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Processing X-ray data on board the SMILE SXI

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ABSTRACT

SMILE (Solar Magnetosphere Ionosphere Link Explorer) is a collaborative mission between the European Space Agency and the Chinese Academy of Sciences that is scheduled to be launched in 2024 and will be placed in a highly elliptical, inclined, orbit. The on-board instrumentation will study interactions between the solar wind and the Earth's magnetosphere-ionosphere system by imaging the soft X-ray emission that results from solar wind charge exchange whilst simultaneously collecting information about the northern aurora with a UV imager and investigating the solar wind and magnetosheath plasma and magnetospheric field conditions using a Light Ion Analyzer and a magnetometer.

The SXI (Soft X-ray Imager) is a wide field 'lobster-eye' telescope that is equipped with two 4510 x 4510 pixel CCDs with 18 μm pixel pitch. It will image X-rays (300 eV-2000 eV) through focusing optics that consist of an array of Micro Pore plates.

The predicted X-ray event rate is expected to be low and the instrument will operate in photon counting mode so the SXI is designed to maximize the useful information returned to earth by identifying and storing individual events on board the spacecraft before transmitting the relevant information back to earth. This study investigates the baseline methods that will be implemented on-board to isolate and extract these events from the images amongst a more complicated particle background. The detector response is modelled and verified with calibration data from the CCD270.

The work presented here by the Centre for Electronic Imaging at the Open University demonstrates the proposed method for isolating individual soft X-rays from images taken using the SMILE SXI and subsequently sorting these X-rays into data packets suitable for transmitting to earth. Different methods are tested with simulated and real data to optimize the proportion of useful events transmitted.

Keywords: SMILE, SXI, CCD, X-Rays, simulation, calibration

1. SOLAR WIND MAGNETOSPHERE IONOSPHERE LINK EXPLORER (SMILE)

Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a joint venture between the European Space Agency and the Chinese Academy of Sciences that is to observe interactions between the Solar wind and the Earth's magnetosphere [1]. Launch is scheduled for 2024.

1.1 The onboard instruments

The spacecraft will carry a suite of four different instruments:

- A Soft X-ray Imager (SXI) will observe the shape, location and motion of the magnetospheric boundaries using soft X-ray band emission from Solar Wind Charge Exchange (SWCX).
- An Ultra-Violet Imager (UVI) will observe the Earth's northern auroral regions
- A Magnetometer (MAG) will record the magnitude and orientation of the magnetic field local to the spacecraft. It will also detect any discontinuities or shocks in the solar wind as it passes over the spacecraft.
- A Light Ion Analyzer (LIA) will determine the properties and behavior of the solar wind and magnetosheath under various conditions by measuring the three-dimensional velocity distribution of solar wind ions.

1.2 The SMILE orbit

After launch SMILE will be raised to a highly inclined elliptical orbit where it will pass in and out of the Earth's radiation belts every 51 hours [2]. This orbit is shown in Figure 1.

Figure 1 - The SMILE operational orbit (ESA)

At apogee (~127,000 km) the spacecraft's altitude will be high enough to look back towards Earth and image X-rays emitted from the magnetopause, bow shock and magnetospheric cusps within the SXI Field of View [2]. The simultaneous imaging of the Earth's northern auroral region using the UVI will also be optimized from this viewpoint. At perigee (5000 km) SMILE will pass close enough to ground stations on Earth to allow for efficient transfer of the approximately 36 GBit of data that is expected to be generated by the four main instruments per orbit [2].

Over the 3-year mission lifetime SMILE will encounter radiation damage, primarily from trapped and solar protons. The planned orbit has the additional benefit of allowing SMILE to spend approximately 80% of its lifetime outside of the intense radiation environment trapped within the Earth's Van Allen belt that can cause damage to various parts of the spacecraft and can particularly degrade the performance of the CCDs that form the focal plane of the SXI. At the lower altitudes, required to transmit data to Earth, an aluminium Radiation Shutter Mechanism (RSM) will close across the face of the CCDs to provide additional shielding to the focal plane from the trapped radiation present in this region.

2. SOFT X-RAY IMAGER (SXI)

The Soft X-Ray Imager (SXI) is one of the primary instruments onboard SMILE and has been optimized to photon count soft X-rays over a science band of 200 eV to 2 keV. The instrument is being led by the University of Leicester (UK), with contributions from many collaborating institutions across Europe. A 3D model of the instrument is shown in Figure 2.

Figure 2 - A CAD model of the SMILE Soft X-ray Imager showing the CCDs mounted in the Detector Plane Assembly (DPA), with electrical connections to the Front End Electronics (FEE). Additional control electronics are within an EBOX (not shown here). The instrument is led by the University of Leicester.

The Detector Plane Assembly (DPA) consists of 2 large area Charge-Coupled Devices (CCDs) that cover a total sensitive area of approximately 8 x 14 cm. Micro-Pore Optics (MPOs) are used to focus the X-rays from a wide field of view towards the detector plane. A large optical baffle is included to shield the focal plane from stray light. A radiator is thermally coupled to the DPA to passively cool the CCDs to their operating temperature range of -120 to -100°C. The Front End Electronics (FEE) box is housed underneath the DPA and provide the appropriate clock and bias supplies to drive the CCDs, process the analogue output signals of the CCDs and control other aspects of the SXI.

2.1 The CCD370

The two CCDs in SMILE SXI's focal plane have a frame transfer architecture and have been developed by Teledyne e2v to optimize their soft X-ray detection efficiency over the primary science energy band of the instrument (200 eV to 2000 eV) [3]. In their standard operating mode the CCD370s onboard SMILE will be operated with 6x6 pixel binning.

The CCD370 was adapted, by Teledyne-e2v, from the CCD270 - an optical device developed for the PLATO mission [3]. The different devices use the same package design and this allows the same mechanical and electrical interfaces to be used, thus adopting qualification heritage and saving time and cost to the SMILE program. The CCD370 is optimised for soft X-ray sensitivity by not including the anti-reflective coating present on the CCD270, as well as increasing the output responsivity to improve the readout noise. These properties are shown in Table 2-1.

Table 2-1 - Detector properties for SMILE CCD370

Property	Units	Value
Sensitive silicon thickness	μm	16
Native pixel size	$\mu\text{m} \times \mu\text{m}$	18×18
Image area size	pixels	4510 columns $\times$ 3791 rows
	mm $\times$ mm	81.18×68.24
Store area size	pixels	4510 columns $\times$ 719 rows
Responsivity	$\mu\text{V electron}^{-1}$	~ 7
Output nodes	-	2
Serial registers	-	1

A further improvement made to the devices has involved improving their Charge Transfer Inefficiency (CTI), which is a key characteristic that is degraded during CCD's lifetime by radiation interacting with the silicon lattice and forming defects (traps). By narrowing the transfer channel in the serial register and introducing an additional Supplementary Buried Channel (SBC) in the parallel region of the sensor the CTI has been improved by reducing the volume of silicon in which traps can occur [3].

3. DATA PROCESSING ONBOARD THE SMILE SXI

Due to the limited data transfer available per orbit it will not be possible to transfer all of the data acquired by the SXI in full image format. Instead, an Event Detection Unit (EDU) embedded into the FEE will be used to identify events that appear to be soft X-rays within the instrument's science energy band. Each event can then be further sorted using a Data Sorting Algorithm (DSA) embedded in SXI's Data Processing Unit, before being stored in the Spacecraft Computer and ultimately transmitted to Earth as shown in Figure 3.

Figure 3 - A flowchart showing the data processing steps from the output of the CCDs, initial fast image processing in the EDU, classification and sorting of identified X-ray events by the DSA, and finally to storage on the spacecraft computer for downlink to ground.

3.1 The Event Detection Unit (EDU)

The EDU algorithm is to be built into the Front End Electronics (FEE) and is designed to identify features within each raw CCD image that are likely to be soft X-rays, or other features of interest.

The algorithm will be applied on a pixel-by-pixel basis, inspecting the pixels along a row. 5 rows must be observed at a time. Each pixel is inspected and if the following is true, the pixel is identified as an ‘event’:

1. The central pixel contains more signal than the ‘single pixel threshold’.
2. The pixel is a local maximum with more signal when compared individually to its 8 nearest neighbours.
3. The pixel contains more signal than ‘single pixel threshold’ + local signal background from any optical loading.

Figure 4 - a 5 x 5 pixel area showing pixels that are to be used to determine Local Signal Background (blue) as well as pixels that may encounter 1st (yellow) and 2nd (green) order CTI effects.

The ‘single pixel threshold’ will be uniquely tuned for each CCD output node and can be updated from the ground. Nominally, it will be set to $\sim 4.5 \sigma$ of the readout noise for each output node’s readout chain, but may be increased to account for additional noise from e.g. optical loading.

The ‘local signal background’ is calculated for each potential event by taking the median of pixels shown in blue in Figure 4. This provides a dynamic measure of the background which is expected to vary slightly throughout each orbit and Earth-year as background sources in the field of view and stray light from the sun/earth/moon vary. The pixels marked in yellow may contain signal from the X-ray event due to CTI smearing effects as the mission approaches its end of life, and the green pixels that may also contain signal due to serial CTI smearing charge deferred from parallel CTI. Therefore the pixels marked in green and yellow in Figure 4 and are ignored for the calculation of the local signal background. Each 5x5 pixel array that meets the above criteria is classed as a ‘detected event’, which is packed for data transfer to the Data Processing Unit (DPU) in the SXI EBox. Each 321 Bit detected event packet consists of the 5 x 5 pixel array, which is centered on the detected event, as well as the corresponding CCD, row and column number.

3.2 The Data Sorting Algorithm (DSA)

Once events are detected they are sent from the FEE to the Data Processing Unit (DPU). Here the event can undergo subsequent sorting so that further sorting can be undertaken if required, such as separating events that are clearly from instrument background or pixel defects in the CCDs. The events are to be sorted by the Data Sorting Algorithm (currently under development).

4. SOFT X-RAY SIMULATION

In order to assess the ability of the EDU and DSA to correctly identify soft X-rays of the appropriate energy, whilst rejecting other events such as Galactic Cosmic Rays (GCR) it will be necessary to simulate the different types of event.

4.1 X-ray interactions

X-rays are simulated interacting at a random location within the 16 μm thickness of silicon that makes the CCD. The specific depth of interaction is randomly determined for each X-ray from an energy-dependent probability distribution derived from the attenuation coefficient of silicon [4]. The number of electron-hole pairs released for each X-ray interaction is then randomly determined assuming an average energy of 3.65 eV electron-1 and a Fano factor of 0.12 [5].

4.2 Charge spreading

The appearance of each event depends upon how charge spreads between the position in which the X-ray initially interacts and the electrodes that detect this charge before it is used to produce an image. Analytical solutions to model the charge spreading have previously been developed to simulate this charge diffusion and drift process in a back-illuminated CCD [6].

To simulate the charge spreading through the silicon the depth of the detector can be considered as two separate regions: a depleted region and a field free region. The path of electrons will be dominated by either drift in the electric field or diffusion, in these regions respectively.

The depleted region describes the thickness of silicon closest to the electrodes. In this region the silicon doping and voltage applied to the surface electrodes depletes the silicon of free carriers so that electron drift to lowest potential formed by the pixel electrodes. When X-rays interact in this region very little charge spreading occurs between electrodes because the electric field is strong.

The field-free region describes the remaining thickness of silicon, from the depletion region boundary to the back surface of the device. When an X-ray interacts here, charge diffuses through this region until it crosses the depletion boundary into the depletion zone (assuming recombination is negligible). An illustration of charge spreading in both of these regions is shown in Figure 5.

Figure 5 - Charge spreading in field-free and depletion zones

The analytical charge spreading models from [6] are adopted in the simulations described here, to determine the distribution of electrons across neighboring pixels from a single X-ray photon interaction. This simulation method approximates the boundary between the depletion zone and the field-free zone as a flat plane. In reality the depth of this boundary varies across each pixel according to potentials applied to each electrode and of the channel stop. We consider this approximation to be sufficiently accurate at this stage for the SMILE SXI simulations, particularly as the instrument will be operating with 6x6 native pixel binning reducing the effects of the charge spreading process.

5. VALIDATION OF SIMULATION

Before the simulations described above can be used it is necessary to compare the simulated events to real X ray data and then tune factors such as depletion depth, read noise and the gain to ensure the simulation outputs representative data for further testing.

5.1 Collection of X-ray data

X-ray data was collected using both the CCD270 and CCD370 within the SMILE calibration camera, as shown in Figure 6. An ^{55}Fe isotope source that produces K-alpha X-rays at ~ 5.9 keV and K-beta X-rays at ~ 6.5 keV was used in this investigation to calibrate the camera and then as a direct comparison with simulated X-rays of the same energies.

Figure 6 - A CCD mounted in the UHV-compatible test camera system developed for SMILE SXI activities at the Open University laboratory. The protective cover shown here is removed before testing.

5.2 Event splitting

A method of comparing the simulated X-rays with those observed during laboratory testing involves counting the proportion of ‘event splits’ that occur with both sets of data. The ‘event split’ describes the number of pixels within a detected 5x5 event packet that is greater than a specific split threshold. Figure 7 illustrates each event likely split type with an appropriate name.

Figure 7 - Event splits

A set of X-ray events were detected from an ^{55}Fe source using a CCD270 without any on-chip binning of pixels. Events were detected using a threshold of 4 x sigma (approximately 80 eV). The same threshold was then used to determine the number of splits per event. Based on these values Mn K-alpha X-rays from the CCD270 data yielded approximately 51% ‘single’ events, 26% ‘double’ events, 10% ‘triple’ events and 13% ‘four plus’ events.

Events of the same energy were then generated using the simulation with a variety of different field free depths between 0 μm (100% depleted) and 16 μm (100% field free). These values are plotted in Figure 8. The splits for the equivalent X-ray data, detected using an un-binned CCD270 is plotted on top in red. A good correlation between the real and the simulated data can be seen at a field free depth of approximately 3.9 μm .

Figure 8 - Event splits for simulated Mn K-alpha plotted against different field free depths. Red lines show event splitting for real X-ray data from un-binned CCD270.

5.3 Charge distribution

A further validation of the simulation method involved comparing the charge spread to different pixels for each of the event split types defined in Figure 7.

Figure 9 shows, in orange, the average proportion of charge spreading to each of the pixels that make up the central 3x3 array for all detected 'single' events detected using the un-binned CCD270. The equivalent simulated data is shown in blue. The simulation includes a field-free depth of 4 μm , as defined above, and simulated detector noise of 5 e- RMS. A good correlation between the plots can be seen, with a small amount of trailing charge present in each of the corners.

Figure 10 shows an equivalent plot for all detected 'double' events detected using the un-binned CCD270. Again the equivalent simulated data is shown blue. A good correlation is seen again between the simulated events and the real X-ray data. As with the single data there is a small amount of trailing charge present in each of the corner pixels but this only represents a small proportion of the charge.

Figure 11 shows an equivalent plot for all detected 'triple' events where a reasonable correlation is again observed, though the fewer number of experimentally observed events of this type increases the statistical noise of this plot so some of the features are harder to identify. Figure 12 shows the plots for all detected 'four plus' events – events with four or more pixels above the split threshold.

Equivalent plots were also generated for binned events and corresponding simulation. Good agreement was observed in each of these plots with reduced charge splitting due to the much larger effective size of the binned pixels.

Figure 9 - Distribution of charge between inner 3x3 pixels for 'single' events from un-binned CCD270 X-ray data compared to equivalent simulation.

Figure 10 - Distribution of charge between inner 3x3 pixels for 'double' events from un-binned CCD270 X-ray data compared to equivalent simulation.

Figure 11 - Distribution of charge between inner 3x3 pixels for ‘triple’ events from un-binned CCD270 X-ray data compared to equivalent simulation.

Figure 12 - Distribution of charge between inner 3x3 pixels for ‘four plus’ events from un-binned CCD270 X-ray data compared to equivalent simulation.

6. CONCLUSIONS AND FURTHER WORK

The SMILE SXI instrument will observe X-ray photons to study the dynamic effects between the solar wind and the Earth's magnetosphere and ionosphere. X-ray photons observed with the CCDs in SXI's focal plane will be identified from the images using an algorithm described here. To verify the performance of the algorithm, named the EDU, as well as better understand the behavior of the CCDs, a simulation package is being developed and experimentally verified. It has been demonstrated here that the simulation parameters to tune the charge sharing between pixels from individual X-ray photons have been identified to produce a good correlation with experimental data in terms of event splitting and charge spreading. These simulations will be further used to investigate the detection efficiency of the EDU and help to maximize the science return of SMILE at limited data rates.

The experimental verification shown here is limited to above 5.9 keV which is higher energy than the SXI science range. A further calibration campaign is scheduled that will use monochromatic soft X-rays from the BESSY-II synchrotron in Berlin. This will provide a greater understanding of the detectors response to X-rays with the SMILE science band and allow for further tuning of the simulations, as well as quantum efficiency measurements against the facility's primary radiometric standard.

Further work is ongoing to incorporate unfocussed instrument background events into the simulation. This involves Monte-Carlo Geant4 simulations of the Galactic Cosmic Ray's (GCR) flux and their interactions with the spacecraft and instrument shielding. These simulations are used to produce a detailed understanding of how the environment and instrument design influences the background signal observed by the CCDs. Assessment of the EDU's performance with X-rays observed with radiation-damaged devices will also follow.

7. ACKNOWLEDGEMENTS

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