Analysis of On-Orbit ACIS Squeegee Mode Data

Shanil N. Virani and Paul P. Plucinsky

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-70, Cambridge, MA 02138

Catherine E. Grant and Beverly LaMarr

Center for Space Research, Massachusetts Institute of Technology, 70 Vassar St., Cambridge, MA 02139

Abstract. The MIT and CXC ACIS teams have explored a number of measures to ameliorate the effects of radiation damage suffered by the ACIS FI CCDs. One of these measures is a novel CCD read-out method called “squeegee mode”. A variety of different implementations of the squeegee mode have now been tested on the I0 CCD.

Our results for the fitted FWHM at Al-Kα and Mn-Kα clearly demonstrate that all the squeegee modes provide improved performance in terms of reducing CTI and improving spectral resolution. Our analysis of the detection efficiency shows that the so-called squeegee modes “Vanilla” and “Maximum Observing Efficiency” provide the same detection efficiency as the standard clocking, once the decay in the intensity of the radioactive source has been taken into account. The squeegee modes which utilize the slow parallel transfer (“Maximum Spectral Resolution”, “Maximum Angular Resolution”, and “Sub-Array”) show a significantly lower detection efficiency than the standard clocking. The slow parallel transfer squeegee modes exhibit severe grade migration from flight grade 0 to flight grade 64 and a smaller migration into ASCA g7. The latter effect can explain some of the drop in detection efficiency.

There are a few observational penalties to consider in using a squeegee mode. Utilizing any squeegee mode causes a loss of FOV near the aimpoint (4 to 16′′ strips along the full length of the CCDs), as well as the attendant dead-time increase. Secondly, the cost of the software implementation and its testing will be significant. Lastly, each squeegee mode “flavor” would require lengthy, mode-specific calibration observations. Therefore, since an efficacious, ground-based CTI corrector algorithm is now available (see paper by Plucinsky, Townsley, et al. in this proceedings), a scientific judgment will have to be made to determine which, if any, squeegee modes should be developed and calibrated for use by Chandra observers.
1. Introduction

The ACIS Operations team, combining elements from the CXC and the ACIS MIT/IPI team, has been developing and testing the new squeegee modes since the Spring of 2000. In squeegee mode, charge is collected in the top few rows of the CCD and then swept across the imaging array once per readout, thus filling some of the radiation-induced electron traps that cause degraded performance. The development of a novel method of reading out the ACIS CCDs was first developed and tested on ground CCDs that are similar to flight CCDs (see Prigozhin, et al. 2000 for a characterization of the radiation damage of ACIS CCDs). This new mode ameliorates some of the effects caused by the radiation damage suffered early in the mission by the FI CCDs. For a more comprehensive discussion on the design and clocking method of squeegee mode, see Bautz and Kissel (2000). A description of the different squeegee modes is included in an internal MIT/ACIS Memo by Bautz and Grant (2000). That memo also presents an analysis of the squeegee modes and describes the trade-offs in choosing between the various squeegee modes. In this paper, we present the results of the various squeegee measurements on the I0 CCD.

This analysis utilized the standard level 0 and level 1 data products produced by the CXC Data System. The datasets included in this analysis are listed in Table 1. The control run (OBSID 62895) was a long charge transfer inefficiency (CTI) measurement. There are five “flavors” of Squeegee discussed in this paper: L1 “Vanilla”, L2 “Maximum Spectral Resolution”, L4 “Maximum Angular Resolution”, L7 “Maximum Observing Efficiency”, and L9 “Sub-Array near the aimpoint”. Table 1 summarizes the important parameters which distinguish one squeegee mode from another: static integration time, number of

### Table 1. List of I0 Squeegee Tests

| Test   | OBSID  | Date        | Exp(s) | Description                                                                 |
|--------|--------|-------------|--------|-----------------------------------------------------------------------------|
| Control| 62895  | 20 Feb 2000 | 9,023.4| 10, 3.2s, standard clocking                                                 |
|        |        |             |        | (40µs par xfr, no 2x2 sum) “Control” non-Squeegee                            |
| L1     | 62042  | 30 May 2000 | 8,225.5| 10, 3.3s, 16 row sq, 32 row exc win, no 2x2 sum,                           |
|        |        |             |        | 40µs par xfr, 24 flushes, 1010 rev clks “Vanilla Squeegee”                  |
| L2     | 62019  | 21 Jun 2000 | 8,623.6| 10, 1.9s, 16 row sq, 24 row exc window, 2x2 sum,                           |
|        |        |             |        | 320µs par xfr, 24 flushes, 1026+32 rev clks Maximum Spectral Resolution     |
| L4     | 62007  | 01 Jul 2000 | 8,517.3| 10, 3.3s, 2 row sq, 8 row exc win, no 2x2 sum,                            |
|        |        |             |        | 320µs par xfr, 24 flushes, 1026+32 rev clks Maximum Angular Resolution     |
| L7     | 61981  | 30 Jul 2000 | 8,551.5| 10, 1.8s, 2 row sq, 8 row exc win, 2x2 sum,                             |
|        |        |             |        | 40µs par xfr, 24 flushes, 1026+32 rev clks Maximum Observing Efficiency    |
| L9     | 61949  | 30 Aug 2000 | 8,356.9| 10, 1.2s, 2 row sq, 8 row exc win, no 2x2 sum,                            |
|        |        |             |        | 320µs par xfr, 24 flushes, 1026+32 rev clks, 256 row sub-array             |
squeegee rows (2 or 16), number of rows in the exclusion window (8 or 24 or 32), on-chip summing (yes or no), parallel transfer time (40µs or 320µs), number of frame flushes (always 24 for these squeegees), and number of reverse clocks (1010 or 1026+32). In addition, the table includes the average exposure time for these measurements. With all of these squeegee modes, the exposure time varies from row-to-row. The number listed is the correct exposure time for the middle of the CCD or for the middle of the sub-array for squeegee L9. In the analysis presented in this paper, the row-to-row variation in exposure time has been included by computing the exposure for each of the 32 row elements.

2. Methodology

Data from each I0 measurement was separated by node and then further reduced to thirty-one, 32-row region files. Spectra files were generated from the CXC level 1 events files. Events were selected in the ASCA g02346 grade set and were filtered on node and chipy coordinates. The gain was computed using the so-called “local-gain” method, meaning the fitted peak in each 32 row element is used to compute a conversion from ADUs to eV for that element. The prominent lines of the internal calibration source were then fit using Gaussians; the figure of merit employed was the C-statistic.

3. Results and Analysis

The results of this analysis are presented in Figures 1 and 2. Figure 1 shows the fitted values of the FWHM in eV for the I0 CCD at 1.5 keV (Al-Kα) at a focal plane temperature of -110 C, -120 C, and at -120 C using the “Vanilla” squeegee mode. For comparative purposes, the S3 CCD FWHM at -120 C is also overlaid. Figure 2 shows the fitted values of the FWHM in eV for the I0 CCD at 5.9 keV (Mn-Kα) at a focal plane temperature of -110 C, -120 C, and at -120 C using the “Vanilla” squeegee mode. For comparative purposes, the S3 CCD FWHM at -120 C is also overlaid. What is clear from both plots is that squeegee mode improves the spectral resolution of I0 CCD compared to standard clocking.

Figures 3 and 4 displays the quantities ASCA g0234/all grades, ASCA g02346/all grades, ASCA g7/all grades versus row number, where “all grades” means all events which pass the on-board filtering and make it into telemetry, for the Al-Kα and Mn-Kα lines. All of these measurements were executed using an upper event amplitude cutoff of 3750 ADUs and a grade filter which rejected flight grades 24, 66, 107, 214, and 255. Figure 5 is a plot of the detection efficiency for each line as a function of row number. We have included a statistical error bar for the count rate plots at the location of the first data element which is representative of the uncertainties in these measurements. In producing Figure 5, we have corrected for the decrease in intensity of the radioactive source as the data span 6 months. See 3.4 for further discussion.

3.1. Al results

Figure 3 shows the grade distribution as a function of row number for the squeegee measurements and the control run. The enhanced CTI of the FI CCDs
causes events to migrate from ASCA grades g0234 to higher grades. This can be seen in the control run and the squeegee runs. The effect is quite small at Al-Kα, never more than 3% for the grade sets listed here. Squeegees L2 and L4 show a very different behavior with regards to grade migration when the individual ASCA grades are examined. Analysis of the g0 events as a function of row number show that the percentage of grade g0 events is dropping from $\sim90\%$ in the first resolution element to $\sim20\%$ by the top of the CCD. ASCA grade 2 is the beneficiary of these counts as it increases from its nominal value of 5% to over 80% of the events at the top of the CCD. ASCA grade 2 is composed of flight grades 2 (down splits) and 64 (up splits). A further examination of the data reveals that all of the migrating events are going into flight grade 64. The one characteristic which the squeegees L2 and L4 have in common is the slow parallel transfer. Lastly, L2 and L7 both have much higher g0234/all grades ratios than the other modes because both L2 and L7 utilize 2x2 summing.

We suggest that this severe grade migration provides a clue to the cause of the lower detection efficiency seen in Figure 5. A common cause of reduced efficiency in a given grade combination is that events are migrating to grades outside of the chosen set. We will defer a full discussion of this until Section 3.4 in which the decay in the intensity of the radioactive source is included.
3.2. Mn results

The grade distribution versus number row number data are included in Figure 4. The squeegee runs now show greater variability with respect to each other and a larger difference with respect to the control run. Particularly interesting is the grade migration exhibited by squeegee L4. The fraction of g02346 events shows a linear decrease from row 100 to row 400, at which point it flattens out and is much lower than any other measurement. This behavior is also seen in the migration to g7 events. The same effect is seen in L2 but at a reduced level. This is presumably due to the fact that L2 utilizes on-chip summing, which should retain more of the valid X-ray events in the g02346 grade set. The fraction of g02346 and g7 events in the sub-array squeegee L9 lies between L2 and L4. The shorter frame-time of L9 compared to L4 appears to reduce some of this migration indicating that the effect cannot be attributed solely to the short timescale traps.

The grade migration effect seen at Al-Kα for squeegees L2 and L4 is more pronounced at Mn-Kα. Analysis of the individual grade “branching ratios” shows an even stronger migration from grades g0, g3, and g4 to g2 than for Al-Kα. Squeegee L4 also shows a steep increase in the g7 events from row 100 to row 500. The flight grade analysis shows that the migrating events are going
Figure 3. Squeegee mode grade summary plots for the Al-Kα line for all squeegee modes.

into flight grade 64. It is interesting to note that the percentage of g2 events is larger in L2 than L4. The difference between these two squeegees is that L2 uses on-chip summing while L4 does not. This suggests that a significant amount of charge is trailing the center of the event by 2-3 or perhaps even more pixels. Lastly, L2 and L7 both have much higher g0234/all grades ratios than the other modes because both L2 and L7 utilize 2x2 summing.

3.3. Ti results
The results for the Ti-Kα line are not presented in this paper due to space restrictions. However, the Ti-Kα data for I0 resemble the Mn-Kα data. The grade distribution results for Ti are also similar to the Mn results as one would expect given that the performance characteristics of the CCD vary little from 4.5 keV to 5.9 keV.

3.4. Correction for Decay of Radioactive Source
These squeegee tests were run between 3 and 6 months after the control run. The half-life of the Fe55 source is 2.7 yr. Therefore, the intensity of the source decays by ~ 6% in three months and by ~ 12% after six months. In Figure 5 we have corrected for this decrease by simply normalizing the detected count rates of the squeegee measurements to the control run. After applying this correction, squeegees L1 and L7 have the same or higher detection efficiency than the control run across the CCD, with the possible exception of L7 at Al-Kα. The upturn in the detection efficiency for the control run for Al-Kα is probably an artifact of the fitting process. It is interesting that the squeegee runs show a decrease of
the detection efficiency with row number relative to the control run at Al-Kα, but squeegees L1 and L7 match or exceed the control run at Mn-Kα and Ti-Kα. L2 appears to be still lower than the control run near the frame-store and drops more rapidly with row number than the control run. L4 still shows the largest drop with row number, but may now be consistent with the control run near the frame-store. The most important conclusion to be drawn from these data is that squeegees L1 and L7 have the same detection efficiency as the standard clocking at Mn-Kα and Ti-Kα.

The question still remains as to the lower detection efficiency of L2 and L4. The detection efficiency of L4 is $\sim 20\%$ lower than the standard clocking at the top of the CCD. Only about 6% of this difference can be explained by grade migration to ASCA g7. These measurements were executed with the now-standard on-board rejection of flight grades 24, 66, 107, 214, and 255. Of these, flight grade 66 may be the most interesting because it is the closest to flight grade 64 which is exhibiting the tremendous increase. Perhaps there is also a significant migration to grade 66, which would lead to a lower detection efficiency since these events are never telemetered. It is also possible that flight grade 255 is enhanced by this effect.

The variation with row number for L2 and L4 confirm what our analysis of the S0 data indicated (Virani and Plucinsky 2000). The detection efficiency is changing with row number and the percentage decreases are the same for the squeegee runs which utilize the slow parallel transfer. The severe grade migration effect appears to lower the effective detection efficiency around row 200 for Mn-Kα and row 700 for Ti-Kα. The Al-Kα data are not effected until about row

![Figure 4. Squeegee mode grade summary plots for the Mn-Kα line for all squeegee modes.](image)
Figure 5. Detection Efficiency of Squeegee Modes accounting for radioactive decay of the calibration source.

With the improved statistical precision of the Ti-Kα data, we can start to see the energy dependence of this effect. Clearly, the Mn-Kα photons are effected sooner than the Ti-Kα. This is suggestive of a strong dependence on energy in a rather narrow range from 4.5 to 5.9 keV.

One suggested explanation for the lower detection efficiency is that the analysis is confused by the blending of the Kα and Kβ lines as the spectral resolution degrades. We note that this effect should vary in magnitude with row number since the resolution is degrading with row number. However, squeegees L2 and L4 show a discrepancy with respect to the control run in the first 200 rows. Line blending is not an issue in the first 200 rows on I0 since the spectral resolution is still close to pre-launch values and is more than sufficient to resolve the Kα and Kβ lines for Mn and Ti. Line blending may be part of the explanation near the top of the CCD as the discrepancy between the squeegees and the control runs increases with row number. Nevertheless, the lower detection efficiency near the frame-store is a puzzling effect which warrants more investigation.

4. Conclusions

We confirm that all of the tested squeegee modes improve the spectral resolution of the I0 CCD compared to the standard clocking. Our analysis of the detection uniformity indicates that squeegees L1 and L7 have the same detection efficiency as the standard clocking after correcting for the decay in the intensity of the radioactive source, while the squeegees L2, L4, and L9 still exhibit a lower detection efficiency. The discrepancy is as large as 20% for squeegee L4 at the
top of the CCD. L2 and L4 also produce a highly spatially-dependent grade distribution. We suggest that the slow parallel transfer of both these modes is the likely explanation for this effect. We suggest that this effect should be investigated further with the hope that a squeegee mode can be developed which optimizes the spectral resolution, the detection efficiency, and the uniformity of the detection efficiency.

5. Acknowledgments

We thank our ACIS and CXC colleagues, particularly Mark Bautz, Dan Schwartz, and Peter Ford, for many useful ideas over the course of this analysis. SNV and PPP acknowledge support for this research from NASA contract NAS8-39073; CEG and BL acknowledge support for this research from NASA contracts NAS8-37716 and NAS8-38252.

References

Prigozhin, G., et al., “Characterization of the radiation damage in the Chandra X-ray CCDs”, SPIE Proceedings, vol. 4140, August, 2000, pp. 123-134
Bautz, M. and Kissel, S., “Explanatory Note on Squeegee Mode”, Internal MIT/ACIS Memo, 23 May 2000
Bautz, M. and Grant, C., “Choosing an ACIS Squeegee Mode”, Internal MIT/ACIS Memo, 15 August 2000
Virani, S. N. and Plucinsky, P. P., “Analysis of ACIS Squeegee Mode Data on Chip S0”, Internal CXC/ACIS Memo, 29 August 2000