the low-flux case (test 1.001), agreement is good between the ACIS count rate predicted from the BND analysis and the measured ACIS ("photon") count rate (§2.2.3; Table 3), suggesting that the error in the HRMA plus ACIS effective area at 1.487 keV is less than 5%.

2.2.3 ACIS count rates and pileup fractions

ACIS event and photon count rates (Table 3) were determined via analysis of event pulse height amplitude (PHA) spectra constructed from the telemetry and HST event lists for each test (Figure 2). To construct these spectra, events were screened such that only those in ASCA grades G02346 were included. Each PHA spectrum displays a main peak at $\sim$ 380 ADU (corresponding to the energy of individual Al Kα photons), and one or more peaks at integer multiples of the main peak. These additional PHA peaks (which we refer to as "pileup peaks") represent the accumulation of events consisting of two or more photons. For test 1.001, two- and three-photon pileup peaks are well detected ($\sim$ 500 and $\sim$ 20 counts, respectively), but four-photon events are not detected. For test 1.003, pileup peaks are well detected out to the "3rd pileup peak" (four-photon events), while for test 1.005, pileup peaks are well detected out to the "5th pileup peak" (six-photon events).

Figure 2 illustrates how analysis of a monochromatic source in the spectral domain offers a relatively unambiguous, quantitative method to assess pileup. To this end, we calculated the counts in each "spectral line" (i.e., in the main peak and in each pileup peak) and we used these results to calculate single- and multiple-photon event count rates (Table 3, columns 3–6). The single-photon event rate is simply the count rate in the main PHA peak, while the multiple-photon event rate represents the sum of the count rates in all pileup peaks. Since one can deduce the number of photons in each event from the total PHA of the event, the count rates in each line were weighted appropriately to produce *photon* (as opposed to event) count rates (columns 7, 8). Lastly, we calculated the *pileup fraction*, which we define here as *the fraction of detected events that consist of more than one photon* (columns 9, 10).

Table 3 demonstrates excellent agreement between the results of analysis of telemetry and HST data; discrepancies are generally on the order of the statistical uncertainties in the respective results. There do appear to be systematic errors of similar order, and these are likely due to the different definitions of ONTIME (Table 1) and the slightly different reduction techniques employed.

As expected, the single-photon count rate depends non-linearly on predicted count rate (i.e. photon flux) in the presence of significant ($> 3\%$) photon pileup; this is perhaps pileup's most obvious symptom. However, it is also apparent that the total *photon* count rate does not keep pace with the predicted count rate. We conclude that as count rate and hence pileup fraction increases,

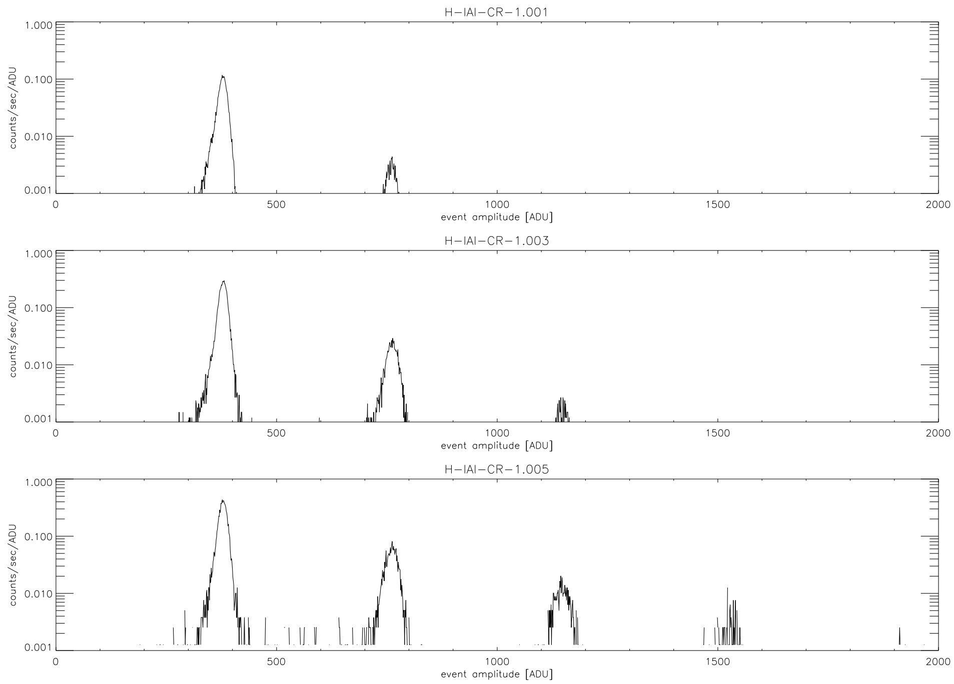

Figure 2: Event pulse height spectra constructed from telemetry event lists for XRCF tests H-IHI-CR-1.001, 1.003, and 1.005 (top to bottom). The energy of the source is 1.487 keV (Al Kα). From the top to the bottom panel, source flux increases by about an order of magnitude. The spectral line registered by single Al Kα photons appears at $\sim$ 380 ADU in each panel, while the peaks that appear at integral multiples of this amplitude are pileup peaks (consisting of 2 or more Al Kα photons detected quasi-simultaneously). The intensity of the pileup peaks increases relative to that of the source peak with increasing source flux.

Table 3: ACIS count rates[a] and pileup fractions

TEST ID	COUNT RATES							pileup fraction	
	predicted	single-photon events		multiple-photon events		photons			
		telemetry	HST	telemetry	HST	telemetry	HST	telemetry	HST
1.001	0.302	0.287	0.292	0.011	0.010	0.310	0.302	0.038	0.033
1.003	1.03	0.74	0.72	0.105	0.096	0.96	1.00	0.119	0.118
1.005	3.25	1.08	1.03	0.381	0.356	2.11	2.10	0.256	0.256

a) Count rates are in events per 0.122 sec (38 row) ACIS frame. Statistical errors in count rates are ~1–2%.

a substantial fraction of photons are "lost from the system." For test 1.005 this fraction is $\sim 35\%$. Most of these photons have migrated away from ASCA grades 02346 (§2.2.1) and for this reason are not accounted for in the foregoing spectral analysis. However, grade migration does not account for all of the missing photons, since the fraction of photons absent from the standard ASCA gradeset is only $\sim$23% for test 1.005. It is therefore likely that $\sim 10\%$ of the photons in test 1.005 constitute a false "continuum" of multi-pixel, multiple-photon events whose charge is not fully accounted for by event detection software. These events would be excluded from the count rate analysis described here, since they do not contribute to the PHA peaks that appear at integral multiples of the actual Al Kα peak.

3 Conclusions

We have analyzed a series of three Phase H (HRMA plus ACIS) XRCF pileup tests that vividly illustrate the effect of ACIS pileup in both the spatial and spectral domains. For these tests, conducted with a monochromatic Al Kα (1.487 keV) source, we determine that the inferred ACIS count rates in the absence of pileup range from ~ 0.3 to $\sim$3 counts frame^{-1}, and the corresponding pileup fractions range from $\sim$3% to $\sim$26% (the HRMA beam was well focused for these tests, with a PSF FWHM of $\sim 50\ \mu$m). We find:

- Image quality is only marginally degraded for a pileup fraction of $\sim 25\%$.
- The pileup fraction provides a rough estimate for the fraction of events "lost" from the standard ASCA gradeset (G02346) as a consequence of pileup-induced grade migration.
- For pileup fractions $> 3\%$ (or "no-pileup" count rates $>$0.3 counts frame^{-1}), the count rate of single-photon events becomes significantly non-linear.
- In addition to photons lost due to grade migration, we find that for the highest-flux test analyzed here, a substantial fraction ($\sim 10\%$) of photons do not appear at integral multiples of the principle event amplitude. This effect is likely due to incomplete charge collection for multiple-photon events.