Institution:	**Cardiff University**
Unit of Assessment:	**9**
Title of case study:	**THz detection from the distant universe to the international market.**

1. Summary of the impact

Research and Development activity at Cardiff University's Astronomy Instrumentation Group (AIG) has been commercialised and made available to the international market. Sales have been made to fields including bio-molecular spectroscopy for health science, plasma fusion diagnostics for sustainable energy, and remote atmospheric sensing. This has resulted in economic impact through:

- revenue generated by the Group's spin-out company, QMCI Ltd., which has demonstrated increased global sales of unique AIG technology through commercialisation of the latest THz detection systems and advancing product development and performance;
- exploitation by third parties in the alternative energy and security markets.

2. Underpinning research

The AIG is a recognised world leader in the design, manufacture and integration of THz technology for astronomical instrumentation. This research has been key to the UK involvement in virtually all THz telescopes worldwide and has largely been supported through successive PPARC and STFC rolling grants[3.1] (>£10.5M in the last 13 years at Cardiff).

Prof. Matt Griffin (Deputy Head of School and Director of Research, Cardiff 2001-) is Principal Investigator for the SPIRE instrument on board the *Herschel* Space Observatory, for which the AIG designed and manufactured flight hardware [3.2]; Prof. Peter Ade (2001-) is a Co-Investigator for the High Frequency Instrument on board the *Planck* satellite for which the AIG designed, built, integrated and tested the focal plane unit [3.3, 3.4]. Two other instruments on board *Herschel* also relied on crucial AIG devices (provided via commercial contracts). *Herschel* and *Planck*, launched in 2009, have now completed their hugely successful operational programmes. Already there have been more than 1250 scientific publications resulting from the unprecedented astronomy research possible with these instruments.

The technological challenges of detecting astronomical THz radiation are considerable; small signals at long wavelengths must be detected in the presence of much larger backgrounds. The work of the AIG has been central to the success of astronomy in this region of the spectrum over the last 30 years. This has required the development of highly sensitive detectors operating at ultra-low temperatures (less than 1 K), specialised filters and optics to block unwanted radiation and heat, and innovative low-loss optical designs. These developments have been applied to instruments for ground-based facilities, balloon-borne experiments and many satellite projects. They have resulted in pioneering surveys of the remnant light from the Big Bang and to significant progress in our understanding of the early universe. Since 2001, scientific and technological publications of the academic members of the AIG number in excess of 600.

The AIG has capabilities unique in the world in quasi-optical devices and meta-materials [3.5, 3.6], so that within the THz astronomy community the AIG is the sole provider of many innovative optical devices and materials crucial to successful THz detection and imaging. These devices include band-defining filters [3.5] and thermal shaders to reduce unwanted background radiation, meta-material anti-reflection coatings [3.6] for vacuum windows, and photolithographic polarizers – all of which have seen either invention or significant development at Cardiff since 2001, with much of that development associated with the prototyping and provision of components for *Herschel* and *Planck*. The AIG continues to drive the state-of-the-art in these areas, and this is evidenced by continued STFC support of this activity [3.1].

The AIG also has a long track record of expertise with ultra-sensitive THz detectors [3.4, 3.7], including superconducting Transition Edge Sensor (TES) bolometers and Lumped Element Kinetic Inductance Detectors (LEKIDs) [3.7]. The latter were invented by Dr. Simon Doyle (Cardiff PDRA 01.01.07 to 30.04.12, Lecturer 01.05.12 to present) and have most recently been incorporated into a Cardiff THz passive imaging camera [3.8], currently being developed commercially by QMCI Ltd.

3. References to the research (citation numbers: on Oct. 29 2013; from ADS unless otherwise stated)

3.1 PPARC/STFC Grants held by AIG at Cardiff University, totalling over £10.5M. (Refs: **PI Gear** et al. PPA/G/S/2001/00422, PPA/G/0/2002/00015, PP/D001048/1, ST/G002711/1, ST/J001538/1; **PI Griffin** et al. PPA/G/R/1999/00060, **PI Ade** et al. PPA/G/R/2001/00467).

3.2 **Griffin,** M. et al., *The Herschel-SPIRE Instrument and its In-flight performance*, A&A, 518, L3 2010 [10.1051/0004-6361/201014519] [Griffin-1; 563 citations]

3.3 **Ade**, P. A. R. et al., *Planck Pre-Launch Status: The Optical Architecture of the HFI*, A&A, 520, A4 (2010) [10.1051/0004-6361/200913039]; 11 citations.

3.4 **Ade**, P. A. R. et al., *Planck Early Results. IV. First Assessment of the High Frequency Instrument in-flight performance.* A&A, 536, A4 (2011) [10.1051/0004-6361/201116487]; [Ade-1; 75 citations]

3.5 **Ade**, P. A. R., and **Tucker**, C. E., *A Review of Metal Mesh Filters,* Proc. SPIE. 6275, 2006 [10.1117/12.673162; [36 citations; this paper reviews the theory of metal mesh technology and also contains much original material on the Cardiff devices specifically, which is not published elsewhere].

3.6 **Zhang**, J., **Ade**, P. A. R., **Mauskopf**, P., **Moncelsi**, L., Savini, G., and **Whitehouse**, N., *New Artificial Dielectric Metamaterial and its Application as a Terahertz Antireflection Coating*, Appl. Opt. 48, 35, 6635, 2010 [10.1364/AO.48.006635] [5 citations]

3.7 **Doyle**, S., **Mauskopf**, P., Naylon, J., Porch, A, and **Dunscombe**, C., *Lumped Element Kinetic Inductance Detectors*, Journal of Low Temperature Physics, 151, 530, 2008 [10.1007/s10909-007-9685-2] [68 citations in Google Scholar]

3.8 **Wood**, K., **Doyle**, S., **Pascale**, E., **Rowe**, S., **Hargrave**, P., **Dunscombe**, C., **Grainger**, W., **Papergeorgiou**, A., **Spencer**, L., and **Mauskopf**, P., KIDCAM, *A Passive THz Imager*, Proc. IRMMW, 2011 [http://dx.doi.org/10.1109/irmmw-THz.2011.6105184]

4. Details of the impact

As a result of the Cardiff AIG research outlined in section 2, high sensitivity, ultra-cold (4 kelvin or less) THz detection systems are now used in the fields of bio-medical imaging and bio-molecular spectroscopy for health science, plasma fusion diagnostics for sustainable energy, remote atmospheric sensing, synchrotron and free-electron laser diagnostics and artwork analysis and curation. These instruments all incorporate the enabling technologies developed for astronomy by the AIG: detectors and cryogenic systems, band selection filters and quasi-optical components described above.

Economic impact: Spin-out

This technology is made available to the global market via an SME spin-out company, *QMCI Ltd*.* QMCI is co-located with the AIG in the Cardiff School of Physics and Astronomy and is a market leader in many aspects of THz instrumentation, offering customised THz systems for many applications [5.1]. Its close collaboration with the AIG ensures that technology is adapted swiftly and appropriately for commercial, civil and governmental users, and that knowledge transfer and exchange between academia and industry is rapid.

According to QMCI Managing Director, Dr Richard Wylde [5.2], “Since 2008 the aggregate business volume transacted by QMCI is in excess of £4 million, of which more than 80% depends directly on contributions made by the AIG”. More than 90% of the activity is 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 utilises experienced local representatives in Japan, China, and Korea.

The interaction of QMCI with the **Atacama Large Millimetre Array (ALMA) project** (2009-2012) is a good example of the economic spin-out of AIG technology. ALMA, the world’s largest ground-based telescope, a 66-antenna facility in Chile, required development of a special filter to enable the telescope to make unique solar observations, without saturation of the sensitive detectors, or

UV damage to underlying optical components. The specification for this solar attenuator was very precise and could not be met by any technique which ALMA scientists had investigated. Using their metal mesh filter capabilities [3.5], AIG academics and QMCI technical staff designed and prototyped several devices which were tested on-site and approved by ALMA. By March 2012, ninety of these highly specialised devices had been delivered to the project. During the same period QMCI provided AIG anti-reflection coated quartz vacuum windows and cooled THz polarisers for more than half of the ALMA receivers, generating >£1M business. Gie Han Tan, EU Front End IPT Manager of the ALMA project states [5.3], "Only with these innovative, high-quality components developed and manufactured by QMC Instruments Ltd., the exceptional sensitivity of the ALMA sub-millimetre receivers could be fully exploited. The solar attenuators provided by QMCI Ltd to the ALMA Project enable a unique capability" (sic).

Further evidence of economic exploitation through sole-supplier status is provided by the sale of AIG polarizers and windows to the HIFI instrument [5.4] and quasi optical filters to the PACS instrument [5.5], both on the *Herschel* Space Observatory. These bespoke components were unavailable through any other source, met full flight quality assurance specification and generated sales to QMCI in excess of £0.5M.

Economic impact: third party exploitation

QMCI products are on the market to end users across a range of industries, building on research undertaken by the AIG for the *Herschel* and *Planck* satellites [3.2, 3.3], and using the same research-funded development skills and facilities. With exclusive access to AIG technology, QMCI is a supplier of ultra-high performance cryogenic detector systems. It is the only commercial source of the world's leading THz meta-material and filtering devices [3.5] and has recently brought to the market the only commercially available cryogen-free bolometric THz detector system.

The three examples below illustrate how AIG research, commercialised through QMCI, has enabled technological and economic impact.

Fusion diagnostics for JET and ITER: The **J**oint **E**uropean **T**orus is the largest magnetic confinement experimental nuclear fusion facility in the world, with the primary focus on achieving fusion as the sustainable world energy source. The **I**nternational **T**hermonuclear **E**xperimental **R**eactor project is currently building the world's largest experimental tokamak nuclear fusion reactor with the aims to make the long-awaited transition from experimental studies of plasma physics to full-scale electricity-producing fusion power plants. QMCI supplied AIG bolometric detector technology to JET and now to ITER, representing, according to Alan Costley, former Head of the ITER Diagnostic Section, "a major breakthrough" in the creation of a powerful diagnostic technique to enable the "study and understanding of many important physical phenomena that occur in the plasmas, some of which limit plasma fusion performance" [5.6]. The sustained application of Cardiff research and continued collaboration with the fusion industry has led to the incorporation of the same AIG technology on every major tokamak device and all major next-generation nuclear fusion reactors around the world: including, within the REF period, EAST in China, KSTAR in Korea and a design contract for the future fast-scanning Michelson Interferometer for ITER-India.

THz camera: In 2010 the giant Japanese corporation, **NEC** commissioned QMCI to provide a filter, based on unique AIG technology [3.5], in order to reject high frequency radiation in a THz camera they were developing. The inclusion of the filter solved the serious issue of ghost image generation in the device and cleared the way for the launch of the ***Soltec THz Imager*** instrument (see figure) [5.7]. In 2011 the first successful use of the camera by rescue workers in fire-scenes was reported and Naoki Oda, Executive Engineer for NEC states [5.8] that, "This world leading filter technology is very important for the

The Soltec THz Imager (IRV-TF083) [5.7]. Product IRV-TF030, built and mounted by the AIG, can be seen as the front copper-coloured element of the camera.

success of the THz imager". The AIG filter technology is now a standard component (IRV-TF030) in these cameras, with more than 40 units sold since 2011 at a total revenue of ~ £1M.

A new generation of detector devices has been developed by the AIG and has recently been introduced to the commercial market by QMCI (2012). These offer ultra-low noise, single pixel and array detectors that operate in entirely mechanical cooled systems. Before this innovation, sensitive THz detectors were restricted to single pixel devices cooled by scarce and expensive liquid helium, dependent on specialised skills using a process that is costly, time-consuming and potentially dangerous. According to Masa Fukumuro (Sales Manager of Japanese company *Infrared Limited*), "QMCI offers the only commercially available, cryogen-free THz bolometer system. It has had a big effect in Japan, China and also in Asian countries where supply of liquid cryogens is a problem in the last two years" [5.9]. Richard Wylde, Managing Director of QMCI [5.2] states that, "To date, and in the period September 2012 - November 2013, £800k sales of these systems have been made", and is confident that sales figures will grow with such a revolutionary new product range, thus securing future revenue and jobs for this SME.

* Both the AIG and *QMCI* were formerly at Queen Mary, University of London; however the revenue and impact claimed here are as a result of technological research and developments made in the last 13 years at Cardiff. The whole AIG moved institution in 2001 and Queen Mary no longer hosts an active research group in this field.

5. Sources to corroborate the impact

5.1 QMCI web site confirms QMCI's relationship with AIG (go to http://www.terahertz.co.uk/ and take the 'QMC Instruments' link on the top right).
5.2 Letter from Managing Director of QMCI Ltd. confirming the statement attributed to him and the impact of contribution of AIG technology on QMCI sales around the world.
5.3 Letter from the ALMA European Front End Project Manager at ESO, confirming the statement attributed to him and the impact of AIG components provided to the ALMA project.
5.4 Contract close-out certificate for provision of *Herschel*-HIFI LOU Windows Assembly itemising delivery of AIG-manufactured components for the instrument.
5.5 Example end Item Data Package for delivery of components for the *Herschel*-PACS instrument, itemising delivery of AIG-manufactured quasi-optical filters.
5.6 Letter from the (now retired) Head of the ITER Diagnostic section (1994-2009) confirming the statement attributed to him, the technological impact of AIG systems on the fusion industry and the sustained involvement of AIG technology provided by QMCI.
5.7 The NEC Soltec THz Imager website provides product brochures and technical details for IRV-T0831 and IRV-TF030 [http://www.solteccorp.com/uncooled-thz-imagers]
5.8 Letter from Executive Engineer, NEC Corporation, Japan, confirming the statement attributed to him and the impact that AIG filters have had on the sensitivity and sales of Soltec THz Imager.
5.9 Letter from Sales Manager, *Infrared Limited*, Japan, confirming the statement attributed to him and the impact that AIG cryogen free technology has on industrial researchers in Japan.

Copies of all webpages, documents and testimony are available from the HEI on request.