Institution: University of St Andrews

Unit of Assessment: UoA 09: Physics

Title of case study: Commercialisation of high-performance millimetre wave feedhorn antennas

Period when the underpinning research was undertaken: 2004 - 2019

Details of staff conducting the underpinning research from the submitting unit:

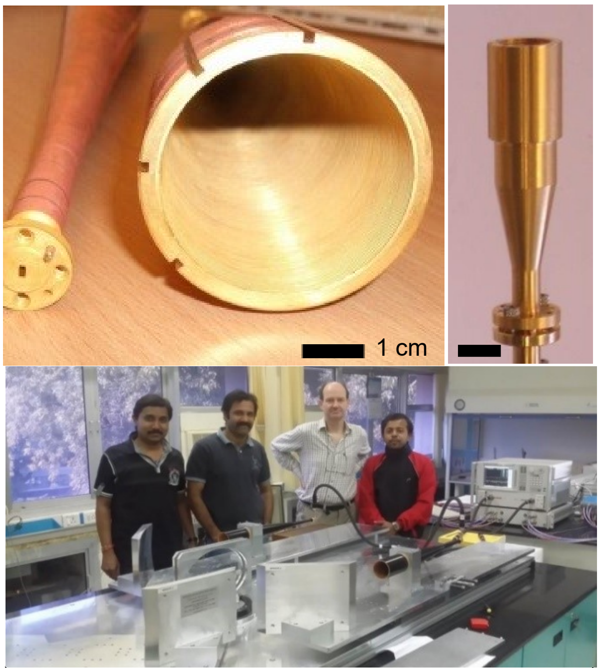
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Graham M. Smith	Professor	01 May 1993 – present
Duncan A. Robertson	Principal Research Fellow	01 August 2000 – present

Period when the claimed impact occurred: 01 August 2013 - 31 December 2020

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

Section B

1. Summary of the impact



‘Ultra-Gaussian’ corrugated feedhorns (top) and as part of a quasi-optical system delivered to a customer in India by Thomas Keating Ltd.

High-performance feedhorns designed at St Andrews have achieved direct global sales totalling approximately GBP1,300,000 for our industrial partner, Thomas Keating Ltd, between August 2013 and January 2020. These antennas have been critical components within larger quasi-optical systems, which have achieved sales totalling approximately GBP3,400,000 in that period. This amount represents 33% of the company’s turnover and has enabled this SME to create 10 jobs (headcount: 10; FTEs: 10) and grow its workforce to 50 people. This economic impact stemmed directly from our research on high-performance corrugated feedhorn antennas and how they can be used to reduce losses, scattering, and standing waves in quasi-optical systems. The original work was done under an EPSRC Basic Technology grant in which Thomas Keating Ltd was the industrial partner. These horns are now used in at least 13 countries worldwide and bring performance benefits to end-users in applications as diverse as EPR and DNP spectroscopy, metrology, and satellite remote sensing, including the NASA/MIT TROPICS CubeSat mission. As a result of this industry-academia partnership, Thomas Keating Ltd has become the world’s leading supplier of high performance corrugated feedhorns and quasi-optical instrumentation.

2. Underpinning research

A millimetre wave corrugated feedhorn antenna converts an electromagnetic waveguide mode to a desired optical beam with high efficiency. These antennas are often used in high performance quasi-optical instruments to couple signals optically between sources and detectors for applications associated with metrology, materials characterisation and magnetic resonance, such as electron paramagnetic resonance (EPR) and dynamic nuclear polarisation (DNP). Feedhorn antennas are also commonly used to illuminate larger reflector or lens antennas in imaging radars, line of sight communication systems, satellite radiometers for remote sensing and meteorology, and advanced telescopes for measuring molecular clouds or the cosmic microwave background.

Key performance attributes for feedhorn antennas include: beam quality / purity / symmetry, level of sidelobes, frequency scalability, and size and weight (especially important for satellite applications). The design challenge is to precisely excite and optimally phase a set of electromagnetic modes within the antenna, which will then couple with high efficiency to a desired optical beam, such as a free space fundamental Gaussian (laser-like) beam. High coupling efficiency to a desired optical beam over wide bandwidths is often a critical design specification in high-value radiometers, telescopes and quasi-optical systems.

The original motivation for Prof. Smith's Millimetre Wave & EPR Group at St Andrews to develop advanced corrugated feedhorns was for next-generation EPR spectroscopy instrumentation, under an EPSRC Basic Technology Project between 2004 and 2007. At the time, conventional linear profile corrugated horns were available which have a Gaussian coupling efficiency of approximately 95% to 98%. However, the 2% to 5% of residual higher order modes could get trapped or scattered in the quasi-optics of our EPR system, which would have seriously limited its performance.

We first analysed how the antenna's internal profile affects the generation and phasing of electromagnetic modes within corrugated horns and their effect on optical beam quality. We then developed a design which generates the optimum amplitudes of the first two modes in the antenna and phases them correctly at the aperture to achieve a Gaussian coupling efficiency of 99.7%. The design was commercialised by our industrial partner, Thomas Keating Ltd, from 2007 under the name "ultra-Gaussian" horns. Their performance has been a major selling point in larger millimetre wave systems. The increase in Gaussian coupling efficiency appears small, but results in higher purity optical beams, lower losses and lower standing waves in quasi-optical systems, as reported in 2007 [R1]. These ultra-Gaussian horns were instrumental in the realisation of our state-of-the-art EPR spectrometer system, 'HIPER', in 2009 [R2], now a major part of the facilities available within the interdisciplinary Centre for Magnetic Resonance at St Andrews.

We reported detailed analysis and experimental verification of the ultra-Gaussian design in 2013 [R2], showing high purity beams over a wide 20% relative frequency bandwidth. We also confirmed scalability of the design with gain and frequency.

In 2013, we developed a much more compact design [R3] that further improved beam purity (greater than 99.9% Gaussian coupling) by optimising the first three antenna electromagnetic modes. This low mass, low volume geometry is particularly attractive for space applications and was verified experimentally in 2016 [R4].

This compact design methodology was applied to the challenging requirements for a NASA-funded quad-band radiometer instrument to be flown on the MIT Lincoln Lab CubeSat mission called TROPICS (Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats). This large constellation of miniature satellites is designed to offer continuous real-time monitoring of tropical cyclones. The antenna design (2018), which is critical for meeting system performance, uses a pair of miniature dual-band horns, multiplexed by polarisation, to illuminate a small parabolic reflector (the primary collecting antenna of the radiometers) within the tight physical constraints (10x10x10cm) of the Cubesat form factor [R5].

We have developed a new design methodology that significantly extends the bandwidth of high performance feedhorns over what has been achieved before. Typically, between approximately 40% to 50% relative bandwidth is now achievable with high coupling efficiency to a wide variety of optical beams including: Gaussian beams, Airy beams (for maximum aperture efficiency) and constant gain beams. This is a major advance which is currently being evaluated for multiple applications associated with quasi-optical instrumentation, radar and radiometry.

3. References to the research

The research described was supported by peer-reviewed grants and all papers below were published in internationally recognised peer-reviewed journals and conference proceedings.

R1. P. A. S. Cruickshank, D. R. Bolton, D. A. Robertson, R. J. Wylde, G. M. Smith, "**Reducing standing waves in quasi-optical systems by optimal feedhorn design**", *Proc. Joint*

32nd Int. Conf. Infrared Millimeter Waves 15th Int. Conf. Terahertz Electronics, pp. 941-942, 2007.DOI: 10.1109/ICIMW.2007.4516802

R2. P. A. S. Cruickshank, D. R. Bolton, D. A. Robertson, R. I. Hunter, R. J. Wylde, and G. M. Smith, **"A kilowatt pulsed 94 GHz electron paramagnetic resonance spectrometer with high concentration sensitivity, high instantaneous bandwidth, and low dead time"**, Review of Scientific Instruments, 80, p. 103102, 2009. DOI: 10.1063/1.3239402

R3. J. McKay, D. A. Robertson, P. A. S. Cruickshank, R. I. Hunter, D. R. Bolton, R. J. Wylde and G.M.Smith, **"Compact Wideband Corrugated Feedhorns With Ultra-Low Sidelobes for Very High Performance Antennas and Quasi-Optical Systems"**, IEEE Antennas and Propagation, 61, (4), pp 1714-1721, 2013. DOI: 10.1109/TAP.2013.2243097

R4. J. E. McKay , D. A. Robertson, P. J. Speirs , R. I. Hunter, R. J. Wylde, G. M. Smith., **"Compact corrugated feedhorns with high Gaussian coupling efficiency and -60 dB sidelobes"**, IEEE Transactions on Antennas and Propagation, 64, (6), pp 2518 - 2522, 2016. DOI: 10.1109/TAP.2016.2543799

R5. I. Osaretin, W. Blackwell, R. Wylde, S. M. Tun, G. Smith, "**High-Performance Reflector Antenna Design for the TROPICS Mission",** IEEE Int. Symp. Antennas and Propagation & USNC/URSI National Radio Science Meeting, pp. 1719-1720, 2018. DOI: 10.1109/APUSNCURSINRSM.2018.8608857

4. Details of the impact

Commercialisation of our research on high performance millimetre wave feedhorn antennas (described in Section 2) has led to **sustained economic impact** since 1 August 2013 for our industrial partner Thomas Keating Ltd. **Global sales across at least 13 countries** of St Andrews designed ultra-Gaussian horns have totalled GBP1,300,000 within sales of quasi-optical systems which incorporate them **worth GBP3,400,000**. This increase in business has **created 10 new jobs** (headcount: 10; FTEs: 10)**,** allowing Thomas Keating Ltd to grow their workforce (headcount: 50; FTEs: 50). **Thomas Keating Ltd is now the world's leading supplier of high performance, high frequency corrugated feedhorns and quasi-optical instrumentation.** The high performance of our feedhorn designs and the quasi-optical systems and antennas in which they are used have **brought significant performance benefits to a diverse range of end-users worldwide**.

Translation of research designs into commercial products

This successful economic and end-user impact has been possible because of the very close working relationship between the Millimetre Wave & EPR Group, headed by Prof. Graham Smith, at the School of Physics and Astronomy at the University of St Andrews, and the staff of Thomas Keating Ltd, particularly their Managing Director. This collaboration dates back to the 1990s but is central to the delivery of the impact from our feedhorn research since our EPSRC Basic Technology and Translation grants on which Thomas Keating Ltd was the industrial partner. The company took our research designs and perfected their manufacture using advanced electroforming technology and then subsequently marketed them commercially.

Our first new feedhorn design [R1] was fabricated for us by Thomas Keating Ltd for our 'HIPER' EPR spectrometer [R2]. Realising the performance attributes of this design would be widely applicable for users of quasi-optical systems worldwide, Thomas Keating Ltd began marketing our design under the 'ultra-Gaussian' or 'UG' name [S1].

Between August 2013 and 2019, EPSRC Impact Acceleration Account funding supported the design and characterisation of several novel feedhorn designs (fabricated by Thomas Keating Ltd at cost). This included the very compact high performance design in 2016 [R4] suitable for space applications, which has led to our latest designs which couple free space beams with very high efficiency over a full waveguide band (>40% relative bandwidth) in 2019.

Commercial success and economic growth for Thomas Keating Ltd

Between August 2013 and January 2020, **Thomas Keating Ltd's sales of St Andrews designed high-performance feedhorns** have consistently achieved **approximately GBP200,000 per year** with a **total of GBP1,300,000**. This is **within sales of larger quasi-optical systems incorporating these feedhorns** that have consistently achieved **sales of over GBP500,000 per year with a total of GBP3,400,000,** which amounts to **33% of the company's turnover**. As a result, the company has **grown its workforce by 10 staff** (headcount: 10: FTEs: 10) from 40 to 50 people (headcount: 50; FTEs: 50). Within the above, total sales of feedhorns and quasi-optical systems specifically for EPR and DNP exceeds GBP660,000. **Thomas Keating is now the world's leading supplier of millimetre wave electroformed feedhorns and quasi-optical EPR and DNP systems** [S2].

Thomas Keating Ltd's Managing Director states: "*The link with St Andrews has been really crucial to the transit of our toolmaking business, whose origins go back to the 1780s, to an export driven scientific Instrument business (Queens Award for Export 2012). Very little toolmaking remains in the UK as manufacturing has left these shores. Without this transit, our business may well not have survived and prospered. The impact has been wider than the pure financial numbers might suggest as we are known around the world for our Quasi-Optics systems based upon UG horns. This generates both direct and related sales and thereby sustains a profitable (i.e. corporation tax paying) business whose employment has risen from 40 to 50*" [S2].

The **global customer base covers at least 13 countries from Hong Kong and South Korea, to the USA and throughout Europe.** In order to further extend international market reach, Thomas Keating Ltd has partnered with leading US-based Test & Measurement company, Keysight Technologies, to supply quasi-optical benches with their vector network analyser instruments for the characterisation of the dielectric properties of materials. Keysight's 2019 application note states: "*At mm-wave and submm-wave frequencies, Quasi-Optical Tables are ideal. They can be purchased from Thomas Keating Ltd, or through Keysight Special Handling Engineering*." [S3, p. 25].

Quasi-optical scatterometer delivered to ESA showing two gold plated ultra-Gaussian horns.

End-user benefits of high performance feedhorns

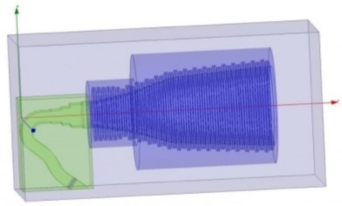
In many cases, the feedhorns have been an enabling technology in high performance instruments that have **delivered state-of-the-art results to end-users across diverse applications** including EPR, satellite radiometers, antenna testing, and metrology [S2], as explained below.

Thomas Keating Ltd, as the world-leading supplier of millimetre wave quasi-optical systems for **EPR and DNP spectroscopy,** has delivered multiple systems internationally which incorporate ultra-Gaussian horns. **These include EPR quasi-optical systems** that were copies of the St Andrews 'HIPER' system and which **are now National facilities at two US National Labs** (National High Magnetic Field Lab and Pacific NorthWest National Lab) [S4, S5]. The 'HIPER' system itself is now a key part of the facilities at the Centre of Magnetic Resonance at St Andrews.

A Professor at the Institute for Physical Chemistry, University of Stuttgart, explains the benefits these horns bring to EPR and DNP: "*we started using carefully designed quasi-optical bridges made by Thomas Keating Ltd in the UK. These bridges include tailor-made ultra Gaussian horns that allow for an enormous improvement in beam quality. As a consequence of using such radiation horns, we have been able to strongly increase the quality of our measurements*" [S6]. Using the horns and quasi-optics has enabled him to switch from using large, expensive, and unreliable vacuum tube-based signal sources to smaller, cheaper, and more reliable solid-state sources. It says "*it is only because of the improvement in beam quality that we have been able to adopt the competing technology of solid-state THz sources that are much more sustainable in terms of future procurement and also substantially cheaper*" [S6].

The benefits of ultra-Gaussian horns are also felt in **metrology and material characterisation**. Automotive supplier Continental uses a quasi-optical measurement system from Thomas Keating Ltd for production testing of radomes and bumper/paint layer optimization for 76 to 81GHz collision avoidance car radar. Their requirements are to measure the transmission loss and reflection from avoidance car radar. Their requirements are to measure the transmission loss and reflection from samples. A low transmission loss is desirable as it maximises the detection range of the car radar. Accurate measurements of the reflection are required to minimise errors in the angle measurement algorithm of the radar sensor. Their Head of Advanced Engineering Radar, states: "*By using the ultra gaussian horns and the mirrors, the complete setup showed"* a transmission loss *"of better than -0.5 dB"* (i.e. transmission of 89%) *"and we could remove the loss of the setup much easier."* This allows them to make more accurate measurements of the loss of samples. He goes on to say *"Previously, reflection measurements had almost been impossible...*" and since using the ultra-Gaussian horns and quasi-optical bench "*the reflection measurements had been much more consistent*" [S7]. This enables them to improve the angular accuracy of their radar units.

Our designs have also been used for **satellite remote sensing**. In 2017 MIT Lincoln Laboratory contracted Thomas Keating Ltd to supply compact, high frequency, dual-band feedhorns and reflector antennas for the TROPICS CubeSat constellation. Graham Smith delivered the compact feedhorn designs (based on Rx) which exceeded the stringent electromagnetic and space constraints. Mission Principal Investigator at MIT LL, said: "*Prof. Graham Smith designed two ultra-compact feedhorns … for the TROPICS satellites to meet a set of extremely ambitious requirements for size and performance... This antenna system is the first of its kind to deliver such high performance in a compact package and is a key enabling technology for the TROPICS mission and the CubeSat constellation missions*." [S8] This design success **enabled Thomas Keating Ltd to win USD500,000 in initial design and production contracts** over a leading US supplier, delivering the first 7 units in 2019.



TROPICS compact horn (top) & antenna assembly (right).

5. Sources to corroborate the impact

S1. Thomas Keating Ltd's Ultra Gaussian Corrugated Horns webpage, p. 1, (March 2020) http://www.terahertz.co.uk/tk-instruments/products/corrugatedhorns/ultra

S2. Letter from Managing Director, Thomas Keating Ltd, pp.1-2 (April 2020)

S3. Keysight Application Note 5989-2589 "Basics of Measuring the Dielectric properties of Materials" https://www.keysight.com/gb/en/assets/7018-01284/application-notes/5989-2589.pdf, p.25 (Jan 2019).

S4. https://nationalmaglab.org/user-facilities/emr/instruments-emr/hiper (Sept. 2020)

S5. https://www.emsl.pnnl.gov/emslweb/10.25582/inst.34136 (Sept. 2020)

S6. Letter from a professor at the Institute for Physical Chemistry, University of Stuttgart, Germany, p. 1 (March 2020).

S7. Email from the Head of Advanced Engineering Radar, Advanced Driver Assistance Systems Business Unit, Continental, Germany, p. 1 (Feb 2020).

S8. Letter from the TROPICS Mission Principal Investigator, MIT Lincoln Laboratory, Lexington, MA, USA, p. 2 (March 2020).