Institution: University of Manchester

Unit of Assessment: UoA9 Physics

Title of case study: The Square Kilometre Array - in Africa, Australia and the UK

1. Summary of the impact

The international Square Kilometre Array (SKA) radio telescope, due for completion in the next decade, will be the world's largest astronomical instrument. It will be built by international industry at a cost of over €2B. The larger part will be sited in Africa (9 countries) with a complementary part in Australia. The impact to mid-2013 is on: i) international science policy and priorities (€26M); ii) multi-faceted human capacity building in Africa (401 bursaries); iii) business and employment involved in the construction of two large-scale SKA "precursor" instruments in South Africa and Australia (over €150M with 800 jobs in South Africa); iv) the local north-west economy (over €5M) where a new limited company to coordinate the SKA's design and construction has been established at Jodrell Bank.

2. Underpinning research

The next transformational step in radio astronomy, which will shape its future for many decades, is the SKA. The originating idea 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 €32M 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. Throughout, Manchester researchers have been central – both in the invention and generation of the original ideas and in the experimental development leading to the design of a transformational instrument. The key players have been: Professors P. Wilkinson (1993-present), R. Spencer (1993-2010), M. Kramer (1998-2008), S. Garrington (1993-present), P. Diamond (1998-2009), R. Schilizzi (2008-present), Dr. A. Faulkner (2004-9).

Science insights: The SKA science case focusses on six key ideas. Kramer and Wilkinson were lead authors on papers originating two of these: "Strong Field Tests of Gravity using Pulsars and Black Holes" [1] and "Exploration of the Unknown" [4] respectively. The research insights are:

- Pulsars will provide the most precise tests of General Relativity. The many millisecond pulsars discovered with the SKA will also probe the stochastic gravitational wave background.
- The legacy of the SKA will arise from new types of observations it alone will permit. This puts an onus on its designers and operators to allow for the exploration of the unknown. A philosophy was outlined enabling c21st radio astronomers to add to the many discoveries made in the c20th.

Technological research: The pan-European SKA Design Study Programme (SKADS 2005-9) was a systematic study of technological solutions for the SKA—primarily as a flexible "electronic telescope" based on phased aperture arrays (AAs). Wilkinson chaired the SKADS Board and was P.I. of the UK programme. SKADS showed that at low frequencies AAs are able to deliver high survey speeds coupled with high dynamic range and extreme flexibility, consonant with SKA as "discovery instrument". Faulkner (SKADS Project Engineer on the UK grant) played a leading role in the AA programmes [2,5]. Diamond (now International SKA Director) and Schilizzi (International SKA Director 2003-11) led the SKA Preparatory phase during which the global radio astronomy community developed a first system design for the SKA, prior to the site decision in 2012. The SKA Project Execution Plan [6] was led by Schilizzi. AAs are a pivotal feature of the SKA design for the lower part of its frequency range. For the many individual antennas of the SKA to be combined coherently as a single telescope, their signals must be synchronised to a few picoseconds over distances greater than 100km. This has been achieved over an optical fibre data transport network using a technique developed at Jodrell Bank for the e-MERLIN array [3] and now in routine array operation. This research and experience provided the confidence that an affordable fibre-based synchronisation system could be provided for the SKA and is the basis for Manchester's international leadership of the SKA data transport and synchronisation development.

3. References to the research

The global radio astronomy community is involved in the SKA and hence the research, which has formed an accepted part of the development path, is perforce of at least 2* quality. The 2004

science case [1,4] was published in book form to maximise its ease of distribution to the community. The technological research [2,3,5,6] has been published in conference reports or on public web sites.

Key Publications

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", New Astronomy Reviews, vol 48, "Science with the Square Kilometre Array"; ,eds C.Carilli, S. Rawlings, pages 993-1002, 2004. 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" http://www.skads-eu.org/PDF/SKADS_White_Paper_100318_dist.pdf
3. R. McCool, M.Bentley, M.K. Argo, R. Spencer, S. Garrington "Transfer of a 1486.3 MHz frequency standard over installed fibre links for local oscillator distribution with a stability of 1 picosecond. " Presented at ECOC 2008 (European Conference on Optical Communications) published by IEEE http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4729488 DOI: 10.1109/ECOC.2008.4729488

Supporting Publications

4. P.N. Wilkinson, K.I. Kellermann, R.D. Ekers, J.M. Cordes, T. Joseph, T.J. W. Lazio, "The Exploration of the Unknown" New Astronomy Reviews, vol 48, "Science with the Square Kilometre Array"; eds C.Carilli, S. Rawlings, pages 1551-1563, 2004. DOI: 10.1016/j.newar.2004.09.036
5. R.T. Schilizzi, P. Alexander, J.M. Cordes, P.E. Dewdney, R. D. Ekers, A.J. Faulkner, B. M. Gaensler, P. J. Hall, J. L. Jonas, K. I. Kellermann; "Preliminary Specifications for the Square Kilometre Array", SKA Memoradum 100, (2007) http://www.skatelescope.org/uploaded/5110_100_Memo_Schilizzi.pdf
6. R.T. Schilizzi & 18 co-authors", "Project Execution Plan – Pre-construction phase for the Square Kilometre Array" (2011) http://www.skatelescope.org/uploaded/38221_SKA_Project_Execution_Plan.pdf

4. Details of the impact

Manchester has been at the heart of the science arguments and the technical development programme which has established the viability of the SKA. Over the past decade the concept has been defined both scientifically and technically by hundreds of astronomers and engineers in over 60 research institutions in a dozen countries with some outputs in Section 3. The sites have been selected; precursor instruments have been constructed in several countries; the international organisation has been formed; pre-construction design funding is in place and international industry is closely involved in the planning. Impact from the scientific and technical research programmes is in four areas: international science policy and priorities; human capacity building outside UK academia; economic impact from contracts for non-UK infrastructures; economic impact from the establishment of the international SKA Organisation as a limited company in the UK to lead the design and construction of the SKA.

4.1 Science policy and priorities [A]: The policy impact began when the coordinating international "SKA Organisation" (SKAO) was formed in 2011. The SKAO has representatives from Australia, Canada, China, Germany, Italy, Netherlands, New Zealand, South Africa, Sweden and the UK (chair) with India as an associate member. These partners together committed a total budget of €120M for the "pre-construction" design phase in 2012Q2-2016Q3, On a pro rata basis ~25% (€30M of which €3.9M is for the SKAO see Section 4.4) can be attributed up to 31 July 2013. The site decision was taken in May 2012 and broke new ground in that the SKA will be the first fully international science infrastructure to be embedded in Africa. The higher frequency "dish" array will be built in the Northern Cape Province, South Africa and there will be SKA telescope outstations in Namibia, Botswana, Zambia, Mozambique, Kenya, Ghana, Madagascar and Mauritius. Complementary lower frequency and "survey" arrays will be built in Australia.

Europe-South Africa [B]: The South African SKA programme has been directly influential in creating new political links between Africa and Europe. The African-European Radio Astronomy

Platform (AERAP) was set up in May 2012 as a response to the European Parliament's Written Declaration 45/2011 'on Science Capacity Building in Africa: promoting European-African radio astronomy partnerships'. This call was repeated by the Heads of State of the African Union, in their decision 'Assembly/AU/Dec.407 CXVIII', for radio astronomy to be a priority focus area for Africa-EU cooperation. AERAP's aim is to "enable major research and technological advances that will drive socioeconomic development and competitiveness in both Africa and Europe". The European Parliament's AERAP Group was established in November 2012 to secure on-going political support for its activities. AERAP is now coordinating a strategic "Framework Programme for Cooperation" shaped around European investment in science infrastructure; human capital development; ICT and big data; education and public awareness.

4.2 Human Capacity Building in Africa [C,D,E,F]: The importance of the SKA project to South Africa can be judged from the address to the National Assembly by the Science and Technology Minister Derek Hanekom in May 2013. "[the decision] to host the greatest portion of the Square Kilometre Array radio telescope [in South Africa], was a massive acknowledgement of the capabilities of our scientists and engineers, and the advances our country has made in science and technology…The construction of the 64-dish MeerKAT has commenced, and will be completed by 2016. On its own, the MeerKAT will be the largest radio telescope in the Southern Hemisphere." Minister Hanekom's immediate predecessor Naledi Pandor said "Radio astronomy partnerships with Africa can make a valuable contribution to economic development… By training a new generation of highly qualified scientists to work on African projects, they can boost the region's human capital and keep many of Africa's brightest young minds in Africa." A significant part of the build-up of scientific/technical education and training in Africa can be directly attributed to the SKA.

The approach to "bottom up" scientific and technical capacity-building associated with SKA South Africa is impressive and multifaceted. In the period 2008-13, 401 young people benefited from SKA South Africa bursaries and scholarships, including many students from other African countries, comprising: Post-Doctoral Fellowships (39); Bursaries for Post-graduate (207), Undergraduate (103), BTech and National Diploma (28) students together with Internships (10) and Artisan programmes (14). The total is currently growing at over 90 per year. At the top level five new research chairs dedicated to science and instrumentation of astronomy have been established: at Rhodes University, Stellenbosch University, the University of Cape Town, the University of the Western Cape and the University of the Witwatersrand. A new generation of scientists is growing in Southern Africa—in 2003 there were 12 practising radio astronomers, while already by 2011 this had grown to over 60.

The SKA has also stimulated interest in astronomy undergraduate education in the African partner nations with developments in Madagascar, Botswana and Ghana; however Kenya has taken a lead. Since 2009 the University of Nairobi has enrolled 53 undergraduate students in Astronomy & Astrophysics, and in 2013 the first cohort of 14 graduated with a BSc. These students are largely inspired by the SKA and many hope to get SKA or other scholarships to enable them pursue postgraduate studies.

4.3 National infrastructures [A,G,H]: Starting after 2008 and as pivotal components of their strategies for winning the site competition, both South Africa and Australia began to construct €150M SKA "precursor" radio telescopes (KAT-7/MeerKAT and ASKAP respectively). Constructing these new national infrastructures has opened up new areas of business resulting in commercial contracts for both local and international companies and new local employment within the projects. The construction of KAT-7 has been completed, while that of ASKAP is largely completed and that of MeerKAT is well underway.

Over 120 young scientists and engineers are working on the MeerKAT project, based at the engineering office in Cape Town, and at universities and companies across South Africa and Africa. 75% of the total contract will be spent in South Africa. Project delivery is led by Aurecon (infrastructure); Stratostat Datacom (antennas, with technical help from General Dynamics SATCOM Technologies); Brink & Heath Civils (roads); EMSS Antennas (receivers). The project has added 800 construction jobs in an area with 25% unemployment. The site infrastructure work alone has created jobs for 269 adults and 191 youths. As well as those of construction, the project has demanded that South African companies acquire new skills. LJ du Toit, EMSS managing director, has stated "MeerKAT's electromagnetic (EM) requirements have grown significantly since [2005], and I am proud to say that we as a company have grown with it, and have managed to

keep up with the technology needs". Stratostat Datacom's owner Alan Geldenhuys' focus is to engage local industry, especially in terms of local content, skills transfer and the upliftment of surrounding communities: "We foresee a great sense of community with the local towns' people". The economic effects on the North Cape Province reach down to local levels. For example in the town of Carnarvon, MeerKAT contracts to the value of €400k from eight "emerging contractors" and orders to the value of €2.5M from 30 suppliers have been awarded. These emerging contractors have obligatory participation goals which require worker training and they have been assisted in registering with South African Construction Industry Development Board and with registering workers with the Department of Labour. MeerKAT is also providing further business and entrepreneurship training to local suppliers/contractors. It should be noted that normal issues of economic displacement are much less relevant in developing economies.

4.4 Employment and the local economy in Cheshire [I,J]: The SKAO is now constituted as an independent UK company, limited by guarantee. Its Office moved to a new building at Jodrell Bank Observatory in November 2012. The successful UK (Manchester, Cambridge and Oxford) proposal to host the Office attracted letters of support from 19 UK companies, from the Minister for Universities & Science, from MPs and representatives of Regional Government (available on request). The Office is supported entirely by the International Organisation with funding totalling €22.8M through 2015 of which 17% (~€3.9M) had been spent by 31 July 2013. The final staff target is 49 FTE, 19.6 of whom, drawn from the international community, were in place by 31 July 2013. The impact on the local economy is greater than the up-front spend; the net multiplier is ~1.5, giving a total economic impact to 31 July 2013 of ~£4.5M (€5.3M).

5. Sources to corroborate the impact:

[A] *Information concerning the international SKA Organisation:* International SKA web site (http://www.skatelescope.org/).

[B] *Information concerning the political links between Africa and Europe:* African-European Radio Astronomy Platform web site http://www.aerap.org/

[C] *Information concerning South Africa Government views of human capacity bulding:* South African Science Ministers' speeches: Hanekom to the National Assembly 6 May 2013; Pandor: to the National Editors Forum 29 March 2011

[D] *Information concerning human capacity building arising from SKA:* Presentation by SKA South Africa Project Director & South African SKA web newsletters and fact sheets 2011-2013

[E] *South Africa SKA Bursaries*: spreadsheet supplied by HCD Manager SKA South Africa

[F] *Astronomy Education in Kenya*: SKA South Africa Newsletter July 2013, and email from Professor Paul Baki (University of Nairobi)

[G] *Industry involvement and employment in MeerKAT construction*: SKA South Africa newsletters and African Business Review web video

[H] *MeerKAT jobs*: email from SKA SA General Manager: Infrastructure & Site Operations

[I] *SKA Office manpower and spend:* emails from SKA Office

[J] *Local benefit cost ratio*: SQW Consulting report to NWDA April 2009 (see page 17)