Institution: University of Kent

Unit of Assessment: 15 General Engineering

Title of case study: Radio-Frequency Engineering for Antenna Systems

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

We have developed enabling technologies for the defence, automotive and identification industries, the health service and the wider community where our contributions enable end users to maximise performance for a given cost. Work on Frequency Selective Surfaces (FSS) produced sub-reflectors for aerospace (BAE Systems – mm/sub-mm satellite radiometers for earth observations). Small antenna and RFID work led to new products in the automotive industry (Harada Industries), on-line fuel management systems (Timeplan Ltd), wireless smoke detectors (EMS Group), connectors (Martec), antennas (Panorama Antennas Ltd) and for Digital TV (Mitsubishi). Millimetre-wave over fibre systems linked antennas have supported the acquisition of new astronomical data, through the international ALMA (Atacama Large Millimetre Array) project, facilitating deeper public understanding of the universe.

2. Underpinning research (indicative maximum 500 words)

Our longstanding and widely recognised work on RF engineering includes research in low profile antennas and FSS integrated into buildings [2, 5], vehicles [1], and onto people [6], as well as low-cost signal transport for wireless/mobile communication at mm-wave frequencies [3,4]. The team has comprised J. Batchelor (1997-, Reader), N. Gomes (1990-, Reader), B. Sanz-Izquierdo (2013-, Lecturer), R. Langley (1979-2005), T. Parker (1967-, Emeritus Professor) and P.A. Davies (1980-, Emeritus Professor). Key researchers include B. Sanz-Izquierdo (2003-12), P. Shen (2001-10), I. Garcia-Zuazola (2005-08), M. Ziai (2011-) and P. Taylor (2012). Sanz-Izquierdo worked for Harada Industries in 2012 before returning to a permanent lectureship at Kent in 2013.

Compact and low profile antenna and FSS technologies are required for integration within structures, such as buildings, within vehicles and onto people. It is a major research challenge to make these designs efficient, small and low profile with respect to wavelength using materials such as plaster board, composite car body panels and human tissue where losses may be high, variable and poorly quantified. Buildings are complex in structure and influence the availability of radio channels within them. WiFi connectivity and mobile phone coverage is increasingly required to be universal, but significant problems are caused by radio signal blockage, interference and demand outstripping channel supply. The design of antennas and FSS for intimate integration into buildings has involved research on new low profile screens which can switch the channels that are permitted or prohibited within certain spaces. Originating in 1994, this long term initiative has defined designs that operate at the correct bands on building materials such as plasterboard and with conducting materials made from ink or low grade foils and with active control to switch in and out various bands [5]. Our work on multiband antennas for buildings in 2003 produced compact novel multiband, balanced planar inverted-F antennas in the European project ROSETTE [2] and led to our multiband antenna contribution to the project ISIS (FP6-IST-26592), where a resulting patent 'Langley and Batchelor GB2416625(A)' was published in February 2006.

We have created antennas for close integration with vehicles. Having hosted the Harada Europe Research and Development Centre (http://www.harada.co.uk/ResearchAndDevelopment.aspx) on the Kent campus (1997-2002), this established collaboration engendered new low profile multiband antennas for vehicles and on-glass antennas that are now a car industry norm. From 2001 to 2006, through recognition of the importance of car body structure on radiation patterns at VHF, our on-glass slot antenna modelling led to optimised antenna designs and positioning, identifying the significance of roof pillar position on radiation patterns at VHF [1]. Work on hidden antennas followed where the issue of nulls (dead spots in the radiation pattern) was identified as being due to the roof pillar spacings at broadcast radio bands. Work with DSTL for armoured vehicle mounted antennas commenced in 2010.

Our work on antennas which are closely integrated with other structures was extended in 2009 to passive UHF RFID where our patented surface independent 1mm RFID tags for conducting surfaces or bottles (e.g. fire extinguishers) are significantly thinner than commercial alternatives, which are typically several millimetres thick. An emerging RFID application is tagging people for identification (patients), security (locks) and ticketing where the major challenge is to obtain useful performance on biological tissue. In 2011, we published on-skin tag designs to create the world's first transfer tattoo RFID [6]. This work is now EPSRC funded (EP/J000086/1) in collaboration with

inkjet expert Prof. Yeates (University of Manchester) with whom fabrication cost, sintering, ink formulation and layer deposition issues together with substrate treatments are investigated.

Our work on radio signal distribution to antenna units through optical fibre (radio over fibre) examines low-cost signal transport for wireless/mobile communications and high performance systems at mm-wave frequencies. While optical fibre provides an excellent, broadband and low-loss transmission medium for signals modulated up to terahertz frequencies, at these higher frequencies, significant care needs to be taken to mitigate against dispersion and nonlinear effects. Exemplar work, pushing performance boundaries at high frequencies, was carried out in collaboration with Rutherford Appleton Labs (RAL), developing optical heterodyning photomixers detecting signals at up to 700 GHz (PPA/G/S/2000/00021, PP/B50014X/1), and the National Radio Astronomy Observatory (NRAO), USA developing reference sources for photonic millimetre-wave generation, and specifications for the optical transport of millimetre-wave reference signals. This work contributed to the international radio astronomy project ALMA. We developed a unique optical fibre frequency comb generator with unparalleled frequency span, tunability and stability [3], continuing in STFC and EPSRC funded projects (eg. EP/E021107/1). Our work on polarization effects in the fibre distribution of millimetre-wave reference signals [4], which required correction to equivalent fibre length variations of the order of micro-metres in 16km spans, led to major redefinitions of design requirements for fibre deployment and moving fibre parts, such as the antenna cable wrap (NRAO/Kent patent filing: 8127.006.US) and the fibre stretchers used in line length correction. Our contribution to the ALMA project has been cited by Prof Alwyn Seeds (UCL) as exemplar work on millimetre-wave/THz signal transport in an invited tutorial at the Annual Meeting of the IEEE Photonics Society in 2011.

The work has been funded by EPSRC, PPARC, NRAO, DSTL, CDE (Centre for Defence Enterprise) and the European Commission with academic partners in the UK (Sheffield, Manchester, RAL), France (IRSEEM in Rouen, IEMN in Lille), USA (NRAO) and New Zealand (Auckland). It has received industrial funding from Panorama Antennas Ltd, Mitsubishi ViL, RF Axicom Ltd and Martec Ltd. The total value of awards underpinning the group's impacts since January 1993 is £6.3 million and key grants since 2001 are specified in Section 3.

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

References to the key outputs (references [2]*, [4]* and [6]* best indicate the quality of the underpinning research):

[1] **Batchelor, J.C**., Langley, R.J., and Endo, H., 'On-glass mobile antenna performance modelling', IET Proceedings on Microwaves, Antennas and Propagation, vol.148, no.4, pp.233-238, 2001. DOI: 10.1049/ip-map:20010549. *This paper contains work on conformal antennas for automotive applications and was submitted by **Batchelor** to RAE 2008.*

[2]* **Sanz-Izquierdo, B.**, **Batchelor, J.C.**, Langley, R.J., and Sobhy, M.I., 'Single and double layer planar multiband PIFAs', IEEE Transactions on Antennas and Propagation, vol.54, no.5, pp.1416-1422, 2006. DOI: 10.1109/TAP.2006.874323. *This paper, submitted by **Batchelor** for RAE 2008, describes a highly space efficient multiband antenna with good balancing properties.*

[3] Shen, P., **Gomes, N.J.**, Davies, P.A., Huggard, P.G., and Ellison, B.N., 'Analysis and demonstration of a fast tunable fiber-ring based optical frequency comb generator", OSA/IEEE Journal of Lightwave Technology, vol.25, no.11 pp.3257-3264, 2007. DOI: 10.1109/JLT.2007.906818. *This paper describes the unique optical comb and millimetre-wave signal generation unit demonstrated at Kent and was submitted by **Gomes** to RAE 2008.*

[4]* Shen, P., **Gomes, N.J.**, Shillue, W.P., Albanna, S., 'The temporal drift due to polarization noise in a photonic phase reference distribution system', OSA/IEEE Journal of Lightwave Technology, vol.26, no.8 pp.2754-2763, 2008. DOI: 10.1109/JLT.2008.927780. *This output, submitted by **Gomes** to REF 2014, was the basis of the fibre distribution network design for ALMA.*

[5] **Sanz-Izquierdo, B.**, Parker, E.A. and **Batchelor, J.C.**, 'Dual-band tuneable screen using complementary split ring resonators', IEEE Transactions on Antennas and Propagation, vol.58, no.11, pp.3761-3765, 2010. DOI: 10.1109/TAP.2010.2072900. *This paper describes structures with novel biasing circuits, which offer independent tuning of two bands.*

[6]* Ziai, M.A. and **Batchelor, J.C.,** 'Temporary on-skin passive UHF transponder tag', IEEE Transactions on Antennas and Propagation, vol.59, no.10, pp.3565-3571, 2011. DOI: 10.1109/TAP.2011.2163789. *This paper describes the world's first temporary skin based RFID patch and is submitted by **Batchelor** to REF 2014.*

Key research grants

Davies and Gomes, PPARC (PPA/G/S/2000/00021), 'Photonic local oscillators for sub-millimetre wave heterodyne receivers', £214k, 2001-03.

Gomes and Batchelor, Interreg ERDF, 'ROSETTE – Radio-Optical Systems Engineering in Transmanche Telecom', £159k, 2003-05.

Davies and Gomes, PPARC (PP/B50014X/1), 'Photonic Local Oscillators for the ALMA project', £311k, 2004-06.

Gomes and Batchelor, Interreg ERDF, 'EXTRACTT – Extending Training, Research and other Co-operation within Transmanche Telecom', £137k, 2005-08).

Gomes and Batchelor, FP6-IST-26592, 'ISIS – InfraStructures for broadband access in wireless/ photonics and Integration of Strengths in Europe', £109k, 2006-08.

Gomes, EPSRC (EP/E021107/1), 'COMCORD: Coherent optical/millimetre-wave communication system with remote references delivery', £389k, 2007-2010.

Batchelor, EPSRC (EP/J000086/1) "Digital Fabrication of UHF Electromagnetic Structures", £418k, 2012-14.

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

The impact since 2008 of our antenna research resides in the development and exploitation of low profile antennas for a wide range of stakeholders including contributions to challenging areas such as their integration into buildings, vehicles and indeed onto people. This work has had particular impact on policy and practice in the defence and security domains. Kent research impacted on the revolutionary design and construction of ALMA, the largest and most sensitive telescope in the world at millimetre and sub millimetre wavelengths.

Numerous individual impacts resulted from Kent's underpinning research on mounted antennas, such as ceiling access point design for Panorama Antennas (2010) [S1], development of internal digital TV antennas for Mitsubishi VIL (2008), RFID wireless fuel management for Timeplan Ltd (2010-12) and pinless connectors for Martec Ltd (2008-11) [S2]. Given the commercial requirement for modern antennas to add almost no cost, while being embedded, compressed and optimised within larger products comprising a number of cutting edge technological subsystems, it is difficult to quantify the economic impact of the antenna alone. [Text removed for publication].

Our vehicle-mounted antenna work led to sustained impact through the team's association with Harada throughout this REF assessment period [S3]. Additionally, Batchelor's work with DSTL (Fort Halstead) and Roke Manor Ltd in 2010 analysed ground penetrating electromagnetic fields and the most suitable launching antennas. [Text removed for publication]. This was part of a multi-faceted programme demonstrating the viability of a military capability. Our study underpinned the feasibility of this new capability and since 2010 the level of interest has risen such that MoD is now running a ~£5M concept demonstrator programme. Specialised applications under operational conditions are planned. Quoting [S4]: Our work "progressed UK MoD Science and Technology understanding such that we [DSTL] hold a leading position in regard to international efforts to develop such capability. The UK retains this leading edge, which, in part, was supported by the output and access to the technical capabilities of your research group at the University of Kent".

Our body-centric communications and skin-mounted antenna work produced printed transfer tattoo RFID tags [S5]. This work was Highly Commended in both the 'Electronics' and 'Medical Technology' categories of the IET Innovation awards in 2011. Reports followed on national radio (2011) and in the Central Government edition of Public Service Review (issue 23, 2012). This work in collaboration with Yeates (Manchester), Great Ormond Street Hospital and DSTL resulted in an enabling technology for future passive wireless sensor networks. In May 2013 we launched a spin-out company, Mioband, to licence and fabricate our RFID technologies for wireless monitoring, rehabilitation and surveillance. We have received £70,000 in 2013 from DSTL (Fort Halsted) and as subcontractors to Evidentia Ltd. (CDE Contract 'Finding the Threat') to raise the Technology Readiness Level (TRL) of our passive RFID tags on-skin [S6]. In April 2013, DSTL Scientific Assessors rated our Tattoo tag as excellent 'with a high likelihood that it will go into service'. Our disruptive transfer tattoo RFID designs led in April 2013 to Batchelor's invitations to join the Steering Committee of the National Centre for Digital Fabrication offering services to industry and the DSTL Antenna Working Group with attendees from DSTL, MoD, GCHQ and HMGCC. In May 2013 our RFID technology was showcased to central government security staff [Text removed for publication].

Our work integrating Frequency Selective Surfaces (FFS) into buildings was instigated by Canterbury prison for preventing illicit mobile phone use. This work was supported and then publicised by the National Policing Improvement Agency in their Automotive and Equipment Section of the AES Newsletter (2009). We demonstrated through international collaboration with the University of Auckland that FSS can be manufactured in common wall materials. Impact on professional practice followed in 2010 when Kent joined the committee of the Wireless Friendly Buildings Forum (http://www.wfbf.org.uk/), a consortium of architects and civil engineers, led by consulting architects Buro-Happold. This involvement has been key in facilitating uptake of the technology with, for example, our work being presented to the Metropolitan Police at a Wireless Friendly Buildings Forum meeting in 2011. In March 2013 LD Consultants included our FSS screening technology in their bid to provide communications to the new central law court complex (Euro 575m) to be built in the Batignolles district of Paris [S7].

Our input to the ALMA (http://www.eso.org/sci/facilities/alma.html) project was so significant that a visit was made to the high-site in Chile by our key researcher for the commissioning of the phase reference distribution system [S8]. ALMA was the major radio astronomy project of the past decade: up to 66 radio telescopes, scanning at up to 900 GHz, and separated by up to 16 km, work as a synchronised single telescope, thus enabling unprecedented resolution. The benefits to an in-depth understanding of the universe are significant: already ALMA observations have shown that stars were being born in the early universe much earlier than previously thought, generating significant public interest [S9]. The operation as a single array telescope is only possible due to the precise reference signal distribution system underpinned by the Kent research [S8, S10].

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

S1. Director, Panorama Antennas Ltd, will confirm that new products marketed by his company have arisen from collaboration with researchers at Kent.

S2. Engineering Manager, Martec Ltd, will confirm that a successful Knowledge Transfer Partnership with the University of Kent has led to a new product range of wireless connectors.

S3. R&D leader and Product Manager, Harada Europe R&D Centre, will confirm that research collaboration with Kent has impacted on printed screen antennas, among other designs that have been installed in vehicles.

S4. Principal Engineer, DSTL (Fort Halstead), will confirm that research at Kent has provided insight and impact in enabling technologies to be deployed by the armed forces.

S5. Technical Services Manager, Axicon Auto ID Ltd, can confirm that RFID expertise at Kent has enabled his company to complete contracts for external clients in the global packaging industries.

S6. Chairman, Video Vest Ltd (http://www.videovest.co.uk/index.htm), can confirm that Kent RFID and networking expertise developed new wireless technologies for assessment by central government security.

S7. Managing Director, LD Consultants (www.ld-consultants.co.uk), can confirm that research expertise in Frequency Selective Surfaces as wireless architecture has been included in a bid to fit the new Paris Central Law Complex.

S8. National Radio Astronomy Observatory, Charlottesville, VA, USA will confirm the contribution to the design of the phase reference distribution system, and its significance, and the need for Dr Shen of the University of Kent to visit the high-site for commissioning.

S9. *The Independent* news article “Science fiction becomes science reality as Chile unveils $1.4bn ALMA telescope” [http://www.independent.co.uk/news/science/science-fiction-becomes-science-reality-as-chile-unveils-14bn-alma-telescope-8533254.html] and other articles confirm the significant public interest generated by the research enabled by ALMA.

S10. UK ALMA Project Manager, Science and Technologies Facilities Council, Rutherford Appleton Labs, UK will confirm the significant public interest in ALMA, and the important contribution made by the University of Kent.