Institution: Cardiff University

Unit of Assessment: Physics (9)

Title of case study: The commercialisation of Terahertz technology: from astronomy to the international market

Period when the underpinning research was undertaken: 2001 – 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:
Carole Tucker	Professor	2001 – present
Peter Hargrave	Professor	2001 – present
Peter Ade	Professor	2001 – present
Simon Doyle	Reader	2008 – present
Matt Griffin	Professor	2001 – present
Georgina Klemencic	Lecturer	2015 – present

Period when the claimed impact occurred: 2013 - 2020

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

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

Detection and manipulation of Terahertz (THz) radiation requires sensitive response to small signals at long wavelengths in the presence of much larger backgrounds. Cardiff research in THz astronomical instrumentation developed a series of interlinked technologies including sensitive detector systems, sub-kelvin coolers, and unique optical components. These technologies have been adapted and commercialised through three partner organisations, with applications in semiconductor materials characterisation, fusion plasma diagnostics, electron spin resonance spectroscopy, and security imaging. The research enabled >£7M in global sales for spin-out company QMCI Ltd., doubled revenue to £500K per annum for Chase Cryogenics Ltd., and launched Sequestim Ltd., a new company employing three staff and securing over £1.1M in private and public-sector funding.

2. Underpinning research (indicative maximum 500 words)

Cardiff University's Astronomy Instrumentation Group (AIG) is a recognised world leader in the design, manufacture, and integration of THz (also known as far-infrared/sub-millimetre) technology for astronomy instrumentation. Its research has been key to UK involvement in virtually all THz telescopes worldwide, and supported through successive PPARC, STFC, UK Space Agency, European Space Agency, and European Union research and development grants, totalling >£31M since 2001.

AIG research explores the THz spectral region, which contains the signatures of star formation, galaxy-formation and evolution, and of the Cosmic Microwave Background radiation used to probe the Big Bang. The requirement for ever-more sensitive THz instruments has driven the AIG's development of the critical underpinning technologies, such as filters and quasioptics, detectors, and cryogenics, with these technologies then being exploited in commercial applications.

Since 2001, the AIG has held leadership positions in many high-profile multi-national astronomical instrument collaborations. Ade was Co-Investigator for the High Frequency Instrument (HFI) on the *Planck* CMB satellite **[3.1]**, for which the AIG designed, built, integrated, and tested the focal plane unit. Griffin was Principal Investigator for the SPIRE instrument on the *Herschel* Space Observatory **[3.2]**; for this project, AIG designed and manufactured several flight subsystems, including filters and cryogenic hardware. Hargrave was Co-Investigator and Cardiff lead on the NASA-led BLAST balloon project **[3.3]**, with AIG designing the optics and providing cryogenic hardware and filters. Furthermore, Tucker led the production of the globally unique filters and quasi-optical components **[3.4]** that are core to the success of these and many other experiments and instruments.

These projects required highly sensitive detectors operating at ultra-low temperatures **[3.1, 3.5]**, specialised filters and optics to select observational bands and block unwanted radiation and heat **[3.4]**, innovative low-loss optical designs **[3.3]**, and novel cryogenic systems **[3.6]** to cool the detectors and lower the photon background. The key innovations that enabled the impact are listed below:

2.1. Filters and quasi-optical components

The AIG has unique capabilities in quasi-optical devices and meta-materials **[3.4]** and is the sole global provider of many innovative optical components and materials crucial to successful THz detection and imaging. These include band-defining and thermally controlling filters, novel meta-material flat lenses, dichroics, polarization modulators, and other more specialised, bespoke devices. The filter components, for example, are critical for controlling the radiation incident on detectors – confining it to a well-defined frequency band, whilst rejecting unwanted out-of-band radiation. They are also very important for thermal control of cryogenic instruments.

2.2. Ultrasensitive detectors

The AIG has designed, built, and tested bolometric detector systems for many astronomical instruments, as well as for commercial partners. A major activity was the design, build and test of the focal plane unit for the *Planck*-HFI satellite instrument **[3.1].** This instrument comprised an array of photon-noise-limited bolometric detector units covering nine frequency bands, and cooled to 0.1 K, integrating bolometers provided by NASA (Jet Propulsion Laboratory) with coupling optics and filters made at Cardiff.

In 2007, Doyle and colleagues invented the Lumped-Element Kinetic Inductance Detector (LEKID) **[3.5]**, a highly innovative, and relatively simple to fabricate, superconducting detector that can be implemented as large arrays with a multiplexed readout. This technology has since been incorporated in several astronomical experiments, including the Cardiff-led MUSCAT instrument for the 50-m diameter Large Millimeter Telescope in Mexico.

2.3. Continuous cryogen-free cooling

The AIG has worked for many years with commercial partner Chase Instruments Ltd. on the design and evolution of sub-kelvin cooling systems. Facilitating this partnership, their Technical Director, Dr Simon Chase, holds a visiting researcher post in the School. This collaboration recently culminated in the first demonstration of true *continuous* cooling to 0.3 K in a cryogen-free cooling system **[3.6]**. This is now offered as a commercial product and has also been incorporated into the MUSCAT instrument, acting as a pathfinder for future applications in astronomy.

The unique capabilities of the Cardiff AIG are internationally recognised. NASA Program Scientist, Dr Dominic Benford, stated that "*The Astronomy Instrumentation Group at Cardiff University are acknowledged world leaders in the supply of critical components for astronomical instruments… Collaboration with Cardiff University has enabled many NASA-funded projects to reach their mission goals*" **[5.1]**.

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

[3.1] Ade, P. A. R., et al., *Planck 2013 results IX: HFI spectral response,* Astronomy & Astrophysics, 571, A9, 2014. http://dx.doi.org/10.1051/0004-6361/201321531 (132 citations)

[3.2] Griffin, M. J., et al., *The Herschel-SPIRE instrument and its in-flight performance,* Astronomy & Astrophysics, 518, L3, 2010. https://doi.org/10.1051/0004-6361/201014519 (1477 citations)

[3.3] Pascale, E., et al., *The Balloon-borne Large Aperture Submillimeter Telescope: BLAST*, Astrophysical Journal, 681, 400, 2008. https://doi.org/10.1086/588541 (128 citations)

[3.4] Ade, P. A. R., and Tucker, C. E., *A Review of Metal Mesh Filters*, Proc. SPIE. 6275, 2006.
https://doi.org/10.1117/12.673162 (295 citations)

[3.5] Doyle, S., et al., *Lumped element kinetic inductance detectors,* Journal of Low Temperature Physics,151, 530, 2008.
https://doi.org/10.1007/s10909-007-9685-2 (150 citations)

[3.6] Klemencic, G., et al., *A continuous dry 300 mK cooler for THz sensing applications,* Review of Scientific Instruments, 87, 045107, 2016.
https://doi.org/10.1063/1.4945691 (8 citations)

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

Technologies and techniques developed exclusively by the Cardiff AIG were exploited by three commercial partners, as outlined below.

4.1 QMC Instruments Ltd. (QMCI)

AIG technologies are predominately made available to the global market via Cardiff University spin-out company QMCI, an established market leader in many aspects of THz instrumentation, offering customised systems for applications in astronomy, hot plasma fusion diagnostics, and electron spin resonance spectroscopy **[5.2]**. QMCI's close collaboration with the AIG ensures that technology is adopted swiftly and appropriately for commercial, civil, and government users. QMCI Sales Director, Mr Ken Wood **[5.3]**, provided two examples shown below:

- QMCI has sold, since 2014, more than 40 cryogen-free systems which rely on the metal mesh filter and detector technology developed by the AIG, valued at approximately £75K each. The detector systems and associated readout technology are particularly valuable in second and third world countries where liquid cryogens are not readily available.
- A new generation of detector array systems was developed by the AIG and introduced to the commercial market by QMCI in 2012. These ultra-low noise arrays reduce cost by removing the need for more expensive helium-3 based systems. These sophisticated systems command prices in the range of £100-£250K.

As a result, QMCI confirmed that, "*Since 2014 we have collaborated closely on business worth in excess of £7 million, comprising more than 160 individual sale contracts with customers in more than 30 countries. This entire business volume relies directly on the unique terahertz detector and filter technology invented, developed and supplied by the AIG*." **[5.3]**.

More than 90% of QMCI products are exported (30% Europe; 30% US; 30% Far East). The company employs five highly skilled technical staff in Cardiff, makes use of AIG academic consultants and facilities, and has experienced local sales representatives in Japan, China, Russia, Singapore and Korea **[5.3]**.

4.2 Chase Cryogenics Ltd.

Chase Cryogenics Ltd. utilised the Cardiff AIG research to produce the first commercially available continuous-operation helium-3 fridge. This device allows continuous operation at temperatures around 300 mK. Previously, maintaining temperatures at this level was only possible for periods of up to ~48 hrs before the system had to be "recycled", meaning a break in operations of several hours before the required operating temperature could be achieved again, and requiring expert technical operation.

This system is now a commercially available product, and the CEO of Chase Cryogenics Dr Lee Caroline Kenny, stated: "*I would like to emphasise just how important the work done [by the AIG] has been for the commercial success of this company*". Kenny also continued to confirm: "*As a direct result, in the last five years the turnover of the company has doubled to ~£500k per year*" **[5.4]**.

Other Chase Cryogenics systems and products, developed from the Cardiff research collaboration over many years, have found application in projects worldwide, such as NASA's Deep Space Optical Communications project, and the European Space Agency's Ariane 6 launchers. Dr Kenny confirmed that "*I believe that working with the AIG has been of tremendous benefit to this company and we look forward to continuing our collaborative partnership in future*." **[5.4]**.

4.3 Sequestim Ltd.

A new spin-out company from the AIG, Sequestim Ltd., was formally launched in 2019. The company commercialises new cameras for millimetre-wavelength video-rate scanning of humans and vehicles, with unprecedented sensitivity and resolution. Example images from one of the Sequestim cameras are shown in Figure 1, illustrating impressive sensitivity and resolution from a *passive* (i.e., non-illuminating) camera working at video-rate. This sensitivity is enabled by the unique combination of the Cardiff-developed filters, detectors, cryogenics, and optics, as outlined in Section 2. These cameras are Cardiff AIG inventions, and the first system patent has been filed **[5.5]**.

Figure 1. Top: Example output (frame captures) from the Sequestim personnel camera system, showing a variety of hidden threat items. Bottom: Example of an image taken with the truck scanning application. The image was taken of an occupant concealed inside the cargo area of a truck, as it drove past at 30 mph. Note the detection of a gun in the occupant's pocket.

Sequestim holds a 25-year exclusive license to develop and exploit the technology for applications in THz security imaging. It currently employs three full-time staff and has developed its camera using three phases of UK government funding totalling over £1.1M **[5.6]**.

In December 2018, a Sequestim camera was installed for trial passenger security screening in Cardiff Airport, with demonstrations provided to the UK Aviation Minister, the First Minister for Wales, Delta Airlines, International Airlines Group (IAG – holding company for British Airways & Iberia, among others) **[5.7]**. Following this, the camera system has been demonstrated in Cardiff University to other major transport and security stakeholders, including Amazon (head of loss-prevention), to technical advisors to the Chinese and Indian governments (for transport hub security applications), and to the owners of Dubai International Airport. The cameras have attracted interest due to their ability to scan people as they traverse a short corridor, without requiring the removal of outer clothes, significantly reducing queuing time **[5.7]**. In August 2019, a modified camera was demonstrated to UK Border Force and the Home Office for border security applications (Figure 1, bottom). As a result, Sequestim

secured investment from private investor group Cambridge Angels in July 2020, despite disruption due to Covid-19 travel restrictions **[5.6]**. These investment details cannot be provided due to confidentiality.

4.4 Summary

Cardiff's astronomical instrumentation research led to a series of innovations that have been commercialised for wider usage. As a result, during the REF period the research generated >£7M in sales across 30 countries for QMC Instruments Ltd., doubled the revenue of Chase Cryogenics Ltd. to £500k per annum, and enabled the 2019 launch of Sequestim Ltd., a new company already attracting significant investment (over £1.1M), and supporting new jobs.

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

[5.1] Testimony: Dominic Benford, Program Scientist, Astrophysics Division, NASA/HQ

[5.2] QMC Instruments Ltd. website

[5.3] Testimony: Ken Wood, Sales Director, QMC Instruments Ltd.

[5.4] Testimony: Lee Caroline Kenny, CEO Chase Research Cryogenics Ltd.

[5.5] New UK Patent Application No. GB2001711.7 "Systems and Methods for Terahertz Imaging". In the name of Sequestim Ltd.

[5.6] Testimony: Rob Spurrett, Chairman of Sequestim Ltd.

[5.7] Cardiff Airport confirms Sequestim Camera demonstration. "New passenger scanner uses spaces technology to speed up airport security", News, Cardiff Airport website