Institution: Cardiff University

Unit of Assessment: Physics (9)

Title of case study: Enabling next generation global weather satellite systems

Period when the underpinning research was undertaken: June 2001 – December 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:
Peter Ade	Professor	2001 – present
Carole Tucker	Professor	2001 – present
Peter Hargrave	Professor	2001 – present
Rashmi Sudiwala	Senior Research Fellow	2001 – present
Matt Griffin	Professor	2001 – present

Period when the claimed impact occurred: 2015 - 2020

Is this case study continued from a case study submitted in 2014? No

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

The next generation of European meteorological satellites require state-of-the-art MicroWave Sounder (MWS) instruments for improved global weather forecasting capability over the next twenty years. Cardiff research in metamaterial technologies and quasi-optics provided a unique dichroic-based solution for these instruments that accurately splits a single beam into seven frequencies. The research enabled Airbus Defence & Space to win a €156M contract to develop the new advanced MWS instruments, with Thomas Keating Instruments Ltd. (TK) winning an €8.5M subcontract from the Airbus award (providing 50 person-years of employment to TK employees). Additionally, the TK subcontract enabled further market expansion for the company, specifically over £500K in contracts for Chinese meteorology satellites also incorporating Cardiff dichroic technology.

2. Underpinning research (indicative maximum 500 words)

Astronomy and Earth observation instruments are required to operate in precisely specified frequency bands. This requires filters and other optical components to manipulate the incoming light and direct it to the detectors, with stringent performance requirements. Since 2001 the Cardiff Astronomy Instrumentation Group (AIG) has developed a unique capability in the design and production of filters and quasi-optical components for far infrared to millimetre wavelength (50 µm - several mm) applications. In-house production facilities provide excellent quality assurance and process control, and bespoke components can be created for a given application, with performance conforming precisely to theoretical model predictions. This expertise enabled the Cardiff AIG to supply filters and quasi-optical components to most ground-based, airborne, and satellite-based astronomical instruments working at these wavelengths.

2.1. Underpinning dichroic technology

The dichroic technology is based on metal-mesh structures embedded in or supported on dielectric substrates. Grid patterns can be produced to form capacitive, inductive, or resonant structures with the geometry tuned to specific application requirements. Grids can be stacked to achieve the desired frequency response with very low loss **[3.1]**. A dichroic is a special form of filter, acting as a frequency-selective mirror. Dichroics should exhibit high transmission for frequencies on one side of the transition frequency, and act as a near perfect flat mirror to reflect radiation on the other side of the transition.

Metal-mesh frequency-selective quasi-optical components – such as filters and dichroics – have been developed for the far infrared and submillimetre since the 1960s but require specialist modelling and manufacturing techniques to provide highly-accurate and controlled wavelength manipulation. The AIG's research combined detailed modelling (including electromagnetic solvers, transmission-line theory, and Floquet mode analysis) with comprehensive investigations of material properties and manufacturing processes **[3.1]**. This approach enabled the design and production of dichroics and other components for ground-based and space-borne instruments. The excellent in-band transmission and sharp frequency transition from transmission to reflection of a typical Cardiff dichroic are illustrated in Figure 1. This remains a globally-unique capability in this frequency range.

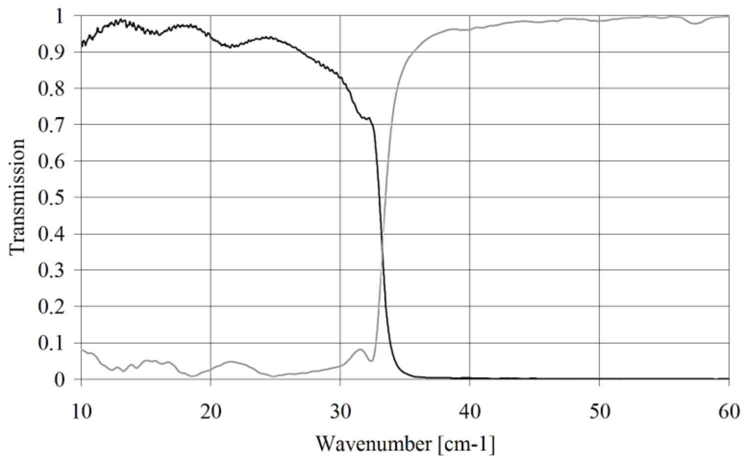

Figure 1. *Air-gap dichroic; Black = transmission, grey = reflection. Note the excellent in-band transmission and sharp frequency transition from transmission to reflection*

2.2. Refinement of dichroic technology for space-based observations

In 2008, the AIG provided a large-diameter (~300 mm) dichroic to be deployed on a major ground-based astronomy facility, the SCUBA-2 camera on the 15-m diameter James Clerk Maxwell Telescope (JCMT) on the summit of Maunakea in Hawai'i. SCUBA-2 is a dual-wavelength camera with two large detector focal planes. The AIG dichroic beam-splitter enabled both focal planes to have the same simultaneous field of view on the sky, whilst observing in two distinct passbands **[3.2]**.

The AIG also developed and provided filters and dichroics for SPIRE, one of the three scientific instruments on board the European Space Agency's Cornerstone (1€B-class) mission, the *Herschel* Space Observatory, launched in 2009 **[3.3, 3.4]**. The SPIRE instrument was led by Cardiff (Griffin PI). Two dichroics, provided by the AIG, were used in series to split the incoming light from the telescope into three frequency bands, enabling three detector arrays to view exactly the same overlapping patch of the sky in three different passbands simultaneously.

Prior to the launch of *Herschel*, the SPIRE instrument technology was also deployed on a scientific and technical pathfinder, the 2005 NASA BLAST experiment **[3.5]**, a stratospheric balloon-borne telescope for which the AIG built the cold optics as well as the filters and dichroics. The AIG also provided, as a commercial contract, similar components to one of the other *Herschel* instruments, the German-led PACS instrument, as the only supplier capable of building components meeting their requirements. These instruments have been hugely productive and scientifically influential (e.g., **[3.4, 3.5]**).

Cardiff led two further studies, funded by the UK Space Agency, to develop a next-generation hyperspectral microwave sounding capability, as a potential future replacement for MWS and similar heterodyne radiometers **[3.6]**. This technology is based on superconducting filterbank spectrometers and is a highly active ongoing research area in Cardiff, working in collaboration with the University of Cambridge.

In summary, Cardiff's expertise in metamaterial optical filters has been applied to the design of dichroic plates and enabled the realisation of complex quasi-optical networks. The unique dichroic technology was developed and validated for use in leading ground-based, balloon-borne, and space-borne astronomical observatories. Drawing upon this expertise, the AIG used this research to devise new solutions for satellite observation systems, which led to the collaboration to develop the Microwave Sounder (MWS) technology described in Section 4.

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

[3.1] Ade, P. A. R., et al., *A review of metal mesh filters*, Proc. SPIE 6276, 6275OU, 2006. https://doi.org/10.1117/12.673162 (295 citations)

[3.2] Holland, W. S. H., et al., *SCUBA-2: the 10 000 pixel bolometer camera on the James Clerk Maxwell Telescope*, MNRAS, 430, 2513, 2013. https://doi.org/10.1093/mnras/sts612 (325 citations)

[3.3] 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)

[3.4] André, Ph., et al., *From filamentary clouds to prestellar cores to the stellar IMF: Initial highlights from the Herschel Gould Belt Survey*, Astronomy & Astrophysics, 533, A119, 2011. https://doi.org/10.1051/0004-6361/201014666 (864 citations)

[3.5] Devlin, M. J., et al., *Over half of the far-infrared background light comes from galaxies at z>=1.2*. Nature, 458, 737, 2009. https://doi.org/10.1038/nature07918 (143 citations)

[3.6] Goldie, D., et al., *First characterization of a superconducting filter-bank spectrometer for hyper-spectral microwave atmospheric sounding with transition edge sensor readout,* Journal of Applied Physics, 127, 244501, 2020. https://doi.org/10.1063/5.0002984 (1 citation)

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

The next-generation of European weather satellites (MetOp-SG) will enable a significant improvement in global weather forecasting through a series of new on-board MicroWave Sounder (MWS) instruments. The challenging performance requirements for the MWS instruments could only be met by a quasi-optical network solution enabled by Cardiff-developed dichroics. This quasi-optical network design was incorporated into an Airbus-led consortium bid to supply the MWS instruments for EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites). As a result, Cardiff's research:

- enabled Airbus Defense & Space to win a €156M contract for the design and supply of the MWS instrument;
- secured a €8.5M sub-contract from Airbus, for design and manufacture of the MWS optics, for UK-manufacturer Thomas Keating Ltd., creating almost 50 person-years of employment and facilitating expansion into the Chinese market.

4.1. Enabling EUMETSAT Satellite Technology

Between 2006 and 2018, EUMETSAT launched the first generation of polar-orbiting satellites, collectively named MetOp, which provide the primary inputs for European and global weather prediction agencies. In 2014, EUMETSAT announced the second generation of MetOP satellites (MetOP-SG), including a tender for three new MWS instruments.

These MWS instruments represent a significant improvement over current satellite sounding capabilities, offering nearly twice the number of spectral channels and almost twice the sensitivity, with predicted reductions in forecasting errors of around 15% **[5.1]**. They are 24-channel microwave radiometers covering 23.8 GHz – 230 GHz with a challenging set of requirements, including a wide range of co-located radiometric frequency channels within a single instrument, fed by a single main antenna. The incoming radiation must be split into seven frequency bands to feed receivers at the various foci. Each MWS receiver must view exactly the same ground scene through the main antenna, and therefore dichroics must split the frequency bands exactly to the MWS requirements, whilst simultaneously maintaining excellent beam quality, beam co-alignment, and very low end-to-end loss.

Airbus Defence and Space, the world's second-largest aerospace company, submitted a tender to develop the MWS instruments. The Airbus-led proposal specified a unique quasi-optical network design that incorporated Cardiff AIG dichroics. Commenting on the application of the AIG technology in the proposed design, Bob Podmore, the Airbus MWS Project Manager wrote: "*The predicted performance of our instrument solution exceeded the demanding European Space Agency and EUMETSAT requirements, fully supporting the Airbus project to supply three microwave sounder instruments*" **[5.2]**.

In December 2014, Airbus announced they had secured the €155.5M contract to deliver the three MWS instruments **[5.3]**. Cardiff AIG technology was pivotal in securing this contract, with Airbus stating that "*The state-of-the-art performance of this [quasi-optical network] is enabled by the dichroic plates that are uniquely supplied by Professor Peter Ade's group in Cardiff University, and these should be seen as the enabling technology*" **[5.2]**.

At the announcement of the contract award, Greg Clark, Minister for Universities, stated: "*This is a fantastic example of UK expertise in the development of world leading innovative satellite technologies and services*" **[5.3]**.

4.2. Securing subcontracts to design and build the MWS quasi-optical networks

Cardiff AIG has a long collaboration with Thomas Keating Ltd. (TK), a UK-based high-precision manufacturer of scientific instruments including for astronomy, cosmology, and atmospheric remote sensing. Following the successful Airbus tender, in September 2015 ESA and Airbus confirmed they would subcontract TK for the design and build of MWS technology, worth approximately €8.5M **[5.4]**.

Dr Richard Wylde, TK managing director, confirmed the role of the AIG research within the subcontract to develop the MWS technology, and stated: "*We have been able to combine the AIG's quite unique THz metamaterial filter technology and measurement capabilities with our own Quasi-Optical Electromagnetic design and manufacturing expertise*" **[5.5]**. The combination of TK's technical experience and Cardiff AIG research "*provided a solution to the highly challenging requirements that no other bidding consortium could match*". Dr Wylde additionally commented that this proposed solution *"would not be possible without the dichroics that are uniquely supplied by the Cardiff AIG*" **[5.5]**.

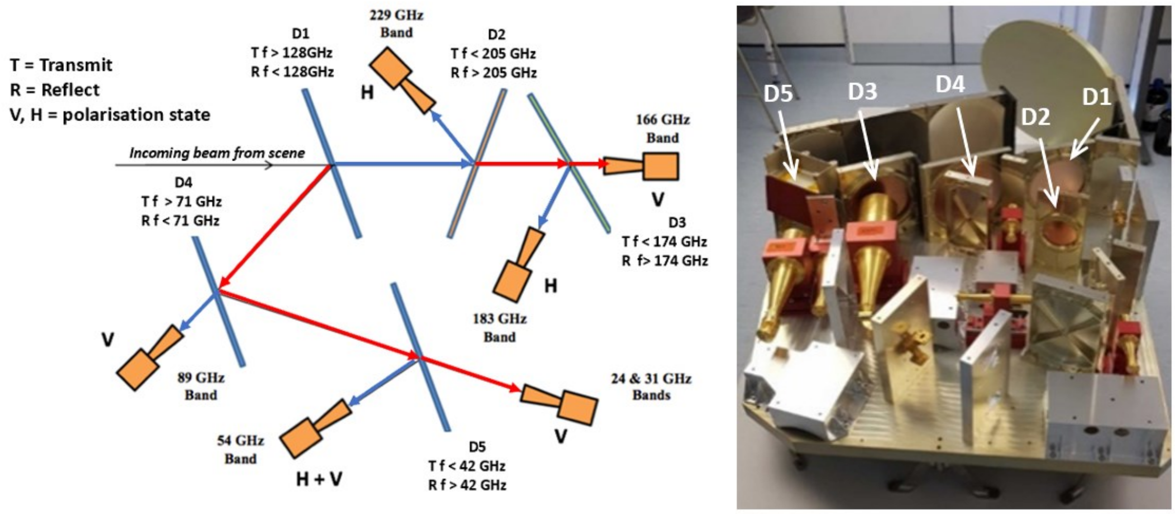

Figure 2. *Left: MWS quasi-optical network design with five dichroics enabling the input beam to be split into seven bands. Right: Engineering model of one of the MWS quasi-optical networks in the Cardiff AIG environmental testing chamber. The copper-coloured discs are the dichroics that efficiently split the incoming radiation (from the large elliptical mirror at the top) into the required frequency bands, with sharp transitions and very low loss.*

The complexity and scale of the MWS project provided TK with approximately 50 person-years of construction, calibration, and verification work in collaboration with Cardiff University **[5.5]**. The Quasi-Optical Networks (Fig. 2) are being assembled and tested in a custom-built facility in the Cardiff AIG laboratories, prior to delivery to Airbus. The Cardiff–TK partnership was praised by Airbus for delivering the required components: "*Throughout the development and build phase, the Cardiff University Astronomy Instrumentation Group have employed their* *unique capabilities in precision test and measurement to demonstrate that the as-built QON assembly meets the requirements for the MWS instruments*" **[5.2]**.

The scale of the MWS project and the subcontract to TK have been well publicised in the field. This approach also enabled TK to develop similar quasi-optical network designs for an equivalent series of Chinese weather satellites, with an initial contract value from the Shanghai Spaceflight Institute of around £500K to TK. Dr Wylde attributes this contract to the positive reputational gain in the remote sensing community from the well-publicised Cardiff AIG-TK collaboration on MetOp-SG MWS, with high expectation of further related work from Chinese and US customers **[5.5]**.

4.3. Summary

Cardiff's AIG dichroics proved to be an essential enabling technology for a set of three MWS instruments to fly on the next generation of global weather satellites. Airbus Defence and Space secured the €156M contract to supply the MWS instruments, enabled by a quasi-optical network design using dichroics developed by Cardiff. A subcontract was then delivered to AIG collaborator TK Ltd. for €8.5M, providing 50 person years of employment, as well as expansion of their business to China.

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

[5.1] Tennant, G., Hurd, D. and Kangas, V., *The NWP contribution from the microwave sounder (MWS) on MetOp-Second Generation*," Proc. 14th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment (MicroRad), 115, 2016, doi: 10.1109/MICRORAD.2016.7530517.

[5.2] Letter: Bob Podmore, Airbus MWS Project Manager, Airbus Defence and Space UK. Received 26th February 2020.

[5.3] "Airbus Defence and Space signs contract for Microwave Sounder instruments", Airbus Press Release, 9th Dec. 2014; Airbus website; accessed 27th February 2020.

[5.4] "ESA and Airbus placed €8.5m orders with Thomas Keating Ltd", UK Space trade association website news story, 15th September 2015; accessed 27th February 2020.

[5.5] Letter from Dr Richard Wylde, MD of Thomas Keating Instruments Ltd.