Institution: The Open University

Unit of Assessment: B7 Earth Systems and Environment Sciences

Title of case study: The Centre for Electronic Imaging, industrially sponsored research benefiting the UK economy

1. Summary of the impact

Professor Holland's group, the Centre for Electronic Imaging (CEI), has a long-established collaboration with UK-based imaging specialist e2v that has enabled the company to grow its business in international space missions and increase competitiveness. The CEI has helped develop e2v's understanding of the processes at work in imaging sensors, and improved image sensor designs and test methodologies. CEI has also studied space radiation damage on the sensors, trained more than 30 engineers in testing of e2v products, and was instrumental in the company's successful £3.8m Regional Growth Fund award in 2012 – funding that will create around 100 jobs by 2016.

2. Underpinning research

The Centre for Electronic Imaging (CEI) is a research group led by Professor Andrew Holland. Its members have been, and are, involved in several international space missions including XMM-Newton, Chandra, Swift, GAIA, Chandrayaan-1 and 2, UKube-1 and Euclid. The CEI is dedicated to the research and development of advanced technologies for electronic image sensing and provides knowledge exchange and training between the UK technology industry and academia. The CEI is a collaboration between The Open University and e2v Technologies plc, which provides sponsorship contributing towards the support of PhD studentships and some of the research positions. Being a research group within a university, the CEI maintains academic independence, while the sponsorship and close collaboration with e2v maintains industrial relevance and focus to the research.

The work of the CEI is to perform basic and applied research into silicon imaging sensors. This research follows several key themes:

- Modelling, including 3D device simulation, of new structures within imaging sensor technology. Key outputs were the understanding of how the narrow channel effect can impact charge transfer, particularly in Gaia and Euclid (Seabroke, Murray, Holland, Clarke, Stefanov; 2008–present).

- Design of new imaging sensors, and contributions to the design work at e2v, for example contributing to the design of the CCD273 detector at e2v for the Euclid mission where we recommended changes to the width of the buried channel implant for improved space radiation hardness, and have made inputs into modifications of the semiconductor processing of polysilicon electrodes to provide greater control of clock phase overlaps, leading to increased yield and manufacturability (Holland, Murray; 2004–present).

- Development of new test methodologies and new fundamental understanding of the physical processes at work, for example providing refinements to the mean variance, or photon transfer curve, test technique (Murray) and the subsequent deviation from Poisson statistics (Stefanov), and refining the knowledge of charge traps, and their capture/release time constants on device operation through measurement and modelling (Hall; 2008–present).

- The study of space radiation damage on the sensors, and its impact on the scientific performance of instruments using the technology, with many examples in publication (Gow, Holland, Hall, Murray), and an exploration of the use of p-type silicon for improved radiation hardness over n-type silicon (Gow, Murray; 2005–present).

3. References to the research (indicative maximum of six references)

Holland, A.D. (1993) 'The effect of bulk traps in proton irradiated EEV CCDs', *Nuclear Instruments and Methods in Physics Research*, A, vol. 326, pp. 335–43.

Katz, D., Munari, U., Cropper, M., Zwitter, T., Thévenin, F., David, M., Viala, Y., Crifo, F., Gomboc, A., Royer, F., Arenou, F., Marrese, P., Sordo, R., Wilkinson, M., Vallenari, A., Turon, C., Helmi, A., Bono, G., Perryman, M., Gómez, A., Tomasella, L., Boschi, F., Morin, D., Haywood, M., Soubiran, C., Castelli, F., Bijaoui, A., Bertelli, G., Prsa, A., Mignot, S., Sellier, A., Baylac, M.-O., Lebreton, Y., Jauregi, U., Siviero, A., Bingham, R., Chemla, F., Coker, J., Dibbens, T., Hancock, B., **Holland, A.,** Horville, D., Huet, J.-M., Laporte, P., Melse, T., Sayède, F., Stevenson, T.-J., Vola, P., Walton, D., Winter, B. (2004) 'Spectroscopic survey of the galaxy with Gaia - I. Design and performance of the radial velocity spectrometer', *Monthly Notices of the Royal Astronomical Society*, vol. 354, pp. 1223–38.

Lowe, B.G., **Holland, A.D**., Hutchinson, I.B., Burt, D.J. and Pool, P.J. (2001) 'Swept charge device, a novel CCD-based EDX detector: First results', *Nuclear Instruments and Methods in Physics Research*, *Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 458, pp. 568–79. DOI: 10.1016/S0168-9002(00)00918-9.

McEntaffer, R.L., Murray, N.J., **Holland, A**., Lillie, C., Casement, S., Dailey, D., Johnson, T., Cash, W. and Oakley, P. (2009) 'Off-plane x-ray grating spectrometer for the international x-ray observatory', *Proceedings of SPIE – The International Society for Optical Engineering*, 7360.

Smith, D.R., Gow, J. and **Holland, A.D**. (2007) 'Proton irradiation of swept-charge devices for the Chandrayaan-1 X-ray Spectrometer (C1XS)', *Nuclear Instruments and Methods in Physics Research*, *Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 583, pp. 270–7.

Turner, M.J.L., Abbey, A., Arnaud, M., Balasini, M., Barbera, M., Belsole, E., Bennie, P.J., Bernard, J.P., Bignami, G.F., Boer, M., Briel, U., Butler, I., Cara, C., Chabaud, C., Cole, R., Collura, A., Conte, M., Cros, A., Denby, M., Dhez, P., Di Coco, G., Dowson, J., Ferrando, P., Ghizzardi, S., Gianotti, F., Goodall, C.V., Gretton, L., Griffiths, R.G., Hainaut, O., Hochedez, J.F., **Holland, A.D**., Jourdain, E., Kendziorra, E., Lagostina, A., Laine, R., La Palombara, N., Lortholary, M., Lumb, D., Marty, P., Molendi, S., Pigot, C., Poindron, E., Pounds, K.A., Reeves, J.N., Reppin, C., Rothenflug, R., Salvetat, P., Sauvageot, J.L., Schmitt, D., Sembay, S., Short, A.D.T., Spragg, J., Stephen, J., Strüder, L., Tiengo, A., Trifoglio, M., Trümper, J., Vercellone, S., Vigroux, L., Villa, G., Ward, M.J., Whitehead, S., Zonca, E. (2001) 'The European Photon Imaging Camera on XMM-Newton: The MOS cameras', *Astronomy and Astrophysics*, vol. 365, pp. L27–L35.

Key grants supporting the work of the CEI:

2010-11: £45k for International X-ray Observatory (IXO) study and £75k for a CASE studentship awarded by UKSO to Professor A. Holland for a project entitled 'Development of the Reflection Grating Spectrometer concept for IXO'.

2012-16: £574,263 awarded by UKSA (via STFC) to Professor A. Holland for project entitled 'the Euclid mission implementation phase'.

2008-12: £760k awarded by STFC and later UKSA to Professor A. Holland for a project entitled 'Gaia Data Flow System'.

2013-18: £1.5m awarded by UKSA to Professor A. Holland for a project entitled 'The CMOS Image Sensors for the JANUS camera on JUICE'.

2012-15: £335k from e2v/BIS awarded to Professor A. Holland for project entitled 'research and development of CCD and CMOS Imaging Technology' as part of a £3.8m Regional Growth Fund award to e2v for research, development and expanded production at its Chelmsford headquarters.

Ongoing e2v sponsorship for the group:
2008-2013 Phase 1 £700k
2013-2018 Phase 2 £1m awarded by E2v to Professor A. Holland for sponsorship of the CEI.

4. Details of the impact

The CEI research impact on the space sector of e2v imaging business takes a number of forms ranging from modifications to fundamental understanding, and may directly impact the work or instrument performance of a space mission by enhancing performance which enables a telescope to see deeper into the universe, or to hold a particular performance for longer while operating in space where radiation damage limits equipment lifetimes.

One of the key impacts of CEI research and training is through support of the collaborating company, where continued support provides an increase in UK competitiveness, exports and job protection and job creation. This is directly evidenced through the CEI involvement in the BIS Regional Growth Fund grant to a value of £3.8m, where around 100 new jobs in the high-performance space sector will be created. The e2v CEO Keith Attwood was recently quoted in the CBI magazine saying:

> 'By rethinking how it can get more out of its technology across the business – and working with the University of Nottingham and The Open University – e2v has expanded the size of its potential markets from £2bn to £3.5bn a year.'

An example of impact arising from the activity of the CEI in space instrumentation is in ESA's Euclid project, where the work of the group has led to changes in the electronics which drive the image sensors to achieve up to a factor 2 times improvement in radiation hardness (and hence making the instrument able to meet its performance specification while in orbit in space, which otherwise would have suffered a degradation beyond the scientific performance requirements). This work has primarily occurred during 2011–2013.

A second example of impact is the CEI space-science research programme which has created a tangible benefit to e2v is in the development of CMOS image sensors (CIS) for space applications, in collaboration with e2v. As a result of over six years of background research being conducted through two consecutively sponsored PhD students, in 2013 CEI were awarded a co-investigator role funded by the UK Space Agency to work with e2v to develop and supply a new type of CMOS image sensor into the visible camera consortium of ESA's JUICE mission, destined for Jupiter with launch 2022. This grant from UKSA will provide a £1m contract to e2v for the sensor supply, which we will then pass on to our collaborators in DLR-Germany. Besides being a large industrial procurement contract, it will represent one of the first high profile space missions to adopt this new technology, which has been under development within e2v for eight years, and will act to showcase the technology and its improvements over older technology, and will lead to further overseas sales into the other space agencies around the world.

A third example is work on the Gaia mission resulting in a 2013 Sir Arthur Clarke Award for Space Achievement – Industry/Project Team, awarded to e2v, for work on Gaia and other missions, where the OU CEI is working as part of the High Performance Imaging Team at e2v.

Finally, CEI is undertaking more basic R&D into CIS which will yield benefits further downstream. As a direct result of CEI underlying R&D, in 2013 e2v has already submitted an initial Patent Application to support our development of thicker detectors which will improve sensitivity at wavelengths in the IR and X-ray ranges. This patent will be used as part of e2v's Patent Box to protect its business interests, improve competitiveness, and win more contracts in these areas.

A separate but key form of CEI impact has been PhD and CPD-level professional training that resulted in nine industrially-sponsored CASE students achieving PhDs since 2008, with all of

them going on to full-time employment in science research and high-technology companies, with a further three students due to complete in the coming year, and a further six being trained mid-PhD. In the last 12 months CEI has also trained 13 external professionals at a 'CCD Basics Workshop', a three-day on-site residential training course, where organisations such as ESA and SSTL (Astrium) consider the course as an option for their engineers' personal career development.

In summary, the work with the CEI industrial sponsor, e2v, has many spillover benefits to UK industry which helps competitiveness, winning new contracts, and training scientists and engineers and thus secure jobs within the UK economy. These additional benefits might arise for example through recommendation of a minor process modification during manufacture, or through achieving a deeper understanding of the processes at work in the sensors, which may then be communicated to potential customers, helping secure future contracts.

5. Sources to corroborate the impact

External sources corroborating impact:

1. E2v CEO statement about the significance of winning the Regional Growth Fund grant in 2012 with the Open University and Rutherford Appleton Laboratory http://www.e2v.com/news/e2v-wins-regional-growth-fund-award/
2. Over 20 documents on CCD damage lodged on the ESA Livelink system (http://www.rssd.esa.int/index.php?project=LIVELINK) available on request.
3. Winner of 2013 Sir Arthur Clarke Award for Space Achievement – Industry/Project Team, awarded to e2v, for work on Gaia, and other missions, where the OU CEI is working as part of the High Performance Imaging Team at e2v (http://www.bis-space.com/2013/07/17/11367/sir-arthur-clarke-awards-2013-winners)
4. E2v CEO presentation on the benefits of a high performance technology company having strategic partnership with the Open Univeristy. (http://epc.ac.uk/wp-content/uploads/2013/04/Keith-Attwood-EPC-conf-KDA-4-13-v3.pdf)

Beneficiaries who could be contacted to corroborate impact:

5. Chief Design Engineer, e2v Techologies PLC
6. Head of the School of Physics and Astronomy, Manchester University
7. Group Chief Technology Officer, e2v Techologies PLC
8. Euclid VIS Principal Investigator, Mullard Space Science Laboratory/University College London
9. Head of Space Science, United Kingdom Space Agency