Institution: The Open University		
Unit of Assessment: B9 Physics		
Title of case study: Innovative image sensors for space, industry and science		
Period when the underpinning research was undertaken: 2008-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Andrew Holland	Professor of Electro-optics	2008 - present
Dr David Hall	Senior Lecturer	2009 - present
Dr Konstantin Stefanov	Senior Research Fellow	2012 - present
Dr Matthew Soman	Senior Research Fellow	2013 - present
Dr Neil Murray	Research Fellow	2008 - 2016
Period when the claimed impact occurred: 1 Aug 2013 - 31 Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Image sensor research conducted at the Centre for Electronic Imaging at The Open University has been crucial to the design of novel space-based imaging instruments. Our work on radiation damage effects in image sensors has resulted in impacts on **commerce and the economy** including:

- Contracts [text removed for publication] to Teledyne e2v for Charge Coupled Devices and CMOS image sensors;
- Novel image sensors with enhanced specification have enabled the selection of 4 missions by the European Space Agency (ESA) and NASA, and opened commercial opportunities in Medical and Scientific imaging;
- Development of a world-leading camera by an SME with sales accounting for 20% of turnover;
- Support for 250 UK jobs in the Teledyne e2v group.

2. Underpinning research

The Centre for Electronic Imaging (CEI), a collaboration between The Open University and Teledyne e2v (Te2v), is dedicated to the research and development of advanced image sensor technologies. Led by Professor Andrew **Holland**, the CEI has over 30 academics, researchers and PhD students. Since its formation in 2004, CEI members have contributed to over 14 international space missions led by European, US and Indian agencies.

Our fundamental semiconductor research has led to improvements in device design and the development of new analysis methods for in-flight and laboratory use. In 2014, a **new technique called 'trap pumping'** was developed **[O1]** for characterisation of defects in silicon caused by spaceborne radiation. Trap pumping has orders of magnitude greater sensitivity in defect identification than previous methods and provides a **step change in the understanding of radiation damage effects**. This knowledge was used to optimise the operation and the working temperature of the imagers and has led to key developments in the applications of Charged Coupled Devices (CCDs) for space-based imaging **[O2]**, including the development of radiation hard p-channel CCDs **[O3]**.

Since 2013, we have been developing soft-X ray imaging systems and analysis software that improve the energy and the spatial resolution of Electron Multiplying CCDs (EMCCDs), opening up new applications in synchrotron imaging **[O4]**. Following this research, we demonstrated excellent **single-photon-counting performance in electron multiplying CCDs** (EMCCD) after irradiation equivalent to that experienced in-flight. Subsequently, through further device design and simulation, we showed for the first time that CEI-modified Te2v **EMCCDs are suitable for space-based astronomy**.

The CEI demonstrated a new charge transport channel and output in CCDs with a factor of 4 improvement in radiation hardness and much reduced readout noise. Coupled with optimisation of the operating conditions, we showed that the **X-ray detection threshold can be improved** from 2,000 eV to below 300 eV in a large area CCD, even at the expected end-of-life irradiation dose in a space environment.

Further expanding our sensor and radiation damage expertise, we formed a new research team on complementary metal-oxide-semiconductor (CMOS) image sensor development. With UKSA funding, the CMOS research team was able to **qualify the Te2v CIS115 sensor** for the harsh radiation environment that will be experienced by ESA's JUICE spacecraft around Jupiter and its moons. Furthermore, the team has optimised the linearity and image lag behaviour of CIS115 **[O5]**, leading to better performance of the flight camera.

Working under a grant jointly awarded to the CEI and Te2v during 2012-2015, the CMOS research team was tasked with addressing several challenges in image sensor technology. The most pressing of these was increasing the sensitivity to near-infrared (NIR) light of silicon devices based on the ubiquitous pinned photodiode photosensitive element. Simulation work yielded a novel pixel design, subsequently called 'HiRho CMOS', for which a **patent application was granted [O6]**. The new pixel delivers **an order of magnitude higher NIR quantum efficiency** than CMOS image sensors available in 2020 and was experimentally proven in 2016 in a project funded by the UK Space Agency **[O7]**. This invention also allows CMOS image sensors to be adopted as soft X-ray detectors due to the much thicker sensitive detector volume, marking another milestone in the adoption of CMOS technology over the previously preferred CCD. Presently, a sensor based on this patent is being developed by us for the forthcoming THESEUS X-ray space telescope led by ESA.

3. References to the research

O1. **Hall, D.J.**, **Murray, N.J.**, **Holland**, **A.D.**, Gow, J., Clarke, A., Burt, D. (2014) "Determination of in situ trap properties in CCDs using a "single-trap pumping" technique", IEEE Transactions on Nuclear Science, 61(4), 1826-1833. https://doi.org/10.1109/TNS.2013.2295941

O2. **Hall, D.**, Gow, J., **Murray, N.**, **Holland, A**. (2012) Optimization of device clocking schemes to minimise the effects of radiation damage in charge-coupled devices, IEEE Transactions on Electron Devices, 59(4), 1099-1106. https://doi.org/10.1109/TED.2012.2185240

O3. **Murray, N.J.**, **Holland, A.D.**, Gow, J.P.D., **Hall, D.J.**, **Stefanov, K.D.**, Dryer, B.J., Barber, S., Burt, D.J. "Assessment of the performance and radiation damage effects under cryogenic temperatures of a P-channel CCD204s", Proc. SPIE 9154, High Energy, Optical, and Infrared Detectors for Astronomy VI, 91540) (2014). https://doi.org/10.1117/12.2069289

O4. **Soman, M.R.**, **Hall, D.J.**, Tutt, J.H., **Murray, N.J.**, **Holland, A.D.**, Schmitt, T., Raabe, J., Schmitt, B. (2013) "Developing a CCD camera with high spatial resolution for RIXS in the soft X-ray range", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 731, 47-52. https://doi.org/10.1016/j.nima.2013.04.076

O5. **Soman, M.R.**, Allanwood, E.A.H., **Holland, A.D.**, **Stefanov, K.**, Pratlong, J., Leese, M., Gow, J.P.D., Smith, D.R. "Electro-optic and radiation damage performance of the CIS115, an imaging sensor for the JANUS optical camera onboard JUICE", Proc. SPIE 9915, High Energy, Optical, and Infrared Detectors for Astronomy VII, 991515 (2016). https://doi.org/10.1117/12.2234290

O6. **Stefanov, K.D**. "CMOS image sensor with backside biased substrate", UK Patent GB2524044 (2019), US Patent no. 10,325,955, filed on 12 March 2014.

O7. **Stefanov, K.D.**, Clarke, A.S., **Holland, A.D**. "Fully Depleted Pinned Photodiode CMOS Image Sensor With Reverse Substrate Bias", IEEE Electron Device Letters, Vol. 38, No. 1, pp. 64-66 (2017). https://doi.org/10.1109/LED.2016.2625745

4. Details of the impact

Our ground-breaking research in CCDs and CMOS image sensors has led to benefits for industry and space agencies. Impacts in the area of **commerce and the economy** include increased sales, new and improved products, and protected jobs for a range of beneficiaries, including a large UK-based multinational (Teledyne e2v), its subsidiary (Teledyne AnaFocus), ESA and a SME (XCAM Ltd.). The improved performance of our novel, patented technology has also created opportunities beyond space, in Medical and Scientific imaging.

Impact on Teledyne e2v

Our strategic collaboration with Te2v over the last 16 years (12 years at the OU), as well as our close working relationships with the Space Agencies, who are a core market for Te2v products, have been our primary **pathways to impact.** This is confirmed by the comments of the Te2v President (Space & Quantum) and Site Director at Chelmsford, who says:

"*The [CEI-Te2v] collaboration brings both parties increased academic and commercial success, with the CEI producing key IP for future projects and being involved with over GBP4M of Teledyne e2v customer contracts in the past 12 months alone*" **[C1]**.

The Chief Engineer of Te2v explains:

"Teledyne e2v is a world-leading manufacturer of CCD and CMOS image sensors for science and space applications. Our high-performance devices have been deployed in a large number of ground and space-based telescopes such as Hubble, VLT and Gaia, and also in numerous space probes by ESA and NASA, such as New Horizons. Our image sensor sales are almost exclusively for export and [text removed for publication] we employ around 250 staff in the UK. Understanding radiation damage effects in CCDs and CMOS image sensors is very important to our business. The research conducted by the CEI has been crucial in mitigating the radiation damage effects in CCDs for many space-based imaging instruments" **[C2]**.

CEI's research **[O1]** has greatly improved the radiation resistance of CCDs used in major ESA and NASA space missions such as Euclid, SMILE and the Nancy Grace Roman Space Telescope (formerly WFIRST). Our research has improved the performance of CCD technology through design and optimisation **[O2]**, so that the science requirements of the missions can be met. By demonstrating this, the sensors were adopted for the missions, resulting in major contracts for CCD manufacture to Te2v. The Chief Engineer continues:

"*The CEI-Te2v collaboration has been crucial to demonstrate that CCDs are suitable for the Euclid, SMILE, and WFIRST space missions. This has helped us secure contracts for CCD manufacture [text removed for publication] [during the period 2013-2020] supporting a significant fraction of the jobs at our plant in Chelmsford*" **[C2]**.

Our work on CMOS imaging technology started much later than that on CCDs, but the impact is increasing rapidly and is on track to prove equally significant. Following the radiation characterisation and optimisation conducted at the CEI, the Te2v-made CIS115 has been adopted into ESA's billion-euro JUICE mission to Jupiter [text removed for publication]**[C3**, p.1**]**. JUICE makes full use of the excellent radiation performance of CIS115 **[O4]** and its higher operating temperature. This allows the spacecraft to be lighter and survive longer in the harsh radiation environment in orbit around Jupiter for greater scientific return. Our research has been crucial for the selection of CIS115 and for the achievement of the mission's planned objectives.

CIS115 has now been adopted by several future space missions, such as ALTIUS (funded by the Belgian Institute for Space Aeronomy [text removed for publication]), and for an instrument on the future Comet Interceptor spacecraft. Due to extensive characterisation and optimisation conducted at the CEI, the CIS115 sensor is now being offered by Te2v as a fully space-qualified product **[C4]**.

Using a patent **[O6]** generated by the CEI, Te2v has developed a new product line of CMOS image sensors with ten-fold increase in their near-infrared quantum efficiency, aimed at the scientific and space markets. The Chief Engineer at Te2v testifies:

"*The IP in CMOS image sensors generated by the CEI is now being used to develop two new image sensor families at Te2v. The first one to be launched is the HiRho fully depleted sensor with enhanced near-infrared sensitivity, based on a patented invention at the CEI. We have already received [text removed for publication] contracts from ESA with a follow-on contract expected soon for the development of these sensors for space-based imaging. Over the last few years we have been observing an increased demand for CMOS imagers with high quantum efficiency at visible and near-infrared wavelengths for various applications, including astronomy and adaptive optics, but also for hyperspectral imaging from space, microscopy, spectroscopy and surveillance. The development of such high QE devices will help strengthen our market position*" **[C2]**.

Teledyne AnaFocus has also developed a new product based on the same patent **[O6]**, aimed at industrial time-of-flight and machine vision applications. The VP and General Manager of Teledyne e2v and Teledyne AnaFocus comments:

"*By using the HiRho patented technology invented at Open University **[O6]**, we have developed a new Time-of-Flight CMOS image sensor with much increased near-infrared sensitivity […][text removed for publication]we have also established a dedicated team […] and created 15 new jobs. Furthermore, Teledyne e2v has started two new projects in Medical and Scientific imaging with HiRho technology, which will allow both new products to benefit from this invention and achieve outstanding performance*" **[C5]**.

Impact on XCAM

XCAM is an SME based in Northampton that specialises in providing innovative CCD and CMOS-based solutions for challenging imaging applications **[C6]**. Long-term collaboration between the CEI and XCAM has helped develop expertise in complete camera systems, with demonstrated history in vacuum-compatible applications and large-area, multi detector solutions. XCAM's CEO states:

"*Through collaboration agreements with the Centre for Electronic Imaging (CEI), we have worked together to apply their research outputs (e.g. Soman et al. (2013) NIM-A, vol. 731 pp 47-52) **[O4]** into next-generation X-ray cameras designed for the Resonant Inelastic X-ray Scattering technique at synchrotron facilities*" **[C6]**.

[Text removed for publication.]

Impact on ESA and the UK Space Agency

The European Space Agency (ESA) is tasked with delivering space capability to its 22 member states, with much of the UK's role directed by the UK Space Agency (UKSA). ESA and the UKSA conduct space exploration, earth observation and technology development for the benefit of the citizens of Europe and the world.

Cryogenic irradiation and trap pumping, two of the new research methods developed and championed by the CEI **[O1]**, have helped reduce the radiation damage effects in CCDs and have increased the performance of the Euclid VIS instrument. This is equivalent to increasing the lifetime of this EUR600,000,000 space telescope by 20% (an additional year) **[O2]**, with the corresponding greater scientific return. Without our radiation damage research Euclid would not have been selected by ESA, and no contracts for CCD manufacture would have been placed. UKSA's Director of Programmes states:

"*New techniques developed and demonstrated by the CEI […] have had a dramatic improvement on the understanding of radiation damage in silicon with subsequent impact to many space missions using CCDs*" **[C7]**.

UKSA's Director of Programmes continues:

"*Furthermore, CEI research on Teledyne e2v's p-channel CCDs has firmly established that p-channel CCD technology can offer better radiation hardness than the usual n-channel CCDs. The results of their initial study **[O3]** generated great interest in the technology and led to the production of a new device based on the results of the initial research by the CEI*" **[C7]**.

Our research into p-channel CCDs resulted in two follow-on contracts between ESA and the Open University [text removed for publication] **[C1]**. Our research into soft X-ray detection by CCDs **[O4]** enabled the required science performance for the SMILE mission to be met and this joint European-Chinese satellite to go ahead. Modified Te2v EMCCDs are now (2020) in production for NASA's Roman Space Telescope, the first use of this technology in space-based astronomy. The new devices are being tested in the CEI laboratories in collaboration with NASA's Jet Propulsion Laboratory.

5. Sources to corroborate the impact

C1. President Space & Quantum, Site Director Chelmsford, Teledyne e2v.
C2. Chief Engineer, Space Imaging, Teledyne e2v.
C3. Purchase order for CIS115 under a grant funded by UKSA.
C4. CIS115/SIRIUS™ datasheet - (DOA 26 October 2020).
C5. Vice President & General Manager, Teledyne e2v and Teledyne AnaFocus.
C6. CEO of XCAM Ltd.
C7. Director of Programmes, UK Space Agency.