Institution: Queen's University Belfast

Unit of Assessment: 9 (Physics)

Title of case study: Development of high performance cameras for imaging applications with Andor Technology plc

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

As standard commercially-available imaging systems were unable to deliver the performance necessary for our astronomy research programmes, we formed a partnership with Andor Technology to develop two new specifically-tailored novel imaging systems: one to allow high-speed, high cadence imaging over an array of detectors whose capture times were precisely synchronised (for solar research); one to combine large format CCD detectors with a thermoelectric deep cooling design, removing the need for a separate, expensive cooling system (for exoplanet research). This partnership contributed to the development of new imaging products within Andor Technology (2008 – present), for which the company estimates a current total revenue value of over £1.7M per year. It has also helped Andor to maintain a leading position in the scientific camera market on a global scale, via the press and industry coverage obtained for the new technology development.

2. Underpinning research (indicative maximum 500 words)

Solar research:

High cadence observations of astronomical sources has been a growing field within astrophysical science and there is a clear need for such observational data in solar physics. Many solar research topics involve the observation of phenomena over small sizes (few tens of km) and short timescales (one second or less), in particular those related to the variable Sun and its influence on the Earth. Solar flares and other events can seriously affect satellite communications, GPS systems and power grids, the most famous example being the blackout in Quebec in 1989, which cost the Hydro-Quebec power company alone over $10M.

In the mid-2000's, Profs Mathioudakis, Keenan and collaborators realised the need for the development of specialist equipment to allow progress in the understanding of solar phenomena at a much greater level of detail than previously achieved [1, 2]. Their development of high-cadence, multi-wavelength imaging systems, in collaboration with Andor Technology, has allowed unique high-frequency imaging of the solar atmosphere. In particular, the Rapid Oscillations in the Solar Atmosphere (ROSA) instrument provides images of the solar atmosphere simultaneously at 6 wavelengths, at a rate of up to 200 images per second per wavelength, with a resolution of better than 100 km [3]. ROSA was part-funded by a PPARC grant for £246K awarded to Keenan and Mathioudakis in September 2007, followed by STFC grants for £99K in August 2009 and £51K in August 2012 and an FP7 Integrated Infrastructures Initiative grant in April 2013 for €223K to Keenan and Mathioudakis to support ROSA operations. Since its successful deployment in August 2008, ROSA has been extensively used to investigate high-frequency waves in the Sun. It is now one of the top requested instruments at the Dunn Solar Telescope in New Mexico, the prime US facility for solar ground-based observations. Mathioudakis and Dr Jess subsequently won the inaugural Andor Insight Award for scientifically-captivating imaging obtained with Andor equipment (November 2011), which attracted extensive publicity, e.g. see:
http://phys.org/wire-news/54477731/stellar-success-for-queens-solar-stars.htm

Exoplanet research:

One of the most important scientific advances in recent years has been the discovery of exoplanets, i.e. planets orbiting stars other than the Sun. The best method for discovering exoplanets is through transit surveys (watching for the dip in the light from a star resulting when the planet passes directly between the star and the observer during its orbit). When coupled with follow-up observations, such transit surveys provide measurements of planetary masses and densities, and potentially spectroscopy of planetary atmospheres. The most successful Earth-based transit discovery systems to date have been the Andor camera-based SuperWASP (Wide Angle Search for Planets) facilities, whose development was led by Prof Pollacco and colleagues (note that Pollacco left QUB in August 2012). Although the SuperWasp project officially began in 2000/2001, its genesis can be traced back to the mid-1990's when, together with the team at ING in La Palma, Pollacco developed a series of cameras with wide fields-of-view, known as CoCam. When it became clear that these cameras might allow exoplanet transits to be discovered, plans were developed to build WASP (Wide Angle Search for Planets) in 1999/2000. Observations using WASP in Summer 2000 demonstrated the ability to detect planetary transits, thus prompting further system developments and the creation of the SuperWASP-North and -South projects [4], funded by an initial PPARC grant for £105K to Pollacco, Keenan and Fitzsimmons in April 2001, and a subsequent PPARC award for £464K in April 2008 to Pollacco and Keenan to operate the SuperWASP-North facility. To date, these facilities have led to the discovery of >90 transiting exoplanets, with more to be announced [5, 6]. More importantly, in terms of impact, the development of these cameras and their world-wide visibility through the WASP exoplanet programme has led to significant sales for Andor in this market. The societal impact has also been large, with many press and TV-radio articles, including BBC reports, e.g. see:
http://news.bbc.co.uk/1/hi/northern_ireland/7322979.stm

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

[1] *"High-frequency oscillations in a solar active region coronal loop"*, D. R. Williams, K.J.H. Phillips, P. Rudawy, M. Mathioudakis, P.T. Gallagher, E. O'Shea, F.P. Keenan, P. Read, B. Rompolt. *Monthly Notices Royal Astronomical Society* **326**, 428 (2001); journal impact factor = 4.90; ISI ranking = 9/56; DOI: 10.1046/j.1365-8711.2001.04491.x; cited 62 times (according to WoK, October 2013).*

[2] *"High-frequency oscillations in a solar active region observed with the Rapid Dual Imager"* D.B. Jess, A. Andic, M. Mathioudakis, D. S. Bloomfield, F.P. Keenan. *Astronomy and Astrophysics* **473**, 943 (2007); journal impact factor = 4.59; ISI ranking = 10/56; DOI: 10.1051/0004-6361:20077142; cited 16 times (according to WoK, October 2013).

[3] "*ROSA: A High-cadence, Synchronized Multi-camera Solar Imaging System"* D.B. Jess, M. Mathioudakis, D.J. Christian, F.P. Keenan, R.S.I. Ryans, P.J. Crockett. *Solar Physics*, **261**, 363 (2010); journal impact factor = 2.78; ISI ranking = 18/56; DOI: 10.1007/s11207-009-9500-0; cited 23 times (according to WoK, October 2013).*

[4] *"The WASP project and the SuperWASP cameras"*, D. L. Pollacco *et al.*, *Publications of the Astronomical Society of the Pacific*, **118**, 1407 (2006); journal impact factor = 2.44; ISI ranking = 20/56; DOI: 10.1086/508556; cited 247 times (according to WoK, October 2013).*

[5] *"WASP-1b and WASP-2b: two new transiting exoplanets detected with SuperWASP and SOPHIE"*, A. C. Cameron *et al.*, *Monthly Notices of the Royal Astronomical Society* **375**, 951 (2007); journal impact factor = 4.90; ISI ranking = 9/56; DOI: 10.1111/j.1365-2966.2006.11350.x; cited 127 times (according to WoK, October 2013).

[6] "WASP-3b: a strongly irradiated transiting gas-giant planet", D. Pollacco *et al.*, *Monthly Notices of the Royal Astronomical Society*, **385**, 1576 (2008); journal impact factor = 4.90; ISI ranking = 9/56; DOI: 10.1111/j.1365-2966.2008.12939.x; cited 108 times (according to WoK, October 2013).

*Output best indicates the quality of the underpinning research.

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

ROSA (Rapid Oscillations in the Solar Atmosphere):

The detectors in our SuperWASP and ROSA instruments were developed in collaboration with Andor Technology plc, one of the world leaders in detector technology, which employs over 300 people in 16 offices worldwide, and distributes its products to 10,000 customers in 55 countries. Our successful partnership with Andor allowed them to identify large format CCD and high-speed ultra-sensitive EMCCD scientific cameras as a growing market for astronomical applications, as they were unaware of the increasing importance of high cadence observing in astrophysics research. In addition, the partnership allowed Andor to become involved in the European Solar Telescope (EST) Consortium, and provided access to EU/FP7 funding for Andor of €81K (2008 – 2011) for a preliminary detector Design Study for the EST. This in turn has potential applications to other solar telescope designs around the globe, such as the Advanced Technology Solar Telescope (ATST) in the USA and the National Large Solar Telescope (NLST) in India. Most importantly, the drive for science excellence in our programmes pushed existing detector technology to its limits, and was directly responsible for Andor's development of these large format, low noise, high-speed cameras. Andor has now been identified (by the EST and ATST Consortia) as one of only two companies worldwide which have the capability to provide cameras that can meet the stringent science requirements of the next generation of solar telescopes (i.e. large format, synchronised and fast readout).

For ROSA to operate successfully, it has been necessary to solve the problem of accurately synchronising up to 6 cameras at high cadence, so that all images are obtained at exactly the same time with an accuracy of a few microseconds. Andor worked with Mathioudakis and Keenan to develop the synchronisation hardware and software infrastructure to achieve this. Following its successful development, this directly expanded Andor's understanding of high bandwidth data handling and multi-camera synchronisation, identified as a key future area in terms of providing `added-value' to camera systems. In particular, high bandwidth solutions are highly complementary to next-generation scientific CMOS technology, an area of innovation that is presently being spearheaded by Andor. This new ground-breaking technology offers the ability to acquire large format data at very fast frame rates with extremely high sensitivity and is already resonating with a broad diversity of scientific applications, including in biophysics (e.g. investigating neurotransmission at individual synapses in brain tissue), drug discovery (e.g. imaging biological reactions such as drug binding) and high-cadence astronomy (including solar physics).

Our partnership with Andor has directly led to the development of imaging products comprising of camera (or multi-camera) systems combined with high bandwidth data handling

and real-time processing units. The sales of these products generated over £1.4M in 2012, and is estimated by Andor to grow to more than 300 systems per year in the next 5 years, corresponding to a revenue of £3.8M per year. This has also helped Andor to maintain a leading position in the scientific camera market on a global scale, particularly in the consistently growing and relatively well-funded area of astronomy.

Super-WASP and the Next Generation Transit Survey (NGTS):
We have collaborated with ANDOR on the development of large format, deep-depleted CCDs needed for the Next Generation Transit Survey (NGTS) project. Although NGTS will use large-format deep depleted CCDs from e2v Technology, (Chelmsford), it is the Andor low noise camera architecture and deep cooling technology that makes these devices usable. Building on the heritage of the SuperWASP project, we conducted a prototype experiment on La Palma (November 2009 – March 2010) using Andor's 1K x 1K iKon-M 934N BR-DD deep-depleted CCD. This experiment proved the viability of high-precision photometry with such technology. Our results led directly to the development of a new camera product (the larger format 2K x 2K iKon-L 936 deep-depleted CCD) by e2v-Andor-QUB for NGTS. As the largest format, deep-depleted cameras that only need thermoelectric cooling rather than bulky and expensive cryogenics, this is a major advance in professional imaging systems. These devices have now become part of the Andor product portfolio. Andor Technology is currently the sole company marketing these devices, and sales have amounted to greater than £500K in only 18 months since the product came into the market.

We note that our case study clearly provides impact as defined in Annex C of the Guidance on Submissions, namely under paragraph 5 – *change or benefit to the activities, performance, policy and process of an organisation*. Specifically, our partnership with Andor led to the decision to develop new imaging systems and the resultant revenue from these.

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

[1] Andor technology: http://www.andor.com/

[2] sCMOS camera: http://www.andor.com/scientific_cameras/neo_scmos_camera/

[3] Astronomical uses of Andor cameras:
http://www.andor.com/learning/applications/Astronomy/

[4] Letter of support from Products Manager at Andor Technology plc, confirming partnership with QUB, the QUB contribution to detector development, and Andor sales figures for relevant products.

[5] Press release on use of sCMOS camera for next-generation of solar telescopes:
http://www.nso.edu/press/H-Beta

[6] Testing and evaluation of Andor camera, Chapter 2 of PhD thesis of James McCormac (Queen's University Belfast, 2012), available at:
http://star.pst.qub.ac.uk/ref/mccormac_phdthesis.pdf