Institution: University College London (UCL)

Unit of Assessment: 9 – Physics

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

Period when the underpinning research was undertaken: 2004 - 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:
Alan Smith	Professor of Detector Physics	1990 – present
Dave Walton	Head of Photon Detection Systems	Pre-1990 – present

Period when the claimed impact occurred: 2013 - 2020

Is this case study continued from a case study submitted in 2014? Y

1. Summary of the impact (indicative maximum 100 words)

Research conducted within the Department of Space and Climate Physics at UCL has had a significant impact upon Teledyne-e2v Ltd (T-e2v, formerly e2v), a manufacturer of charge-coupled devices (CCDs). Through working collaboratively with T-e2v, UCL has helped the company to secure major contracts and business with a total value of more than [TEXT REMOVED FOR PUBLICATION] since 2013. This includes a contract for the supply of CCDs for the European Space Agency (ESA) mission PLATO [TEXT REMOVED FOR PUBLICATION]. Furthermore, the symbiotic relationship has contributed to the establishment of T-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 (indicative maximum 500 words)

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.

The MSSL group has worked closely with CCD manufacturer e2v Ltd, (T-e2v from 2017) for many years on a programme of CCD characterisation and modelling (**R1-R5**). This partnership involves the detailed design and manufacture of CCDs by T-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 informed T-e2v's next generation of devices and their optimal use. The programme has so far involved the characterisation of more than 300 T-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 an 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. The lists of studies that MSSL has been involved with that have led to improved understanding of CCDs is presented in Table 1.

In many of the projects, a customer that is an expert in detector technology was involved, working with MSSL to optimise mission performance (for example, Lockheed Martin for GOES SXI (**R1**) and Hinode FPP; and ESA for Eddington (**R2, R3**), Euclid, Gaia (**R4, R5**) and PLATO). The mode of collaborative working through customer(ESA)/supplier(T-e2v)/science groups (including MSSL) working groups developed for Gain proved highly effective for Euclid and has been adopted for PLATO (chaired by Professor Smith at MSSL).

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, (**R1**) and the evaluation of novel concept L3CCDs (a new type of CCD).

Table 1. Examples of studies in which 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	
GOES SXI 1999-2000	Lockheed Martin (US) contract	55	Multiple satellites in the GOES series. Reference (**R1**).
Hinode EIS 2003-2006(launch)	PPARC grant	8	
Hinode FPP 2003-2006(launch)	Lockheed Martin (US) contract	36	Direct result of GOES SXI project.
Eddington prototype 2004-2005	ESA contract	4	References (**R2**) and (**R3**).
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 2008-2019	ESA and STFC grant	50	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.
PLATO 2017- present	ESA	3	Beginnings of a >100 CCD characterisation programme

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

R1. Stern RA, Shing L, Catura P, Morrison M, Duncan D, Lemen JR, Eaton T, Pool P, Steward R, **Walton DM**, **Smith A.** (2004) Characterization of the flight CCD detectors for the GOES N and O solar x-ray imagers, *Proceedings of SPIE*, 5171, 77-88. doi:10.1117/12.506346

R2. **Walton DM**, **Smith A**, Cropper MS. (2002) CCD issues for Eddington. 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 – pdf available at: http://adsabs.harvard.edu/abs/2002ESASP.485..211W

R3. **Walton DM**, Bonhomme PM, Card RP, Davison GP, Guttridge PR, Hailey MR, Lamoureux H, Rees KJ, Rousseau AD, Thomas PD, Winter B, Waltham NR. (2007) A high stability multi-CCD focal plane for ESA imaging missions. *Nuclear Instruments and Methods in Physics Research Section A*, 573, 253-256. doi:10.1016/j.nima.2006.10.260

R4. Seabroke G, Holland A, **Cropper M.** (2008), Modelling radiation damage to ESA's Gaia satellite CCDs. *Proc. SPIE,* vol 7021. doi:10.1117/12.790968

R5. **Seabroke G**, Holland A, Burt, D Robbins BM (2010) Silvaco ATLAS model of ESA's Gaia satellite e2v CCD91-72 pixels. *Proc. SPIE*, vol 7742. doi:10.1117/12.856958

References (R2) and (R3) best indicate the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

MSSL research has underpinned improved performance of T-e2v devices. Since 2013 it has enabled the company to win major contracts, led to improvements in its CCD technology, and enhanced its standing in the space market. The e2v relationship with MSSL and UCL has been one of the foundations of T-e2v space science imaging business (**S1**).

Improved commercial performance and competitiveness of T-e2v

The success of space missions is critically dependent on the performance of the CCDs, since their main data product is the output from these devices. Hence, reliability of the CCD devices and their performance are of utmost importance to space agencies and sponsors of space missions.

The primary beneficiary of MSSL's body of research is T-e2v Ltd., a UK-based company that develops a range of innovative technologies including CCDs. The company employs 1,600 people, roughly a third of whom are scientists and engineers. Its annual sales were approximately GBP147,000,000 in 2018.

[TEXT REMOVED FOR PUBLICATION] The Gaia and Euclid missions have included the largest and second largest CCD focal planes ever built for space, with 109 and 36 CCDs, respectively. Including 26 cameras, the PLATO mission is equipped with 104 large CCDs and

will be the largest number of pixels used in a detection system (>2,000,000,000,000), twice that of Gaia, the record holder before PLATO.

MSSL's engagement with T-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" (**S1**). Indeed, the track record that T-e2v has secured as a result of the research collaboration, is unrivalled. "The enhanced reputation and improved capability that this experience has built at T-e2v has made possible for the company to be a credible supplier to the next ESA science missions". [TEXT REDACTED FOR PUBLICATION] (**S1**).

Improved understanding of space missions requirements and technical capabilities

In addition to enhancing T-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 T-e2v of mission science requirements and their implications for CCD design" (**S1**). The insight that the MSSL team have brought to T-e2v on the mission science requirements and how these translate into CCD performance needs, have enabled them to better understand how to design and optimise detectors for particular applications. The company acknowledged these insights as "invaluable in allowing [them] to address other customers with similar requirements and being able to offer solutions rather than simply asking questions" (**S1**). T-e2v stated that "in this high technology marketplace this [understanding of space mission requirements] is a very strong selling point" (**S1**).

T-e2v note that "the strong technical liaison between MSSL and the Lockheed Martin Solar Physics group, enabled them 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" (**S2**). Through this, the company has built its experience and capabilities for Solar Imaging. As a result, T-e2v has been able to "address requirements for NASA Explorer Mission IRIS (the Interface Region Imaging Spectrometer), Solar Terrestrial Relations Observatory (STEREO) and the National Oceanic and Atmospheric Administration's Solar Ultraviolet Imager" (**S1**).

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

S1. Supporting statement from Chief Engineer at T-e2v Ltd. corroborates the influence of MSSL work on company performance, reputation and an improved understanding of device design and optimisation.
[TEXT REDACTED FOR PUBLICATION]