Citation

Crews, Chiaki; Buggey, Thomas W.; Jones, Lawrence S.; Endicott, James and Holland, Andrew D. (2024). X-ray optimised CMOS image sensors for the Auroral X-ray Imaging Spectrometer (AXIS). In: Proc. SPIE 13103, X-Ray, Optical, and Infrared Detectors for Astronomy XI, article no. 1310309.

URL

https://oro.open.ac.uk/99696/

X-ray optimised CMOS image sensors for the Auroral X-ray Imaging Spectrometer (AXIS)

Chiaki Crews*[a], Thomas W. Buggey[a], Lawrence S. Jones[a], James Endicott[b], Andrew D. Holland[a,b]
[a] Centre for Electronic Imaging, The Open University, Milton Keynes, UK;
[b] XCAM Ltd, Northampton, UK

ABSTRACT

The Auroral X-ray Imaging Spectrometer (AXIS) instrument proposed by the Indian Space Research Organisation's (ISRO) Space Astronomy Group plans to gather spectral information of the Earth's aurorae in the 0.3 – 3 keV band from a low Earth polar orbit for the first time. A trade-off study comparing possible Teledyne e2v (Te2v) detectors to meet preliminary instrument requirements previously concluded that the backside-illuminated (BI) CIS221-X, a prototype CMOS image sensor (CIS) optimised for soft X-ray detection, was a viable option. This paper introduces the current preliminary instrument requirements for AXIS and the compact Nuscis camera electronics from XCAM Ltd that will be used with the CIS221-X to produce an engineering model of the instrument. Continued studies on the CIS221-X for AXIS will include the optimisation of operating conditions in particular for the less well-studied pixel variants of the detector, and calibration with soft X-rays.

Keywords: CMOS sensors, X-ray detectors, X-ray imaging, X-ray telescopes, soft X-rays

1. INTRODUCTION

Highly energetic particles originating from solar wind precipitate along the magnetic field lines in the Earth's upper atmosphere and interact with atmospheric constituents, causing effects such as auroral emissions in polar regions. Such interactions vary as a function of local time, latitude, season, and solar cycle, and extend from optical wavelengths to hundreds of keV under high geomagnetic activity. Although certain missions have studied some of these dynamics in the UV and X-ray bands (e.g. IMAGE[1] and Polar[2]), auroral soft X-rays of <2 keV have yet to be studied in detail. Previously, only one set of observations of the Earth's northern aurorae has been conducted in the soft X-ray range by Bhardwaj *et al.* using the Chandra X-ray Observatory's HRC-I (High Resolution Camera) instrument; however, these did not have the energy resolution required for detailed scientific conclusions to be drawn[3]. Branduardi-Raymont *et al.* therefore previously proposed an instrument to perform observations of the soft X-ray aurorae from a low-Earth polar orbit[4]; this instrument concept has since been adopted by the Space Astronomy Group at the Indian Space Research Organisation (ISRO), and named the Auroral X-ray Imaging Spectrometer (AXIS).

AXIS is proposed to be launched into a low Earth polar orbit to study X-rays in the energy range of 0.3 keV to 3 keV, with a spatial resolution of a few tens of km (utilising a pinhole optic). The broad scientific objective of AXIS is the spectroscopic observation of soft X-ray emission from Earth's upper atmosphere. These emissions may occur due to the following phenomena, all of which have temporal and spatial variability:

- Electron bremsstrahlung causing aurorae in polar regions
- X-ray fluorescence emission triggered by solar X-rays
- X-ray scattering by atmospheric atoms
- Solar wind charge exchange (SWCX) emission

The final point is a secondary objective of AXIS due to the different orientation and longer exposure times required to detect such emissions compared to the requirements for auroral observations. SWCX is an interesting but poorly studied process where solar wind interacts with the Earth's atmosphere leading to loss of neutral species, and X-ray spectroscopy in the proposed energy range has the potential to map the extent and variability of this phenomenon.

X-Ray, Optical, and Infrared Detectors for Astronomy XI, edited by Andrew D. Holland,
Kyriaki Minoglou, Proc. of SPIE Vol. 13103, 1310309 · © 2024 SPIE
0277-786X · doi: 10.1117/12.3017845

Such observations would have strong synergies with the European Space Agencies (ESA) and the Chinese Academy of Science's (CAS) upcoming SMILE mission, which will explore the processes occurring between the solar wind and Earth's magnetosphere in polar regions from a higher-altitude, highly elliptical orbit (varying between 5,000 km and 120,000 km in altitude). The SMILE payload includes a soft X-ray imager to study X-rays in the 0.2 keV to 2.5 keV band. The combined information from the two soft X-ray payloads thus has the potential to build a detailed picture of the processes occurring throughout the Sun-Earth connection.

2. PRELIMINARY INSTRUMENT REQUIREMENTS

A previously reported trade-off study by Jones *et al.*[5] found that Te2v's backside-illuminated (BI) CIS221-X X-ray detector was a suitable candidate to meet AXIS detector requirements, compared to the baselined CCD201-10 (an electron multiplying CCD). This detector is a result of optimisation of CMOS image sensor (CIS) technology for soft X-ray detection for the ESA THESEUS mission's Soft X-ray Imager (SXI) instrument. Three-quarters of this prototype detector's sensitive area is made up of three variants of 40 µm-pitch pixels of 35 µm-thick high-resistivity silicon, covering an area of 15.4 mm × 20.5 mm. The best-performing pixel variant (#3) has previously been extensively characterised[6], but it is feasible to use all three CIS221-X 40 µm pixels for soft X-ray detection, albeit with further work on the optimisation of operational voltages required to achieve the best performance of the remaining two of three pixel variants (for image lag in particular). Certain requirements such as operating temperature and frame rate will also require further tests to determine the best parameters to utilise to meet requirements.

A full preliminary list of AXIS instrument requirements is provided in Table 1. Since the detector trade-off study[5], the energy range of interest has been extended from an upper limit of 2 keV to 3 keV to capture more of the bremsstrahlung spectrum, and the energy resolution requirement has been relaxed from 100 eV to <150 eV FWHM at 500 eV. For reference, the latest results from the CIS221-X pixel variant #3, using single-pixel events and per-pixel gain calibration, have resulted in a measured energy resolution of 130 keV at 5.9 keV (Mn fluorescence) and under 80 keV at 1.5 keV (Al fluorescence)[6].

End-of-life (EOL) total ionising dose (TID) and total non-ionising dose (TNID) levels will be calculated based on further information as the instrument design and spacecraft orbit parameters are determined. It is important that the X-ray detector has a tolerance to these EOL dose levels such that it can collect the scientific data of interest throughout its operational lifetime. Prior tests have shown that, similar to other CIS, the CIS221-X is tolerant to a TID of ~60 krad(Si) with no concerning degradation observed in characterisations performed for the THESEUS SXI (N.B. the expected TID for AXIS is currently much lower than this).

In addition, a large field of view (FOV) is needed to meet science requirements of the instrument, due to the auroral ovals typically being between 60° to 80° latitudes, expanding to lower latitudes during solar storms or sub-storms. Observing large areas of these aurorae is desirable as the satellite moves across the poles, noting that they are also dynamic (with variability in the timescale of tens of minutes, sometimes less) and occur in unpredictable locations. This drove the decision to use a pinhole optic; the size of this will need to be balanced between expected X-ray count levels – which need to be sufficient to understand temporal changes in the aurorae as well as collecting spectral data – and spatial resolution that can be achieved. It is likely that two pinhole cameras positioned side-by-side such that there is a small overlap in their FOVs will be implemented to cover the total FOV required.

Table 1: Preliminary requirements for AXIS. Further details including more specific calibration, temperature control, and data handling requirements are to be added in future as the instrument design progresses.

Requirement	**Value/range**	**Comments**
General		
Power AXIS Nuscis+CIS	<20 W <8 W	TBC
Mass AXIS Nuscis+CIS	<10 kg <400 g	TBC
Operational lifetime	~2 years	
X-ray detector		
Dimensions	Active area: 13 mm × 13 mm	Based on baselined detector; CIS221-X will have 15.4 mm × 20.5 mm
Pixels	< 50 µm pitch	To be specified based on over-sampling PSF produced by pinhole
Energy range	0.3–3 keV	
Energy resolution	<150 eV FWHM (total incl. noise, DC) at 500 eV	At end-of-life (EOL) for nominal LEO mission. TBD by selection of operating temperature, frame rate, dark background subtraction, etc
Quantum efficiency	>60% at 500 eV – 3 keV	Requirement for FMs; EM performance will be determined by available devices
Visible light-blocking capability	1×10^{-7}	TBC – based on CLASS & C1XS, but not calculated specifically for AXIS. Existing OBF on CIS may not meet this specification and may need to be augmented by separate filter
Imaging mode	Photon counting for spectral information	Performed on-board
Radiation hardness to EOL TID and TNID levels	5 krad(Si) and 3×10^{9} cm^{-2} 10 MeVp	TBD; dependent on operational lifetime, orbit parameters incl. altitude, shielding design, instrument and spacecraft design
Optics		
Pinhole diameter	<300 µm	TBC
Focal length	1 cm	TBC
Orbital altitude	400-500 km	TBC
Field of view (FOV)	>140° target	TBC – may require two-camera solution; dependent on altitude (of S/C and aurorae), pinhole diameter, focal length, detector dimensions
Spatial resolution	<50 km target <10 km desirable	TBC; dependent on altitude of aurorae, instrument FOV and detector pixel size

3. NUSCIS

The baseline camera electronics for the AXIS detectors is XCAM's next generation CubeSat and small satellite imaging system, NuSCIS. At the core of NuSCIS is an Imager Controller Board (ICB) which is designed to command a wide range of CCD and CMOS devices. The CIS221-X can be driven directly from the ICB where there are options for temporary storage of science data or direct transfer to the satellite onboard computer. The ICB has both an FPGA and micro-processor providing options for data processing at the level of the camera (where additional camera level memory can be provided via an expansion port), or through direct connection to a more powerful processor. A temperature controller board can also be included with the system; however, in this instance, the detector will be cooled by a separate system provided by ISRO.

When in orbit, NuSCIS camera electronics would be powered on for operation prior to passing over each polar region, and powered off for SAA passes. As a baseline the following operating modes are assumed:

- Mode 1: Science mode, running continuously with background subtraction per frame and X-ray event detection. Possibly saving 1 whole image every N for download to capture any effects like anomalously high straylight or dark current;
- Mode 2: Background image generation mode, where a number of frames are averaged and saved to give a reference background image which is subtracted from all the raw Mode 1 images. Mode 2 might be initiated at the start of an observation, once the detector temperature has stabilised;
- Mode 3: Capture of a small number of whole frames to be downloaded either for health monitoring or diagnosis of issues during the mission.

In "Mode 1" the system requires the capability of performing on-board event detection – either within NuSCIS' ICB, or the onboard computer. Background images generated from operating "Mode 2" would be used to subtract from the live data, requiring further on-board processing prior to event detection (to account for inter-pixel non uniformity and the fact that the CIS221-X has anomalously high dark current). 10-100 X-rays (or clusters of interest) per second might be expected across 384 × 512 = 196608 pixels per frame, which need to be identified by the event detection algorithm and extracted as events. In a 10-minute time period where there might be ~10,000 events (which should largely be from X-ray photons, but might include signals from penetrating charged particles, and possibly an on-board X-ray calibration source), if for each "event" a 25-byte word is attached to describe the event location and timing, this would create 0.25 Mbytes of data. It is currently envisaged that NuSCIS will operate the CIS221-X at 20 fps minimum in the engineering model (EM).

4. FUTURE WORK

Next steps will include the optimisation of detector operating parameters when using frame rates expected for reading out all 40 µm pixels in the CIS221-X with NuSCIS. The THESEUS SXI detector operating temperature was set to -40°C, but some previous tests and models have suggested that operating at a temperature of approx. -20°C for 20 fps would have an acceptable dark current level to enable the AXIS energy resolution requirement to be met. Further increases in frame rate should further increase this temperature, as well as the development and implementation of an event detection algorithm that balances a trade-off between resolution and event count rate. Additionally, optimisation of operating voltages for the less well-studied 40 µm pixel variants #1 and #2 is needed to reduce the impact of image lag.

Calibration of the detector, plus event detection algorithm and energy resolution tests using all the above operating parameters, will be conducted at the BESSY II soft X-ray beamline with monochromatic peaks of energies between 300 eV and 1900 eV (the upper limit being determined by the beamline).

ACKNOWLEDGEMENTS

This work is funded by the UK Space Agency (UKSA) International Bilateral Fund. The authors would like to thank Dr Shyama Narendranath and her colleagues of the Space Astronomy Group at ISRO's U R Rao Satellite Centre for their contributions.

REFERENCES

[1] Burch, J. L., “The first two years of IMAGE,” Space Sci. Rev. **109**(1–4), 1–24 (2003); https://doi.org/10.1023/B:SPAC.0000007510.32068.68

[2] Østgaard, N., Stadsnes, J., Bjordal, J., Germany, G. A., Vondrak, R. R., Parks, G. K., Cummer, S. A., Chenette, D. L. and Pronko, J. G., “Auroral electron distributions derived from combined UV and X-ray emissions,” J. Geophys. Res. Sp. Phys. **106**(A11), 26081–26089 (2001); https://doi.org/10.1029/2001JA000031

[3] Bhardwaj, A., Randall Gladstone, G., Elsner, R. F., Østgaard, N., Hunter Waite, J., Cravens, T. E., Chang, S. W., Majeed, T. and Metzger, A. E., “First terrestrial soft X-ray auroral observation by the Chandra X-ray Observatory,” J. Atmos. Solar-Terrestrial Phys. **69**(1–2), 179–187 (2007); https://doi.org/10.1016/j.jastp.2006.07.011

[4] Branduardi-Raymont, G., Kataria, D., Walton, D. M., Fazakerley, A. N. and Coates, A. J., “EXACT : A study of the Earth’s aurora using a Cubesat,” Eur. Planet. Sci. Congr. 2010, 579 (2010).

[5] Jones, L. S., Crews, C., Soman, M., Ivory, J. and Holland, A. D., “Evaluation of sensors for the detection of energy resolved very soft x-ray fluorescence,” 43 (2022); https://doi.org/10.1117/12.2629344

[6] Townsend-Rose, C., Buggey, T., Ivory, J., Stefanov, K. D., Jones, L., Hetherington, O., Holland, A. D. and Prod’homme, T., “Electro-optical characterization of a CMOS image sensor optimized for soft x-ray astronomy,” J. Astron. Telesc. Instruments, Syst. **9**(04), 1–10 (2023); https://doi.org/10.1117/1.JATIS.9.4.046001