Institution: University College London (UCL)

Unit of Assessment: 9 – Physics

Title of case study: Supporting e2v Ltd. in developing capability as a supplier for major space science missions

1. Summary of the impact

Research conducted within the Department of Space and Climate Physics at UCL has had a significant impact upon e2v Ltd., a manufacturer of charge-coupled devices (CCDs). Through working collaboratively with e2v, UCL has helped the company to secure major contracts and business [text removed for publication]. This includes two contracts for the supply of CCDs for the European Space Agency (ESA) missions Gaia (€20 million) and Euclid (€10 million). Furthermore, the symbiotic relationship has contributed to the establishment of e2v as Europe's leading supplier of high-quality CCDs for space science applications and has underpinned an improved understanding of device design and optimisation within the company.

2. Underpinning research

The Department of Space and Climate Physics (also known as the Mullard Space Science Laboratory, or MSSL) at UCL includes an Instrument Science Group that develops high-specification cameras for use on scientific spacecraft and undertakes fundamental research in the field of imaging sensors, including CCDs. CCDs are optical sensors that take the form of a two-dimensional pixelated array. They have revolutionised the acquisition of image information; for example, modern digital cameras are based on devices of this kind. The success of scientific applications is often critically dependent on the precise response of CCDs in their expected environment; for space science applications, this environment is a satellite operating in the harsh conditions of space.

Since 1995, the MSSL group has worked closely with CCD manufacturer e2v Ltd. on a programme of CCD characterisation and modelling [1-6]. This partnership typically involves the detailed design and manufacture of CCDs by e2v, followed by the scientific evaluation and characterisation of the devices in specialist facilities at MSSL. This characterisation is within the context of performance and process models, and includes aspects such as noise sources and electron mobility, diffusion and loss. Test data are simulated and interpreted to quantify underlying device properties, and device performance is estimated. The models that are used have been either developed at MSSL or adapted from those in the published literature. The results and evaluations from the research at MSSL then go on to inform e2v's next generation of devices and their optimal use. The programme has so far involved the characterisation of more than 250 of e2v's CCDs.

The collaborative studies function within a virtuous circle, in which research insights relating to the improvement of CCDs are shared, and understanding builds from project to project. Insights that have resulted from the programme of research are in areas including the physical processes of the devices, such as electron mobility and diffusion, noise sources, linearity, electron loss mechanisms, sensitivity, temperature dependence and set voltage dependence; camera design optimisation; device specification; and CCD data interpretation (calibration) during data analysis. For example, the MSSL group showed how linearity of response could be increased beyond full-well capacity through pixel integration, and the point spread function dependency on wavelength gave insight into the electron diffusion in the drift region of the CCDs.

Much of this CCD research was conducted as part of studies of future space mission concepts, of which there are many more than actual space missions, due to the way that technical risk is mitigated and selections are made. Such studies are very comprehensive and are often competitive against other mission concepts. These collaborative CCD studies were conducted between 1996 and 2002 for the space mission Integral, which was launched in 2002 [1, 2]; in 1999 and 2000 for the GOES Solar X-ray Imager (SXI) [3]; in the early 2000s for the planned space mission Eddington [4, 5]; in the mid 2000s for the FPP (Focal Plane Package) and EIS (Extreme-

Ultraviolet Imaging Spectrometer) [6] instruments on the space mission Hinode, which was launched in 2006; from the late 2000s to the present time for the current space missions Gaia and Euclid; and for a number of other space missions. Often a customer that was an expert in detector technology was also involved, working with MSSL to optimise mission performance (for example, Lockheed Martin for GOES SXI [3] and Hinode FPP; and ESA for Eddington [4, 5], Euclid and Gaia).

For actual flight missions the emphasis was on device specification, device characterisation, identifying optimal operating conditions, screening and preparation for exploitation. Important developments that have formed part of this work include the examination of back illumination in CCDs that had been thinned to create extreme ultraviolet sensitivity, and the evaluation of novel concept L3CCDs (a new type of CCD) as a potential mission device for Gaia.

The table below lists a number of studies that MSSL has been involved with and that have led to improved understanding of CCDs.

Project start-end	Prime contractor	Number of CCDs	Comment
Integral flight camera 1996-2002(launch)	European Space Agency contract	5	References [1] and [2].
GOES SXI 1999-2000	Lockheed Martin (US) contract	55	Multiple satellites in the GOES series. Reference [3].
Hinode EIS 2003-2006(launch)	PPARC grant	8	Reference [6].
Hinode FPP 2003-2006(launch)	Lockheed Martin (US) contract	36	Direct result of GOES SXI project.
Eddington prototype 2004-2005	ESA contract	4	References [4] and [5].
Gaia 2007-2010	ESA and STFC grant	around 150 (including all flight devices)	Helped secure Gaia selection as an ESA mission.
Plato study 2008-2011	UK Space Agency grant	0	Followed Eddington study. Several initial devices manufactured for ESA. Prototype readout electronics designed and built at MSSL. MSSL contributed to the devices' specification.
Euclid study 2008-present	ESA and STFC grant	5 to date	Helped secure Euclid selection as an ESA mission.
Moses 2004	STFC grant	7	Part of the evaluation of a novel far UV spectral imager that flew on a sounding rocket.
Back illuminated CCDs 2003	PPARC grant	5	Enhanced the group's understanding of a particular device configuration: charge diffusion and point spread function in back-thinned devices.
L3CCDs for Gaia 2004-2005	ESA	5	Part of Gaia pre-selection evaluation.

Key UCL researchers: Alan Smith (Head of Detector Physics group 1990-2005; Head of Department 2005-present; Professor of Detector Physics 1998-present) and Dave Walton (Research Fellow 1990-present; Head of Photon Detection Systems group 2006-present).

3. References to the research

[1] The CCD and readout electronics for the OMC instrument on *Integral*, D. M. Walton, P. D. Thomas, J. L. Culhane, B. Jordan, A. Smith, A. P. Dibbens and L. J. Bradley, *Astronomy and Astrophysics*, 411, L275-L279 (2003) doi:10.1051/0004-6361:20031453

[2] OMC: An Optical Monitoring Camera for INTEGRAL – Instrument description and performance, J. M. Mas-Hesse, A. Smith, et. al, *Astronomy and Astrophysics*, 411, L261-L268 (2003) doi:10.1051/0004-6361:20031418

[3] Characterization of the flight CCD detectors for the GOES N and O Solar X-ray Imagers, R. A. Stern, L. Shing, P. Catura, M. Morrison, D. Duncan, J. R. Lemen, T. Eaton, P. Pool, R. Steward, D. Walton and A. Smith, *Proceedings of SPIE*, 5171, 77-88 (2004) doi:10.1117/12.506346

[4] CCD issues for *Eddington*, D. M. Walton, A. Smith and M. S. Cropper, In: *Proceedings of the First Eddington Workshop on Stellar Structure and Habitable Planet Finding*, F. Favata, I. W. Roxburgh and A. Gimenez (eds.), ESA SP-485, 211 (2002) – pdf available at: http://adsabs.harvard.edu/abs/2002ESASP.485..211W

[5] A high stability multi-CCD focal plane for ESA imaging missions, D. M. Walton, P. M, Bonhomme, R. P. Card, G. P. Davison, P. R. Guttridge, M. R. Hailey, H. Lamoureux, K. J. Rees, A. D. Rousseau, P. D. Thomas, B. Winter and N. R. Waltham, *Nuclear Instruments and Methods in Physics Research Section A*, 573, 253-256 (2007) doi:10.1016/j.nima.2006.10.260

[6] The EUV Imaging Spectrometer for Hinode, J. L. Culhane, L. K. Harra, A. M. James, K. Al-Janabi, L. J. Bradley, R. A. Chaudry, K. Rees, J. A. Tandy, P. Thomas, M. C. R. Whillock, B. Winter, G. A. Doschek, C. M. Korendyke, C. M. Brown, S. Myers, J. Mariska, J. Seely, J. Lang, B. J. Kent, B. M. Shaughnessy, P. R. Young, G. M. Simnett, C. M. Castelli, S. Mahmoud, H. Mapson-Menard, B. J. Probyn, R. J. Thomas, J. Davila, K. Dere, D. Windt, J. Shea, R. Hagood, R. Moye, H. Hara, T. Watanabe, K. Matsuzaki, T. Kosugi, V. Hansteen and Ø. Wikstol, *Solar Physics*, 243, 19-61 (2007) doi:10.1007/s01007-007-0293-1

References [1], [4] and [5] best indicate the quality of the underpinning research.

4. Details of the impact

The primary beneficiary of the research described in section 2 is MSSL's collaborator on much of the work: e2v Ltd. e2v is a UK company that develops a range of innovative technologies including CCDs. It employs 1,600 people, roughly a third of whom are scientists and engineers, and has annual sales of around $370 million. The MSSL research has underpinned improved performance of e2v within the REF impact period; it has enabled the company to win major contracts, led to improvements in its CCD technology, and enhanced its standing in the space market. e2v's Chief Engineer (Imaging Applications) confirmed the importance of UCL's work to the company: "the e2v relationship with MSSL and UCL has been one of the foundations of our space science imaging business" [A].

The development of new generations of CCDs is an expensive affair, costing millions of pounds, yet cannot be left to chance once a future space programme is selected. e2v tends to undertake new device developments under contract from customer organisations (rather than fund such developments fully themselves). Prior to selection it is necessary to first demonstrate the science performance and reliability of devices. MSSL's engagement with e2v and assistance in areas such as this – in addition to their joint research with e2v on prior space missions – has enabled the company to secure two major contracts with ESA that have been active within the REF impact period: a €20 million contract (2007 to 2011) for the supply of CCDs for the Gaia mission, due to be launched in late 2013; and a €10 million contract (2012 to 2016) for the supply of CCDs for the visible (VIS) instrument on the Euclid mission, due to be launched in 2020 [A]. Gaia and Euclid will include the largest and second largest CCD focal planes ever built for space, with 109 and 36

CCDs respectively. The success of both missions is critically dependent on the performance of the CCDs, since their main data product is the output of these devices. Interpretation of the CCD signals therefore delivers the primary mission objectives.

MSSL's engagement and work with e2v has also enhanced the company's standing in the competitive space market, and has assisted them in becoming Europe's dominant and preferred supplier of CCDs for space science applications [B]. Indeed, the track record that the research has helped e2v to secure is unrivalled. This enhanced reputation and improved ability to secure contracts was recognised by the company's Chief Engineer, who, speaking about the impact of the joint Gaia mission research on the Euclid contract and other business activities, said: "The supply of custom CCDs to the Gaia mission is still the largest space contract that we have won […] and the support of MSSL in making this mission feasible is of course significant. The capability that this experience has built at e2v now makes it possible for us to be a credible supplier to the next ESA science missions. For example, we have recently won a contract for €10M for supply of CCDs to the Euclid VIS instrument [text removed for publication]" [A].

The influence of MSSL research on the success of e2v is further emphasised by the Chief Engineer, who praises "the strong technical liaison between yourselves and the Lockheed Martin Solar Physics group, which enabled us to supply CCDs into several programmes from SXI on GOES, to all of the Hinode instruments, the HMI and AIA instruments on the Solar Dynamics Observatory, and has built both our experience and reputation for Solar Imaging such that we have also been able to address other opportunities such as IRIS (the Interface Region Imaging Spectrometer), STEREO, and SUVI [text removed for publication]" [A]. This liaison comprised collaborative CCD research and was manifest in part in a joint publication (reference [3] in section 3).

In addition to enhancing e2v's reputation and helping them to secure large contracts, the symbiotic relationship between the company and MSSL has led to an improved understanding at e2v of mission science requirements and their implications for CCD design. The Chief Engineer said: "the insights that the MSSL team have brought to us on the mission science requirements and how these translate into CCD performance needs have enabled us to better understand how we can design and optimise our detectors for particular applications. This insight has been invaluable in allowing us to address other customers with similar requirements, being able to offer solutions rather than simply asking questions. In this high technology marketplace this is a very strong selling point." [A]

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Supporting statement from Chief Engineer (Imaging Applications, Space Science and Astronomy Business) at e2v Ltd. – corroborates that MSSL research helped e2v to win major contracts (including two with ESA worth a total of €30 million), enhanced the company's reputation and ability to secure contracts, and led to an improved understanding of device design and optimisation. Available on request.

[B] ESA Study Scientist at European Space Research and Technology Centre (ESTEC) can be contacted to corroborate the claim that MSSL research has enhanced e2v's standing in the competitive space market and assisted them in becoming Europe's dominant supplier of CCDs for space science applications. Contact details provided separately.