Institution: University of Hertfordshire		
Unit of Assessment: 9 – Physics		
Title of case study: Upskilling the first generation of radio astronomers and developing human capital in STEM in Africa, South-East Asia and Latin America		
Period when the underpinning research was undertaken: 2006 – 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:**
Mark Thompson	Professor	2004 – present
Antonio Chrysostomou	Reader	1998 – 2015
Martin Hardcastle	Professor	2004 – present
Jan Forbrich	Senior Research Fellow	2016 – present
Matt Jarvis	Reader	2007 – 2012
Period when the claimed impact occurred: 2014 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Cutting-edge techniques in interferometry, astronomical survey science and data analysis, developed through collaborative radio astronomy research at the University of Hertfordshire (UH), were translated into an intensive programme of human capital development in low and middle-income countries in Africa, Southeast Asia and Latin America. UH co-designed the Development in Africa with Radio Astronomy (DARA) initiative, leading its delivery in Zambia and Madagascar, as well as technical training in Botswana and Mozambique. UH led the design and delivery of a related programme in Thailand and contributed to the delivery of a DARA 'spin off' in Latin America. In engaging hundreds of young people in graduate, master's and PhD-level training, the programmes have upskilled key sections of the workforce in these economies. This has led to entrepreneurial activity and job creation; prepared these countries to exploit economic opportunities from new radio telescope networks; and enabled the engagement of thousands of schoolchildren in Science, Technology, Engineering and Mathematics (STEM). The programmes influenced the allocation of £5.5m in UK Government overseas aid, strengthening UK soft power. Their efficacy in capacity building is recognised in ministerial statements and independent evaluations.

2. Underpinning research (indicative maximum 500 words)

Radio astronomy encompasses a wide range of techniques and technologies that have direct impact on the economy. A canonical example is digital signal processing for astronomical radio interferometers; this was used to solve multi-path interference in wireless internet technologies. UH's Centre for Astrophysics Research (CAR) carries out core radio astronomy science, with an emphasis on single-dish and large-sky interferometric surveys. The observing, data reduction and analysis techniques, developed through STFC-funded research [**G1**-**G3**], underpinned the design of human capital development training by UH researchers and partner institutions in Africa and Southeast Asia. Funded by the Newton Fund (UK aid budget), the programmes are: *Development in Africa with Radio Astronomy* (DARA), led by the University of Leeds with UH, Universities of Manchester, Oxford, Bristol and Central Lancashire, and *Capacity Building for Thai Radio Astronomy* (Radio Capaci-Thai), led by UH with Leeds and Manchester and the National Astronomical Research Institute of Thailand (NARIT). They use the draw of new facilities in their respective geographies – the Square Kilometre Array (SKA), the world's largest radio telescope, and the Thai National Radio Telescope (TNRT) – to engage students in radio astronomy and broader STEM training to close skills gaps and facilitate wider capacity building.

The SKA is hosted by South Africa with Australia and eight African partners: Ghana, Kenya, Zambia, Namibia, Botswana, Madagascar, Mozambique and Mauritius. These partners are converting 30m-class telecommunications antennas to form single-dish radio telescopes that can be connected to a Very Long Baseline Interferometer (VLBI). Known as the African VLBI Network (AVN) and set to span sub-Saharan Africa, this network will be linked to its equivalents in Europe and Australia, enabling mapping of the Milky Way in unprecedented detail. The

conversion of telecommunications antennas and their incorporation into VLBI Networks is described in **3.1**; this demonstrated the benefits of incorporating the Goonhilly Earth Station 30m antennas into the UK's national radio astronomy facility. The simulations and analyses in **3.1** were instrumental in planning the AVN. Subsequently, the first such African antenna to be converted was the 32m dish at the Ghana Radio Astronomy Observatory (GRAO), which is now used as a training facility for DARA students from across Africa.

The Methanol Multi-Beam (MMB) survey, combining single-dish and interferometric techniques, was the largest survey of the sky for 6.7 GHz methanol masers [**3.2**, **3.3**, **3.4**]. These masers are key tracers of massive star formation. MMB is the most complete search to date, revealing a population of variable sources and details of the underlying structure of the Milky Way. It linked evolution of star formation to maser luminosity for the first time. Thompson and Chrysostomou were CIs in an international consortium. Thompson led the observational programme and multi-wavelength exploitation; Chrysostomou was a founding member of the MMB Consortium and co-designed the initial survey. The survey's single-dish element involved a purpose-built, multi-beam receiver. The practical observatory training for DARA students is built directly on the MMB survey techniques and results, with **3.3** used to select specific maser targets for observation.

In **3.5**, high-resolution radio interferometry of the Orion Nebula Cluster was used to identify variability of young stellar objects. This paper (lead author: Forbrich) demonstrated that broadband digital interferometry (to be deployed in the SKA and TNRT) provides a new perspective on high energy processes in timescales as short as minutes. Papers **3.6** and **3.7** detail the design, techniques and results from the Low Frequency Array (LOFAR) Two Metre Sky Survey (LoTSS), the deepest and widest survey of the sky yet, carried out at 100 MHz frequencies. A novel direction-dependent pipeline was developed to produce high-resolution images from LoTSS data; CAR led its implementation. The observation, data analysis and high-performance computing techniques optimised for **3.5**-**3.7** were incorporated into DARA and Radio Capaci-Thai training.

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

3.1 Klockner HR, Rawlings S, Heywood I, Beswick RJ, Muxlow TWB, Garrington ST, Hatchell J, Hoare MG, **Jarvis MJ**, Jones I, van Langevelde HJ. Goonhilly: a new site for e-MERLIN and the EVN. Proceedings of Science. 2011 Aug 03;125. 022. https://doi.org/10.22323/1.125.0022
3.2 Green JA, Caswell JL, Fuller GA, Avison A, Breen SL, Brooks K, Burton MG, **Chrysostomou A**, Cox J, Diamond PJ, Ellingsen SP, Gray MD, Hoare MG, Masheder MRW, McClure-Griffiths NM, Pestalozzi M, Phillips C, Quinn L, **Thompson MA** et al. The 6-GHz multibeam maser survey – I. Techniques. Monthly Notices of the Royal Astronomical Society. 2009;392(2):783-794. https://doi.org/10.1111/j.1365-2966.2008.14091.x
3.3 Caswell JL, Fuller GA, Green JA, Avison A, Breen SL, Brooks K, Burton MG, **Chrysostomou A,** Cox J, Diamond PJ, Ellingsen SP, Gray MD, Hoare MG, Masheder MRW, McClure-Griffiths NM, Pestalozzi MR, Phillips CJ, Quinn L, **Thompson MA** et al. The 6-GHz methanol multibeam maser catalogue – I. Galactic Centre region, longitudes 345° to 6°. Monthly Notices of the Royal Astronomical Society. 2010;404(2):1029-1060. https://doi.org/bzj3tt
3.4 Green JA, Breen SL, Fuller GA, McClure-Griffiths NM, Ellingsen SP, Voronkov MA, Avison A, Brooks K, Burton MG, **Chrysostomou A**, Cox J, Diamond PJ, Gray MD, Hoare MG, Masheder MRW, Pestalozzi M, Phillips C, Quinn LJ, Richards AMS, **Thompson MA** et al. The 6-GHz multibeam maser survey – II. Statistical analysis and Galactic distribution of 6668-MHz methanol masers. Monthly Notices of the Royal Astronomical Society. 2017;469(2):1383-1402. https://doi.org/10.1093/mnras/stx887
3.5 Forbrich J, Reid MJ, Menten KM, Rivilla VM, Wolk SJ, Rau U, Chandler CJ. Extreme radio flares and associated X-ray variability from young stellar objects in the Orion Nebula Cluster. The Astrophysical Journal. 2017 Jul 27;844(109). https://doi.org/10.3847/1538-4357/aa7aa4
3.6 Shimwell TW, Röttgering HJA, Best PN, **Williams WL**, Dijkema TJ, de Gasperin F, **Hardcastle MJ**, and 65 others including **Smith DJB**. The LOFAR Two-metre Sky Survey - I. Survey Description and Preliminary Data Release. Astronomy & Astrophysics. 2017 Feb 9;598. A104. https://doi.org/10.1051/0004-6361/201629313

3.7 Shimwell TW, Tasse C, **Hardcastle MJ**, Mechev AP, **Williams WL**, Best PN and 95 others including **Smith DJB**. The LOFAR Two-metre Sky Survey - II. First data release. Astronomy & Astrophysics. 2019 Feb 19;622:1-22. A1. https://doi.org/10.1051/0004-6361/201833559

Key underpinning grants
G1 STFC Consolidated Grant programme (ST/G002622/1). £1,810,837. 2009 – 2012
G2 STFC Consolidated Grant programme (ST/J001333/1). £1,325,753. 2012 – 2015
G3 STFC Consolidated Grant programme (ST/M001008/1). £2,164,853. 2015 – 2019

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

Most African countries joining the SKA have very little or no expertise in radio astronomy. Through the co-design and delivery of DARA, based on research pushing the boundaries of radio survey and interferometry science, CAR has played a central role in building the human capital required to build self-sustaining radio astronomy hubs in Africa. Beginning in October 2014, DARA has provided young people with transferable skills for wider job and wealth creation [**5.1**-**5.4**, **5.10**]. UH's Thompson led the development and delivery of DARA in Zambia and Madagascar [based on **3.1**-**3.4**] and UH's Forbrich and Hardcastle led the development and delivery of technical training [based on **3.5**-**3.7**] in Botswana, Mozambique and Zambia. Thompson applied these techniques and principles to the design and delivery (as lead) of a similar capacity building programme in Thailand from February 2017. This programme supported the Thai Government to develop the advanced skills the country required to deliver its flagship infrastructure project: a 40m radio telescope that will allow Thailand to further develop its instrumentation design capabilities and access international astronomy and geodesy VLBI research networks [**5.7**].

Upskilling workforces and building STEM capacity in developing economies

A key aim of DARA is to achieve a 'multiplier effect'; the first generation of radio astronomers in these eight African countries will train future cohorts, helping to dispel the notion that the only career destination for graduate physicists is teaching. Researchers from UH and partner institutions designed and delivered radio astronomy and related-skills training at graduate, master's and PhD-level. The graduate-level intensive programme lasts eight weeks, spread over a year and including four weeks at a radio telescope site. It includes computer programming and data reduction techniques for radio astronomy using the likes of Python and Linux. Over the impact period, 264 students from eight African countries participated [**5.1**]. An evaluation [**5.2**] by the Newton Fund said that participants had gained the following technical skills: expertise in radio antennas and instrumentation; radio astronomy observation; data reduction and analysis; astrophysics. They gained the following transferable skills: awareness of commercial opportunities in the space sector; science outreach experience; high-level computing; English language skills in a technical context [**5.2**]. Of 264 students, 31 were accepted onto MSc/PhD programmes, including at UH [**5.1**]. From the first cohort of 10 Zambian students, five went on to international postgraduate study, with one UH PhD student taking a research-active engineering lecturer post at the University of Zambia in 2020. Trainees used their skills to find employment or set up businesses in fields such as earth observation, satellite services and data analysis [**5.2**].

A follow-up survey of 156 DARA trainees [**5.3**] demonstrated the following key outcomes:

- 97.4% described their experience of the study programme as 'very positive' (67.3%) or 'positive' (30.1%); it was 100% in the UH-led countries of Zambia and Madagascar.
- 32% said the graduate-level training had already helped them 'further their career'; this figure was 75% in Zambia and 59% in Madagascar.
- Jobs secured by participants that were attributed to participation in DARA included: data analyst; senior technicians for remote sensing and GIS; telescope operator; lecturer; teacher; research scientist; knowledge transfer associate; engineer; metrologist.

Longer-term impact was demonstrated via individual case studies. One Zambian participant said the UH-led training had secured him employment as an environmental engineer and led to him co-founding a consulting firm that offers remote sensing satellite services. He said: *'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 programme introduced me to Agri Big Data which can help in decision making in agriculture and increase Zambia's agricultural productivity [**5.2**]*.'* A Zambian student who studied an MSc in radio astronomy at UH in 2016-17 secured a Visiting Lecturer post at UH and in July 2019 delivered a DARA radio astronomy workshop to students at the University of Zambia [**5.4**]. After DARA graduate-level training in 2017, a Botswanan student was accepted onto a funded PhD in astrophysics at UH; she plans to seek employment as a big data analyst in a leading bank [**5.4**]. A DARA alumna from Ghana launched a start-up that trains children and young adults in Python programming [**5.3**]. Two DARA MSc and PhD students from Ghana founded, in 2019, a start-up that provides high-volume data storage and processing [**5.1**]. The University of Zambia said that *'as a result of the training',* DARA students had secured international scholarships and MSc/PhD study in the UK, noting that these opportunities *'would be impossible or difficult without the project'* and that these students *'will form the basis of the human resource that will be required for the meaningful participation of Zambia'* in the SKA [**5.5**]. DARA won a Better Satellite World Award in 2018. The organiser, the Society of Satellite Professionals, said: *'We couldn't help but be impressed by DARA's work … to help grow expertise in these fields in Africa. The … powerful combination of technology and business acumen is already paying dividends for the students who have undertaken courses* [**5.6**].'

Building on DARA, UH secured Newton funding in 2017 to lead Radio Capaci-Thai [**5.7**, **5.9**]. The main outcomes were: STEM outreach to a wide cohort of Thai undergraduate students; the upskilling of a selected cohort of Thai and Southeast Asian undergraduates; technological skills transfer in radio-frequency engineering, data processing and low noise amplifier design. More than 150 Thai science and engineering students attended a UH-led, in-depth seminar series across nine Thai HE institutions in 2017. This led to intensive summer schools in 2017 and 2019; 52 Thai and other South East Asian undergraduates received training in radio astronomy, antenna and receiver design, software development and data processing [**5.7**]. Twenty-three NARIT staff attended the schools to develop their skills and access hands-on training. Six Thai Government engineers and three research assistants from NARIT received advanced radio astronomy training.

Stimulating interest in STEM among young people in low-income countries

DARA students are also trained as outreach ambassadors. As of 2019, DARA alumni had delivered STEM sessions to 30 schools and 4,000 students to promote science-based careers [**5.2**]. In 2018 the Office of Astronomy for Development (OAD), a joint project of the International Astronomical Union and the South African National Research Foundation, invited funding proposals from DARA students. Awards included a programme of school visits to the Ghana Radio Astronomy Observatory; a programme to engage underprivileged schools in rural Namibia in the role that radio astronomy plays in society; a programme to engage high school students in Madagascar in the opportunities afforded by the SKA/AVN [**5.8**]. DARA survey responses showed how the outreach training had been put into practice. Representative comments [**5.3**] included: '*I currently organise and sponsor astronomy seminars, workshops and talks in schools and event centres. It* [DARA] *has boosted my confidence in stand-up talks*'; '*After the basic training my confidence level in organizing astronomy outreach, teacher training workshop[s], public presentations has gone up immensely*'; '*To promote the knowledge and experience I acquired from DARA, I set up a facility to promote astronomy through seminar, workshops often in schools and educational events. My hope is to…project the idea across the country*'; '*We enrolled an outreach and development program in rural Kenya. The project has been cited by OAD as a success story*'.

Influencing allocation and distribution of the UK's Government's overseas aid budget

The Newton Fund is part of the UK's Official Development Assistance. In co-designing DARA, CAR research has influenced the allocation and distribution of £5.41m of the UK Government's overseas aid budget (an impact indicator as per REF 2021 guidelines) in eight African countries,

Thailand, Colombia and Mexico [**5.2**, **5.9**]. This comprises: £4.13m to Africa (Thompson as CI); £0.50m to Thailand (Thompson as PI; Forbrich as CI), £0.37m to Colombia (Thompson as CI) and £0.40m to Mexico (Forbrich as CI) [**5.9**]. DARA Big Data in Colombia was designed to build capacity in big data science and the Mexico project involved skills training for a new national radio astronomy facility [**5.9**]. The Thailand, Colombia and Mexico projects were built on the DARA Africa model. The value that the Newton Fund attaches to this model is demonstrated by their allocation of £5.41m based on outcomes of the initial £0.83m DARA grant. An initial £59,440 grant for the Thailand programme led to a follow-on grant of £0.45m [**5.9**].

Benefitting governments in developing economies and strengthening UK soft power

Representatives of the African governments involved in the SKA and AVN have endorsed the value of DARA. A joint ministerial meeting in 2018 noted that: '*DARA was specifically designed to support the African SKA and AVN projects and it is making valuable contributions to strengthen radio astronomy in partner countries. DARA courses are important for capacity building in high performance computing and data science, key technologies to support and develop radio astronomy* [**5.10**].' An independent evaluation [**5.11**] of the Newton Fund's impact in South Africa highlighted DARA as one of three case studies. It said DARA had '*helped support the UK to position science and innovation as a central part of the bilateral relationship with South Africa*' and '*in terms of soft power*' was '*often referred to as a joint success story by both countries*'. The fact that '*the DARA model is now moving beyond Africa*' demonstrates that '*the DARA project is catalytic and has proven how politically salient the idea of astronomy for development is among academic institutions, governments and funders*'. The report concluded: '*DARA has been very successful in terms of the human capital development outcomes, institutional linking and upskilling. The action also has managed to scale up and leverage funding*.' DARA 'spin-off' projects in Colombia and Mexico have raised the prospect of an AVN-style network in Central and South America. Teams from Peru, Columbia, Ecuador, Mexico, Brazil, Argentina, Uruguay and Honduras have announced a plan to lobby their governments to create a network of telescopes in Latin America [**5.1**].

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

5.1 Summary of a University of Leeds-led evaluation of the DARA initiative, September 2020: https://medium.com/university-of-leeds/a-space-science-project-in-africa-is-opening-up-new-horizons-b6a67658abc9
5.2 Newton Fund case study: Promoting STEM skills and economic development through radio astronomy, October 2019: https://www.newton-gcrf.org/impact/stories-of-change/promoting-stem-skills-and-economic-development-through-radio-astronomy/
5.3 Results of a follow-up survey of DARA alumni (available as anonymised Excel spreadsheet)
5.4 Weblinks to corroborate the individual case studies of Zambia participants in DARA: https://www.dara-project.org/mubela-mutale; https://sarrvesh.github.io/dara2019.html; https://www.darabigdata.com/kushatha-ntwaetsile
5.5 Corroborating statement from the Dean, School of Natural Sciences, University of Zambia.
5.6 DARA a winner at the Better Satellite World Awards, 2018: https://www.goonhilly.org/pr-dara
5.7 Corroborating statement from the Executive Director of NARIT, Thailand.
5.8 List of funded DARA 'Astro4Dev' projects, 2018, Office of Astronomy for Development: http://www.astro4dev.org/blog/2019/01/11/dara-astro4dev-projects/
5.9 List of Newton Fund awards that followed on from the success of DARA in Africa:
Thailand: https://gtr.ukri.org/projects?ref=ST%2FR006555%2F1
Colombia: https://gtr.ukri.org/projects?ref=ST%2FR001944%2F1
Mexico: https://gtr.ukri.org/projects?ref=ST%2FR002320%2F1
5.10 Report on joint ministerial statements from SKA Africa Partner Countries meeting: https://economist.com.na/39211/education/science-and-technology-ministers-meet-to-discuss-progress-on-africas-sensitive-radio-telescope-projects/.
5.11 Thematic Impact Study – South Africa, Newton Fund Evaluation, July 2018 (PDF, pp. 8-16)