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Evolution of temperature-dependent charge transfer inefficiency correction for ACIS on the Chandra X-ray Observatory

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ABSTRACT

As the Advanced CCD Imaging Spectrometer (ACIS) on the Chandra X-ray Observatory enters its seventeenth year of operation, it continues to perform well and produce spectacular scientific results. The response of ACIS has evolved over the lifetime of the observatory due to radiation damage and aging of the spacecraft. The ACIS instrument team developed a software tool which applies a correction to each X-ray event and mitigates charge transfer inefficiency (CTI) and spectral resolution degradation. The behavior of the charge traps that cause CTI are temperature dependent, however, and warmer temperatures reduce the effectiveness of the correction algorithm. As the insulation on the exterior of the spacecraft degrades with time, the temperature of the ACIS focal plane can increase by several degrees for some spacecraft orientations. A temperature-dependent component was added to the CTI correction algorithm in 2010. We present an evaluation of the effectiveness of this algorithm as the radiation damage and thermal environment continue to evolve and suggest updates to improve the calibration fidelity.

Keywords: Chandra X-ray Observatory, ACIS, radiation damage, charge transfer inefficiency, CCDs, X-rays

1. INTRODUCTION

The Chandra X-ray Observatory, the third of NASA's great observatories in space, was launched just past midnight on July 23, 1999, aboard the space shuttle *Columbia*.[1] After a series of orbital maneuvers, Chandra reached its operational orbit, with initial 10,000-km perigee altitude, 140,000-km apogee altitude, and 28.5° inclination. In this evolving high elliptical orbit, Chandra transits a wide range of particle environments, from the radiation belts at closest approach through the magnetosphere and magnetopause and past the bow shock into the solar wind.

The Advanced CCD Imaging Spectrometer (ACIS), one of two focal plane science instruments on Chandra, utilizes charge-coupled devices (CCDs) of two types, front- and back-illuminated (FI and BI).[2] Soon after launch it was discovered that the FI CCDs had suffered radiation damage from exposure to soft protons scattered off the Observatory's grazing-incidence optics during passages through the Earth's radiation belts.[3] The BI CCDs were unaffected. Since mid-September 1999, ACIS has been protected during radiation belt passages and there is an ongoing effort to prevent further damage and to develop hardware and software strategies to mitigate the effects of charge transfer inefficiency on data analysis.[4,5]

The eight front-illuminated CCDs had essentially no CTI before launch, but are strongly sensitive to radiation damage from low energy protons (~100 keV) which preferentially create traps in the buried transfer channel. The framestore covers are thick enough to stop this radiation, so the initial damage was limited to the imaging area of the FI CCDs. Radiation damage from low-energy protons is now minimized by moving the ACIS detector away from the aimpoint of the telescope during passages through the Earth's particle belts. Continuing exposure to both low and high energy particles over the lifetime of the mission slowly degrades the CTI further.[4,6] As of January 2000, the parallel CTI at 5.9 keV of the ACIS FI CCDs varied across the focal plane from $1-2\times10^{-4}$

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at the nominal operating temperature of –120° C with a rate of increase of roughly 2×10^{-6}/year. Parallel CTI in the framestore array and serial CTI were not affected by the initial radiation damage and remain negligible with upper limits of $< 10^{-6}$.[7]

The two back-illuminated CCDs (ACIS-S1,S3) exhibited CTI in both the imaging and framestore areas and the serial transfer array before launch, but are less sensitive to the low energy particles scattered off the optics which damage the FI CCDs because they cannot reach the transfer channel. The parallel CTI at 5.9 keV of the S3 BI CCD was 1.5×10^{-5} at a temperature of –120° C at the beginning of the mission with a strong non-linear flattening of pulseheight at low row numbers due to CTI in the framestore array. The serial CTI is much larger, 8×10^{-5}. BI CCD CTI has been increasing at a rate of roughly 1×10^{-6}/year. In this paper we focus on parallel CTI rather than serial CTI, since the transfer distances are much longer (256 pixels versus 1024 pixels) and the evolution is more pronounced.

Measured CTI is a function of temperature. Detrapping time constants decrease as the temperature increases so that different populations of traps can become more or less important. If the detrapping time constant drops below the pixel transfer time or becomes much longer than the typical distance between charge packets, charge is no longer lost to the trap. The distribution of trap time constants at a particular temperature determines the CTI, so temperature can positively or negatively correlate with CTI. Conversely, the temperature dependence of CTI reflects the particular blend of electron traps. A study of the temperature dependence of ACIS CTI was done in 1999[3] and again in 2005,[8] which showed that while the FI CCD CTI-temperature relation was mostly unchanged, the BI CCD CTI-temperature relation had evolved, presumably because the ongoing accumulated radiation damage produced a different trap population than the initial pre-launch CTI.

ACIS continues to perform well and produce spectacular scientific results, however the response of ACIS has evolved over the lifetime of the observatory due to radiation damage and degradation of thermal control. The ACIS instrument team has produced a software tool, a post-facto correction of event pulseheights, which was implemented in the standard Chandra data processing pipeline in 2004 and provides some performance improvement.[5] A temperature-dependent component was added to the CTI correction algorithm in 2010. The time-dependence of event pulseheights due to CTI and other electronic gain changes is corrected using a time-dependent gain file, with no additional correction for changing line widths.

This calibration paradigm has generally worked well, but was developed under the assumption that temperature variations would be small deviations from the nominal focal plane temperature. As will be shown in Section 3, this is no longer the case, as all spacecraft temperatures continue to rise and with temperature variations within a single observation of up to 5° C. In this paper, we have attempted to evaluate the effectiveness of our current CTI correction calibration and suggest directions for improvements.

2. DATA

All of the results discussed use data taken of the ACIS External Calibration Source (ECS) which fully illuminates the ACIS CCDs while ACIS is stowed. Since the discovery of the initial radiation damage, a continuing series of observations of the ECS have been undertaken just before and after the instruments are safed for perigee passages to monitor the performance of the ACIS CCDs. ACIS is placed in the stowed position exposing the CCDs to the ECS which produces many spectral features, the strongest of which are Mn-Kα (5.9 keV), Ti-Kα (4.5 keV), and Al-K (1.5 keV). The data are taken in the standard Timed Exposure mode with a 3.2 second frame time. X-ray events on ACIS CCDs can produce charge packets which occupy multiple pixels and so are recorded as 3 x 3 pixel event islands. We compute CTI from the center pixel pulseheight alone. Typical exposure times for each observation range from 4 to 8 kiloseconds. All standard observations are taken at the nominal focal plane temperature set-point of –120° C, although the actual temperature during the observation may be warmer, as discussed in Section 3. Figure 1 shows the spectrum of the ACIS ECS and labels the important features. The ECS is powered by the radioactive isotope Fe-55 which has a half-life of 2.7 years, so the count rate from the ECS has dropped precipitously over the seventeen year lifetime of Chandra.

The frequent cadence of ECS observations, roughly twice every three days, allows for close monitoring of ongoing radiation damage and rapid investigation of potential instrument anomalies, while still providing a long-baseline for detailed studies of performance changes. In addition to the regular ECS observations near perigee,

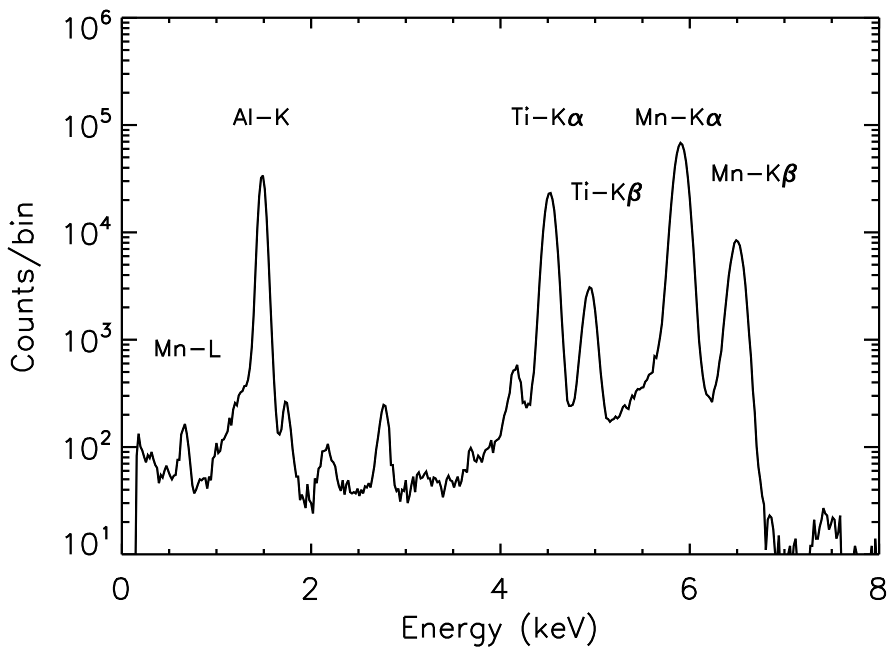

Figure 1. The spectrum of the ACIS External Calibration Source on the ACIS-I3 FI CCD. Only data from the first 256 rows are included to minimize CTI degradation. Lines used for calibration and monitoring purposes are labelled. The remaining features are instrumental.

much longer exposures are often undertaken during long duration radiation shutdowns due to solar storms while the external environment is still too active to restart science observations.

The full illumination of the focal plane by the ECS enables mapping of detector performance down to the level of a few pixels. In particular, the charge transfer inefficiency correction included in the standard pipeline processing utilizes maps of the electron trap uniformity.[5] These maps include the known gradient in the radiation damage across the focal plane, as well as variations in charge loss from column to column due to the Poisson variation in the number of traps in each column. A substantial fraction of the improvement provided by the CTI correction is due to the mapping of this fine structure in the trap density.

3. ACIS THERMAL ENVIRONMENT

ACIS uses a combination of passive radiators and active heaters to maintain thermal control. While the focal plane temperature set point has remained at −120° C for most of the Chandra mission, thermal control has become more difficult with time, particularly for some spacecraft orientations where the heat load on the ACIS radiator and/or focal plane is increased, and near perigee where the solid angle of the warm Earth as viewed by the ACIS radiator can be significant. Chandra is a complicated machine and the pointing constraints of other spacecraft components are not always favorable for ACIS focal plane cooling. Because they occur close to perigee, ECS observations are more likely than science observations to be warmer than nominal by as much as 5–10° C in the worst cases. The availability of warmer calibration data, however, has proved invaluable for developing a temperature-dependent charge transfer inefficiency correction that is now part of standard pipeline processing.[8]

The time history of ACIS focal plane temperature during science observations is shown in Figure 2. An obvious trend is that the excursions to warmer temperatures have increased with time. An exception is the reduction in number of warmer observations in 2008 when the ACIS detector housing heater was turned off. This heater was turned back on in mid-2015. It's clear that the density of observations with temperatures in

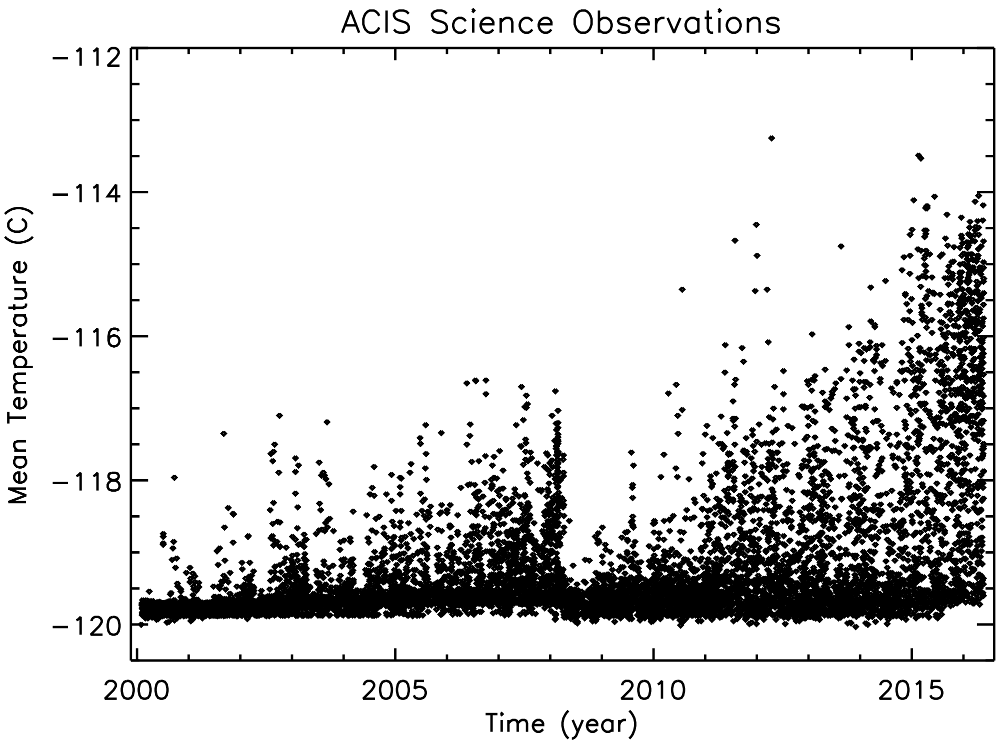

Figure 2. The time history of ACIS focal plane temperature during science observations since January 2000. Each data point is the average for a single observation, so the exposure time can range from a few to hundreds of kiloseconds and the temperature may have varied by many degrees during the observation.

the −118° C to −114° C range has increased since that time, due both to the heater and to the overall warming trend. There are plans to turn this heater off again in mid-2016. The Chandra mission planning team makes use of a predictive temperature model during observation scheduling to purposely prevent the focal plane from exceeding −114° C, which puts an upper bound on the temperature distribution. This plot helps demonstrate how the current thermal environment differs from 2000-2010, when the temperature-dependent calibration was established. Quantitatively, the percentage of observations with "cold" temperatures ($< -119.2°$ C) has dropped from 99% in 2000, to 68% in 2007, to 33% in 2015.

4. ACIS CTI CORRECTION

The ACIS instrument team developed a model for ACIS CTI which is being used to correct each event and improve the instrument performance.[5] The correction uses a map of the electron trap distribution, a parametrization of the energy dependent charge loss, and the fraction of the lost charge re-emitted into the trailing pixel to correct the 3x3 pixels in the event island. The energy- and position-dependence of CTI are measured independently from each other. The position dependence and the magnitude of charge loss are stored as a "trapmap", which is proportional to CTI, while the energy dependence is parameterized as a single power-law for each CCD. As the calibration of the CTI correction parameters requires summing the ECS data over longer time periods and is somewhat time-consuming, and, as the evolution of ACIS CTI seemed to be gradual and small compared to the initial CTI damage, it was decided to separate out the time-dependent part of the calibration. This is done through a time-dependent gain file, "tgain", which sums up three months of ECS data and calculates a position dependent correction to the summed event pulseheight.

As Chandra approached its first decade on orbit, these temperature excursions became larger and more frequent. The temperature variations can produce significant calibration changes for locations far from the

CCD readout, particularly on the FI CCDs with higher CTI. As the warmer temperatures are uncontrolled, there can be variations within a single observation as high as 4–5° C. The current temperature-dependent CTI correction algorithm works on an event-by-event level, using a linear-fit to the CTI-temperature relation and the temperature at the time the event data was taken, to adjust the trapmap. At the time it was developed, the correction reduced temperature-dependent pulseheight change to $< 0.1\%$ / degree. The temperature-dependent line width was not significantly improved by the correction, possibly because the charge loss is stochastic.

5. EVALUATION OF CURRENT CORRECTION

To test the accuracy of ACIS calibration, we use data that have gone through standard processing with released Chandra Calibration Database products, in exactly the same way as a Chandra user following CIAO threads (Chandra Interactive Analysis of Observations: http://cxc.cfa.harvard.edu/ciao). The data are grouped into 64×64 pixel regions, one-year time bins, and one-degree temperature bins. We fit the Al-K (1.5 keV) and Mn-Kα (5.9 keV) lines using standard response products convolved with a Gaussian. If the calibration is accurate, the fitted line centroid should be the known line energy, and the fitted line width should be consistent with zero. The ACIS calibration team strives for a gain calibration accuracy of 0.3%. For many regions, even at high temperatures and late times, the fitted line centroid is consistent with the known line energy within the stated calibration accuracy. The line width evolution is less well measured, but plans are underway to recalibrate the response products to better match the data at later times.

The motivation behind re-examining the temperature-dependent CTI correction is threefold. The algorithm was designed assuming the temperature deviations were small so that the temperature-dependence of CTI could be assumed linear. The original calibration data was primarily from data colder than –116° C. If the trap population is changing, if the ongoing radiation damage is different from the initial radiation damage on the FI CCDs or the pre-launch BI CCD CTI, the temperature-dependence of CTI could be evolving. In addition, there could be problems with the original CTI correction itself, independent of temperature, if, for example, the energy-dependence is changing. In this section, we concentrate on the aimpoint CCDs, the BI CCD ACIS-S3 and the FI CCD ACIS-I3, and assume that each is representative of its CCD type.

5.1 BI CCD CALIBRATION

The last of the three motivations has already been shown in the temperature-CTI measurements done in 1999 and 2005, which showed the FI CCDs had essentially the same temperature-dependence, but the BI CCD temperature-dependence was evolving.[8] An additional temperature scan in 2013 further proved this. Figure 3 shows the CTI versus temperature for the BI CCD ACIS-S3 from –120° C to –60° C in 1999, 2005, and 2013. While the temperature-coverage is not uniform and the counting statistics have decreased with time, the sense of the CTI-temperature dependence has clearly changed sign. Radiation-produced CTI is now as important on the BI CCDs as the intial pre-launch CTI. This is not the case for the FI CCDs, as the initial CTI degradation from the radiation belts is similar enough to the subsequent long-term radiation damage that the CTI-temperature relation has roughly the same slope.

As was already stated, the slope of the CTI-temperature relation for the BI CCD ACIS-S3 has changed over time. This should appear in the line centroids as an offset in data with warmer focal plane temperatures that changes with time. Figure 4 shows exactly that for the Mn-Kα line at 5.9 keV. As the CTI correction is generally smaller on the BI CCDs than on the FI CCDs, the line centroids remain within the 0.3% calibration margin, but a systematic offset that changes with time can be seen for data at higher temperatures (right panels), that is not seen in the cold data (left panels). The line centroids of the warm data are all systematically higher in 2000 (top right panel) and and lower in 2013 (bottom right panel). The same trend is also seen in the data for the Al-K line at 1.5 keV with somewhat poorer statistics due to the weaker line flux, but is not shown here.

This change in the BI CCD CTI-temperature relation can be measured and calibrated in exactly the same way as the non-evolving version in the current Chandra CALDB. Figure 5 shows the linear fit to the CTI vs temperature for data in three-year time bins. The value has been slowly increasing with time. The dotted line indicates what is in the current CALDB products, which is slightly too high for the earliest data and much too low for the most recent data. A time-changing temperature-dependence could be easily implemented in the

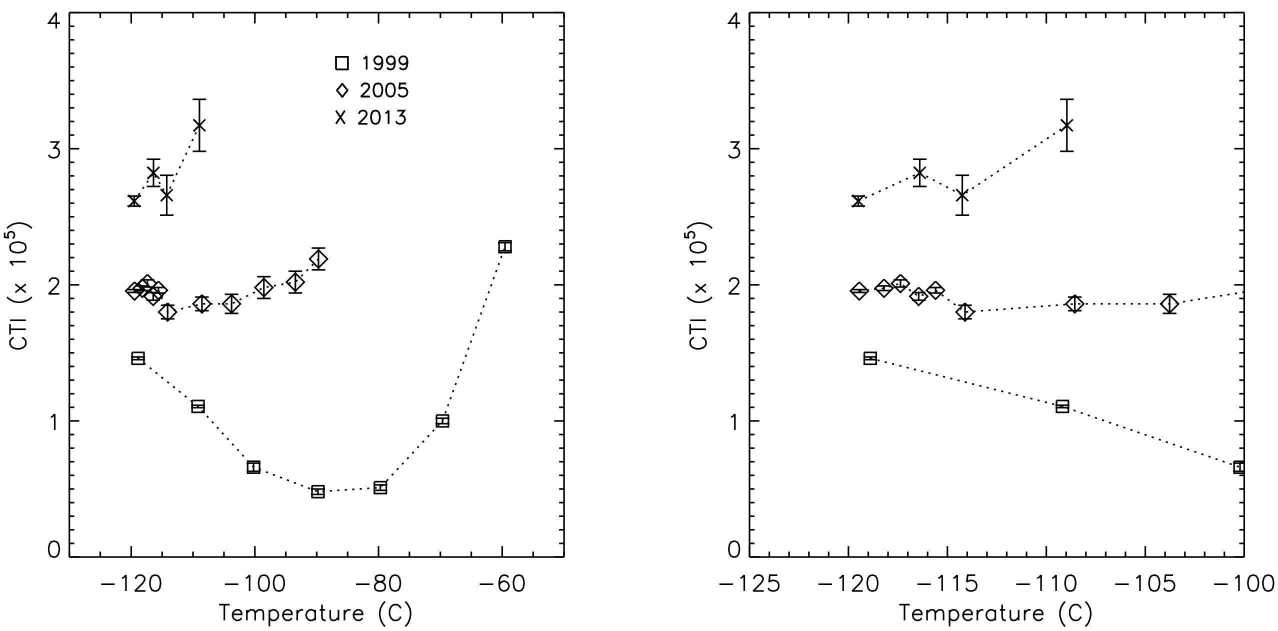

Figure 3. Parallel CTI as a function of temperature for the BI CCD ACIS-S3 at three different times, in 1999, 2005, and 2013. Both plots show the same data with the right plot zoomed in to the lower temperatures. The CTI has increased with time due to radiation damage but the slope of the CTI-temperature relation has also changed significantly.

current CALDB paradigm without any additional software changes and would improve the already quite good energy scale calibration for the BI CCDs.

5.2 FI CCD CALIBRATION

For the FI CCD ACIS-I3, both the data quantity and the fitting quality are lower than for the BI CCD in the previous section. The observing time is shorter and, since the overall CTI is higher, the lines are broader and harder to fit well. Figure 6 shows the same type of data for the FI CCD as was seen in Figure 4 for the BI CCD. Examining first the cold data (left panels), the distribution of line centroids is much broader, indicating that there is variation along the ChipX direction that is not being captured in the calibration products. For the most part the fits are within the 0.3% envelope, but may point to areas for improvement. The colors that appear above and below the mean are consistent between time periods, so the spatial variation along ChipX does not appear strongly time dependent. There is also a hint that the data points at the higher ChipY, where CTI is most important, are systematically low and dropping with time. The higher temperature data (right panels) have much poorer statistics than the cold data, but some observations can be made here as well. Again, there is a drop at higher ChipY that seems to increase with time. The variation along ChipX is much less obvious due to the data quality, but may follow some of the same trends as the colder data. There may also be a small systematic offset between time-periods for the warm data, which may indicate a change in the CTI-temperature relation is necessary. For the most part, these appear to be a problem with the CTI correction, rather than the time- or temperature-dependence, as will be explored next.

Examining the Al-K line at 1.5 keV in addition to the 5.9 keV line can help point to the root of the problem. Figure 7 shows the line energy as a function of ChipY after averaging over ChipX for both 1.5 and 5.9 keV lines. The data taken at the nominal focal plane temperature (solid lines) have a distinctly different shape between the two energies, changing from upward to downward curving. The droop at high ChipY is not seen at the lower energies at all. Warmer temperatures appear to worsen the problem. This suggests that the CTI correction itself needs improvement, as any small problem in the cold data will be magnified in the warmer data as seen here.

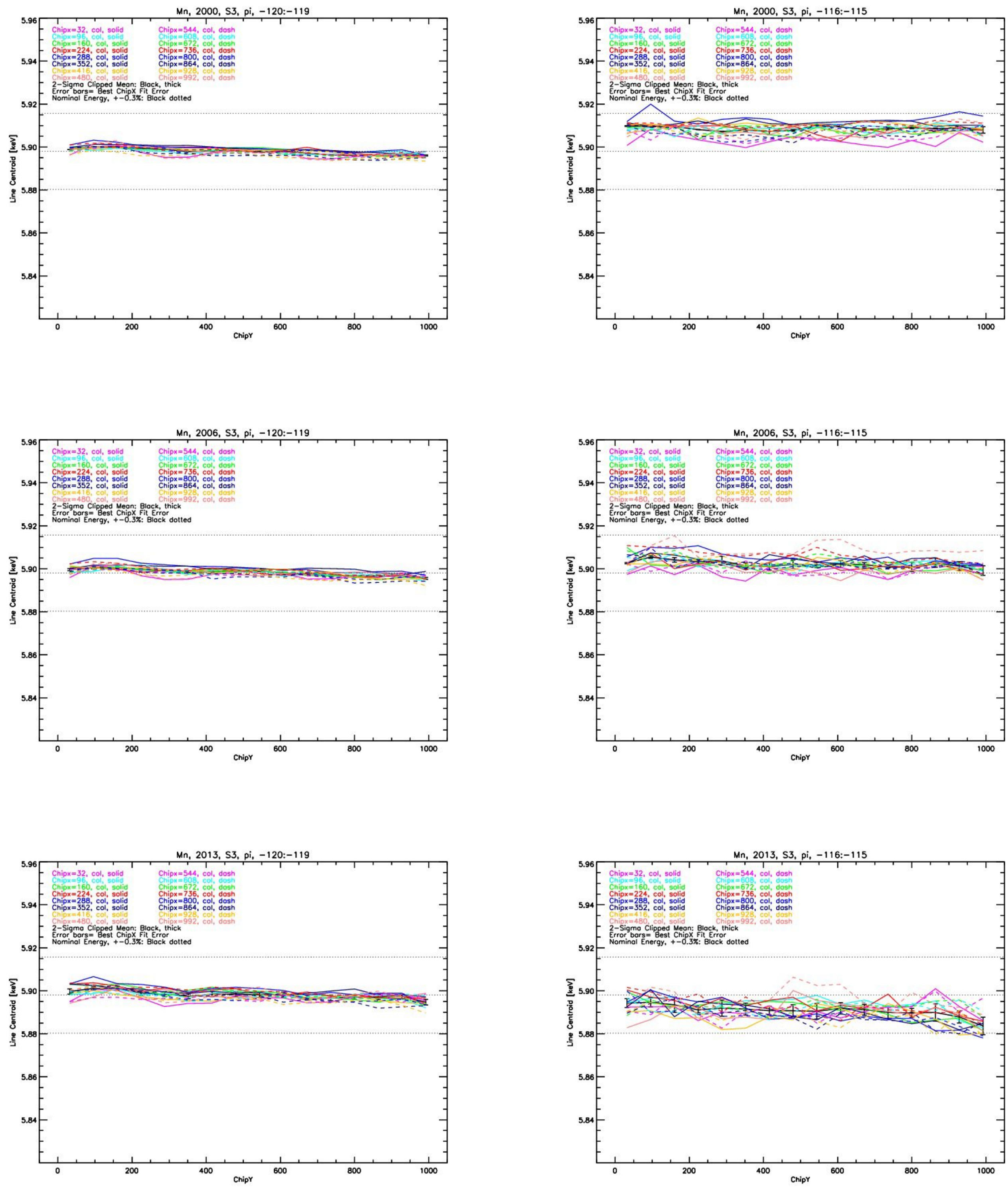

Figure 4. Fitted line centroids at 5.9 keV for the BI CCD ACIS-S3 as a function of ChipY. The different color lines represent different ChipX values. The black lines with error bars are an average over all ChipX values. The horizontal dotted lines enclose ±0.3% around the known line energy. Data from three epochs are shown: 2000 (top), 2006 (middle), and 2013 (bottom). Data on the left are at the nominal focal plane temperature, while data on the right are between –116° C and –115° C.

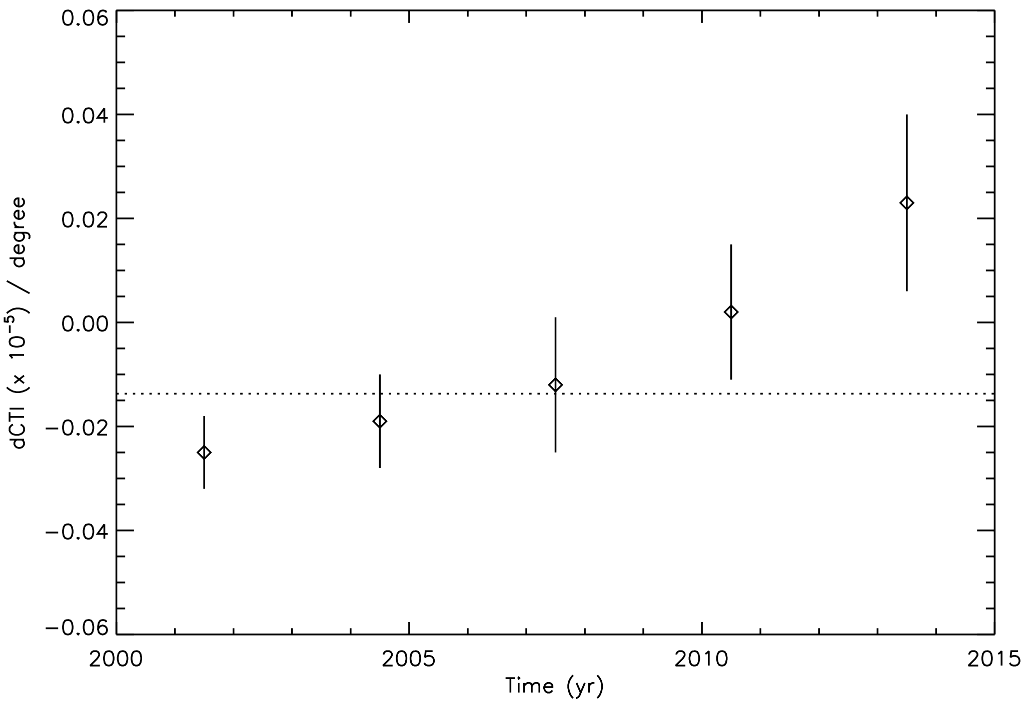

Figure 5. The CTI-temperature relation for the BI CCD ACIS-S3 as a function of time. The dotted horizontal line shows the value in use in the current Chandra CALDB.

Both the spatial calibration and the energy dependence are suspect due to the high-row droop and the differing shapes overall. Any problems with the temperature-dependence are likely smaller and are difficult to see at the present time. As the solution may involve changes to multiple components of the CTI correction calibration, resolution may take more time and additional analysis.

6. CONCLUSIONS

We have presented an evaluation of the effectiveness of the temperature-dependent CTI calibration that is currently in use for Chandra ACIS data analysis. For the BI CCDs, the primary problem is the lack of time-dependence of the CTI-temperature relationship in the calibration. We present data that could be used to add a time-dependent component to the Chandra CALDB as it currently exists without any changes of the software. The FI CCDs present a more complicated problem where it is not obvious which calibration axis (time, position, or energy) would offer the most straightforward solution. Determining a path forward will require additional analysis and testing of potential calibration changes. With a few exceptions, however, the overall fitted line energies are well within the promised calibration envelope of $\pm 0.3\%$.

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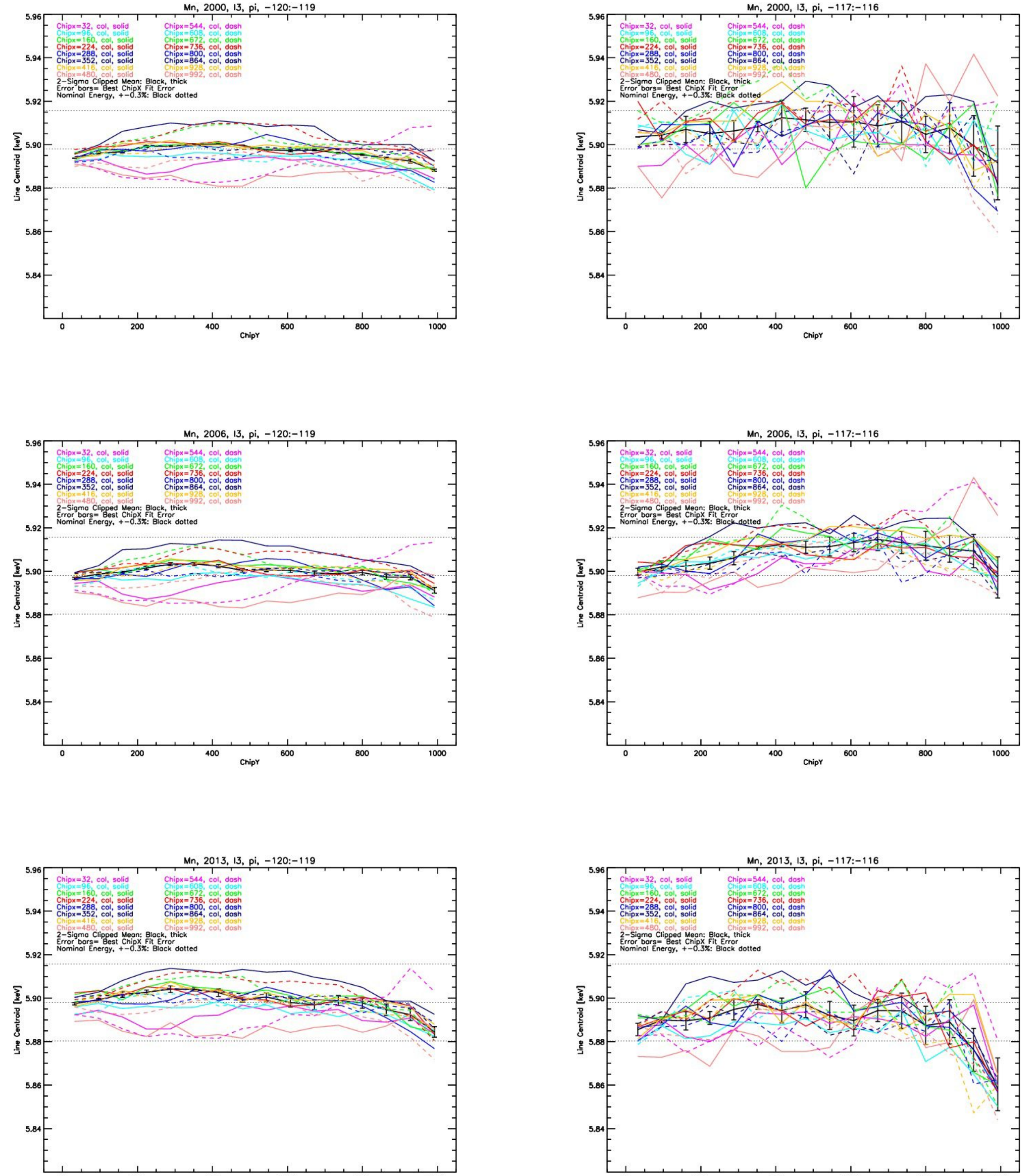
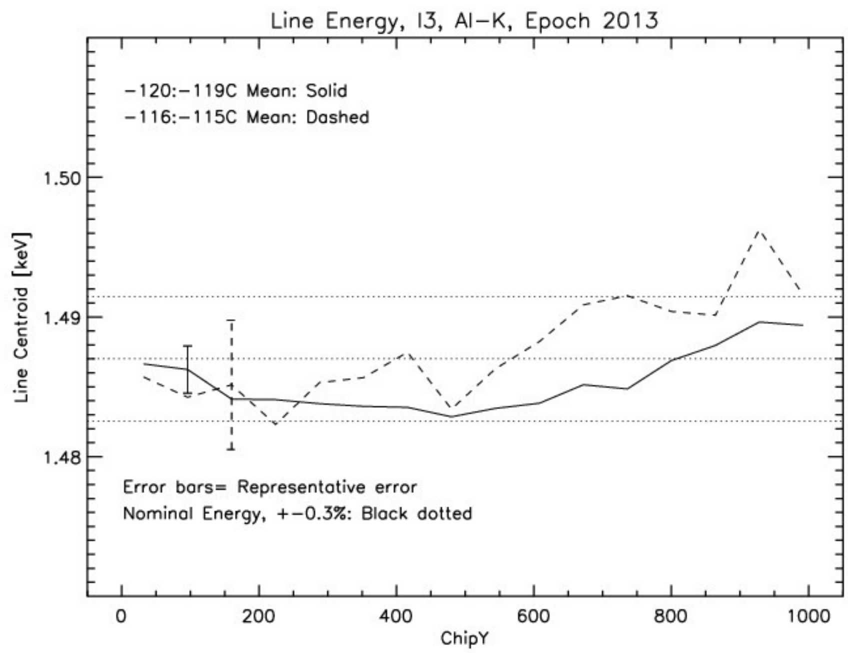


Figure 6. Fitted line centroids at 5.9 keV for the FI CCD ACIS-I3 as a function of ChipY. The different color lines represent different ChipX values. The black lines with error bars are an average over all ChipX values. The horizontal dotted lines enclose ±0.3% around the known line energy. Data from three epochs are shown: 2000 (top), 2006 (middle), and 2013 (bottom). Data on the left are at the nominal focal plane temperature, while data on the right are between –117° C and –116° C.



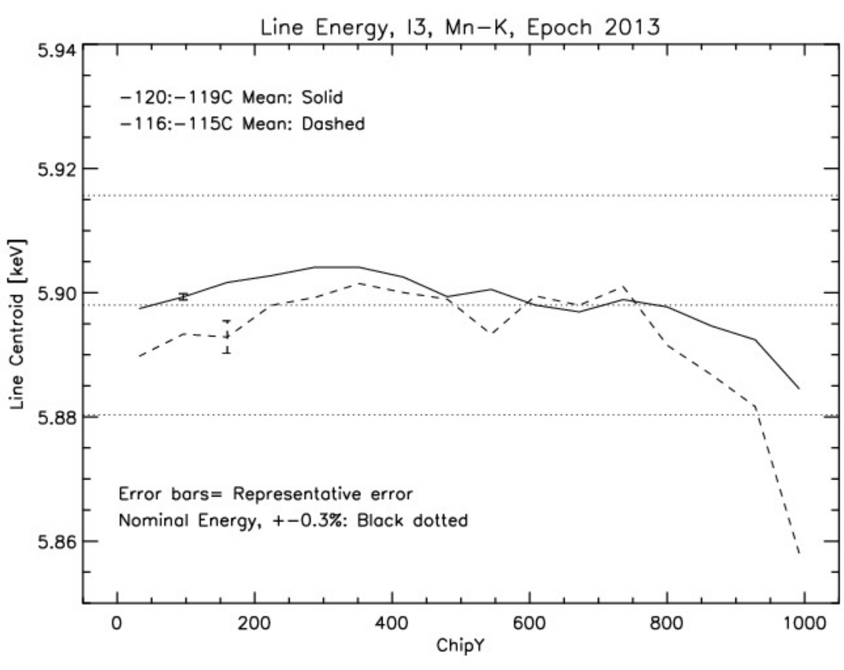


Figure 7. Fitted line centroids, averaged over ChipX for the FI CCD ACIS-I3 as a function of ChipY for the Al-K line at 1.5 keV (top) and the Mn-Kα line at 5.9 keV (bottom) in 2013. The solid line is for data at the nominal focal plane temperatures, while the dashed line is between –116 and -115° C. The horizontal dotted lines enclose ±0.3% around the known line energy.

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