Institution: University of Oxford		
Unit of Assessment: 9: Physics		
Title of case study: Radio astronomy technology for the global satellite and space industry		
Period when the underpinning research was undertaken: 2005 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
Mike Jones	Professor of Experimental Cosmology	2005 – Present
Steve Rawlings	Professor of Physics	2005 – 2012
Angela Taylor	Professor of Experimental Astrophysics	2005 – Present
Period when the claimed impact occurred: 1st August 2013 – 31st December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Technical capabilities developed for astrophysics and cosmology research at Oxford supported the growth of a start-up company, Goonhilly Earth Station, from its birth to becoming a major player in the global satellite communications industry. This long-term collaboration has supported job creation and secured UK participation in international commercial space projects and supported companies such as SES, Planet Labs and SpaceX. This same radio-astronomy expertise that rejuvenated an aging satellite-communications site in the UK was then put to use overseas in Africa and Mexico to create new jobs and foster a high-technology science industry through training and technology transfer. The same team also collaborated with local industry in the UK, enabling a company (Oxford Cryosystems) to enter a new market that secured large long-term contracts for their products (including a GBP500,000 contract for the MeerKAT radio telescope).

2. Underpinning research (indicative maximum 500 words)

This case is based on the research programme in Experimental Radio Cosmology in Oxford Physics. The research is based on concepts of designing and building novel instruments and telescopes to answer fundamental questions in cosmology and astrophysics that cannot be addressed with existing common-user facilities. Many of the underlying science goals are based in cosmology – the Cosmic Microwave Background (CMB), and the history of structure formation in the universe.

The main research activity has been the observation of the CMB at centimetre wavelengths: the measurement of its angular-power spectrum in intensity and polarization, the detection of secondary anisotropies such as the Sunyaev-Zel'dovich effect **[1,2]**, and more recently the characterisation of the Galactic foreground emission that hinders the precise measurement of CMB polarization **[3]**. The ultimate goal of these measurements is to understand the physics of inflation by detecting the signature of the primordial gravitational-wave background, which is imprinted in the polarization of the CMB.

The development of the universe on large scales is also traced by the evolution of active galaxies, which contain supermassive black holes at their centres. These often evolve into powerful sources of radio emission, allowing them to be detected across the entire observable universe. Radio telescopes such as e-MERLIN **[4]** and (in the future) the Square Kilometre Array (SKA), which combine high sensitivity with high angular resolution, are used to image the cores of these galaxies, and are able to distinguish, for example, between radio radiation generated directly because of the black hole and emission from the bursts of star formation that are also associated with active galaxies.

Our research programme required the development of techniques in very high-sensitivity radio measurements, across the whole range of techniques in radio astronomy – design of antennas, cryogenic receivers, broadband signal-processing systems both analogue and digital, and processing and analysis of the output data. The development of these techniques is itself also a significant area of research; Oxford has made state-of-the-art developments in

all these fields. For example, **[5]** describes the C-Band All-Sky Survey (C-BASS), a project led by Oxford, in which two ex-telecommunications antennas were modified to improve their performance, fitted with cryogenic receivers, and used to survey the sky at 5GHz to identify foreground emission contaminating the CMB. The instrument concept as well as all the key technical features of the instrument were designed and built in Oxford, which also manages the data-analysis and science exploitation effort.

Due to this record in developing innovative experiments such as C-BASS, Oxford Physics was selected by the Square Kilometre Array Organization (SKAO) to develop the main multi-frequency cryogenic receiver package ('Band 3-4-5') for the SKA, the world's largest radio telescope. The design required a high degree of innovation in cryogenic and Radio Frequency (RF) design to meet the requirements of sensitivity, power consumption and cost over the very large frequency range of 1.6 – 15.3GHz **[6]**. Amongst many other science goals, this receiver will provide the SKA with one of its key science capabilities, the ability to resolve the pebble-scale accretion in protoplanetary disks, complementing the ability of ALMA to image dust disks. SKA development has been funded by the UK Government with two explicit goals: to provide astronomers with the tools to make future discoveries, but also to provide UK industry with the opportunity both to construct components for the SKA and to benefit from the new technologies involved.

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

1. Implications of the Cosmic Background Imager Polarization Data, Sievers, J.L. et al including Jones, M.E. and Taylor, A.C. The Astrophysical Journal, Volume 660, Issue 2, 2007. DOI: 10.1086/510504 (journal article).
2. The Cosmic Background Imager 2 Taylor, A.C. Jones, M.E. et al, Monthly Notices of the Royal Astronomical Society, Volume 418, Issue 4, 2011 DOI: 10.1111/j.1365-2966.2011.19661.x (journal article).
3. The C-Band All-Sky Survey Jones ME, Taylor AC, et al, Monthly Notices of the Royal Astronomical Society, Volume 480, Issue 3, November 2018, https://doi.org/10.1093/mnras/sty1956 (journal article).
4. Expanding e-MERLIN with the Goonhilly Earth Station, Heywood I and Rawlings S I et al. Astronomy with Megastructures: Joint Science with the E-ELT and SKA, 2011 https://arxiv.org/abs/1103.1214 (conference proceedings).
5. The C-Band All-Sky Survey, Taylor A C., in proceedings of the 53rd Rencontres de Moriond, 2018. https://arxiv.org/abs/1805.05484 (conference proceedings).
6. MID-Radio Telescope, Single Pixel Feed Packages for the Square Kilometre Array: An Overview. Y IEEE Journal of Microwaves 2020. Pellgrini A et al, Authors include Jones ME, Taylor AC. https://arxiv.org/abs/2010.16317v2 (journal article).

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

Supporting the formation and success of Goonhilly Earth Station

In 2008, Oxford Physics began working with an entrepreneur planning to acquire the Goonhilly Earth Station (GES) site. This site, owned by BT, was the largest commercial telecoms satellite ground station in the world and had been in operation since 1962. Due to the obsolescence of large dishes for global satellite communications and their replacement by sub-sea optical cables, it was scheduled to be demolished until Oxford Physics intervened. The team at Oxford Physics realised that the antennas at Goonhilly had significant potential for radio-astronomy research, for example, by adding them to the UK's national radio-astronomy facility, e-MERLIN, which would double its resolution for deep multi-wavelength studies of galaxy evolution. In addition, if fitted with C-BASS-style receivers, they could be used as single-dish radio telescopes to complement Oxford's CMB research. The entrepreneur became the GES CEO and planned a business model including the synergy between radio astronomy and commercial satellite-communications technologies, benefitting from access to Oxford's cutting-edge radio-astronomy technology. For example, cooled receivers, which provide much improved noise performance, are rarely used in communications due to their perceived complexity. Oxford Physics has extensive experience with their design, development and deployment and so would be able to build receivers for

GES antennas that could be used for both commercial communications and research **[5, 6]**. Rawlings lobbied BT in 2008 to preserve the antennas from demolition and engage in efforts to re-purpose the site **[A],** and plans for antennas based on Oxford's research (specifically the C-BASS receiver and digital backend **[5]**) were crucial to the viability of the business model funded in GES's series B investment **[B]**. Goonhilly Earth Station (GES) CEO said: "*The intervention from Professor Rawlings helped persuade BT to stop the demolition"* and *"the strong support from Oxford University in backing the concepts in our business plan assisted in us gaining our first successful venture finance series A funding of £3.8m [GBP3,800,000] in January 2014*." **[B].** GES fully acquired the site from BT in 2014 and has grown from 6 employees (headcount: 6; FTEs: 6) in 2014 to 49 (headcount: 49; FTEs 49) in 2020. GES CEO continued: "*A key part of our business plan is to develop a private global Deep Space Network. To allow us to be competitive, we have worked closely with Professor Jones and Professor Taylor in developing concepts for maintaining the required antenna performance with a lower-cost, smaller aperture solution. Input from the university was critical in helping us to develop a business plan to attract our series B investment. In 2018, following the award of an £8.4m [GBP8,400,000] ESA contract to upgrade our largest 32m antenna for use in deep space communication, we successfully completed our series B investment with UK billionaire, Peter Hargreaves. The investment was worth £24m [GBP24,000,000]. Our close collaboration with Oxford University was an important factor in securing the deal.*" **[B]**. GES now provides spacecraft tracking services to many of the world's largest satellite operators, GES CEO said: "*We are now a major player in the global ground station business, supporting the operations of companies such as SES, Planet Labs and SpaceX, including the recent first privately-operated crewed flight to the International Space Station". "We provide services to all the world's leading space operators, we are building the world's first private global deep space network and we have a diverse and broadening portfolio in space systems consultancy, space AI and machine learning, high performance computing, space situational awareness, training, education and outreach. None of this transformation would have been possible without the outstanding and bold collaboration with Oxford University".*

The Consortium of Universities for Goonhilly Astronomy (CUGA) (Oxford, Manchester, Leeds, Herts, Durham and Central Lancashire) coordinates research with GES. While other universities made cash contributions, Oxford Physics supplied a cryogenic receiver based on the C-BASS project, allowing both radio astronomy and communications use. This was commissioned in 2019 and is now used by GES for UK Government contracts in space situational awareness **[B]**. In July 2020, GES was awarded GBP1,700,000, via the Cornwall and Isles of Scilly Local Enterprise Partnership (LEP), from the UK Government Getting Building Fund as part of a GBP3,770,000 project to invest in a production facility for cryogenic receivers for radio astronomy and communications (the 'Receiver Factory') **[C]**, directly based on research carried out in Oxford Physics for C-BASS and SKA **[B]**.

Enabling local industry

During the research and development stage of the cryogenic receiver for the C-BASS Southern Sky survey **[3,5]** it became clear that a new, low-power, low maintenance coldhead would need to be integrated into the system in order to allow long-term operations at the remote desert site where observations were to take place. Existing solutions were not viable, but a market survey uncovered a potential solution from Oxford Cryosystems (OCS) which was being used in the field of X-ray crystallography. Oxford Physics approached OCS, who were previously unaware of the applications of their equipment in radio astronomy, and from 2015 collaborated with OCS to successfully integrate OCS equipment into a research receiver (for C-BASS), and recognize the potential application of OCS products to MeerKAT, a South African radio telescope with which Oxford Physics had long-standing research links **[3,6].** This resulted in OCS winning a GBP500,000 contract to supply coldheads to MeerKAT, completed in 2018, with a further GBP100,000 contract in 2020. OCS Managing Director commented: *"During this work we retained close links with Prof Jones and his team, who provided invaluable insight into the requirements of a radio telescope receiver, technical information on temperatures and heat loads but also practical insight into radio frequency interference, operating conditions, power budgets and so forth"* **[D]**. OCS coldheads were then selected as

the baseline for SKA in 2014. Based on this successful collaboration, in 2014 STFC funded Oxford Physics and OCS to develop a helium compressor for the SKA, combining their respective skills in radio instrumentation and cryogenics. OCS Managing Director commented said: "*This collaborative effort over a period of over 10 years made it possible for the SKA cryogenics contract worth approximately €8 million [EUR8,000,000] to be awarded to the UK. We are in pole position to supply both coldheads and compressors to the SKA project.*" "*Thanks to the research and collaboration with Profs Jones and Taylor and their team over this 10-year period, Oxford Cryosystems has become a strong player in a completely new market… The relationship is…a shining example of how collaboration between academia and industry can be of great benefit to both parties, delivering substantial impact for the UK economy*" **[D]**. Since 2014, Oxford Physics has been developing the Band 3-4-5 receiver package for SKA **[6]**. Against strong competition from other countries, the UK has been conditionally allocated the construction contracts for this and the SKA cryogenics. The Head of the SKA Project at STFC said: "*STFC's support has enabled the University of Oxford to lead the UK's interests in SKA MID Frequency Band 5 and MID Frequency Cryogenic Systems. This work is unique to the University of Oxford and no other UK university has played a role in these areas. This work has required the University of Oxford to work closely with UK Industry, the SKA Organisation (SKAO) and international partners, establishing strong collaborations from which UK research may benefit in the future. As a result of the research conducted at the University of Oxford, the UK has been conditionally allocated construction work to deliver both the SKA MID Band 5 Receivers and MID Cryogenic Systems for the MID Frequency Antennas. These contracts are estimated to be worth €11.6M [EUR11,600,000] and €8.5M [EUR8,500,000] respectively and are expected to be delivered by UK Industry. This represents approximately 17% of the construction work currently allocated to the UK and brings economic and societal return on the UK's investment in the SKA*" **[E]**.

Societal impact from fostering new technology and skills development overseas

Development in Africa with Radio Astronomy (DARA) is a Newton Fund project (2015) with Oxford, other UK universities and GES which uses radio astronomy as a vehicle for human capital development (HCD), developing high-tech and business skills in the eight African countries that will host SKA antennas: Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia. Oxford Physics taught a programme on radio telescope design and observations at an annual four-week residential course based at the Hartebeestoek Observatory, South Africa. The course included lectures and practical workshops where the students learned the underpinning physics and techniques required to build and use radio astronomy receivers as well as data analysis techniques. The modules all drew upon Oxford's recent research background and experience, in particular on the development of the SKA and CBASS receivers and the data analysis and science exploitation of the CBASS data **[5, 6]**. The DARA partner organisations have trained 140 students to date in radio astronomy, sharing technical and commercial expertise that inspires the students to boost economic growth by setting up their own businesses and passing on their knowledge and skills to the next generation. The Chair & Director of the Centre for Radio Astronomy Techniques & Technologies, Rhodes University, South Africa explained: "*A key aim of DARA is to impart generic skills that have application beyond Radio Astronomy, and that are particularly relevant to the developing economies in Africa. Examples include data analytics, telecommunications systems, and digital and radio frequency electronics. This use of Astronomy as a platform for driving training and research in modern technologies is consistent with the strategy of the South African Department of Science and Innovation. Such initiatives are seen as essential to enable social development and economic sustainability in the context of Africa....Past students have returned to their home countries and have used the skills that they acquired to good effect at academic institutions and within industry*" **[F]**. One participant from Zambia who took part in the DARA training programme has graduated as an Environmental Engineer. As well as working in this capacity for large companies he has started a small consulting firm with some of his university classmates. The DARA experience inspired him to try and expand the services that his small business can offer by utilising remote sensing data from satellites. *"It is because of the knowledge that I acquired through the DARA training program that barely a few months after I completed the training I got a job. The DARA*

program introduced me to Agri Big Data which can help in decision making in agriculture and increase Zambia's agricultural productivity. Agri Big Data is an exciting program one which I believe holds the answer to agricultural success for the developing countries of the world especially in Africa" **[G]**. The impact of the project was recognised by the Society of Satellite Professionals International (SSPI) with "The Better Satellite World Awards," in 2018, recognising the space-related project most likely to improve the world.

In a further Newton Fund HCD project with the Instituto de Radioastronomía y Astrofísica (UNAM) and the Mexican state of Hidalgo, Oxford Physics has provided the design of the receiver equipment (based on the C-BASS project) as part of a project to upgrade a satellite-ground-station antenna for modern radio astronomy. The converted antenna is a centrepiece of Hidalgo's strategy to shift their economy from mining to science-based industry **[H]** and the Tulancingo Radio Observatory is one of three laboratories forming the core of a strategic plan to position Hidalgo as a national leader in space-related science, technology and innovation **[I]**. The company Centro de Ingeniería y Desarrollo Industrial (CIDESI) benefitted from the collaboration with Oxford Physics, as the Head of Laboratory for Radio Astronomy Instrumentation at UNAM explained: *"Perhaps most significant was the development of human resources, as the engineering staff of CIDESI became acquainted with the special and demanding needs of the radio astronomy community for precise and reliable drive systems and antenna controls. Although CIDESI was already quite skilled in this area, their experience with the Oxford group served to develop their contacts with the academic/scientific community, beyond the manufacturing community that they generally serve. Their new-found expertise has permitted them to contract for services at state universities within Mexico which operate small radio telescopes, not only providing an essential support service to the universities but also generating multiple contracts for CIDESI at the level of [GBP10,000 to GBP20,000]"*. The primary contractor involved in the antenna conversion has also benefitted from the new experience gained on steerable antennas and is now able to seek similar contracts across Latin America. The Head of Laboratory for Radio Astronomy Instrumentation at UNAM commented: "*The transfer of these skills, developed in the research environment of Oxford, has had an extensive and diverse impact within Mexico… The State of Hidalgo and various subcontractors within Mexico have also directly benefitted from the Oxford radio group's involvement in Mexico… The radio observatory forms the foundation of the Hidalgo effort to attract high-tech industries to the state and to become the national leader in space technologies"* **[I]**.

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

[A] Letter from Prof Rawlings, University of Oxford, to British Telecom (the essential role of Oxford Physics in the formation of GES).
[B] Letter from CEO, Goonhilly Earth Station Ltd (describes how underpinning research and technology developed at Oxford Physics has been key to GES success and development).
[C] Press release from the Cornwall and Isles of Scilly Local Enterprise Partnership announcing the GES successful bid for funds for the 'Receiver Factory' (confirms Government funding of GES project based on Oxford Physics R&D).
[D] Letter from Managing Director, Oxford Cryosystems Ltd (confirms collaboration with Oxford Cryosystems and subsequent impact on their business).
[E] Letter from Head of SKA Project, STFC (confirms award of SKA Band-345 construction contract to the UK, based on Oxford Physics R&D).
[F] Letter from Chair & Director, Centre for Radio Astronomy Techniques and Technologies, Rhodes University (confirms Oxford Physics' role in DARA).
[G] Article from Newton Fund website on DARA (confirms Oxford Physics' role in DARA and subsequent impact).
[H] Article from Oxford Business Group on Hidalgo economy (highlights the impact of Oxford Physics R&D in development of science/technology strategy for the Mexican state of Hidalgo).
[I] Letter from Head of Laboratory for Radio Astronomy Instrumentation, Institute of Radioastronomy and Astrophysics, Mexico (describes the impact of the Oxford Physics Newton Fund Project in Mexico).