Institution: The University of Manchester		
Unit of Assessment: 9 (Physics and Astronomy)		
Title of case study: Establishing and directing the World's most significant radio astronomy infrastructure investment: the Square Kilometre Array		
Period when the underpinning research was undertaken: January 2000 – 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:**
Andrew Faulkner	Senior Research Associate	2004–2009
Simon Garrington	Professor	1993–present
Keith Grainge	Professor	2013–present
Michael Kramer	Professor	1999–2009
Anna Scaife	Professor	2015–present
Richard Schilizzi	Visiting Professor (2008), Director of SKA Programme Development Office (2009–2011), Professor (2012–2017), Emeritus Professor (2018–present)	2008–present
Ralph Spencer	Professor (1972–2010), Professor Emeritus (2010–present)	1972–present
Benjamin Stappers	Professor	2007–present
Peter Wilkinson	Professor (1980–2014), Professor Emeritus (2014–present)	1980–present
Period when the claimed impact occurred: 1 August 2013 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The international Square Kilometre Array (SKA) radio telescope, due for construction this decade, will be the world's largest scientific facility, built at a cost of ~EUR2,000,000,000 by a consortium of 15 member countries. The larger part of the instrument will be sited in Africa (nine partner countries) with a complementary part in Australia. The University of Manchester's (UoM) Jodrell Bank Centre for Astrophysics (JBCA) has been central to the establishment of this multinational radio astronomy infrastructure. The impact in the 2013-2020 period is on: i) international science policy and priorities, with the establishment of the SKA Organisation (SKAO) as an Inter-Governmental Organisation (IGO) at Jodrell Bank Observatory (GBP16,500,000); ii) UK business return (EUR121,900,000); and iii) the local North-West economy (~GBP6,200,000).

2. Underpinning research

The next transformational step in radio astronomy, which will shape its future for many decades, is the Square Kilometre Array (SKA), an international project to develop the world's largest radio telescope combining hundreds of dishes and millions of low frequency antennae in South Africa and Australia. When synchronised to within a picosecond, this array will have a collecting area in excess of one square kilometre, with the promise of dramatic advances in multiple fields and the opportunity to address fundamental challenges in physics. Researchers from UoM have made critical contributions to the SKA programme since its inception, including the scientific justification for construction, technical design elements, and supporting technologies that enable the SKA to function.

Defining the scientific requirements for the SKA: The originating idea for the SKA arose in Manchester in 1991. In 2004, the international astronomy community came together to describe the SKA's scientific potential and to establish the generic characteristics of a telescope with the required transformational capabilities. In 2005, this science case catalysed EC and pan-European national funding for a coordinated EUR32,000,000 programme of technological research, which gave initial substance to the ambitions. This research in turn formed a major component of the international preliminary design specification in 2011. In 2014, the science case for the SKA was revisited and a full science case was published. From the 2014 science case the SKA Organisation identified 13 "key science priorities" that should drive the design of the telescope. These formed the key reference for the SKA Level 0 Science Requirements, which in turn inform the Level 1 Technical Requirements for the instruments.

UoM researchers have made major contributions towards the scientific justifications for building the SKA, both through advancing the field of radio astronomy and determining how hypotheses could be tested by observing astrophysical phenomena. In particular, UoM researchers outlined the scientific justification for using the SKA to conduct a pan-galactic survey of pulsars, which will allow several physics hypotheses to be tested **[1]** including the possible detection of extremely low-frequency gravitational waves, the "No Hair" theorem for black holes, and the nuclear composition of neutron stars. They showed that tests of General Relativity, which can only be tested in extremely high-gravity environments such as pulsars orbiting black holes, could also be conducted with a sufficiently powerful telescope such as the SKA **[1]**. Pulsar searching and high-precision timing form two of the 13 key science priorities for the SKA.

Detailing the technical requirements of the SKA: In 2010, the Square Kilometre Array Design Study (SKADS) working group, which was chaired by and included several UoM researchers, produced a technical report that detailed the pathway by which a fully functional SKA could be built **[2]**, based partly on the ambition laid out in UoM's early proposals. The SKADS group found that an SKA design that provided the desired level of capability could be built with a budget of EUR1,500,000,000 **[2]**. It laid out a dynamic timetable for construction and identified the improvements in processing and communications technology that would be needed to meet the construction timeline. Specific designs for the telescope component of the SKA were developed in the PrepSKA Work Package 2, a working group led by UoM's Richard Schilizzi **[3]**. This work was the basis for the initial project specification, agreed upon in 2011, and produced the conceptual designs for all major telescope sub-systems of the SKA.

Advancing technology to enable the SKA's successful operation: UoM researchers have also conducted key research into new technologies that will enable the SKA to function. For example, data received by each of the thousands of detectors must be synchronised to within 1 picosecond for the SKA to operate successfully. Paper **[4]**, through crucial experiments conducted at UoM's Jodrell Bank, found that a fibre-based layer-by-layer system could achieve the necessary frequency transfer stabilities of 1 picosecond in 1 second. Stabilities of this level are sufficient to provide the temporal coherence required between the SKA's antennas. This novel technology development, coupled with the expertise in high-volume astronomical data transport built through the UoM-led e-MERLIN project, resulted in UoM being chosen to lead the international SKA Signal and Data Transport (SaDT) Consortium in 2013, with UoM researchers constituting 14 of the 45 members of the working group, including the Chair, at peak project time. The consortium developed detailed designs of the data transport and timing networks for the SKA. This design work was very complex due to the networks' integration into every element of the telescope, reflected by the fact that the final design was captured in 279 separate documents, summarised by UoM researchers in 2018 **[5]**. These designs have since passed Critical Design Review (CDR) by a panel of 32 independent experts, and has been incorporated into the SKA's baseline design.

UoM researchers have also demonstrated that the low frequency technology used for SKA can be calibrated by establishing the flux scale for low-frequency radio astronomy, which resulted in the award of the 2019 Jackson-Gwilt medal of the Royal Astronomical Society to Scaife, with the citation: "*establishes a new flux scale optimised for facilities such as LOFAR* [Low Frequency Array] *and SKA. This work has become the gold standard for flux calibration and now underpins all low-frequency radio observing*". They have also advanced the big data technologies that are required for the SKA to function. In a 2019 paper, UoM researchers defined a processing pipeline capable of handling the huge volumes of data that will be generated by the SKA **[6]**.

3. References to the research (UoM authors in bold)

[1] **M. Kramer**, D.C. Backer, J.M. Cordes, T.J.W. Lazio, **B.W. Stappers**, S. Johnston, "Strong-field tests of gravity using pulsars and black holes", **2004**, *New Astronomy Reviews*, 993-1002. DOI: 10.1016/j.newar.2004.09.020

[2] **A. Faulkner,** A. van Ardenne, S. Torchinsky, A. van Es, P. Alexander, R. Bolton, S. Rawlings. J-G bij de Vaate, D. Kant, J. Bregman, S. Montebugnoli, M. Jones, P. Picard, **P. Wilkinson**, "Aperture Arrays for the SKA – The SKADS White Paper", **2010**, from the SKA website

[3] Various authors, including **R. Schilizzi**, "SKA Conceptual Design", PrepSKA WP2, **2010**, https://prepska.skatelescope.org/ska-design/

[4] **R. McCool**, **M. Bentley**, **M. K. Argo**, **R. Spencer** and **S. Garrington**, "Transfer of a 1486.3 MHz frequency standard over installed fibre links for local oscillator distribution with a stability of 1 picosecond", **2008**, *34th European Conference on Optical Communication*, Brussels, DOI: 10.1109/ECOC.2008.4729488

[5] **K. Grainge**, **B. Alachkar**, S. Amy, D. Barbosa *et al.*, "Square Kilometre Array: the radio telescope of the XXI century", **2017**, *Astronomy Reports*, 61. DOI: 10.1134/S1063772917040059. 15 of the 45 authors are from UoM.

[6] **R. Lyon**, **B. Stappers**, **L. Levin Preston**, **M. Mickaliger**, **A. Scaife**; "A Processing Pipeline for High Volume Pulsar Data Streams", **2019**, *Astronomy and Computing*, 100291. DOI: 10.1016/j.ascom.2019.100291

The body of underpinning research, which was conducted by UoM over many years, was funded by several grants totalling approximately GBP27,200,000. Much of this funding includes SKA design, development and technology funding, including the funds that helped produce the SKADS **[2]** and PrepSKA **[3]** documents.

4. Details of the impact

UoM has been at the centre stage of the scientific and the technical development work that has established the SKA viability, beginning with its inception. Over the past decade, the technical feasibility of the project, including timeframe and cost, has been defined in detail through a formal system engineering process, construction funding has been secured, and the coordinating organisation over-seeing the project has been transformed by international treaty into an inter-governmental organisation (the SKAO) headquartered in the UK and hosted by UoM. Impact from the scientific and technical research programmes is in three areas: international science policy and priorities; economic return to the UK from the SKA project; and local economic impact from the establishment of the first IGO in the North West of England. This impact has been enabled by field-leading fundamental research from UoM, technical designs produced and led by UoM researchers, and technology development specifically targeted at enabling the SKA's systems.

4.1 Science policy and priorities [A, B, C]: The initial co-ordinating body for the SKA, the "SKA Organisation" (SKAO), was formed in 2011 and the site decision for the instruments in South Africa and Australia was taken in 2013, making the SKA-MID telescope the first fully international science infrastructure to be sited in Africa. In 2015, the site decision for the global headquarters of the project was made through a competitive bidding exercise. The bids were assessed on 11 formal criteria, including local research environment. The UK was successful in its bid for the SKA headquarters to be sited at Jodrell Bank Observatory, with the UK case building heavily on UoM's historic and continued contributions to SKA research, as well as their "*long and significant history of world-leading research in radio astronomy*" **[C]**. Letters of support from 19 UK companies, government ministers and local MPs further reinforced the case **[C]**. The GBP16,500,000 construction budget for the headquarters was supported by BEIS (GBP9,800,000), UoM (GBP5,200,000) and Cheshire East Council (GBP1,500,000).

In March 2019, an international treaty was signed by the member countries establishing the SKAO as an inter-governmental organisation **[C]**. IGO status for the SKAO, as proposed in the UoM-led PrepSKA document **[3]**, grants diplomatic immunities and privileges to the SKAO, and reduces project costs by granting exemption from Value Added Tax (VAT) and duties on associated spending **[A]**. Additionally, the SKA's Deputy Director-General highlights that the treaty-based nature of IGO status "*increases the security of project funding, ensures the inviolability of documents and data and ensures SKAO staff may be recruited largely independent of standard immigration processes.*" **[A]**. The SKA treaty was ratified by the UK in December 2020 and the IGO entered into force in February 2021 **[A]**.

4.2 UK business return from the SKA [A, D]: The baseline design for the technical specifications of the SKA instruments and infrastructure commenced in 2013 and was undertaken by nine international consortia. Two of these consortia were led from the UK: Signal and Data Transport (SaDT; University of Manchester) and Science Data Processor (SDP; University of Cambridge). The total earned value of these consortia to the project was EUR38,000,000 **[A]**.

Technical design work was evaluated by a formal system engineering process overseen centrally by the SKAO, culminating in consortium-level Critical Design Reviews (CDRs) which were passed in 2018 (SaDT) and 2019 (SDP). An overall SKA System CDR then began in December 2019, concluding in March 2020 **[A]**. Successful conclusion of the CDR process demonstrated to member states that the project proposal was both feasible and achievable within an acceptable timeframe and cost and the SKAO is currently seeking confirmed financial contributions totalling EUR1,986,000,000 over the period 2021-2030. A "*significant fraction*" of these funds has been secured, and work is continuing to secure the remainder **[A]**. The UK government's Department of Business, Energy and Industrial Strategy (BEIS) has confirmed GBP190,000,000 to support the project: this includes GBP100,000,000 in capital expenditure towards construction, and a further GBP90,000,000 towards operations and support for the HQ between 2021 and 2030.

To date, a total of EUR121,900,000 in construction contracts for the SKA has been awarded to UK organisations, significantly in excess of the UK's capital contribution to the project and many as a direct result of UoM's contribution to the SKA design **[A]**. These contracts include the non-imaging processing component of the SKA Data Processing Tier 1 (primary) contract awarded in 2019 **[A]**. This component has a value of EUR15,000,000, of the total EUR63,400,000 of the Data Processing Tier 1 contract **[A]**, and was awarded based on the expertise in pulsar science at UoM **[1]**. In their 2017 Impact Report, STFC states that some 55 UK companies had already been awarded contracts connected to SKA work for a combined GBP5,900,000 **[D]**. In 2020, as a result of the design work conducted by the UoM SaDT team **[4, 5]** and their track record in this area, the UK was also selected as the Tier 1 lead for the SKA Synchronisation, Timing and Clocks construction contracts, valued at EUR9,900,000 **[A]**.

4.3 Local economic impact from the establishment of the SKAO at Jodrell Bank [A, D, E]: Between August 2013 and July 2020 the SKAO has received in excess of EUR80,000,000 in operational funding from the member states, including BEIS, as well as various EU funding streams **[A]**. This funding includes support for UK-based SKAO staff who oversaw the development of the SKA baseline design and production of prototype components, as well as the outsourcing of technology development.

The SKAO workforce in August 2013 was 26 full-time staff **[A]**. By July 2020 this number had increased to 105 full-time staff, including employees from 20 countries, and recruitment is still ongoing **[A]**. These staff are "*a mixture of scientists, system engineers, domain specialists, software engineers and project managers, supported by business-enabling staff*" **[A]**. The SKAO has also benefited directly from UoM's strong research environment by employing or seconding seven staff directly from the University. The SKA's Project Director emphasises the benefit of recruiting UoM-trained experts, saying, "*Such people are already very familiar with the SKA, having contributed to the design development, and bring technical and other skills that can be immediately deployed to help drive the SKA programme*" **[A]**.

Since the HQ building became operational in November 2018, its staff have been estimated to contribute around GBP6,200,000 annually to the local economy in Cheshire East and the surrounding area, and are estimated to have invested GBP6,000,000 in the local property market **[A, D, E]**.

5. Sources to corroborate the impact

[A] Letter from the SKA's Deputy Director-General and Programme Director, 12 February 2021
[B] Press release from skatelescope.org (SKA becomes IGO)
[C] "The UK proposal to host the SKA Headquarters and International Organisation", available on request
[D] STFC Impact Report 2017, https://stfc.ukri.org/files/stfc-impact-report-2017/
[E] STFC Impact Report 2018, https://stfc.ukri.org/files/stfc-impact-report-2018/