CHANDRA
X-ray Center 60 Garden St., Cambridge Massachusetts 02138 USA

Date: May 15, 2023
From: John ZuHone
To: Chandra Operations Team
Subject: Chandra Radiation Event and Shutdown in March 2023
Cc: MSFC Project Science, CXC Director's Office
File: MAR2023_memo.tex
Version: 1.0

---

1 Abstract

This memo discusses the thought process that the operations team, especially the ACIS operations team, used during the very high radiation week of March 13, 2023. Chandra was shut down via a manual trigger of SCS-107. The key decision points to continue or suspend science operations are reviewed.

During this storm, the accumulated attenuated ACE P3 fluence was approximately 3.3×10^9. The agreed annual budget for this quantity is 2.0×10^{10}. As of April 5th, we have accumulated a summed fluence of about 9.3×10^9, or roughly 47% of the annual budget.

2 Introduction

On March 15th, 2023 *Chandra* experienced a radiation storm which required manual triggering of SCS-107 to protect the ACIS instrument from the damaging soft solar wind protons that increase CTI. This storm followed very quickly on the heels of a storm in the latter weeks of February. Solar activity is increasing in this year as we approach solar maximum.

At this point in the mission, the HRC Anti-Coincidence shield rate, which had been the radiation monitor for some time, was no longer available. The ACIS txings rates serves as the only available way to trigger autonomous shutdowns due to high radiation levels. In this storm, the txings rates were high, but not monotonic, and thus despite the high levels of radiation *Chandra* did not shut down autonomously. This is because the proton spectrum of the storm was relatively soft, and the ACIS txings rates (like the HRC shield rate) are most affected by the higher energy protons.

This memo discusses the properties of the storm, the radiation received in terms of the single-orbit and annual budgets, the differences between various radiation measurements, and the response.

3 March 2023 Detailed Timeline

Note: all times are in UTC.

- 2023:073 **Tuesday March 14, 2023** MAR1323A load is in progress.
- 2023:073:00:25:12.896 RADMON ENABLE
- 2023:073:12:00:00 For the past 12 hours, and essentially since the RADMON ENABLE, ACE P3 rates have been on a steady rise.
- 2023:074 **Wednesday March 15, 2023**
- 2023:074:02:08:57 *Chandra* reaches apogee for the orbit.
- 2023:074:04:10 Space weather alerts go out indicating a CME has hit the Earth's magnetic field, sparking a G1-class storm, and indicating that further storms are likely.
- 2023:074:04:47 Alerts go out to `sot_ace_alert` indicating that an ACE P3 fluence of 3.89×10^8 had been accumulated within a 2-hour period.
- 2023:074:05:15 ACE P3 flux reaches a maximum during the *Chandra* orbit of $\sim 1.4 \times 10^5$.
- 2023:074:11:00 **Comm** begins (90 min); ACIS TXings has not autonomously shut down the spacecraft.
- 2023:074:11:14 A decision is made to call a telecon to discuss manually shutting down *Chandra* during the current comm. During this telecon, the decision is made to shut down.
- 2023:074:11:37:45 SCS-107 runs.
- 2023:075 **Thursday March 16, 2023**
- 2023:075:04:06:42 Originally planned time of RADMON disable from the daily loads.
- 2023:076 **Friday March 17, 2023**
- 2023:076:04:12:00.000 First command of the MAR1723A replan loads.

4 Discussion

The Sun had been active since DOY 72 (March 13). An "extremely rare" farside CME was reported, leaving the Sun with a velocity of 3000 km s^{-1}. Predictions were made for "minor" G1-class storms on DOY 74-75 (March 15-16).

RADMON was enabled, and the science orbit was entered shortly after the beginning of DOY 73 (March 14). For nearly all of this day, ACE P3 rates increased, more steeply in the first half of the day, up to $\sim 2 \times 10^3$, and up to $\sim 2 \times 10^4$ by the end.

At 2023:074:04:10 UTC (12:10 am EDT), space weather alerts go out indicating a CME has hit the Earth's magnetic field, sparking a G1-class storm, and indicating that further storms are likely. Roughly 30 minutes later, alerts go out to `sot_ace_alert` indicating that an ACE P3 fluence of $\sim 3.9 \times 10^8$ had been accumulated within a 2-hour period.

Some discussion between the ACIS Ops team members occurred over email immediately afterward. Given the time of day and the fact that the next contact was not for a little over 6 hours at 11:00 UTC, it was decided that no action should be taken until the early morning before this contact, after there had been time to assess the storm's progress.

Over the next several hours, the ACE P3 flux continued to increase and reached a peak of $\sim 1.4 \times 10^5$ at 5:15 UTC. This flux was roughly maintained for several hours, and then began to fall at roughly 8:45 UTC, but leveled off again at roughly 10:30 UTC at a flux of $\sim 5.8 \times 10^4$. At this point, it was estimated that we had accumulated $\sim 2.9 \times 10^9$ of ACE P3 attenuated fluence for the orbit.

At this point, estimates were made for credible worst-case scenarios for how much additional attenuated fluence would be accumulated between this time and the time of RADMON disable at 2023:075:04:06:42, which was in ~18 hours. If we remained at the current flux of $\sim 5.8 \times 10^4$ for the rest of the orbit, another 3.65×10^9 of fluence would accumulate. A more credible worst-case scenario is one where the rates drop to a lower level and remain steady, or continue to drop at roughly the current rate of decrease. Under these circumstances, it was estimated that up to another $\sim 2 \times 10^9$ of attenuated fluence could accumulate. There were no gratings observations in the rest of the schedule that would have decreased this estimate, and at this time the HRC had not yet been returned to operations, so ACIS would be in the focal plane for the entire rest of the orbit.

Chandra came up on comm at 11:00 UTC (7:00 am EDT). ACIS was still taking data and the txings algorithm had not shut the spacecraft down. Figure 3 shows the txings rates and the trigger limits for increasing values on the FI and BI chips for the length of the storm. On DOY 74, as the ACE rates were rising significantly, the rates on the BI chips were high but did not trigger, in particular because they were below the decreasing and sustained trigger levels, and while above the increasing rate limit, they were not consistently increasing (Figure 4).

At this point, the options were to call for a shutdown at the current comm, or ride the storm out until the next comm, which was not for almost 12 hours at 22:50:01 UTC on the same day. A telecon was called at 11:15 UTC (7:15 am EDT) to discuss the elevated radiation rates and what actions may or may not be taken in response. Some discussion was given to the rates, and to what extent they may decrease over the rest of the orbit. Consideration was given to any time-constrained targets in the rest of the MAR1323 schedule. Finally, the argument that carried the day was the maximum amount of attenuated fluence for an orbit had already been accumulated, and the likelihood that a similarly significant amount would be added. SCS-107 was manually executed at 2023:074:11:37:45.

In the end, the total accumulated fluence for the orbit, computed from the ACE dump data, was 3.3×10^9, slightly higher than the $2.9 - 3.0 \times 10^9$ estimated at the time of the shutdown. This is because in real-time the ACE data has dropouts that occur with varying frequency. Filled-out ACE data can be obtained at a later time from the ACE Science Center FTP site (see Section 7 for more information). If we had not shut down, this data indicated another $\sim 1.4 \times 10^9$ of attenuated fluence would have been accumulated.

The HRC Anti-Co Shield is no longer operational for radiation monitoring. However, we can check the HRC Shield GOES Proxy to determine if there would have been an autonomous shutdown had it been available. The HRC Proxy never went above the trigger limit of 245, and was only moderately large near in time to the storm on DOY 72, before the orbit in question had even started (see Figure 5).

5 Data plots for the July 2023 storm

In Figure 1, we have plotted the 5-minute averaged ACE P3 flux rate, in the usual units, which are protons $\mathrm{s}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{MeV}^{-1}$, throughout the March storm. Also marked are radiation belt passages, the time of manual SCS-107 execution, time of the nominal RADMON disable from the MAR1323 loads, and the start of the MAR1723 loads (the same times are marked in the rest of the radiation vs. time plots). Shortly after exiting the radzone early on DOY 73, the ACE P3 rate rises steeply from its initial low value of $\sim$50. By 2023:073:12:00:00, it has risen to $\sim 2 \times 10^3$, briefly stopping before rising steeply to $\sim 10^5$ over the next $\sim$14 hours.

Rates remain at this level for the next 6 hours, then falling to $\sim 5 \times 10^4$. As noted above, based on the projection that rates may not decline rapidly or even increase again, at this point SCS-107 was executed manually. Rates remain near $\sim 5 \times 10^4$ for another 6 hours, after which there is a steep decline to 10^4 at approximately 2023:074:18:00:00, followed finally by a slow decline back to normal levels over the next few days.

Figure 2 shows the flux from four ACE proton channels (P1, P3, P5, and P7) during the storm. Though only P3 is our proxy for damage to the ACIS CCDs, the other channels can serve as informative diagnostics. Of particular interest is the behavior of the channels P3, P5, and P7 during the steep rise in the first half of DOY 73. Normally the flux in these channels is of a power-law nature, though during this time they are nearly equal, indicating a flat and hard spectrum. This phenomenon often occurs in solar storms (see `https://cxc.harvard.edu/acis/storms` for examples) and can often point to significant

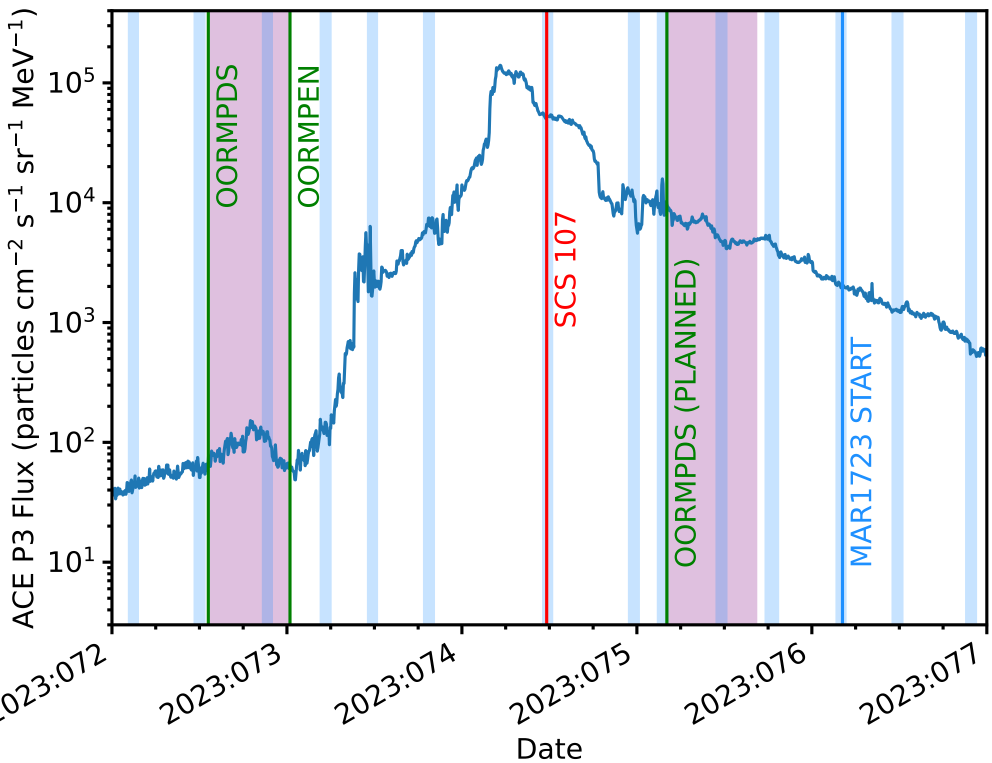

Figure 1: A plot of the ACE P3 flux during the March 2023 storm. Purple shaded regions indicate the radzone passages, during which HRC is in focus. Fluence is integrated when ACIS is in focus, and is counted from radzone exit. Blue shaded regions mark scheduled DSN communications.

P3 flux occurring downstream.

In Figure 3, we present the MIT psci plot of the ACIS threshold crossings as a function of time for the days of the storm. The FI rates never reached their trip levels during the orbit. The BI rates did reach the trip levels, but they were not monotonic and so the txings algorithm never tripped. Figure 4 shows a close-up of the txings rates on DOY 73-74.

Finally, Figure 5 shows the HRC Shield Proxy during the storm. As already noted, the HRC Anti-Coincidence Shield rates are no longer available for radiation monitoring, but had they been, they would not have triggered SCS-107.

6 Lessons Learned

- The operators should not only consider the amount of fluence taken during the orbit, but the amount taken for the entire year so far. The latter should not drive a decision

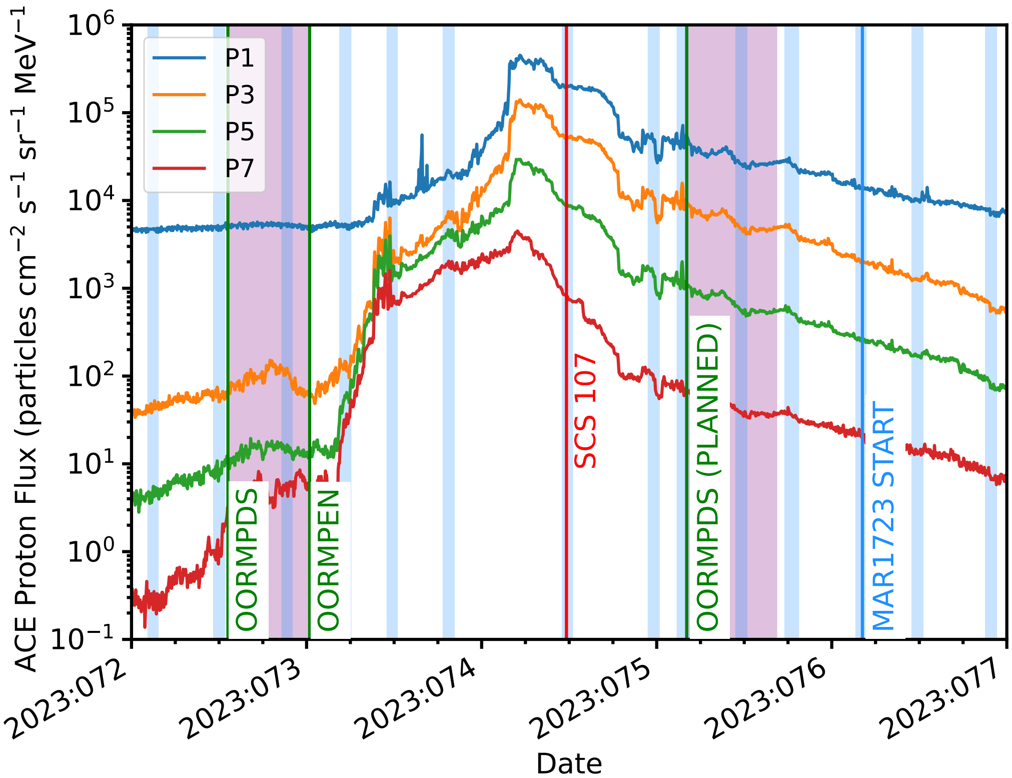

Figure 2: A plot of the flux from the four ACE channels P1, P3, P5, and P7 during the March storm. Shaded regions and vertical lines have the same meaning as in Figure 1.

to ignore the orbital fluence requirement, but may further motivate a decision to shut down if we are significantly ahead of schedule on the yearly fluence budget.

- This storm provided a concrete demonstration of the fact that the ACIS threshold crossings rates can be elevated and even above their limits, and yet not trigger SCS-107 if they are not monotonic.
- The fluence taken per orbit from the fluence integrator must always be recognized as a lower limit–the real-time ACE data is subject to frequent dropouts that are only backfilled later. In this case, the difference between actual fluence and known fluence at the time was modest (∼10%), but this may not always be the case.

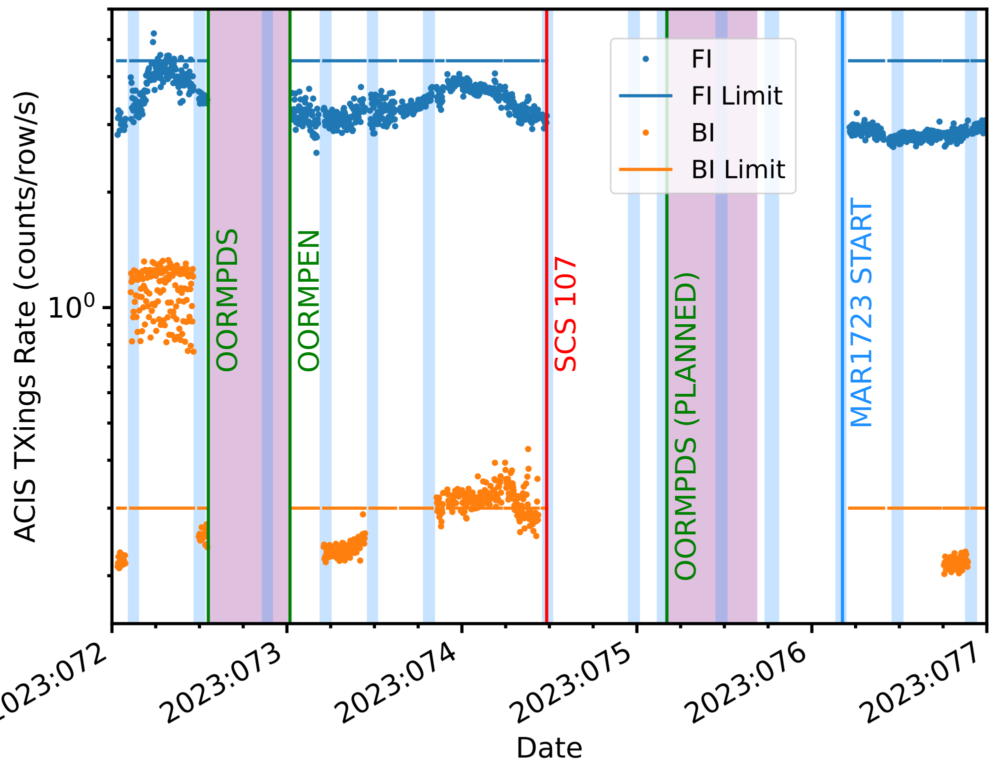

Figure 3: The txings plot for 2023:072-2023:077 (March 13-18). Blue is for FI chips, orange is for BI. The horizontal lines are the increasing values trip thresholds for each type of chip. Shaded regions and vertical lines have the same meaning as in Figure 1. Despite the txings values being above the thresholds for some time, the algorithm did not trip since the data were not monotonic.

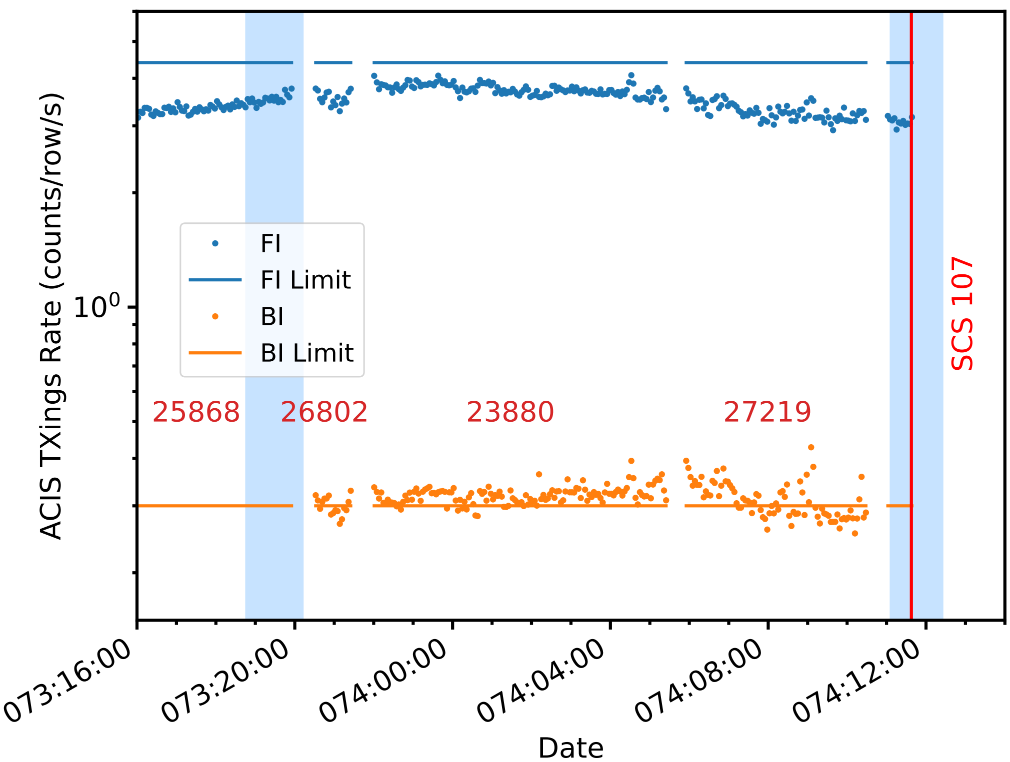

Figure 4: The txings plot for 2023:073-2023:074 (March 14-15). Blue is for FI chips, orange is for BI. The horizontal lines are the increasing values trip thresholds for each type of chip. Individual obsids are labeled. Shaded regions and vertical lines have the same meaning as in Figure 1. Despite the txings values being above the thresholds for some time, the algorithm did not trip since the data were not monotonic.

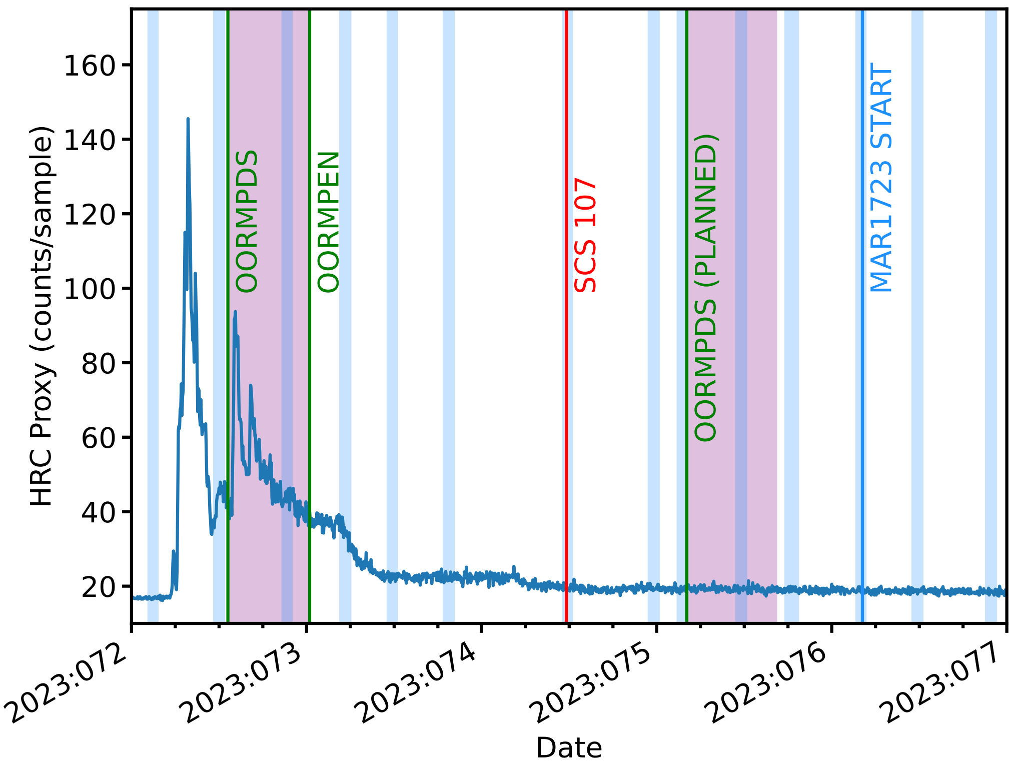

Figure 5: The HRC Shield proxy during the storm. Shaded regions and vertical lines have the same meaning as in Figure 1. Throughout the entire storm, this value was very far away from the trigger value of 245.

7 Resources

The March ACE proton data were too new to be in the final ACE archive. The archive of ACE data stored in ASCII tables at `https://sohoftp.nascom.nasa.gov/sdb/goes/ace/daily/` has gaps that are not back-filled; the full dataset can however be found in the "ACE Browse" archive:

`ftp://mussel.srl.caltech.edu/pub/ace/browse/`

The data are in HDF4 format, which can be converted to HDF5 data by use of a program `h4toh5` which I downloaded from `https://www.hdfeos.org/software/h4toh5.php`. A Python script, `get_ace.py`, which downloads the data and uses `h4toh5` to convert it is available on the HEAD LAN in `/data/acis/ace`. Instructions for downloading the data using this script and extracting the ACE proton channels are given in `/data/acis/ace/README_browse.md`.

The HRC Shield Proxy data are stored in HDF5 format here:

`/proj/sot/ska/data/arc/hrc_shield.h5`.

Thanks to Peter Ford for providing the ACIS txings data.