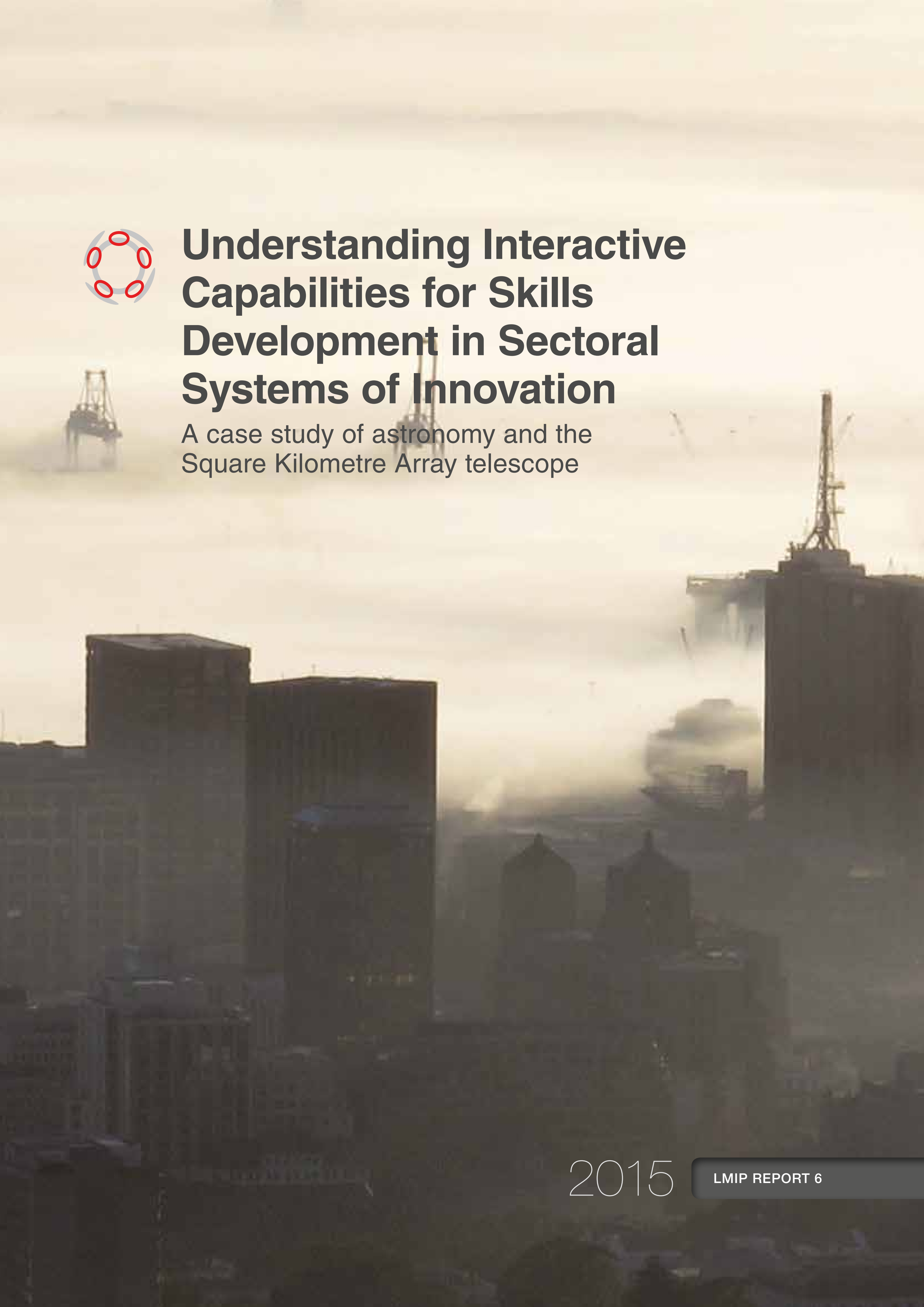


Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation

A case study of astronomy and the Square Kilometre Array telescope

2015

LMIP REPORT 6

2015 LMIP REPORT 6

Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation

A case study of astronomy and the Square Kilometre Array telescope

Michael Gastrow

LABOUR MARKET
INTELLIGENCE PARTNERSHIP

Published in 2015 by the Labour Market Intelligence Partnership (LMIP) Project. The LMIP project is undertaken by a research consortium led by the Human Sciences Research Council, and is funded by the Department of Higher Education and Training.

www.lmip.org.za

This report is published by the Labour Market Intelligence Partnership (LMIP), a research consortium led by the Human Sciences Research Council (HSRC), and funded by the Department of Higher Education and Training (DHET).

Designed, typeset and proofread by COMPRESS.dsl

www.compressdsl.com

higher education & training
Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

HSRC
Human Sciences
Research Council

University of the Witwatersrand Johannesburg

Development Policy
Research Unit

CONTENTS

List of figures iv

List of tables v

South African astronomy acronyms vi

Acknowledgements vii

Preface viii

1. Understanding interactive capabilities for skills development in sectoral systems of innovation: An overview of the conceptual approach, design and methodology and the research project 1

2. The Astronomy sectoral system of innovation 11

3. The Square Kilometre Array 18

4. Firms' strategies to address routine and non-routine skills needs 40

5. The skills supply and skills demand roles of science facilities 54

6. The roles of public and private intermediary organisations in building network alignment around skills development 60

7. Interactive capabilities and dynamic interactive capabilities of universities 67

8. A case study of the SKA's FET college partner 99

9. Conclusion 110

Endnotes 115

References 116

LIST OF FIGURES

Figure 1:	Capability-building processes at the sectoral level	3
Figure 2:	Capability-building processes in the Astronomy sectoral system of innovation	14
Figure 3:	Network map illustrating the skills development networks in the astronomy sector for the SKA	16
Figure 4:	The SKA as locus for global innovation networks	20
Figure 5:	Academic intake for the South African SKA Project Human Development Capital Programme	25
Figure 6:	Firms' network connections	43
Figure 7:	HartRAO network connections	58
Figure 8:	Core Astronomy Advantage Area	64
Figure 9:	Average interaction with public and private intermediary organisations	66
Figure 10:	Capability-building processes in education and training organisations – a generic framework	67
Figure 11:	Interaction with universities	70

LIST OF TABLES

Table 1:	Selection of case studies	7
Table 2:	Research design	7
Table 3:	Fieldwork interviews overview	9
Table 4:	Distribution of PhD astronomers in South Africa in 2005 and 2010	16
Table 5:	Most connected actors in the Astronomy SSI/SKA	17
Table 6:	Perceptions of environmental change in the sector	41
Table 7:	Perception of firms' dynamic interactive capabilities	42
Table 8:	DST expenditure 2009–2016	61
Table 9:	Summary of the roles played by intermediary organisations and other actors	66
Table 10:	Basic profile of SKA higher education partners	71
Table 11:	Student numbers disaggregated by level	71
Table 12:	Student numbers disaggregated by programme area	72
Table 13:	Dynamic interactive capability scale (average scores)	76
Table 14:	Characteristics of academic staff by institution	79
Table 15:	Overview of interactive capabilities at universities relevant to the Astronomy SSI	97

SOUTH AFRICAN ASTRONOMY ACRONYMS

AERAP	African-European Radio Astronomy Platform
ASTRON	Netherlands Institute for Radio Astronomy
CASPER	Center for Astronomy Signal Processing and Electronics Research (Berkeley)
CPUT	Cape Peninsula University of Technology
DST	Department of Science and Technology
HartRAO	Hartebeesthoek Radio Astronomy Observatory
HMO	Hermanus Magnetic Observatory
IAU	International Astronomical Union
NASSP	National Astrophysics and Space Science Programme
NRAO	National Radio Astronomy Observatory (USA)
NRF	National Research Foundation
OAD	Office of Astronomy for Development
ROACH	Reconfigurable Open Architecture Computer Hardware
SAAO	South African Astronomical Observatory
SALT	Southern African Large Telescope
SANSA	South African National Space Agency
SKA	Square Kilometre Array
UCT	University of Cape Town
UFS	University of the Free State
UKZN	University of KwaZulu Natal
UNISA	University of South Africa
US	University of Stellenbosch
UWC	University of the Western Cape
VLBI	Very Long Baseline Interferometer

ACKNOWLEDGEMENTS

This report is the result of a large-scale team effort, and all HSRC staff members and research partners who contributed must be acknowledged. Glenda Kruss of the HSRC conceived of and designed the project to investigate the ways in which alignment between post-school education and training organisations and labour markets can be improved, and was responsible for overall project management. Glenda Kruss and Il-haam Petersen developed the conceptual framework and methodology as well as the interview schedules and analytical templates that guided the research. Il-haam Petersen developed the databases for the network analysis and the analysis of interactive capabilities, while Bongani Nyoka captured the data. Fiona Lewis (consultant) conducted interviews with some of the universities. Jessica Paulse (HSRC) tirelessly scheduled interviews with universities and FET colleges. Tania Fraser (HSRC) was responsible for all logistics and travel arrangements to support fieldwork.

PREFACE

This case study report is a product of the Labour Market Intelligence Partnership (LMIP), a large-scale, long-term research and development project that aims to support the Department of Higher Education and Training's mandate to establish a credible institutional mechanism for skills planning.

Specifically, it reflects research conducted to address the theme of 'Reconfiguring the post-schooling sector'. The aim is to investigate the ways in which alignment between different types of public and private education and training systems and labour markets can be improved. It investigates how organisational capabilities, structures and curriculum mechanisms facilitate or constrain interaction with labour market organisations, in a differentiated post-school sector.

There are two sub-projects in this theme of work. Project 1 is designed to focus on the capabilities of education and training organisations to interact with labour market stakeholders, and is led by Glenda Kruss of the HSRC. Project 2 focuses on curriculum responsiveness and is led by Volker Wedekind of the University of KwaZulu-Natal. The boundaries for the empirical investigation are drawn by four sectoral systems of innovation (SSI):

- Forestry growers (focused in KwaZulu-Natal)
- Sugarcane growers and millers (focused in KwaZulu-Natal)
- Automotive components manufacturers (focused in Port Elizabeth)
- Square Kilometre Array (SKA) (national)

The research attempts to identify appropriate change mechanisms, and hence, provide systemic knowledge to direct funding and interventions where DHET can have leverage in future, and education and training organisations can maintain their core roles in new ways.

This case study analysis forms part of Project 1, which investigates the distinct knowledge and technology base, the main actors, institutions and networks of each SSI, and the ways in which education and training organisations display dynamic interactive capabilities. It should be read in conjunction with a set of inter-related LMIP reports:

- *Report 4: Responding to Shifting Demand for Skills: How do we get firms and post-school education and training organisations to work together?* By Glenda Kruss, Il-haam Petersen, Simon McGrath and Michael Gastrow (2014)
- *Report 7: Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation: A case study of the Tier 1 automotive component sector in the Eastern Cape.* By Simon McGrath (2015)
- *Report 8: Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation: A case study of the sugarcane growing and milling sector in KwaZulu-Natal.* By Il-haam Petersen (2015)

1. UNDERSTANDING INTERACTIVE CAPABILITIES FOR SKILLS DEVELOPMENT IN SECTORAL SYSTEMS OF INNOVATION: AN OVERVIEW OF THE CONCEPTUAL APPROACH, DESIGN AND METHODOLOGY OF THE RESEARCH PROJECT[1]

In recent years, astronomy has emerged as a growing niche within South Africa's national innovation system. The allocation of the Square Kilometre Array (SKA) project to South Africa has accelerated this growth trajectory, which will continue as the instrument scales up over the next decade. The SKA requires a host of competences and capabilities for interaction, including dynamic interaction, to meet its core mandate. From a certain point of view, the SKA organisation itself can even be defined by these capabilities – being able to connect skills, knowledge, technologies, networks, institutions, intermediaries and funding in order to deliver the world's largest science project in a developing country. The context in which this takes place is inherently dynamic, along two major vectors. Firstly, the SKA is operating in the context of very rapid growth in radio astronomy in South Africa, which is largely made up of the organisational growth of the MeerKAT and the SKA itself. Secondly, the technologies underpinning the SKA are rapidly changing and, in areas, not yet developed. This requires advanced capabilities in technology forecasting in order to respond to this challenge through the many interactive capabilities that the SKA requires.

This case study examines the competences, capabilities, interactive capabilities and dynamic interactive capabilities that characterise the sectoral system of innovation (SSI) of the astronomy sector, with a view to identifying the factors that have enabled alignment and success, and the factors that have acted as bottlenecks or constraints. Within this ambit, we focus on the SKA as the flagship astronomy facility in South Africa in the medium term.

Problem statement: The need to build interactive capabilities

This project ultimately focuses on ways to encourage and facilitate more effective interaction between post-school education and training organisations and the labour market.

A central concern of the DHET is to build a credible institutional mechanism for skills planning, with the assumption that it will equip government to encourage education and training organisations and industry to work together more effectively, to mutual benefit, and to address national skills priorities for economic development.

We can identify strategies and mechanisms that have been used in other countries, particularly in advanced developed economies. However, if we identify and adopt such strategies, a problem remains:

> How do we ensure that in the South African context, post-school education and training institutions have the will, matching expertise and capabilities to meet industry demand?

Post-school education and training organisations with distinct historical trajectories respond in diverse ways to government policy and market imperatives. Similarly, different types of firms – whether multinational corporations, large firms, or SMMEs, and whether in primary, secondary or tertiary sectors – respond in different ways to global and local shifts, new technologies and new knowledge. In short, firms or universities or colleges will not *automatically* adopt new skills policy interventions and regulations, or respond to attempts at steering.

Hence, we need an understanding of the ways in which post-school education and training organisations interact with firms and labour market organisations to shape their core activities, in order to identify appropriate *change* mechanisms and strategies. There is no simple blueprint or tried and tested approach that is guaranteed to yield results in the South African context.

What we propose in this project is to develop a framework to analyse existing interaction and interactive capabilities in key sectoral systems of innovation in South Africa, as a basis on which to proceed. For instance, an FET college may have well-qualified engineering lecturers, but there is no way to communicate with local firms, or no support to change curriculum in response to changing technology in firms in a key sector in its immediate location. The intervention required relates to finding dynamic internal and external interface mechanisms. However, another college may lack the qualified lecturers, which means we need different interventions here to improve lecturers' qualifications and pedagogic expertise.

For firms and education and training organisations involved in a sector, such an evidence base can enhance understanding of effective interactions, alignment, organisational strategies, and blockages and gaps, in order to identify specific ways in which to enhance institutional capabilities.

A working framework

The project adopts an innovation systems approach to study skills development in South Africa, an approach that has been used to study university–industry interaction and firm learning in relation to research and innovation, to determine which new insights the approach can provide:

Basically, the theory underlying innovation system analysis is about learning processes involving ***skilful but imperfect rational agents and organisations****. It assumes that organisations and agents have a capability to enhance their competence through searching and learning and that they do so in interaction with other agents and that this is reflected in innovation processes and outcomes in the form of innovations and new competences. (Lundvall 2010: 331)*

We propose a framework that emphasises dynamic interaction, interactive capabilities and network alignment, drawing on the innovation systems approach – specifically, the work of Malerba (2005) and Von Tunzelmann (2010). The approach is dynamic and evolutionary, emphasising change over time, but also how historical trajectories and institutions shape what is possible. '**Interactive capabilities**' are defined as the capacity for learning and accumulation of new knowledge on the part of the organisation, and the integration of behavioural, social and economic factors into a specific set of outcomes (Von Tunzelmann & Wang 2003; 2007 in Iammarino et al. 2009). A good example of interactive capabilities at a university of technology is a work-integrated learning office that has institutional status and sufficient resources to coordinate activities across departments and faculties; build long-term partnerships with firms; and mentor and support students, in a way that is functionally integrated into the organisation's teaching and learning activities and ensures that students are able to receive quality workplace learning to graduate.

Considering that sectors differ significantly in terms of knowledge bases, skills needs and institutional conditions, we focus on analysing the skills and interactive capabilities of specific **sectoral systems of innovation (SSIs)**. Rather than simply emphasising a sector as an industrial concentration, a sector is defined as 'a set of activities which are unified by some related product groups for a given or emerging demand and which share some basic knowledge' (Malerba 2005: 65).

Figure 1 provides a **generic** representation of the actors, potential flows and interactive learning in an SSI in the South African context. It illustrates how the system could be mapped, as a basis for studying skills development networks, and the interactive capabilities of the main actors. We integrate Malerba's (2005) SSI framework and Von Tunzelmann's (2010) interactive capability and network alignment framework, and identify four main building blocks for analysing the interactive capabilities of education and training organisations and the extent of alignment in skills demand and supply:

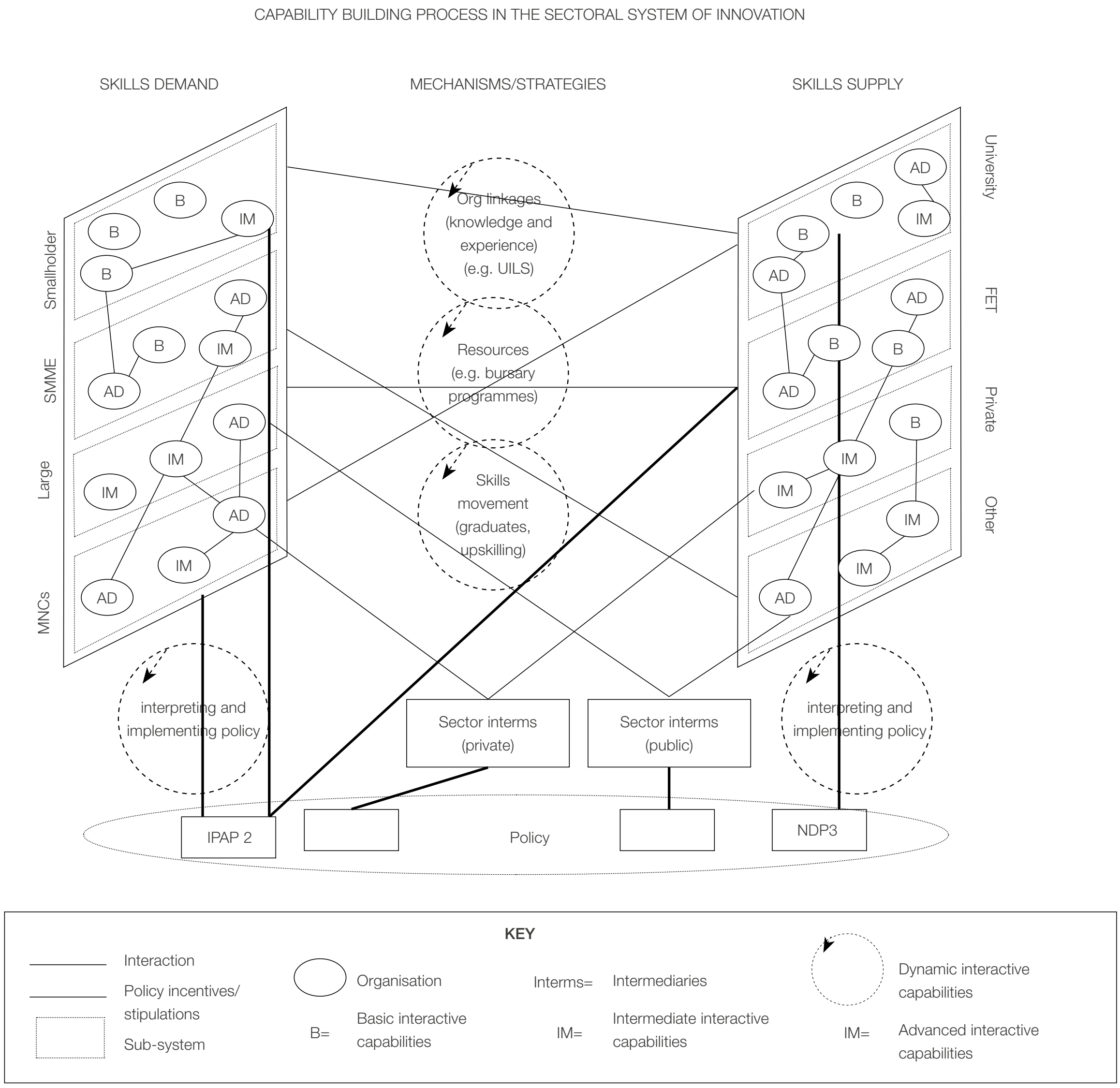
- Common knowledge bases and similar technologies;
- Actors and networks;
- Institutions; and
- Interactive capabilities.

What is highlighted is the need to map the existing *structure, agents, mechanisms/strategies and dynamics of skills developmen*t in specific sectors.

On the left-hand side of Figure 1, we describe the diverse groups of firms operating in the sector – whether multinational corporations, large firms or SMMEs – to identify their distinctive skills needs. The framework highlights the need to investigate the strategies and mechanisms that firms use for meeting their routine and changing skills demands, which may provide pointers as to how education and training organisations can, and do, play a role in addressing skills needs in specific SSIs.

On the right hand side, we analyse the different types of post-school organisations that could be addressing multiple skills demand in the sector – whether public FET colleges, universities or

Figure 1: Capability-building processes at the sectoral level



universities of technology, private FET or HET colleges, or other skills development programmes such as apprenticeships.

Each of the actors – firms and education and training organisations – is embedded in wider institutional environments, which shape, and are shaped by, actors' activities. Hence, at the very bottom of the diagram, we map out the key global, national or regional policy mechanisms that could be shaping demand in the sector, or influencing education and training supply. Firms and education and training actors interpret policy and, depending on their interactive capabilities and strategic goals, respond in different ways and to varying degrees.

Sectoral intermediaries, especially public sectoral intermediaries, play an important role in supporting firms and education and training organisations to be responsive. Between the left- and the right-hand sides, we identify the sectoral intermediaries that serve to connect firms and education and training organisations and align their goals. In the public sector, this includes government departments, agencies like SAQA or QCTO and, critically, the role played by SETAs. In the private sector, intermediaries include industry associations, professional bodies, education and training associations, and so on.

The circular arrows in the middle of the diagram represent some of the typical mechanisms and strategies used to link supply and demand. For example, there may be flows of resources whereby firms provide scholarships and bursary programmes to meet their future skills requirements. Varying degrees of direct involvement are possible, which could include knowledge flows. For instance, the firm provides a list of topics for thesis research or hosts artisans for workplace training.

Working definitions of key concepts

In reading the empirical case study reports, it will be useful to consider the working definitions of key concepts from the innovation systems approach used to design data-gathering and analysis.

Sectoral system of innovation

A sectoral system of innovation refers to 'sets of actors organised around specific types of productive activities and technologies, within distinct geographical and institutional settings' (see Malerba 2005).

Competencies

Competencies stem from inputs to produce goods and services – that is, the preset attributes of individuals and firms, typically produced by organisations such as education and training organisations (Von Tunzelmann & Wang 2003).

In our framework, competencies take two forms:

- Tacit knowledge embodied in the human resources of the organisation and organisational routines; and
- Codified knowledge present in organisational structures, technologies, formal policies or other physical resources.

Interactive capabilities

The capacity for learning and accumulation of new knowledge on the part of the organisation, and the integration of behavioural, social and economic factors into a specific set of outcomes (Von Tunzelmann & Wang 2003; 2007 in Iammarino et al. 2009). It refers to the capacity to form effective linkages with other organisations (e.g. firms, universities). It involves the learning and exploitation of an organisation's competences, and the development of organisational routines for producing desired outcomes.

Dynamic interactive capabilities

The capacity to sense changes in the business and education environment relevant to the organisation and respond effectively and timeously through strategic management. This requires familiarity with the organisation's competencies and interactive capabilities for appropriately adapting, coordinating, integrating and reconfiguring the organisation's competencies and internal and external interface mechanisms/strategies to match the requirements of the changing environment. Here, leadership skills for strategic management are crucial.

Institutions

Institutions broadly refer to rules or guides for behaviour. Different types and levels of 'guides for behaviour' are recognised in the sectoral system of innovation (SSI) approach: formal (e.g. institutional policy, national policy) and informal (e.g. organisational culture), binding (specific regulations) and created by interaction (e.g. contracts), and national (e.g. patent system) and sectoral (e.g. sectoral labour markets).

Education and training organisations

These include a diverse set of private and public education and training organisations – that is, universities, universities of technology, vocational education and training organisations (VET or FET), private colleges, private higher education institutions, and other training providers (e.g. SETAs, training centres operated by industry associations, etc.).

Sectoral intermediaries

These are 'organisations or groups within organisations that work to enable innovation, either directly by enabling the innovativeness of one or more firms, or indirectly by enhancing the innovative capacity of regions, nations or sectors' (Dalziel 2010: 3–4). Intermediaries may play a role as brokers, supporting and initiating inter-organisational networks, and may engage in other activities enabling the innovativeness of firms (e.g. providing training and technology development and related activities such as the provision of access to expertise and equipment).

We distinguish between public and private sectoral intermediaries (see Interakumnerd & Chaoroenporn 2013). Public and private intermediaries differ in terms of their main functions. Public intermediaries tend to focus on public good objectives, especially those related to policy. Private intermediaries, on the other hand, tend to focus more on industry or firm-specific issues.

Identifying spaces for intervention

Understanding the existing interaction within a specific SSI provides a basis from which misalignment, challenges and bottlenecks can be identified. In turn, this can inform planning and targeted policy interventions to address the specific gaps and bottlenecks, and enhance strengths.

The ability of a firm or education and training organisation to respond effectively to changes in the business and institutional environments that impact on skills development depends on their identification of changes that present opportunities, threats or constraints and their internal capabilities to respond. An appropriate response often involves the acquisition of new knowledge and capabilities that transform, and are transformed by, the firm or education and training organisation through learning.

The framework allows us to identify a number of potential spaces for intervention to promote such learning and change, each of which will require specific mechanisms and strategies. These strategies may include the identification of appropriate actors with which to collaborate in order to best address changes and improve performance.

Design and methodology: A set of three vertical case studies

The project uses a multilayered vertical case study design, with the empirical boundaries defined by an SSI, using a combination of:

- desktop and data-based research; and
- key informant interviews at different levels within the firm, sectoral intermediary and education and training organisation actors.

Bartlett and Vavrus (2011) suggest that the vertical case study design makes three important contributions. First, it insists on simultaneous attention to the micro-, meso- and macro levels to enable 'vertical comparison' Second, it emphasises the importance of situating processes under consideration historically to enable comparing across time, or 'transversal comparison'. Third, it emphasises the importance of comparing how similar processes unfold in distinct locations in space or 'horizontal comparison'.

Three such empirical cases were selected, based on the criteria summarised in Table 1. The first criterion was to select across the main sectors in the economy. To define a specific-focus SSI within these main sectoral bands, we were informed largely by convenience in terms of access to an existing or emerging body of research. Using a commissioned background paper, we identified the most significant segment of the value chain, in terms of the proportion of total employment in the sector in a geographical region, to define an SSI for empirical focus. A further criterion was that the final selection of cases represented a mix of un/structured approaches to skills planning and development, in terms of market-led or government steering and incentivisation schemes.

The design of the research is illustrated in Table 2. Each vertical case study was preceded by development of an initial map of the actors in the SSI to identify the structures of their interaction. The map formed part of a sectoral background paper that was commissioned for each of the three sectors. The specific education and training organisations, firms and sectoral intermediaries to be included in the interviews were identified from the initial mapping process, which was elaborated and refined in the course of the fieldwork.

Understanding the policy environment pertaining to the role of each type of actor in skills development is crucial. The fieldwork thus began with interviews with DHET branch managers and other cognate government departments, national or provincial.

To study the scale and degree of network interaction, we asked each of the main actors to identify the other actors with whom they interact in the SSI. This data was analysed using network analysis software, to produce visual maps of the extent and strength of interaction in the SSI.

Interviews with firms complemented by desktop work – using existing databases, internet and secondary sources and the sectoral background paper – centred on the drivers of innovation and technology change in the sector, and the strategies that firms use to meet their skills needs – and skills constraints – across high, intermediate and basic levels of production. We also asked each interviewee to complete a rating scale to assess his or her perceptions of environmental turbulence in the sector and the dynamic interactive capabilities of his or her firm.

These were followed by interviews with SETAs, industry associations and other sectoral intermediaries, such as professional associations and employer associations, to understand their roles in linking demand- and supply-side actors. The purpose of these interviews is to identify present and future skills needs, capacity and constraints in the sector, and the existence and effectiveness of mechanisms to facilitate interaction around skills development between firms and education and training organisations.

At the heart of the case study is an in-depth analysis of the interactive capabilities of each of the education and training organisations that provide qualifications and skills development for the core occupations in the sector. The education and training organisations that are most directly and actively involved with other actors were studied in depth – specifically, their capability-building processes.

One empirical challenge was to select focus knowledge and technology fields, programmes and qualifications in order to provide empirical boundaries that limit the investigation within the education and training organisations. We based this selection on the occupational groupings and levels that are distinctive to the knowledge and technology base of the sector. We excluded four 'Organising Framework for Occupations' (OFO) major groups: community and personal services workers (4), managers (1), clerical and admin (5) and sales workers (6) are generic occupational groups not directly related to our focus sectors. We included four occupational groups, and the qualifications connected to these – professionals (2), technical and trade workers (3), machinery operators and drivers (7) and elementary workers (8). Using the SAQA list of registered qualifications, we identified an initial list of sector-related qualifications for each of these occupational groupings. This allowed us to identify specific programmes or departments within each type of education and training organisation as the empirical focus for the interviews.

Table 1: Selection of case studies

Main sector of economy	Specific sectoral system of innovation	Geographical spread	Un/structured approach to skills planning and development
Primary sector	Agro-processing: sugar millers	KZN	Industry-led schemes and ad hoc
Secondary sector	Automotive: tier 1 component manufacturers	Eastern Cape	Government incentivisation and ad hoc
High technology/big science	Astronomy and the SKA	National/Western Cape	Foresight and planned skills development

Table 2: Research design

Desktop research	Fieldwork interviews	Fieldwork reports	
Sector level			**Integrated synthesis case study report**
Sector background paper	Interviews with policy-makers	Network analysis report	
Firms			
Desktop research and secondary data	Interviews with firms	Narrative report	
Universities			
Desktop research and secondary data	University interviews (core to SSI)	Narrative report	
Desktop research and secondary data	University interviews (not directly active in SSI)		
FET			
Desktop research and secondary data	FET interviews (core to SSI)	Narrative report	
Desktop research and secondary data	FET interviews (not directly active in SSI)		
Desktop research and secondary data	Other college interviews	Narrative report	
Private providers			
Desktop research and secondary data	Interviews with private providers	Narrative report	
Intermediaries			
Desktop research and secondary data	Interviews with private intermediaries	Narrative report	
	Interviews with public intermediaries		

We attempted to study the competences, interactive capabilities and dynamic interactive capabilities within education and training organisations in relation to three dimensions of their activity:

1. What they teach – the approach and mechanisms by means of which programmes are informed by technological drivers and skills needs in the sector (or not, as the case may be);

2. How they teach – the approach and mechanisms that shape the work readiness of graduates, such as workplace learning, internships, apprenticeships or learnerships, in interaction with firms in the sector; and

3. How they facilitate labour market access – the approach and mechanisms that support individuals' labour market transitions, in interaction with firms in the sector.

The analysis relies primarily on in-depth semi-structured interviews within education and training organisations with heads of institutional planning; heads of external interface structures and mechanisms such as careers offices or graduate placement units; and lecturers and trainers in the relevant knowledge fields. Interviews were complemented by desktop research including the consultation of websites, organisational policy documents and overviews of structural arrangements. Each interviewee was asked to complete a rating scale to assess his or her perceptions of environmental turbulence in the education and training sector, and the dynamic interactive capabilities of his or her organisation.

The analysis reflected on the interactive capabilities and strategies of each of the different kinds of actors in terms of their roles and interaction within the SSI. Narrative reports on the different types of actors were prepared by a set of researchers. On this basis, this synthesis case study report on the **Astronomy Sectoral System of Innovation and the Square Kilometre Array** was prepared.

Operational methodology for the Astronomy sectoral system of innovation

The first step in the methodology was to develop a model of the sectoral system of innovation and, within this, to focus on the position and role of the Square Kilometre Array telescope. This entailed desktop research into astronomy in South Africa, with a focus on the main actors and their relationships. Within this model, the key skills requirements and challenges can be framed, and the main interactive capabilities can be identified.

Drawing on this research, fieldwork instruments were customised to reflect the main actors in the sector, including dedicated instruments for university-based astronomy specialists, university management, firms, intermediaries and FET colleges. Interviews with each of these types of actors included a set of semi-structured questions, as well as structured questions about dynamic interactive capabilities, environmental turbulence and network analysis.

Interviews were conducted from September 2013 to February 2014, with senior staff from the main actors involved in the astronomy sectoral system of innovation (see Table 3). This evidence base is supported by additional desktop research, including materials provided by universities and other actors.

All the interviews were recorded in digital audio and transcribed. All interview participants signed confidentiality agreements and consent forms. In addition, for actors in the education sector, an analytical template was completed that provided an overview of competences, capabilities and interactive capabilities. These provided a valuable reference point for characterising these organisations and providing an empirical basis for comparison and categorisation.

The transcriptions were used as a basis for analysis, together with interview notes, supplementary desktop research and data describing network structures, dynamic interactive capabilities and environmental turbulence. Together, these sources of data provide a rich evidence base from which to understand the interactive capabilities present in the astronomy sectoral system of innovation.

Structure of the report

The astronomy sectoral system of innovation in South Africa is explored in Chapter 2. The Square Kilometre Array telescope, within this context, is presented as a case study focus in Chapter 3. The skills needs and strategies of firms in the SKA value chain are explored in Chapter 4, focusing on three in-depth case study firms. This is followed by an examination of the roles of science facilities (also a significant employer in the astronomy sector) in Chapter 5. Chapter 6 investigates the roles of intermediaries in the sectoral system of innovation, particularly in articulating skills supply and skills demand vectors. Chapter 7 focuses on public higher education institutions, the primary locus of skills supply for astronomy. Chapter 8 presents a detailed case study of the single FET college involved in the astronomy sector. Chapter 9 provides an overall assessment of the interactive capabilities for skills development in the astronomy sectoral system of innovation, and for the SKA in particular, and returns to the primary research questions guiding the three case studies for the LMIP's Theme 4:

1. What is the nature and strength of interaction and network alignment in the astronomy sectoral system of innovation (SSI)?
2. What are the main components in the astronomy SSI addressing skills needs?
3. What are the routine skills needs and non-routine changes in the business environment related to skills development of firms in the sector? What are the strategies they use to address these needs?
4. What are the roles of public and private sector intermediary organisations in building network alignment and addressing misalignment in

relation to skills development in the astronomy SSI?

5. What are the interactive capabilities of public and private post-school institutions to address the routine, and changes in, skills needs of firms in the SSI?

6. What is the nature of mis/alignment between dynamic skills supply and demand in the SSI to address skills needs and promote economic development? What are the challenges/constraints/threats to growth and skills development in the SSI?

Table 3: Fieldwork interviews overview

Organisation	Position
FET Colleges	
Kimberley FET college	Academic Manager
Kimberley FET college	Deputy Director: Academic
Kimberley FET college	HoD (Skills)
Kimberley FET college	Campus Manager (City Campus)
Kimberley FET college	Acting Deputy CEO: Corporate Affairs
Firms	
Stratosat Datacom	Owner/Director
Tellumat	Director of Strategic Projects Group
EMSS Antennas	Managing Director
Intermediaries	
NRF	Group Executive: Astronomy
DHET	Deputy Director General
DST	Deputy Director General
International Astronomical Union	Director: Office of Astronomy for Development
Science and Technology Facilities Council (UK)	Astronomy Programme Manager
SAAO	Head of HR
British High Commission	Head of Science and Innovation
Science Facilities	
HartRAO	Administrator
HartRAO	Managing Director
Square Kilometre Array (SKA) telescope	
SKA	MeerKAT project manager
SKA	General Manager: Science, Computing and Innovation
SKA	Manager: Human Capital Development Programme
SKA	SKA project manager
SKA	Business Development Manager
SKA/Rhodes	Project scientist
Universities – astronomy specialists	
Rhodes	HoD Computer Science
Rhodes	Dean of Science
Rhodes	SARCHI Chair
UCT	Deputy HoD: Astronomy
UCT	HoD: Astronomy
UCT	Professor: Astronomy
UKZN	Professor: Astrophysics and Cosmology Research Unit
UKZN	Professor: Astrophysics and Cosmology Research Unit
Stellenbosch	Professor: Engineering
Stellenbosch	SKA Research Chair
UWC	HoD: Physics
Wits	Acting HoD: Computer Science
DUT	Head: Radio Astronomy Technology (RAT) Centre in the Department of Electronic Engineering
Universities – management	
UCT	Executive Director: Development and Alumni Department
UCT	Head of Careers Office
UCT	Institutional Planner
UCT	Deputy Vice Chancellor
UWC	Head of Careers Office
UWC	Institutional Planner
UWC	HoD: Computer Science
UWC	Head: Academic Planning and Curriculim Unit
Wits	Head: Counselling and Career Development Unit

Organisation	Position
Universities – management	
Stellenbosch	Dean of Engineering
Stellenbosch	Head: Careers Office
Stellenbosch	HoD: Computer Science
Stellenbosch	Curriculum Unit
Wits	Acting Head: Student Development and Leadership Unit
Wits	HoD: School of Physics
Wits	Academic Planning Officer
Wits	Deputy Vice Chancellor: Academic
Wits	Deputy Vice Chancellor: Partnerships and Management
Wits	Director: Strategic Planning
UKZN	Deputy Vice Chancellor/Head of College: Agriculture, Engineering and Science
UKZN	Academic Leader: Teaching and Learning (Engineering)
UKZN	Pro-Vice Chancellor: Innovation, Commercialisation and Entrepreneurship
UKZN	College Manager: Public Relations
UKZN	College Dean: Teaching and Learning (Acting)
DUT	Dean: Student Services and Development
DUT	Head: Student Financial Aid Services
DUT	Manager: Student Governance and Development
DUT	Head: Student Counselling
DUT	Head: Sports Services
DUT	Deputy Dean: Faculty of Engineering and the Built Environment (also Head: Mechanical Engineering)
DUT	Head: Centre for Co-operative Education
Rhodes	Teaching and Learning/CHERTL
Rhodes	Careers Office
Rhodes	Community Engagement
Rhodes	Senior Lecturer, Rhodes Business School

2. THE ASTRONOMY SECTORAL SYSTEM OF INNOVATION

Astronomy as a sectoral system of innovation

Astronomy is not, at least in the economics literature, commonly referred to as a sector. However, it enters the analysis of sectoral innovation systems as a clearly defined operational area, including both science and engineering aspects. This is in line with the definition of Malerba (2005), who defines a sectoral system of innovation as 'sets of actors organised around specific types of productive activities and technologies, within distinct geographical and institutional settings'. In the case of astronomy, the productive activity is that of astronomical observation and research. This is unusual, in terms of innovation, in that the productive activity itself is defined by the creation of new knowledge and is itself, per se, an innovative activity that expands the global knowledge frontier. Also, the 'productive activity' is not strictly market-oriented. Astronomy does not enter the public marketplace as a conventional set of products or services. However, it is certainly a productive activity, and it is framed by a market of sorts. At the global level, there is an aggregate demand for astronomy, including astronomy facilities and astronomy research outputs. The sources of this demand include universities (including astronomy departments but also physics, cosmology, engineering, etc.), government-funded research programmes and policies, and external sources of demand such as space programmes, geodetic measurement programmes, GPS management organisations, and so on. On the other hand, there is a global aggregate supply of astronomy facilities (embodied in observational and processing capacities) and research capabilities. In this global marketplace, the sector in South Africa is seeking to expand its supply (of facilities and researchers) and therefore capture a greater share of global demand, thus leveraging a substantial geographical comparative advantage, which grants South Africa excellent natural conditions for astronomy. Within this context, innovation and technological change play a central role and are inherent to the 'productive activity' of the sector.

Astronomy in South Africa

Astronomy has a long history in South Africa (Paterson et al 2005; Wild 2012). Astronomy has long been part of indigenous knowledge systems in Africa, which has been explored extensively in the field of African palaeoanthropology (e.g. Chabalala 2012; Holbrook 2007; Snedegar 1999, 2007). Astronomy played a role in the colonial project in South Africa as far back as 1685, when astronomical observations were made for navigational purposes. South Africa's first observatory was established in 1820 in Cape Town. From the 1950s onwards South African involvement extended to satellite tracking in collaboration with international agencies, including NASA. This built upon South Africa's comparative advantage in astronomy, which requires adequate infrastructure and, importantly, clear skies and low levels of light, dust and radio frequency (RF) pollution. South Africa has retained its geographical advantage with respect to astronomy since that time. The drivers of astronomy are peculiar in that observational capacity is as important in the southern hemisphere as it is in the north. Southern countries with suitable characteristics thus have an advantage in the global competition to host advanced and expensive astronomical instruments.

This competitiveness led to ongoing investments in South African astronomy. The advent of democracy lead to a further massive increase in astronomy support and investment. It is notable that in its first 12 years of rule the African National Congress (ANC) government spent more on astronomy than all governments combined between 1910 and 1993. It is postulated that this is due to its characteristics of reflecting modernity, international standing and validation for African scientific and intellectual capabilities (Gottschalk 2005).

Today these capabilities continue to play an important role in the global astronomy system. South Africa is host to the largest single-lens optical telescope in the southern hemisphere – the Southern African Large Telescope (SALT). However, the Square Kilometre Array telescope is poised to become the flagship astronomy facility in South Africa. This giant radio telescope will become the largest science project ever undertaken in Africa, the world's most powerful telescope by several orders of magnitude, and also one of the largest science installations of any type in the world.

Within the SSI there exists a historical division between optical and radio astronomy. Optical astronomy has, until recently, been by far the dominant mode of astronomy in South Africa, and has received the bulk of funding, facilities and training. Since the advent of the MeerKAT and the SKA, this has changed. The rapid changes currently taking place represent a state of flux, moving towards a future in which radio astronomy will be a far larger and more internationally prominent mode of astronomy in South Africa.

In terms of tacit competences, there are certain challenges in the domain of astronomy. The ability to interact on a personal level, and to negotiate from differing points of view, is not always a strong one. As expressed by a manager at HartRAO:

> Scientists are quite bright people and they're quite opinionated, and very often they see something one way and another scientist sees something another way and there is not always the necessity or the thing to force them together and sometimes there're misunderstandings and sometimes there are genuine character clashes.

The SKA as a case study focus within the astronomy sectoral system of innovation

The astronomy sectoral system of innovation in South Africa offers many lessons for understanding labour market interactive capabilities, structures and mechanisms – particularly regarding how these operate in a high-tech globalised sector. One important lesson that can be learnt from the SKA as a case study is the impact of long-term and well-funded skills development planning in a high-tech sector. The success of the bidding process and the awarding of the main SKA site to South Africa is a great strategic, scientific and technological opportunity. It was made possible by deliberate and large-scale skills planning that has been in place for a decade, and will continue for the foreseeable future. Supporting policy and funding for astronomy began before the origins of the SKA (Gottschalk 2007), but since South Africa joined the SKA organisation and site bidding process, government support has been substantially increased. The successful award of the majority of the project to South Africa is partially a result of this support and the development of the requisite skills in South Africa. As the scale of the project grows, the skills supply produced by bursaries and other forms of coordinated skills development will continue to enter the astronomy sectoral system of innovation and the SKA project in particular.

The case of the SKA offers lessons about how coordinated, well-funded and medium- to long-term skills planning can benefit a high-tech sector. In a sense, the SKA in South Africa has used labour market intelligence to achieve its objectives. Understanding the strategies, mechanisms and implementation of this process, together with the associated competences, capabilities and interactive capabilities throughout the sectoral system of innovation, is one of the main empirical and analytical objectives of the case study.

Moreover, since these competences and capabilities are typically nested within organisations and institutions, our analysis is structured first to analyse these at an organisational level and subsequently at a systemic level.

Main actors and network structure

Academic astronomy and the astronomy conducted at science facilities are largely oriented towards science – the production of new knowledge. Firms that enter the value chains of astronomy facilities are largely involved in engineering and fabrication, including research and development and innovation activities. All of these activities are interrelated, as engineering specifications are derived from science objectives and firms, in most cases, work in collaboration with academics and scientists based at universities and science facilities. The main actors in the astronomy sectoral system of innovation in South Africa consist of the following:

- **The SKA** – the SKA is a large radio telescope that is currently in the design phase. It will be built mostly in South Africa, with components in several African partner countries, as well as Australia and New Zealand. The precursor instruments, used for technology testing and demonstration as well as science applications, include the KAT-7 radio telescope and the MeerKAT radio telescope. The SKA also manages, as a partner facility, the African VLBI network (a network of radio astronomy facilities being established across Africa).
- **Science facilities** – South Africa's public science facilities are funded and managed by the NRF. These include several large telescopes, such as the Southern African Large Telescope (SALT), the largest optical telescope in the southern hemisphere, and HartRAO, a radio astronomy observatory that played a key role in the SKA and that was also previously a NASA observatory.
- **Universities** – most of South Africa's universities play a role in the Astronomy innovation system. Although only UCT has a dedicated Astronomy department, activity also takes place through Departments of Physics, Engineering, Mathematics and ICT. Universities also host some intermediary functions. For example, the National Astronomy and Space Science Programme, which coordinates postgraduate skills development in these sectors in South Africa, is based at UCT.
- **Private intermediaries** – private intermediaries are largely composed of sector bodies such as the International Astronomical Union. However, these play a relatively minor role in the sectoral system of innovation, as astronomy is generally publicly funded.
- **Public intermediaries** – public intermediaries play a central role in the astronomy sectoral system of innovation, primarily as a source of funding and policy support. The main actors are the Department of Science and Technology (DST), the National Research Foundation (NRF) and, in its capacity of higher education planning, the Department of Higher Education and Training. The latter is also involved in the Strategic Infrastructure Projects (SIPs), which include the SKA. The South African Astronomical Observatory, funded by the NRF, plays a key coordination role in the sector.
- **Firms** – the knowledge and technology requirements of astronomy, and of the SKA in particular, are too large to be met without the private sector. Numerous firms are involved at various levels, primarily in research and technology development, as well as in the manufacturing of ICT, dish and receiver components.
- **FET colleges** – only one FET college has a confirmed role in the astronomy sectoral system of innovation through its participation in the SKA's Human Capital Development Programme.

The relationships between these main actors, in the context of capability-building processes within the astronomy sectoral system of innovation, are illustrated in Figure 2. This shows how the primary locus of skills demand includes the SKA organisation and other science facilities, as well as firms in the value chain and research institutes such as the CSIR. The locus of skills supply is centred around universities, but also takes place through the SKA and draws heavily on international sources. The roles of intermediaries are diverse and include the facilitation of interaction with the aims of skills development, research collaboration, funding allocation and public engagement.

Policy support is expressed in the DST's Ten-Year Innovation Plan, as well as through the Astronomy Desk. The most concrete support is through the Astronomy Geographic Advantage Act, which protects the geographical terrain around South Africa's main astronomy facilities from developments that might negatively impact on their astronomy activities. In addition, there has been widespread tacit political support, which has acted as an enabler at all levels of policy formulation and resource allocation.

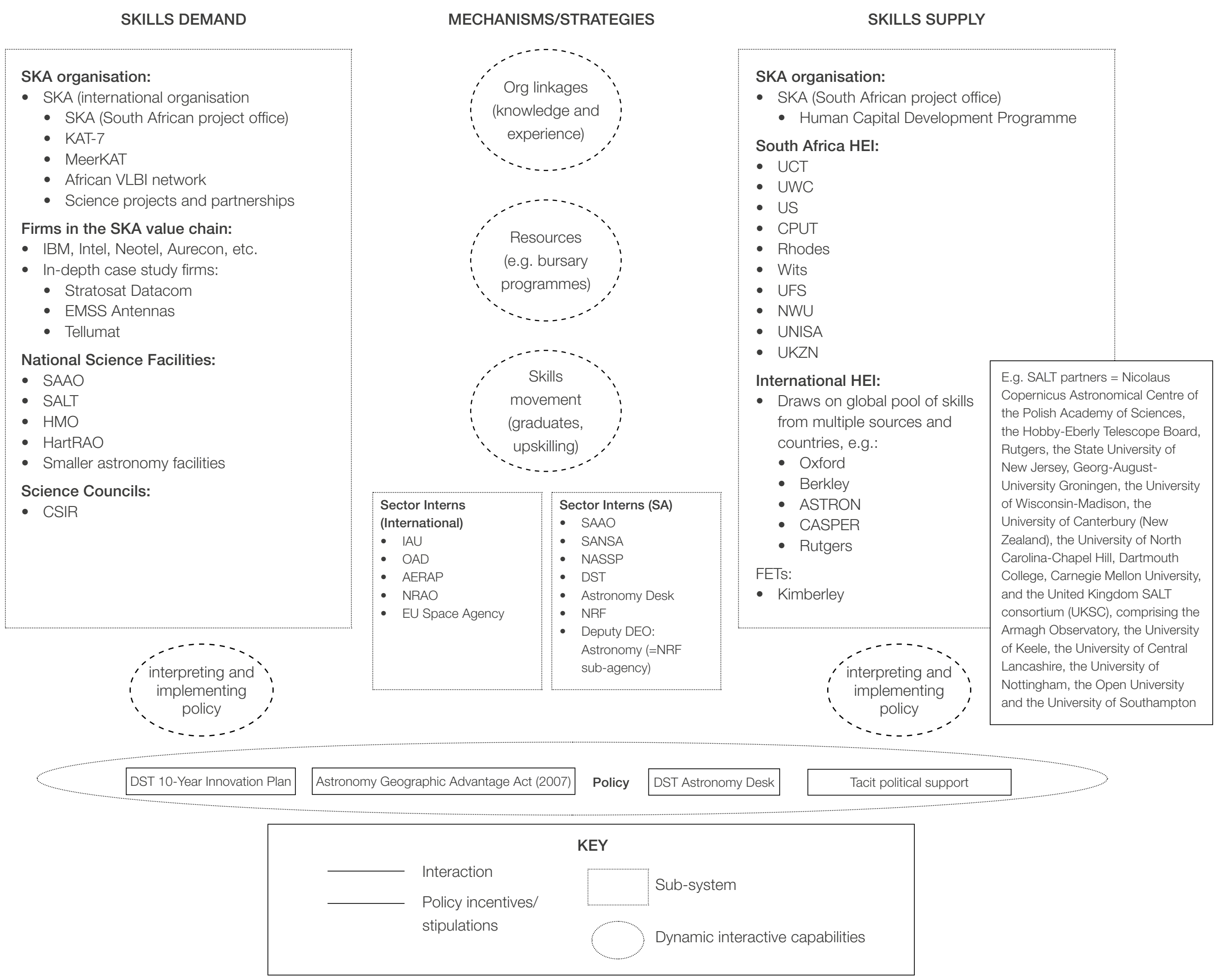
Demand for skills and knowledge

The main sources of demand for skills in the astronomy SSI are the national astronomy facilities, which are coordinated and managed by the South African Astronomical Observatory (SAAO). These include the Sutherland astronomy complex, of which the Southern African Large Telescope (SALT) forms a part, as well as the Hermanus Magnetic Observatory and the Hartebeesthoek Radio Astronomy Observatory (HartRAO) facility. However, radio astronomy is specific to HartRAO, the MeerKAT and the SKA.

This is set to change as the SKA rolls out – in future, radio astronomy in South Africa will be larger than optical astronomy in terms of employment. Growth in demand for skills in the astronomy sector is currently dominated by the emerging needs of the SKA and its pathfinder instruments the KAT-7 and the MeerKAT. This includes skills to support:

- a number of internationally coordinated projects that support the technological requirements of

Figure 2: Capability-building processes in the Astronomy sectoral system of innovation



the SKA, such as the African Very Long Baseline Interferometer (VLBI) project;
- 10 main science projects of the MeerKAT, each of which has an international team of scientists attached to it; and
- hardware development, such as the Reconfigurable Open Architecture Computer Hardware (ROACH) board, which was designed through an international collaboration and is manufactured in South Africa.

Firms play a key role, particularly in technology development. A number of firms have been contracted on a tender basis for the SKA, ranging from basic infrastructure (e.g. Aurecon) to new development at the global technological frontier (e.g. IBM, Stratosat Datacom). Some of these are local firms (e.g. Tellumat and EMSS antennas) that have gained access to large tenders, and have at the same time been elevated to the global stage. Firms in the sector require a range of engineering skills, including electrical, electronic, mechanical, mechatronic, structural, software development and systems engineering skills.

Bharuth-Ram (2011) estimates that the MeerKAT alone will require 40–60 PhD graduates in order to utilise the facility to its full potential. Assuming that on average 50% of the South African science PhDs who qualify will either move abroad or move into other industries, he suggests that it will be necessary to create 80 to 100 PhDs by 2012. In addition, he estimates that three to four PhD astronomers per year are required by the SAAO. These suggestions are aimed at increasing the proportion of South African astronomers at these facilities. In practice, however, astronomy facilities globally are highly international in their staff composition, and international skills are drawn upon where no niche skills are available locally.

Supply of skills and knowledge

Since the rate of PhD production in astronomy was four to five per year in 2010, a vast increase is needed (Bharuth-Ram 2011). To fill the gap, astronomy facilities draw a large proportion of their astronomers from international sources. Bharuth-Ram (2011) identifies limited supervisory capacity within South African universities and facilities as the critical factor limiting the growth of PhD training within South Africa.

The supply of skills is mostly emergent from South Africa's leading research universities, with smaller pockets of skills development from the other institutions. It is apparent that the SKA has stimulated skills development activity across the national system, incentivising students to enter astronomy-related careers and stimulating cognate research. Funding for research is provided through a number of channels. One of these is the SKA organisation itself through its Human Capital Development Programme (HCDP), which funds education at all levels from FET colleges through to postdoctoral fellowships and academic appointments. The DST has also played a central role, providing for the South African Research Chairs Initiative (SARCHI) Chairs in astronomy, as well as funds for the HCDP.

Partnerships with international organisations play a key role in developing skills, and it is common practice for South African astronomers to partner with international teams to achieve their objectives. The SKA is far too large to draw only on the South African pool of talent – instead, it acts as an attractor for international skills, which in turn results in interaction and learning among South African partners. These international partners are numerous, and extend all over the globe.

Interestingly, the location of the SKA head office in Cape Town reportedly acts as a magnet for international talent. In the globalised world of astronomy research, telescopes are located in a large variety of locations, some attractive and some barely habitable. The combination of a world-class city to live in and the world-class site conditions in the Karoo has reportedly attracted astronomers and engineers to the project. On the other hand, there are constraints to bringing in skilled people from abroad. For each case, the SKA has to apply for a scarce skills work visa, which is expensive and an administrative burden.

The lower levels of skills development have not been neglected. The SKA organisation and the DST have expressed the importance of artisan skills for the SKA. This has been manifested in bursaries towards a local FET college in Kimberley. The SETAs as yet have no discernible role in the SKA.

Competences for astronomy have grown rapidly over the last decade, driven by the initiation of large new projects such as SALT and MeerKAT, which in turn have driven increased student and academic interest and rapidly escalated funding.

Table 4: Distribution of PhD astronomers in South Africa in 2005 and 2010

Institution	2005	2010
UCT	10	29
SAAO	15	25
UWC	0	8
UNW	6	7
HartRAO	5	7
KAT	0	6
UKZN	7	6
Wits	3	4
UJ	2	3
UFS	2	2
UNISA	3	1
Rhodes	3	1
Stellenbosch	0	1
UniZul	1	1
TOTAL	57	101

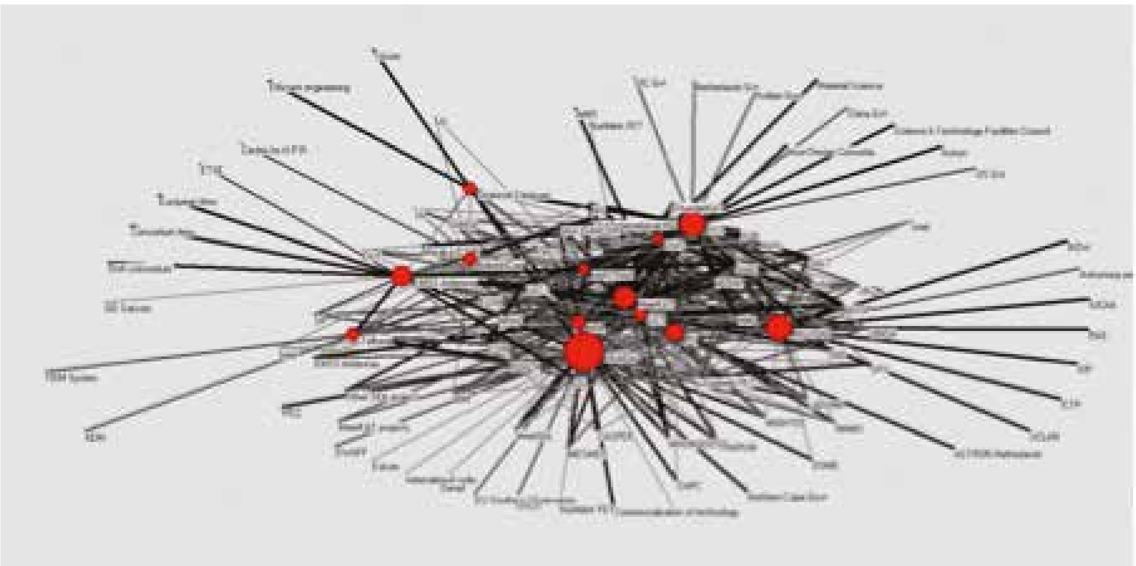
Paterson et al. 2005; Bharuth-Ram 2011

Note that the numbers given above include theoretical cosmologists and particle cosmologists; they do not include people working in the closely related fields of relativity theory or space physics and who often work within the same school/department/research group as astronomers.

Extent of alignment between skills demand and supply

Formal social network analysis (SNA) was used to analyse the interaction between the actors included in the diagram in Figure 3, with a focus on formal and informal interaction related to skills development. SNA provides useful tools for investigating the extent of alignment between skills demand and supply in the astronomy SSI. The sociogram in Figure 3 illustrates the interactions among the actors involved in the skills development networks in the astronomy SSI, focusing on those relevant to the SKA. In this image, the nodes represent actors in the system, and the lines between nodes represent their relationships. A thicker line represents a more substantial relationship with a higher scale of interaction. The circles represent a bridging function – connecting groups of actors. This provides information about how crucial an actor is to the transmission of

Figure 3: Network map illustrating the skills development networks in the astronomy sector for the SKA



Source: Project data

Note: The shade of the lines corresponds with the scale of interaction such that the darker the shade, the greater the scale of interaction (scale: 1 = 'not at all'; 2 = 'isolated instances'; 3 = 'moderate scale; 4 = 'on a wide scale').

Table 5: Most connected actors in the Astronomy SSI/SKA

Organisation	Organisation type	Number of connections
SKA South Africa	Astronomy project	80
MeerKAT	Astronomy project	65
Department of Science and Technology	Public sector intermediary	59
International Astronomical Union/Office of Astronomy for Development	International intermediary	44
National Research Foundation	Public sector intermediary	46
University of Cape Town	University	46
Rhodes University	University	45
HartRAO	Science facility	36
EMSS Antennas	Firm	35

Source: Project data

information through the network, or the actor's role in connecting other actors to each other.

The network consists of 99 actors involved in 902 connections (average interactions = 9.1 interactions per actor). It is apparent that the network has a dense core, with the central actors all interacting with each other. Around this dense core is a large periphery, actors that only interact with a few of the other actors. The actors with the most connections to other actors in the sample were:

The high number of connections reported for the SKA and the MeerKAT are the result of the sample focus on the SKA in South Africa – where the MeerKAT is currently the project focus. These data make it clear that public sector actors play key intermediary roles. However, intermediary roles are also well distributed throughout the system, including amongst universities, science facilities and firms. SNA was also used to identify key channels through which resources can be shared and actors can link to other actors that would not otherwise have been linked (i.e. bridging actors). The results of this analysis are similar, indicating that the most connected actors tend to play bridging roles too: the top-ranked organisations in terms of their bridging function were the SKA, MeerKAT, the DST and the IAU/OAD and EMSS antennas. This group again included public sector intermediaries and international intermediaries as well as the SKA as the core actor in the sample and one of the leading firms in its technology development process.

The rest of this report attempts to explain the interactions illustrated in Figure 3 and elaborate on the structure of the network, and the extent of, and reasons for, the instances of alignment or misalignment. This analysis starts with an introduction to the SKA as the case study focus within the context of the astronomy SSI.

3. THE SQUARE KILOMETRE ARRAY

History

The origins of the SKA organisation lie in the scientific impetus to build a large radio telescope that could use interferometry to develop economies of scale based on using multiple receiver dishes to develop observation capacities many orders of magnitude more powerful than any single telescope or dish previously built. This impetus gathered momentum through a series of multilateral agreements during the 1990s. In 1993 the International Union of Radio Science (URSI) established the Large Telescope Working Group to develop the scientific and technical specifications for such an observatory, and also to mobilise support for its operationalisation. In 1997, eight institutions from six countries (Australia, Canada, China, India, the Netherlands and the United States) signed a Memorandum of Agreement to cooperate in a technology study program leading to a future very large radio telescope. In 2000 a Memorandum of Understanding to establish the International Square Kilometre Array Steering Committee (ISSC) was signed by representatives of 11 countries (Australia, Canada, China, Germany, India, Italy, the Netherlands, Poland, Sweden, the United Kingdom and the United States). This was superseded in 2005 by a Memorandum of Agreement to Collaborate in the Development of the Square Kilometre Array, which provided for the establishment of the International SKA Project Office.

In 2008 a new International Collaboration Agreement for the SKA Program came into effect, which established the SKA Science and Engineering Committee (SSEC) as the primary forum for interactions and decisions on scientific and technical matters for the SKA among the consortium partners. At the same time, the SKA Program Development Office (SPDO) was established to provide a framework to internationalise the technology development and design effort of the SKA. In 2011, the SKA Organisation was formed and the project moved from a collaboration to an independent, not-for-profit, company. The SKA Organisation is a private UK company limited by guarantee. The company does not have a share capital, but has members who are guarantors (with limited liability) instead of shareholders. Directors of the Board are appointed by the members.

In this historical context, the sections below introduce the SKA in terms of the main analytical aspects of this study, thus focusing on networks, actors, competences and capabilities.

The SKA as a global innovation network

The composition of the SKA organisation reflects is global nature and its structure as a global innovation network (GIN). This defined by Chaminade (2009) as a ‘globally organised network of interconnected and integrated functions and operations by firms and non-firm organisations engaged in the development or diffusion of innovations’. The SKA fits this definition well, as its innovation networks span Europe, the Pacific region, China, India and South Africa. As of May 2013, the members of the SKA organisation are:

- Australia: Department of Innovation, Industry, Science and Research;
- Canada: National Research Council;
- China: Ministry of Science and Technology;
- Germany: Federal Ministry of Education and Research;
- Italy: National Institute for Astrophysics;
- Netherlands: Netherlands Organisation for Scientific Research;
- New Zealand: Ministry of Economic Development;
- Republic of South Africa: National Research Foundation;
- Sweden: Onsala Space Observatory;
- United Kingdom: Science and Technology Facilities Council; and Associate member:
- India: National Centre for Radio Astrophysics.

Internally, the SKA is a complicated organisation. At the highest level, it is an international non-profit science project. Its headquarters are in the Jodrell Bank Centre for Astrophysics, in Manchester, UK, where management and senior scientists are based. However, it hosts large project offices in South Africa (Cape Town) and Australia, where the site infrastructure will be based. The project offices operate with a considerable degree of autonomy. The South African project office it is largely staffed by South African scientists and engineers, and the head of the South African project office reports to the SKA board in the UK. Within this basic architecture, the SKA is divided into a number of sub-projects, research consortia and science projects. For example, the technology development for the SKA is parcelled into 10 consortia, each of which operates as a global innovation network to develop the technology for a particular component of the telescope. The 10 work packages, referred to as 'consortia', that make up the SKA are:

- Assembly, Integration and Verification (AIV);
- Central Signal Processor (CSP);
- Dish (DSH);
- Infrastructure Australia and Africa (INFRA AU/ INFRA SA);
- Low-Frequency Aperture Array (LFAA);
- Mid-Frequency Aperture Array (MFAA);
- Signal and Data Transport (SaDT);
- Science Data Processor (SDP);
- Telescope Manager (TM); and
- Wideband Single Pixel Feeds (WBSPF).

Each consortium in itself consists of a global innovation network. For example, the dish consortium consists of an international collaboration among the the following organisations:

- Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia;
- RPC Technologies, Australia;
- National Research Council, Canada;
- Joint Laboratory for Radio Astronomy Technology (JLRAT), China;
- Max Planck Institute for Radio Astronomy (MPIfR), Germany;
- Vertex Antennentechnik, Germany;
- IAF Fraunhofer, Germany;
- National Institute of Astrophysics (INAF), Italy;
- European Industrial Engineering (EIE), Italy;
- Società Aerospaziale Mediterranea (SAM), Italy;
- SKA South Africa, South Africa;
- EM Software and Systems (EMSS), South Africa;
- Spain University Group, Spain;
- Chalmers University/Onsala Space Observatory, Sweden; and
- Omnisys Instruments AB, Sweden.

Then, at a third scale, localised innovation networks, which link to globalised innovation networks, evolve. In this respect, EMMS and the SKA South Africa Project Office are embedded in a global innovation network, which includes local universities, suppliers, the EMSS's international parent company and collaborating firms that are not part of the core consortium.

The SKA, from a network point of view, is thus effectively a hub for numerous innovation networks, each of which are interrelated with the others, and each of which are global in their reach. The effect is the coordination of global innovation networks at multiple scales as well as overlap of global innovation networks in the horizontal sense (i.e. organisations may work on more than one consortium).

The structure characterises the science as well as the engineering. For example, the MeerKAT precursor instrument hosts 10 main science projects, each of which are also global innovation networks in their own right.

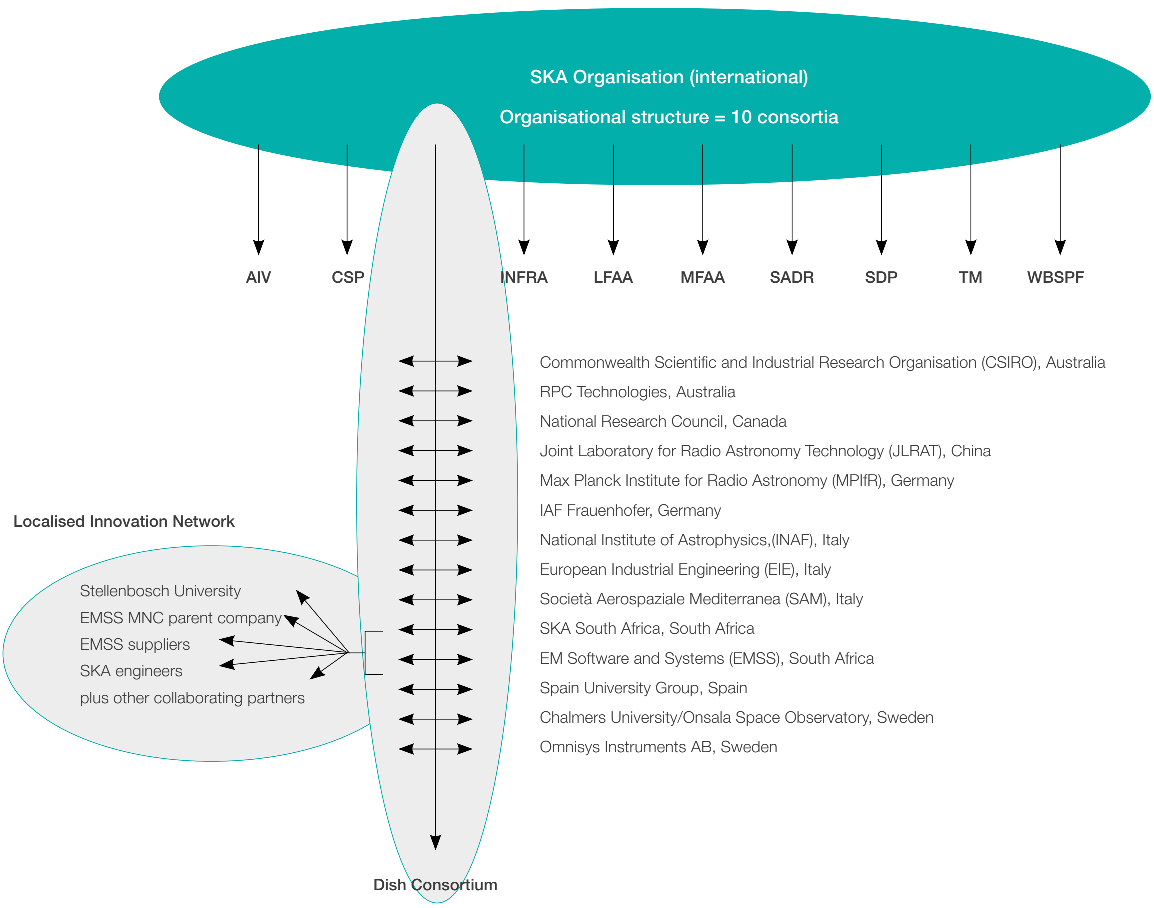
This structure, of 'stacked and overlapping GINS' is illustrated in Figure 4. Here, the global SKA organisation acts as a network hub, within which ten vertical consortia are coordinated. These vertical consortia are each, in turn, an axis around which numerous localised research networks, largely also global in scope, are centred.

The SKA in South Africa

The South African SKA Project Office was established in 2003, with South Africa's preliminary bid to host the project. During the bidding phase for the location of the SKA, precursor or 'pathfinder' radio telescopes were commissioned and built in South Africa, both to test the technology and to illustrate to the international community that South Africa had the requisite capacity in the field. The first of these was the KAT-XDM, a 15-metre antenna located at HartRAO. This was a testing ground for the subsequent precursor, the KAT-7, a set of seven linked satellite dishes. The third and largest precursor is a set of 64 dishes, known as the MeerKAT.

The KAT-7, commissioned in 2010, was the world's first radio telescope with dishes made of composite fibreglass, representing a substantial cost saving and technical innovation based on South African design. The KAT-7 also used ROACH high-capacity circuit boards designed and manufactured in Cape Town, which are now used by various telescopes internationally. Moreover, the KAT-7 is also a useful instrument in its own right, and has already been

Figure 4: The SKA as a locus for global innovation networks



used in astronomy research. KAT-7 is a precursor engineering test bed for the larger 64-dish MeerKAT pathfinder, and has been used to test various system for the MeerKAT array.

The MeerKAT, currently under construction, will form 25% of the first phase of the SKA, and is also a pilot for the design of the antennae. The MeerKAT is entirely paid for by the South African government, as a form of 'in kind' contribution to the SKA. This was a calculated risk by the government, with several possible routes to a positive outcome. If the SKA bid had been unsuccessful, the MeerKAT would still have been the largest radio telescope in the southern hemisphere for the next decade, allowing it to undertake groundbreaking science in its own right. As it stands, the KAT-7 and MeerKAT have provided evidence of South African capabilities in radio astronomy and contributed to the decision to allocate most of the SKA to South Africa.

The MeerKAT is thus a South African contribution to the SKA project, as well as an entry point for South African design capabilities to participate in the SKA engineering and for South African science voices to have an input into this process. It is thus, in essence, a hub for high-level interactive capabilities for all of these actors. South Africa will retain ownership of the MeerKAT until 2020, when it will be integrated with the SKA and form part of its Phase 1 infrastructure.

Thus, when we refer to the 'the SKA' in South Africa, we referring to the KAT-7, the MeerKAT, and the SKA South Africa Project Office, which provides a host to the MeerKAT and all the SKA activities based in South Africa, including the South African Human Capital Development Programme (HCDP). The SKA, in this sense, has many tacit and codified competences required to manage its assets in terms of skills, knowledge and technology, and the capabilities to integrate its various functions in a highly dynamic context. Most of the capabilities directed at skills and knowledge management are located within the HCDP, although there are some – particularly internal – interactive mechanisms that are located outside this function.

Historical trajectories

Within the longer-term historical context, skills and knowledge emanating from ex-military sources have played a prominent part in the SKA:

> It's been a very big influence in our project. Many of the people here have had some interaction, or work, within that military sphere and have then moved over to radio astronomy. Even myself, I did some work at a couple of companies that were in that area and that brings that whole culture of System Engineering and a rigorous approach to engineering projects and their development. So I think it's been very helpful. In fact, that is part of the reason why the government invested in this radio astronomy programme, is because the arms industry was falling away with the new government, and this is seen as a more benign top-down approach to keeping those skills and things going in the country, because really, astronomy is also another very challenging area, just as the military was before. (Management interview: SKA)

Networks and interactive structures thus extend into the ex-military domain, which consists of a long-established group of firms (e.g. Reutech, Denel and Tellumat), academics and government actors. It also illustrates the macro thinking that may have played a part in the top-level political structures that supported the SKA – showing how the SKA represented an opportunity strategically to redeploy and further develop niche capabilities that existed at the national level in a manner consistent with political and technological changes. The defence industry is closely linked with the space industry, with radio technology, and with ICTs, as well as a range of other skills that are relevant to the astronomy-oriented engineering required by the SKA. Much of this technology is also beneficial to the firms, who benefit from the utilisation of the technology for their own uses or for the marketplace.

Another skills domain that has overlapped with the SKA is that of space science and satellite technology, a sector that has seen fluctuations in demand that have resulted in challenges for people working in the sector. People have moved from the satellite industry into the SKA, where it is hoped that the long-term nature of the project will provide more stable ground on which to build capabilities at the national level:

> I will give an example of the problem we have in technology industries in developing countries. So, for South Africa for example, the space industry we build a satellite. It takes three years to build it. We up skill, we train engineers, we get it all ready, we build the satellite. It takes three years, the satellite launches. We don't have enough funds, requirements, etcetera, for a second satellite straight afterwards. So we now have a whole lot of trained people that sit, what do they do? So they inevitably change career or go overseas. I mean, what does a trained satellite engineer do when there is no satellite? Maybe in eight years, when South Africa can afford build another one and has to do the whole process again. So what some others in the same areas need or looking to do is say we need to look at technology projects where the skills are interchangeable. And a lot of people who worked on satellite programmes in South Africa are involved with SKA. So you find these complementary space programs where you do a satellite, then you've got SKA and then maybe a satellite and then a phase of another programme, so that you not losing that skill set. (Management interview: SKA)

African partner countries

The SKA acts as a skills development driver in its African partner countries. For example, the the Ghana Radio Astronomy Project – implemented as part of the SKA project – aims to kick-start a graduate and postgraduate course in astronomy and astrophysics in Ghanaian universities. Similarly, the University of Botswana, the University of Antananarivo in Madagascar and the Eduardo Mondlane University in Mozambique have recently introduced courses in astronomy and astrophysics. In 2013, South Africa announced a donation of R500 000 to Mozambique for a radio telescope, in aid of skills development for its role in the SKA.

The SKA acts as a network node connecting a wide range of African universities. The project hosts conferences focused on human capital development in Africa. In 2012, such a conference focused on extending collaborations between universities in Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia. Partner countries were encouraged to participate in exchanges of lecturers, postdoctoral fellows and course material. International collaboration also involves the co-supervision of postgraduate students and academic sabbaticals.

African Very Long Baseline Interferometer (VLBI) network

The VLBI is an incipient network of new and refurbished radio telescopes spread across the African continent. This will use similar technologies to the SKA to develop radio telescopes and perform radio astronomy. Close institutional relationships between the VLBI network and the SKA are based on these technological and scientific similarities, which have resulted in cooperation in terms of training, technology development and advocacy.

The VLBI will make use of old satellite telecommunications hardware that, prior to the advent of the internet, formed the backbone of Africa's communications infrastructure. Although the need for radio satellite dishes is now largely obsolete for this purpose, many African countries retain mothballed infrastructure that is now being brought into the VLBI network. The network will operate along similar technical parameters to the SKA – essentially comprised of a network of radio telescopes that will be connected using interferometry to provide composite data of a far higher resolution and sensitivity than a single telescope could provide. Politically, a central motivation is to establish network of radio telescopes that is African-owned.

Initial funding for the VLBI came from the African Renaissance Fund (ARF), which approved funding for the initial work to construct a network of radio telescopes in SKA African partner countries. The South African government, through the Minister of International Relations and Cooperation and the Minister of Finance, approved the allocation of R120 million to start construction. The other member countries are also part of the SKA, including Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia.

More recently, the policy position of the European Parliament, expressed through the AERAP, is expected to provide substantial additional funding through the EU's Horizons 2020 funding scheme.

The skills development impact of the SKA

The International Astronomical Union has highlighted the effective role of astronomy in human and economic development. Unlike most sciences, astronomers can participate in frontier astronomical research regardless of their geographic location, and this can have an impact on local development as well as skills and technology development for astronomy. The SKA project, including the MeerKAT, is contributing to the development of astronomical skills across Africa.

Astronomy attracts top scientists and engineers to work in South Africa. This can provide opportunities for local specialists to engage with international partners working at the knowledge frontier. Radio astronomy in Africa has human capital impacts beyond the fields directly associated with it. Like any large ICT project, radio astronomy projects have direct benefits to society through the training of technicians for development and operations and through the attraction of new talent to ICT in general. The construction of high-tech facilities equips civil engineers and construction workers with experience and skills for future employment. Communications and power engineers benefit from the experience of working on the installation of the groundbreaking communications and power infrastructures required for projects like MeerKAT and the SKA.

African astronomy projects have already generated manufacturing spin-offs – extremely fast switching devices built for the High Energy Stereoscopic System (HESS) facility in Namibia are being adapted for commercial sterilisation systems because they create ozone, a strong disinfectant. Significant portions of SALT, KAT-7 and MeerKAT were locally constructed.

The International Astronomical Union has also noted the key role of astronomy as a tool for educating young people. As one of the most approachable sciences, and one that fascinates children, astronomy is an excellent vehicle for introducing them to science and technology. Due to its unique combination of science with inspiration and excitement, it has distinct potential in facilitating education and capacity-building throughout the developing world. As noted by David Davidson, SKA SA Research Chair recipient in Electromagnetics at Stellenbosch University, the SKA project has been attracting top young minds into science and engineering. 'It has definitely put physics back on the agenda as a career option for scientifically minded students.' (http://www.ska.ac.za/newsletter/issues/16/11.php).

Capability-building mechanisms and competences and capabilities for interaction and dynamic interaction

The Human Capital Development Programme

History

The SKA's Human Capital Development Programme has played a central part in the SKA project. In 2005 the South African team submitted the initial bid to host the project. Until that time the focus had been on the telescope site – its attributes suitable to radio astronomy, the prospects for infrastructure development, etc. However, after this bid the project team decided to focus also on the human capital that would be required to use the SKA instrument and on the skills required to participate in its design and construction. At the time, there were five or six practising radio astronomers in South Africa, together with a small pocket of capabilities in terms of radio telescope design and fabrication – largely stemming from the HartRAO facility and its collaborations with universities, amongst which Rhodes University featured prominently.

The HCDP has played a key part in the success of the SKA bid:

> I think it is brilliant how they have done it. It's an essential component of the SKA and I think it has won them the SKA bid – for the world to see that it's not just about building hardware, but it's building a community, building a community with broad skills – not just the astronomers, but the engineers, the computer skills, etc. So, I think it was essential and it was a very clever part of the SKA project to incorporate that from the beginning. (Interview: Woudt)

However, at the scale that the SKA would reach, the number of astronomers and engineers required would need to increase by several orders of magnitude. The number of PhD radio-astronomers would need to increase from six to 60 just to make full use of the 64-dish MeerKAT (Bharuth-Ram 2011), let alone the 3 000-dish SKA. Thus a decision was made to find a way to support students through learning pathways towards radio astronomy and the engineering skills required to design and build radio telescopes, with the overall objective of creating the required research capacity and support capacity for the MeerKAT and, eventually, for the SKA.

The first step was to support postgraduate students at the MSc and PhD levels at South African universities. However, as time went on the range of support was extended to all levels from undergraduate to postdoctoral fellowships and academic positions, as it was realised that a full skills pipeline would be required to meet the coming demand. It was also realised that capacity in the area of technicians would have to be developed, with a focus on skills for site infrastructure. The generic management and operational skills required for the SKA Project Office could be drawn from the broader South African skills pool, and senior management positions would largely be held by scientists and engineers moving into management positions. The range of skills domains to be supported by the programme was thus determined by the skills and knowledge needs of the MeerKAT and the SKA. These included:

- radio astronomy scientists;
- engineers in fields relevant to radio astronomy;
- technicians who are able to upgrade and maintain telescopes on site; and
- artisans who can contribute towards infrastructure development, e.g. bricklaying and welding.

The HCDP has a mandate beyond that of the SKA's requirements – as a publicly funded programme, it has a broader aim of building up the 'ecosystem' of skills required for radio astronomy in South Africa. It is therefore acceptable, and even encouraged, for graduates of the bursary programme to find their way into firms or into academic positions, particularly when these, in turn, are related to the activities of the SKA.

In terms of internal competences within the HCDP, the programme is staffed by a senior manager whose portfolio includes university-related programmes, an officer in charge of the FET programme, an officer in charge of the Outreach and Schools Programme, and an administrator.

Process and structure

After its inception in 2005, the structure of the HCDP evolved into a full skills development pipeline. The process requires re-application at each step: students apply for support for first-year to fourth-year/Honours level, then need to re-apply for a Masters bursary, then re-apply for a PhD bursary and, if required, re-apply for a postdoctoral fellowship. This process provides programme administrators with information about students and control over the range of disciplines and skills that are covered by the programme.

> We have always wanted to be very engaged in the students and very involved in what they doing, so that we could keep an eye on the research that they were doing, to ensure that they were doing the right stuff but also so that we could guide our students into the next level of study. So, one of the things we always insisted on, was that if a student was

at undergrad level going into Honours and was going to be finishing Honours, we would then point them in the right direction of supervisors and point the supervisors in their direction so that they have a better chance of getting into MSc research. (Management interview: SKA South Africa Project Office)

At the higher level, the HCDP supports lecturing positions, professorships and research chairs. SKA postdoctoral fellowships are awarded for a period of two years (plus one additional year if agreed to by the host institution, the candidate and the South African SKA Project). The fellowships are renewable every six months based on progress. Research chairs are the apex of the HCDP, and are used as a base from which to run comparatively large research groups that operate at the global frontier of knowledge production and make a substantial contribution to the knowledge requirements of the SKA.

However, it should be noted that the structure of the 'pipeline' is not entirely vertical – that is, it does not consist largely of students who are supported all the way from undergraduate to postgraduate. Particularly in the earlier years, the pipeline was more horizontal in that bursaries were allocated across the range from undergraduate to postdoctoral fellowships in order to provide a more immediate supply of these skills. Over time, however, there have been more examples of vertical passage through the system, with individuals passing through all of these stages eventually to be employed by the SKA.

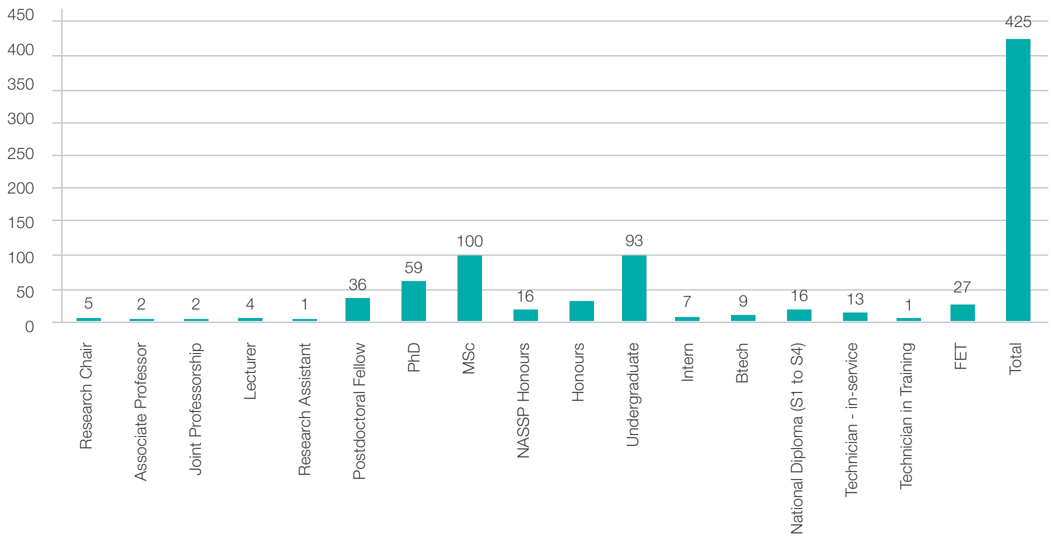
Outputs

By November 2012 the programme had awarded 425 bursaries, grants and fellowships and established five research chairs dedicated to science and instrumentation of astronomy. Figure 5 illustrates the intake of the SKA Human Capital Development Programme as at November 2012. The largest intake has been for MSc students (100), followed by undergraduate students (93) and PhD students (59). Postdoctoral fellows (36) and Honours students (34) have also received support. There have been 27 students based at FET colleges.

Managing skills and knowledge

The knowledge challenges faced by the SKA are extraordinary – including demands at the highest end of the skills spectrum in the arenas of science, engineering and management and a broad range of skills from a variety of disciplines across different parts of the organisation, extending to artisanal and vocational skills required for site infrastructure. Supply chain management is an essential skill, as the telescope consists of thousands of components

Figure 5: Academic intake for the South African SKA Project Human Capital Development Programme



Source: http://www.ska.ac.za/newsletter/issues/18/11.php and sub-components, all of which require supply chain management and different levels of functional integration.

Firstly, then, SKA management highlighted that generic organisational skills constitute an important area of skills demand. This includes top management, office management, HR, supply chain management, project management, process management and finance.

To achieve the science objectives of the SKA, a range of science skills is required. This includes astronomy specialists, as well as specialists in related disciplines of physics, mathematics and cosmology. On a larger scale, however, it is the technical skills that form the bulk of skills demand for the SKA. This also covers a large range of skills, as the establishment of a radio telescope of this magnitude requires skills from almost every branch of engineering. This includes specialist skills in:

- antenna structure;
- computation of flow dynamics;
- cooling technology;
- receiver technology;
- electromagnetic modelling;
- mechanical engineering;
- mechatronic control systems;
- analogue to digital conversion;
- high-speed digital electronics and bulk data transfer;
- software development; and
- radio frequency interference engineering.

A particularly important skills niche is systems engineering, which operates at the interface between science and engineering. A systems engineer translates science requirements into engineering requirements, which is an essential interface that sits at the core of the SKA project.

The SKA also has skills requirements in the vocational and artisanal skills bands, including the skills required to upgrade roads, drill boreholes for water, optical fibre technicians, logistics support and antennae maintenance. Antennae maintenance itself requires a suite of skills, including supply chain management skills to control the flow of parts and spares.

However, management interviews did not report serious difficulties in bringing in the required skills, at all levels. Only a handful were identified as somewhat difficult to find, namely high-end niche ICT skills in specific domains, as well as digital signal processing specialists.

Managing change: Technological change and rapid growth

The SKA operates in a context of rapid technological change, which presents challenges for capability-building mechanisms and interactive capabilities. Because ICTs in particular are constantly and rapidly advancing, the SKA needs to be able to forecast technological changes and build them into its technical and skills planning processes. To this end, they interact with major firms such as Intel and IBM:

> When you look at it, at the electronics and the processes side, the software and the IT that is going to change quite dramatically. You need to understand where those technologies are going. For example if I have to build data hard drive from MeerKAT and I put it down in 2016 then I have to essentially plan for what's going to be in mature technology at that stage not what's matured technology now. So the route we've gone there is to get involved with Intel and IBM and work with them to understand where these technologies are heading. (Management interview: SKA)

Rapid growth has presented serious challenges in terms of the dynamic interactive capabilities required to bring the required skills into the organisation at the right time – a 'build the plane while you're flying it' scenario. This has been accomplished through a combination of tactics, including continued interaction among all the key players to determine future skills requirements and ongoing assessments of future technological scenarios and what their impact might be on skills requirements. In addition, for the management of human resources within the organisation, rapid growth has necessitated the maintenance of holding patterns interspersed with internal assessments of skills requirements and actions to bring those skills in:

> I have also seen, just in the short time I've been here, you're faced with the issue of becoming very large very quickly. We had a core group in the beginning running the bid fight etcetera. Now suddenly, we're all go and got MeerKAT and KAT-7, and everything and suddenly it balloons the organisation. I think it can be difficult where you can be putting people in positions almost Band-Aid-like to keep moving forward because we're all rushing and growing at quite a speed. You tend to get to the point where you say, 'stop everybody and start assessing your organogram and working back and making sure the right areas and skill sets are being addressed', because you can get a couple of engineers overloaded and we need another engineer in this field. You know, that may not be necessary so I would say that the phase that they have been through now, is the sudden growth, they need to now reassess the gaps maybe, once the growth phase is over. (Management interview: SKA)

The SKA deploys a range of strategies and tactics for meeting its complex and rapidly changing skills needs, and has a number of competences and capabilities required to achieve this. In the SKA's organisational culture, a type of meritocracy acts to retain top performers and filter out underperformers. This forms part of a broader system in which some bursary holders who work for the SKA end up migrating to related firms:

> If you take ten people you always gonna have one or two that rise to the top when coming to your organisation, and really drive things. You might have one or two that comes in a solid worker but quite simply just doesn't have the drive or the ability of this other person. You gonna have one or two that doesn't fulfil the promise and then maybe four that goes out into industry and go do something else. That's probably pretty close to what we have. (Management interview: SKA)

The SKA also requires advanced internal interface mechanisms in order to meet its science and engineering mandates. The structure of the SKA is complex, and its interface with the MeerKAT project is also complex. For everything to run smoothly, these interfaces need to operate efficiently.

Interactive capabilities and the management of skills and knowledge domains

The core activity of the HCDP is clearly articulated as one of managing interactive mechanisms and capabilities:

> My role is to facilitate engagements, to set up processes to involve the experts. To get them talking to each other. I rely very heavily on input from my director and my associate director as my support structure, but really my role is to facilitate, and I have an appreciation of the science and engineering and I'm very excited by it and I love the students and they are brilliant ambassadors, but at the end of the day, I'm just facilitating everybody getting together and making this happen. (Management interview: SKA)

The spread of skills domains and research areas supported by the HCDP is carefully planned, and is the product of extensive interaction between the SKA organisation, universities and intermediaries. The MeerKAT and the SKA were both designed to investigate specific science questions, primarily focused on the frontiers of fundamental physics. The SKA organisation interacts with the international groups of scientists working on these projects to discuss the details of the science questions on which they focused. This provides a foundation for deciding on the allocation of funding for skills development and research.

The emphasis of the HCDP has been on funding for applied radio astronomy research, rather than for purely theoretical research. The aim of this is to make maximum use of the MeerKAT and SKA instruments:

> What we try and do is develop our observational radio astronomers so they are not theorists. They are individuals who can actually use a telescope, collect the data, analyse the data and turn it into something, and actually produce science out of it. (Management interview: SKA)

From that position, scientists have developed specifications for the equipment that would be required to conduct their science. This in turn provides parameters for engineering, which helps to inform the funding allocations in this area.

> From an engineering point of view that helps us because it tells us the kind of skills that the engineers need to have, in order to design the kind of instrument that the scientists want. (Management interview: SKA)

The final allocation of funding to skills domains and research topics (for both science and engineering) occurs through intensive interaction with academics. Potential supervisors are invited to submit proposals within the research domains identified by the HCDP, and the HCDP also publicises its interest in particular research topics that potential supervisors can take up. This process has become more focused and effective over time, as the interactive capabilities have deepened and the skills requirements of the MeerKAT and SKA have become more clear:

> Over the years it's become more and more focused. You must remember that the development of the telescopes and the science that they were going to do has also been evolutionary. So as the science has become more defined and the instruments have become more defined so it's helped us to define our research into narrower bands. (Management interview: SKA South Africa Project Office)

The overall process of the HCDP is facilitated by a SKA South Africa Project Office management member who is positioned at the top of the organisation with easy access to senior management. She is placed to consult widely and interact with many different parties in order to coordinate the process and optimise the matching between the skills and knowledge needs of the SKA and the skills and knowledge production that is funded by the HCDP. The most important internal figures are the senior management of SKA South Africa, Bernie Fanaroff and Justin Jonas. They have both detailed and broad knowledge of what is needed to build and use the telescope, coupled with an understanding of the engineering and the science.

Ongoing consultation also takes place with the principal investigators (PIs) of the instrument's main science projects. The manager of the HCDP consults with this group of PIs to establish what their skills requirements are. This interaction has been ongoing since the early stages of the MeerKAT project. Once the basic specifications of the MeerKAT were finalised, and it was established what kind of science the MeerKAT could do, the HCDC sent out a call for proposals to the international scientific community to suggest science projects for the MeerKAT. These were vetted by an international panel, which decided which projects would be successful – that is, which would be given time allocations on the telescope.

There are slightly different processes for undergraduate bursaries on the one hand, and research funding and bursaries on the other, which includes postgraduate, postdoctoral and academic appointment funding. The process for undergraduate applications is much simpler. Here the requirements include that the student be studying towards a BSc with physics and maths as their majors, or towards a BEng with a focus on electronic and mechanical engineering. To make funding decisions, a selection panel, dedicated to undergraduate application, sits and sifts through the applications to focus on the most promising ones. The final selection is then sent to the project manager to approve – his office has the power to include or exclude a student from the final list. The mechanism for applications for postgraduate, postdoctoral and academic research funding is more complex. It begins with a call for applications that is sent out to the research offices of all South African universities, as well as several universities from other African countries. This call includes a list of projects – the student can then select a project from this list and make contact with a relevant supervisor, who can then decide whether to accept the student and proceed to submit an application.

Each application documents in detail what the proposed research will entail. This allows the HCDP to make informed decisions about whether the project is viable from an engineering standpoint, whether it is viable to complete it in the allocated time period, and whether it is relevant to the broader science objectives of the MeerKAT/SKA.

When it comes to processing incoming proposals from potential supervisors, internal interface mechanisms are established to sift through all proposals, identify the most suitable ones and connect them with the funding mechanism. The first stage is for the manager of the HCDP to receive, collate and organise all of the proposals. These are then sent to the top management of the project, who separates the relevant from the less relevant proposals to generate a shorter list of applicants who then proceed to a selection panel. The selection panel sits in September, once all of the proposal are in; in October, the final decisions are made. The selection panel consists of South African and international radio astronomers, who each year spend a few days dedicated to the task of reviewing applications and making recommendations about which of the students and projects should be supported. Before the panel meets, the HCDP manager sends out terms of reference indicating the spread of funding allocations at different levels – for example, 10 PhD bursaries and 10 MSc bursaries, etc. However, these are guidelines – in some years, there are disproportionately more excellent proposals in the MSc category, in which case funding is shifted in that direction after discussion.

The selection panel is a powerful mechanism for direct interaction between the skills supply and skills demand side of the SKA's innovation network. Academics from the main partner universities, as well as representatives of the NRF, serve on the selection committee, thus facilitating salient discussions about what the main areas of demand are and what the capabilities and pipeline are in terms of skills supply.

One of the main selection criteria is a combination of an excellent student and an excellent and relevant project:

> One of the key things we look for is the combination of an excellent student and an excellent relevant project. Sometimes it's a bit heart-breaking because you can see there's an excellent student but the project that's being proposed by the supervisor, you know just falls short of all of the criteria and vice versa. Sometimes there's an excellent project but we know the student won't be able to, you know won't be able to be successful at a postgrad level. (Management interview: SKA)

Also, there are criteria for the inclusion of students from other African countries, for example having four of such students in each category. Equity is also a priority, but the aim is to achieve this within the framework of excellence and relevance, and all students need to have met some academic fundamentals. As such, each proposal is considered on a case-by-case basis:

> It's easy if you got an excellent black South African male or female with an excellent project. That's easy. But in some cases you might find that the student is average but they've got an excellent supervisor and we feel they will go through anyway. There's so many things that you take into consideration and you can't actually document every eventuality or every possibility. (Management interview: SKA)

It is important to note, however, that the bursaries that are awarded through the research chairs are decided upon by the research chairs themselves – not by the SKA's HCDP management. There is thus a level of devolvement in the selection of bursary recipients and their focus areas.

The HCDP also acts as a networking agent. It organises an annual Bursary Conference, bringing together SKA-funded undergraduate students, postgraduate students, postdoctoral fellows, supervisors, Research Chairs, other interested researchers, invited speakers from international universities, and local and international radio astronomers and engineers working on the MeerKAT and SKA. SKA-hosted conferences are part of a broader field-building role for the organisation.

Roy Maartens, the SKA SA Research Chair at the University of the Western Cape, noted that 'the value of the conference lies in the inter-university sense of community that it helps to build between students, supervisors and researchers. Young students get to realise that engineering, computations, astronomy and model building are all connected, and that they are part of a bigger group.' (http://www.ska.ac.za/newsletter/issues/16/11.php)

Interactions with intermediaries

The SKA has a close relationship with its direct funding source, the NRF, which channels public funds from the DST into the SKA. This relationship has, however, been strained at times, particularly with regards to the interactive capabilities required to manage the HCDP. One cause of this, described as a major challenge by SKA management, has been 'interference' by the NRF in the HCDP's administrative processes. In 2010, control of the distribution of bursary funding by the HCDP was taken away from the SKA South Africa Project Office and handed over to the NRF (although the higher components of the programme, focusing on research, remained within the control of the SKA organisation). This was described by SKA management as a major obstacle to the functioning of the programme. Primarily, this was because they lost contact with their own students and, as a result, could not effectively track them. This lead to a loss of control of the range of skills domains that were being funded. This was particularly felt in the area of black undergraduate students, who often faced significant pressures to exit the university after the undergraduate stage in order to seek employment.

> The programme has now been handed back to our control, so we are now resetting ourselves up so that we can administer the programme as we want to. There is a lot of backlog that we need to catch up on, in terms of student information and access to the students, but we are busy working furiously to make sure we can get that, so that we don't lose out on any other opportunities. So, although, the pipeline is definitely working and it's the model that it should be, you know, it's a model that does work. I think we would've been seeing more results from the pipeline if we had had more interaction with the students over the last couple of years.
>
> […] The particular concern is that we started the undergraduate programme, primarily to identify and support black South African students and women South African students because most, particularly black South Africans, if they do a degree they tend to leave university after their degree. They hardly ever consider postgraduate research because they now need to go out and work. So, that was one of the main objectives of our undergraduate programme […] Before the NRF took control of project, during that time it is mostly us encouraging those students to go and do postgrad studies. So, my feeling is that we lost some of those black South African students and woman students because they were not actively pursued, so to speak. (Management interview: SKA)

The SKA lobbied to have this function returned to the organisation, ultimately succeeding in this request on the condition that they use the NRF's online systems to manage bursaries. In other words, the NRF is effectively 'outsourcing' this function to the SKA so that information and management can lie within the SKA rather than be fenced within the NRF. This provides a lesson about the difference between the competences required to manage a large skills development programme (the NRF has the basic structures and systems for this) and the interactive capabilities that are required to actualise this, which include constant interpretation of incoming information, direct contact with students and field-specific engagement with the student's subject matter and fit with the programme:

> I think because the NRF does manage so many grants and bursaries, they thought that it could be just something else that they could handle, but the way in which they drive bursary programmes is different from the way in which we drive them, so as I say, the key

> to this capacity development programme is continuous interaction, is access to information, etcetera, etcetera, which wasn't necessarily happening through the NRF because they are really an administrative body that dispenses bursaries. It's more than an administrative service. (Management interview: SKA)

The SKA also maintains strong ties with the DST, reporting regular and intensive interaction, at both formal and informal levels, between SKA and DST senior management. The substantial political traction enjoyed by the SKA project has resulted in support from other government departments, for example inclusion in the Presidential Infrastructure Coordinating Commission's Strategic Infrastructure Projects (SIPs). This provides a forum to engage with ministers and senior civil servants.

Interaction with universities

Interaction with universities plays a critical part in the Human Capital Development Programme, and in the SKA organisation more broadly. As a knowledge-intensive project, it needs to remain closely connected to universities to deliver on its core mandates. Engagement is well established with the top levels of the university administrations, for example with DVCs and VCs, and with academics at all levels. These are largely informal relationships that succeed on the basis of tacit competences that enable rapid, responsive and informal communication between senior staff. The aim here is to encourage participation in the HCDP and to build stronger links between universities and the SKA.

Engagement with universities takes place through an external interface mechanism, the **Universities Working Group**. This was initiated in 2011, when SKA research chairs were initiated and thus interaction with universities was greatly increased. The group meets on a regular basis to discuss the progress of the project, the scope of research projects and any other items of relevance to the interaction between universities and the SKA. There is also ongoing communication via email and teleconference. The group includes astronomers from the main partner universities, including the University of Cape Town, the University of the Western Cape, the University of KwaZulu-Natal and Wits University, as well as senior management of the SKA project, including Bernie Fanaroff and Justin Jonas. This forms one of the most important interactive mechanisms in the SKA's innovation network, providing a unique and critical point of engagement between the skills supply and skills demand sides of the network. The group is informally arranged, and is not formally institutionalised within either the SKA or the universities. It has no formal mandate – this is aligned with the key role that informal relationships and informal networks play in the astronomy SSI and the SKA's innovation network. The meetings are initiated on the basis of need – to respond to a particular issue or challenge. They can be initiated by a university or by the SKA. As expressed by an academic from UKZN:

> We meet every few months […] we had a meeting recently, a few weeks ago. There's an exchange between the project team and the university representatives, and then that information is taken forward. I think that has helped significantly to improve the communication lines between the SKA and the universities […] It's an informal group, a collection of researchers from the different institutions in South Africa, and they meet with Justin and Bernie and others, and Kim, Daphne, Jasper Horrell. So every few months we meet […] it's kind of informally arranged. If there's something coming up, then we have a meeting. So for example recently we have managed to discuss the SKA Bursary Conference.

Other interaction with universities is focused on individual students, for example working with individual students and supervisors to restructure their proposals if needed. Every year there is an SKA postgraduate research conference, attended by all bursary holders. This seems to be a key event in creating a close-knit community around the project:

> That's where a lot of interaction happens where the universities or the supervisors assist us in developing the programme,

> chairing various sessions, etcetera. So it really is a very integrated community and the conference is great because everyone gets together and they talk and chat and share ideas and students get co-supervised, etcetera. (Management interview: SKA)

The HCDP takes into account the internal operations of universities, aiming not to disrupt. For example, when supporting an academic position, they provide payment at the level that the university suggests for that academic rank.

Another significant forum for engagement with universities is through the National Astrophysics and Space Sciences Programme (NASSP). This network is central to skills development in the South African astronomy sector. NASSP runs an Honours-level astronomy course, which is based at the University of Cape Town but which is a nationally coordinated programme that includes students from many South African and foreign universities. There is an ongoing connection between the NASSP and the SKA's HCDP. The programme receives applications from students looking for funding to study on the NASSP programme, some of whom receive funding. Several SKA staff either lecture on the NASSP programme or take part in its coordination.

There is also interaction around issues of curriculum. With the arrival of large new radio astronomy projects such as the MeerKAT and the SKA, the balance of skills required by the astronomy sector has changed. Previously the focus (so to speak) was on optical astronomy, such as that practiced at SALT. Radio astronomy was only a minor component of the overall astronomy landscape. However, this balance has shifted, with South Africa having become a significant player in the global radio astronomy system.

As such, there have been engagements, both formal and informal, between the SKA and the NASSP to discuss the balance within the NASSP curriculum.

One challenge for the SKA HCDP in its engagement with universities is that of interacting with academics and managing a range of strong personalities. This requires tacit competences for interpersonal communication:

> It's dealing with individuals who see their research as the most critical part of what they are doing. It can become an issue – the whole justification to them of why we didn't support the student or why we're not supporting their particular research, so there's that whole aspect. There's, I don't know how to say this without it sounding terrible, but researchers are opinionated people and so you have a lot of strong personalities at play. Very intelligent people, all driving their own case, but fortunately Bernie and Justin are very well respected in the community and you know people do listen to them and I kind of facilitate that process. (Management interview: SKA)

Research Chairs and funded research programmes

The South African Research Chairs Initiative (SARCHI) is a model used by the DST to support the highest levels of its funding in the national system of innovation. Research Chairs provide a prestigious post at a university and must be filled by an internationally recognised researcher in a particular field. The Chair receives a block of funding on an annual basis and uses the funding to develop a research group in his or her area, including both capacity-development elements (such as postdoctoral fellows or postgraduate students who form part of the research group) and research costs (such as the overheads and equipment required for the research group).

The SKA HCDP funds and manages a dedicated set of Research Chairs that are modelled on this DST system. At the South African universities, these Chairs, together with the SKA-related SARCHIs funded by the DST, have provided points for the attainment of critical mass in research and skills development for the SKA. These are based at Rhodes University, Stellenbosch University, the University of Cape Town, the University of the Western Cape and the University of the Witwatersrand. Other universities are also involved, but available evidence suggests that they play a smaller role and, in most cases, partner with other institutions.

In terms of the interactive capabilities associated with the SKA Research Chairs programme, the HCDP appears to have made an effort to establish forms of interaction that facilitate productive relationships with universities. This is contrasted with the approach of the NRF which, according to SKA management, has acted from the position of gatekeeper to create uncertainty for universities and academics seeking to become involved in the DST/NRF Research Chairs programme.

> The NRF made the universities find a candidate and then hope to goodness the NRF created the position for the person, but then what we did was, we said we must fix to award the position to the university and then give them the option to fill it. Otherwise, you got some international guy who's been sort of, half promised a position and it's just bad, it just doesn't work well that way. (Management interview: SKA)

The SKA HCDP also established two funded research programmes based at universities, looking at specific thematic areas in which there was a shortage of research specialisation in South Africa. One is in Digital Signal Processing for radio astronomy, which is based at UCT. The other is a High Performance Computing programme for radio astronomy, which is located at the University of Stellenbosch, the University of the Western Cape and the University of Cape Town. Again, these programmes were the result of management identifying particular skills and knowledge gaps that were required by the SKA and then establishing the programmes to fill these gaps.

The funded research programmes also operate under a broader mandate to provide high-end skills and knowledge to the broader South African economy. This mandate is derived from the fact that they are publicly funded and are therefore, in a sense, also public skills development mechanisms:

> Those programmes are designed to fund students doing postgraduate work in areas of direct interest to us, like high-performance computing for radio astronomy. In those programmes, and in the general human capital development programme, we're trying to develop the skills within the universities that will service this project now and into the future, but also, people that are trained in these areas, are usually of wider benefit to other industries as well. So we are quite happy if they go off into other industries and start up something and do whatever they need to do, to have enough of them in the country that can help with what we need. (Management interview: SKA)

Interaction with FET colleges

The SKA HCDP also includes a schools and FET programme that focuses on initiatives to improve maths and science education, particularly at schools close to the telescope site. The long-term aim of this has been to provide opportunities for students from those schools to enter the post-schooling bursary options provided by the HCDP. After a few years of running the schooling programme, however, no local participants had achieved at a level that would enable them to proceed to study science or engineering at a university. The schooling programme was thus oriented towards progression into an FET college and vocational training.

The FET programme begins with a selection of students from the local area, with a minimum of Grade 12. This exceeds the minimum requirement for entry into FET colleges (Grade 9). With regards to the FET colleges that were included in the programme, the main partner prior to 2014 was the Kimberley FET college, which has received two cohorts of SKA-sponsored students. However, SKA management were at the time of research negotiating with the Cape Town College to accept students, and were looking at discontinuing the partnership with the Kimberley college.

The FET programme does not include a promise of employment – it is thus broader than simply an initiative to provide skills for the SKA. It also has a social dimension, aiming to increase employability more generally in the communities surrounding the site:

> There's four objectives. One is to up-skill the local community, to make them more employable. Two is the way of giving back to the community, into skills development. Three is to increase the number of artisans for the general economy, and then four for skills for the project. (Management interview: SKA)

With regard to details about the cohorts that have passed through the Kimberley FET college, there are differences between the information provided by the SKA and by the college. According to SKA management, the first cohort included eight students, six of whom passed and were employed by the SKA. The second cohort included fifteen students, only four of whom made it through the first semester. According to the FET college, different staff members reported cohorts of 11, 9, 15 and 20.

However, both the SKA and the college agreed that one reason for poor performance was disciplinary problems among the students:

> It seems as though there was this element of being let loose, so to speak, so it's their first sort of experience for freedom, and having access to their own money. A lot of them didn't focus as much as they should on their studies ... (Management interview: SKA)

At the time of research, the HDCP had allocated another 30 bursaries to the FET sector, but had not yet decided on a college with which to partner. They were in the midst of discussions with Cape Town-based FET colleges, partially as a result of poor performance at the Kimberley FET college. Based on management interviews, there seems to be an underlying tension between SKA management and the Kimberley FET college revolving around the issue of the quality of students from Canarvon that were chosen by the HCDP:

> The problem is that we are quite strict, you get a chance but if you get comments from FET colleges that they don't wanna take more students from Carnarvon and then you need to start being, you know, you've gotta have strict rules in place. We've got bursaries for another 30 coming on for next year, for up to 30 students we can take on. Basically we will lay down the law, again, and those that are serious would make the most of the opportunity. (Management interview: SKA)

When setting the skills agenda for the FET colleges programme, the HCDP also engages well-developed interactive capabilities. There is a participative and informed process that guides decisions about the skills domains to which to allocate funding. The HCDP management meets with the SKA Infrastructure Manager, who indicates what the requirements are likely to be in the future. They also research other facilities, seeking to discover which skills were required for their construction. At the time of research, this had led to the use of 'calculated estimates' of skills requirements. The team was, however, waiting for the SKA operations plan to be finalised by its engineering teams, which would provide more precise details about the staffing requirements of the MeerKAT and the SKA.

Interactions with firms

The SKA has advanced interactive capabilities for engaging with firms, which form a different and distinct set of capabilities from those required to engage with universities and intermediaries.

One of the key management positions responsible for interacting with firms is the Business Development Manager. This is an unusual position, in that the SKA is a science project rather than a revenue-producing organisation. The Business Development Manager thus has objectives beyond revenue growth and profit seeking. The first responsibility is to establish connections with firms that enable the commercialisation of technologies developed within the SKA. This can take a number of forms, including straightforward commercialisation, assistance with the development of local manufacturing capabilities, or even freely distributing technology to educational institutions.

In cases where particular items required by the SKA have previously not been manufactured in South

Africa, as doing so has not been cost effective, the SKA has provided the possibility of new intellectual property and a large client that has spurred the development of a competitive local industry. In such a case the intellectual property would be given to the firm in the form of licensing rights to be able to manufacture the technology. Income derived by the SKA from this endeavour is then returned to the HCDP for spending on skills development and research. This is essentially a windfall for the firm involved.

In the construction of the KAT-7 and the MeerKAT there are numerous firms that have regular contractual relationships with the SKA. However, where firms are positioned to make a contribution to the design, engineering and technology development efforts of the SKA, the interaction takes on a different form. Here, firms benefit from a financial assistance programme, which will continue through the pre-construction design phase until 2016. This is a cost-sharing agreement, in which the SKA covers its direct cost of participation in research. This model, at the time of research, applied to eight firms, as well as research groups based at two universities. An example of a South African firm receiving financial assistance is EMSS Antennas. Before engaging with the SKA, this was a small firm, but since their involvement with SKA design research and benefitting from the financial assistance programme the firm has grown substantially while also providing world-class new technologies.

Larger firms that do not qualify for financial assistance may still take part in research projects at their own cost, in the hope of securing a place in the SKA value chain at a later stage – termed a 'contributing partner'.

Given the time frames of the MeerKAT and SKA, firm-based commercialisation efforts are still at an early stage. These range across the various components required for telescopes and infrastructure, including components for receivers, dishes, housings, ICT hardware and ICT software. The Business Development Manager within the SKA manages relationships with a portfolio of partner firms. The technologies being explored by these firms are mostly at the feasibility stage, the proof of concept stage, or the technology readiness demonstration stage of commercialisation. Some of the more advanced cases are in the prototype and pre-production stages, but none had gone to market at the time of research. It was expected that four or five of these projects would make it to market in 2014. Since no products had been fully commercialised at the time of research, the financial arrangement that would accompany this remained unclear. Management was mooting the idea of routing such income back into the HCDP, which would generate a type of virtuous circle.

From the SKA point of view, one of the main hindrances for firms is tooling up. This is a costly exercise that is not feasible without a market and production scales of sufficient size. The SKA assists in this regard by providing either financial assistance or large-scale orders that make tooling up feasible (for example, an order for parts for 3 000 telescopes). This ongoing and negotiated interaction with firms is an important interactive capability that maintains the SKA's private-sector supply base and its linkages with R&D and innovation capabilities vested in firms.

The SKA assesses the capabilities of firms by whether they can deliver the required products, services, or technology. When asked whether their partner firms, in general, have strong interactive capabilities in terms of scanning for skills and knowledge and bringing these into their own organisations (i.e. into firms), SKA management gave a positive indication:

> The companies that are engineering- and science-based I think do have relationships with the universities anyway. They're always looking for the next bright masters or postdoc coming out of there, so I think they do have relationships, they equally have relationships with us. We also know who's bright and new and coming up or where the skills sets may lie. (Management interview: SKA)

Procurement challenges
In the face of rapid change, multiple mandates, a complex supply chain and internationally agreed-upon time frames, the time-consuming process of procurement and supply chain management, including the procurement of skills and knowledge, presents a major obstacle – described as a bottleneck in the overall capability-building process. In particular, the SKA faces the challenge of meeting the requirements of both the public and private sectors. It must adhere to the complex and slow-moving Public Finance Management Act (PFMA), which requires a detailed and public procurement process. For example, any hardware costing over R10 000 requires three quotes for procurement. However, there are very few pieces of hardware that cost less than this amount, and there are hundreds of components that form part of each of the sub-systems of the telescope, thus creating a procurement nightmare – a huge amount of time is spent just organising and assessing these quotes.

At the same time they need to meet commercial time frames and their obligations to the SKA consortium, both of which require rapid change, flexibility and the ability to manage rapid growth.

> I do think a limiting factor, and this not just for us, it's for any government organisation, is employment. It takes so damn long to employ someone and maybe you want to employ someone and maybe you just want someone for six months and you have to go through the whole supply chain procurement thing. And that I think is the problem where the staff may say, look we've got a plan, in this particular part of the organisation. We are going to need 10 people over the five years and this is how we going to grow and this is what they need to be trained in and they may say that to [the head of the HCDP] and she may produce the people we need and everything may work and then it all falls down at actual employment, through the supply chain manager, this PFMA, and we know what it's there for and that's great. And it can become counterproductive and quite difficult to get through and the problem with that as well, is you, yeah, I don't want to knock supply chain, I mean, it has its benefits of course and I understand why it is there and its preventing the people who are taking advantage but essentially, you know, it also precludes this thing of I worked with this guy and he is great and I know he can solve this problem, we've studied together. You can't put him here, you have to run a whole process. The problem we have at SKA is that we are working on commercial time frames and not government time frames. We are not SANSA or any other government department. We are part of consortia all round the world, with very strict deadlines, very large workloads, and we have to produce results. So we can't waste six months, because we have very strict deadlines. (Management interview: SKA)

This challenge applies to bringing in skilled staff with the required capabilities and to bringing in firms with the required capabilities, thus placing the SKA in a double bind. The PFMA required onerous processes for both:

> The only problem is the procurement process with the firm, which can be just as long 'cos you have to open a tender. You can't just phone the firm and buy something. So with this financial assistance programme, we had a certain amount of time, fair amount of time, to put it together. Those few months I had were too short to run a tender process. So that's crazy. So you can literally what, run two maybe three tender processes a year in the time frames. Also the employment, maybe two get processed a year. It's not quick enough for a project that has to move this quickly. (Management interview: SKA)

This presents a challenge on several levels, and requires well-developed interactive capabilities to manage. Firstly, there are internal interactive mechanisms and tacit competences required to work with the PFMA, rather than against it. This may be particularly problematic with specialists who are not familiar with its requirements and its processes:

> I have two opinions on this issue. One is yes supply chain is sometimes wrong and you can throttle them but on the other if you just understand the process and give them what they want it can be quick and the problem is you have engineers and they think a certain way, so they won't order the stapler, they will wait three weeks and go, lemme get the stapler and the pen, actually I need the rubber and suddenly they have gone over the purchasing limit which means now they need new requirements. (Management interview: SKA)

There also appears to be something of an internal rift between supply chain management within the SKA and the staff who require supply chain services. Overcoming this requires coordination and, perhaps, team-building, with the aim of seeing the broader organisational picture:

> This is gonna sound horrific but they manipulate the system to the best possible outcome for themselves. I think sometimes yes supply chain is at fault, but sometimes its them as well and instead of just saying I've filled in the form and handing it on the desk and getting on with the day. When I need something I fill it in I take it to the supply chain, to the manager, I say this is what I need in this time frame, is this right way to do it? Will you see that it is done in time he says yes absolutely and it is always done? So I think that there is that kind of hand-it-over attitude and unfortunately supply chain is one of those walk through a little bit you know. (Management interview: SKA)

One response is to take a realistic assessment of these process constraints and develop tactics to operate within or around them. The Business Development Manager of the SKA indicated that she had taken this approach:

> I spend of more my time getting approvals for the departures of the norm than I do getting approvals for the normal things. The financial assistance programme nearly blew everyone's mind, but they approved because it wasn't a procurement process. It had to be approved as financial assistance, but it did not qualify has a grant or procurement. So, it was unique. So, I lot of what I do is unique, but you need to do it because this project is not the same as every other project. (Management interview: SKA)

She also consults outside the organisation to see how others have faced the same challenge:

> I chat amongst my counterparts in different government organisations, you know, CSIRs and so on, whatever, they [are] all over their business development type people and essentially each one seems to have its own, we [are] all subject to PFMA and etcetera, but some have slightly different rules and limits to us, and I think not enough time is [being] put into finding just how unique we can make our case with government and what things we can circumvent. You know, we are a technological project that needs to move quickly and I am sure that there are ways to get around certain issues and I started to address that, where we could get unique approvals pertinent to us. (Management interview: SKA)

Even within the SKA, there is a degree of uncertainty about the frameworks for interaction with firms, particularly with the international supply chain and design functions. Firstly, the relationship between the MeerKAT and the SKA is not entirely defined, the process of negotiating financial contributions and supply chain participation for the SKA as an international project is ongoing, and the financial allocations for the SKA have not yet been fully determined. The SKA organisation has not yet decided how to split the allocation of tenders internationally. SKA management indicated that there is no simple formula to be followed. The European Space Agency, for example, works on a principle of 'geographic return': if a country invests a hundred million dollars, they will allocate a hundred million dollars in contracts to that country. The SKA is more complex than this in that the design function and the value chain will be spread out far beyond the host countries and even the non-hosting member countries. This makes it difficult to negotiate long-term contracts, particularly with multinational firms, and further complicates the tasks of procurement coordination and skills planning.

Proposals for change in the post-school sector

From the point of view of SKA management, the primary constraint on skills development and research in the sector is not related to interactive capabilities, which are already well developed. Rather, the main constraint is funding. South African universities, at least the top research universities, are seen as sources of high-quality graduates who are employable in South Africa and abroad and are suitable for postgraduate trajectories.

> Money is the limiting factor. I think you could grow bigger and bigger and bigger but we [are] limited by funding and [...] universities are limited by funding, so there's this huge interest from the international community to be involved in the project, and a number of people who would like to move beyond staff research groups. You need money for their salaries, you need money for student bursaries, so everything comes down to money. (Management interview: SKA)

> In terms of the programmes that are being run by the universities, certainly the students who come out of those programmes are employable. If a student can make it through a physics and mathematics degree at UCT or at Wits or at UJ, or anyone of the big universities in South Africa, they are employable and you know they are mostly good material for postgrad. (Management interview: SKA South Africa Project Office)

Summary

From an innovation systems perspective, the SKA, at the global level, can be seen as a very large global innovation network. The SKA network is densely connected, with the main actors all connected to one another, surrounded by a large penumbra of peripheral actors spread around the world. Moreover, the structure of the network is one of 'stacked and overlapping global innovation networks', in which multiple networks, all global in scale and intensive in their levels of engagement, are connected through the axis of the SKA and MeerKAT, which in turn overlap with other networks in the broader astronomy SSI. Network density, innovation and globalisation are high at several scales, ranging from the global SKA project to the 10 main technology consortiums to smaller innovation networks nested within these consortiums, as well as a wide array of other intersecting science and technology networks. This structure partially explains the richness of interaction, and also its success in facilitating the interaction required to achieve the rapid growth and international success of recent years. Moreover, the interactive capabilities of the SKA (South Africa) extend across Africa. The organisation is driving skills development and interaction in African partner countries through the African VLBI network, bursaries and by acting as a network node for many African universities. The HCDP also plays a networking role, organising an annual conference to facilitate interaction and build a sense of community and critical mass in the area.

The locus of interactive capabilities – at least, those relevant to capability-building – is within the HCDP. Moreover, the HCDP has evolved in the context of rapid and complex change, which has presented its own challenges in terms of capability-building and interaction. This has necessitated advanced technology forecasting and the adoption of an array of tactics to build and absorb capabilities into a rapidly growing organisation.

The HCDP has many advanced interactive capabilities. Firstly, decisions about funding allocations for skills development and research are carefully planned and are the product of intensive and widespread interaction with external stakeholders including universities, principal investigators on science projects and intermediaries. Interaction also takes place internally with SKA scientists, engineers, the business development function and senior project management. All of these interactive capabilities are manifested in distinct relationships with primary stakeholders.

Interactions with intermediaries are important, not least because the SKA is publicly funded and thus has a close relationship with public intermediaries. The closest operational relationship is with the NRF, the direct funding source, although this relationship has had elements of strain and contestation (largely resolved at the time of writing). However, interactive capabilities at the senior level are critical to the SKA's relationships with the DST and NRF. SKA senior management engage frequently with senior officials, in both formal and informal capacities, and this helps to manage relationships and steer the organisation.

In terms of capability-building, relationships with universities are the most critical. Interactive capabilities are well developed. Tacit competences for personal interaction with senior university management are strong, and this enables rapid and responsive interaction at the strategic level. The highest level of formal interaction takes place through the Universities Working Group, which acts as a highly effective forum for the exchange of information about the demand for and supply of capabilities. There is also a high level of interaction with students, with the SKA playing a steering and mentoring role that facilitates the development of competences and research that are required by the organisation. The HCDP also interacts closely with the apex astronomy skills development forum in the higher education sector – the NASSP – including regular and ongoing communication and the positioning of SKA staff within NASSP teaching and administration roles. In this context, both formal and informal interactions between the SKA and the NASSP have influenced the NASSP curriculum, bringing it closer to the emerging needs of astronomy in South Africa and of radio astronomy in particular.

Despite the low level of outputs and outcomes of the SKA's interaction with FET colleges, it seems that interactive capabilities are not a causal factor in this low performance. On the contrary, the interactive capabilities, on the SKA side, appear to be sufficient to guide the process. Internally, the SKA managed a participatory process to establish what the organisation's technical and vocational skills requirements are likely to be. Despite this, however, low levels of competences and interactive capabilities within the FET partner college have undermined performance.

Interactions with firms take on a different character, with aspects of research management, business development and supply chain management, each of which requires distinct competences and interactive capabilities, and each of which the SKA needs to manage successfully for it to deliver on its mandate.

On the whole, the SKA is a success story, showing how sufficient policy support and funding can bolster capability-building and how this can be further supported by advanced interactive capabilities with the main actors in the sectoral system of innovation.

4. FIRMS' STRATEGIES TO ADDRESS ROUTINE AND NON-ROUTINE SKILLS NEEDS

The role of firms in the SKA is central. Firms are involved in all stages of research, technology development, engineering, design and operationalisation. The SKA has a large value chain and many firms, arranged into hierarchical functional consortia, are involved in co-designing and manufacturing the instrument. The composition of firms involved in the SKA will change over the course of the project. Currently, the project is at a stage where basic infrastructure is being developed; thus, civil engineering firms are involved. At the same time, engineering- and technology-focused firms continue to work on the more advanced astronomy equipment and data processing needs of the SKA.

The following tenders were advertised in 2012, all of which drew a number of firms seeking entry to the project:

- Expansion of the road network;
- Construction of an all-weather airstrip at the MeerKAT site;
- Supply, delivery and installation of an uninterrupted power supply at the MeerKAT site;
- Construction of buildings;
- Antenna positioners (each antenna consists of the antenna positioner, the digitiser and the receiver, which is being built by EMSS). The tender for the antenna positioner includes design, procurement, manufacturing, qualification for performance and reliability, as well as the integration and performance qualification of the integrated system, the establishment of the maintenance plan and life cycle costs for the longer term;
- The building management system required to monitor aspects of the building that houses the Karoo Array Processor for MeerKAT, including security access control, HVAC, smoke and fire, as well as the electrical power system and the backup diesel generator;
- The supply and installation of an RFI shielding system in the Karoo Array Processor building to protect the MeerKAT from possible RFI generated by the correlator and other electronic devices inside the building;
- The ICT network – local area network (LAN) at the various sites (Losberg, Klerefontein, Carnarvon, Pinelands and Rosebank in Johannesburg);
- The supply and installation of the fibre optic cable; and
- The construction of the antenna foundations, and the surfacing of gravel platforms around each antenna.

In addition to direct involvement in the infrastructural supply chain for the SKA, firms are also involved in research and design. A good example of this is the ROACH board, a collaboration between SKA engineers, scientists from the University of Cape Town and Tellumat, a South African electronics firm that will assemble the product locally. Is is one example, of several, that illustrates a clustering effect in the Western Cape, in which local universities and firms collaborate with SKA scientists and engineers, also based at the SKA South Africa head office in Cape Town, to develop new technologies.

Examples of other firms in the SKA value chain include:

- MMS and BAE Land Systems, which have built the composite dishes;
- Optic 1, which built the power and fibre optic cables to the site;
- Broadband Infraco, which is connecting the site to Cape Town;
- MESA Solutions, a Stellenbosch-based technology firm working on electromagnetic compatibility;
- IBM, which is working with the SKA towards developing a next-generation big data analytics platform with self-tuning and self-learning capabilities to better analyse large volumes of radio astronomy data. The proposed software may help to automate the process of analysing antenna-collected data, allowing astronomers to observe objects in space more effectively;
- Aurecon, a multinational company with offices throughout sub-Saharan Africa, has been involved in planning and executing the infrastructure for the MeerKAT telescope, including the construction of buildings, roads, foundations for the antennas, the on-site airstrip and the provision of power; and
- Neotel has partnered with the CSIR to install a 10 gigabit per second network to the SALT and SKA sites. This network is a component of the South African National Research Network (SANReN), which is funded by the DST as part of its national cyber infrastructure initiative. The network will connect both the SALT and SKA sites to SANReN's national backbone network in Cape Town.

Case study research has focused in depth on three particular firms in order to gain a more detailed understanding of their position in the sectoral system of innovation, their skills strategies and their interactive capabilities. Each of the firms has contributed to the design and manufacture of high-tech components of the SKA. While these three firms are by no means a representative sample of the SKA value chain, as in-depth case studies they provide qualitative information about the systemic context that is faced by such firms and the range of strategies and responses they employ in order to meet their skills needs.

Skills needs in the sector, challenges and drivers

Firms' assessments of the rate of environmental change in the astronomy sector indicate a generally high rate of change, although the three firms, each with distinct technological foci, report differing experiences of the sources of change. For example, Tellumat, which focuses on manufacturing standardised components, reported a lower rate of change, while EMSS, which is developing advanced new-to-the-world technologies, reported a high rate of change across several categories, including technological change, the importance of new product introductions, a rapidly changing sectoral environment and challenging conditions for technological forecasting. Interestingly, however, neither Tellumat nor EMSS reported that skills needs change frequently in the sector, or that they are

Table 6: Perceptions of environmental change in the sector

Firm	Tellumat	Stratosat	EMSS	Average
The technology in this product area is changing rapidly.	3	2	1	2,0
Technological breakthroughs provide big opportunities in this product area.	4	2	3	3,0
In our kind of business, customers' product preferences change a lot over time.	4	3	4	3,7
Marketing practices in our product area are constantly changing.	2	3	n/a	2,5
New product introductions are very frequent in this market.	4	2	2	2,7
The environment in our product area is continuously changing.	4	2	1	2,3
Environmental changes in our industry are very difficult to forecast.	2	2	1	1,7
Skills needs change frequently in our sector and are therefore difficult to forecast.	4	2	4	3,3
Average	**3,4**	**2,6**	**2,0**	**2,5**

Scale: 1 = Strongly Agree; 2 = Agree; 3 = Agree Somewhat; 4 = Disagree

Source: Project data

difficult to forecast. Stratosat, whose technological intensiveness falls between the other two firms, reported mixed responses.

The questions of how these firms have responded to these sources of change, and why two of the firms report that they are not challenged by changes in skills needs and skills forecasting, are examined in the three case studies.

These sources of change are examined in light of reported capabilities for responding to change. Respondents were asked to rate the effectiveness of their firms for sensing and responding to changes in the business and education environments related to skills development. In most cases, firms reported that they were 'effective' or 'somewhat effective' with respect to these capabilities. The contours of this effectiveness are also investigated in more detail in the case studies below.

Firm interaction for meeting skills development needs

The case study firms interact widely and intensively within the astronomy SSI and the SKA's innovation system. The main partners, aside from the SKA, are other firms, universities and science facilities. Interactions with the SKA and other firms are largely related to collaborative technology development. Relationships with universities are largely related to sourcing skills. Relationships with public sector intermediaries are indirect and related to funding. Finally, relationships with private sector intermediaries are largely institutional in nature and oriented towards networking with other actors. These interactions, and the interactive capabilities underpinning them, are studied in more detail in the three firm-level case studies presented below, with a focus on firms' strategies for meeting their skills demands.

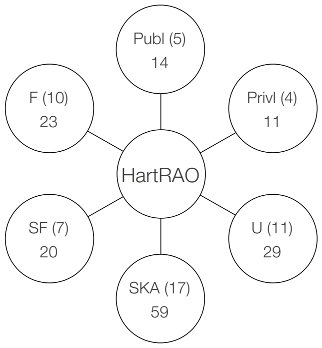
Table 7: Perception of firms' dynamic interactive capabilities

Firm	Tellumat	Stratosat	EMSS	Average
We frequently scan the environment to identify new business opportunities.	2	2	2	2,0
We periodically review the likely effect of changes in our business environment on customers.	3	2	1	2,0
We often review our product development efforts to ensure they are in line with what the customers want.	1	3	1	1,7
We devote a lot of time to implementing ideas for new products and improving our existing products.	1	3	2	2,0
We have effective routines to identify, value and import new information and knowledge.	2	3	1	2,0
We have adequate routines to assimilate new information and knowledge.	2	3	1	2,0
We are effective in transforming existing information into new knowledge.	2	3	2	2,3
We are effective in utilising knowledge for new products.	2	3	1	2,0
We are effective in developing new knowledge that has the potential to influence product development.	2	2	1	1,7
We are forthcoming in contributing our individual input to the firm.	2	2	1	1,7
We have a global understanding of one another's tasks and responsibilities in the firm.	2	3	1	2,0
We are fully aware of who in the firm has specialised skills and knowledge relevant to our work.	2	3	1	2,0
We carefully interrelate our actions to meet changing conditions.	2	3	2	2,3
Staff members manage to interconnect their activities successfully.	3	3	2	2,7
We ensure that the output of our work is synchronised with the work of others.	1	2	1	1,3
We ensure an appropriate allocation of resources (e.g. information, time, reports) within our firm.	1	2	2	1,7
Staff members are assigned to tasks commensurate with their task-relevant knowledge and skills.	1	2	1	1,3
We ensure that there is compatibility between staff members' expertise and work processes.	1	3	1	1,7
Overall, our firm is well coordinated.	2	2	1	1,7
Average	**1,8**	**2,6**	**1,3**	**1,9**

Scale: 1 = Very effective; 2 = Effective; 3 = Somewhat effective; 4 = Not effective

Source: Project data

Figure 6: Firms' network connections



Notes:

1. *F = Firms; Publ = Public Intermediaries; Privl = Private Intermediaries; U = Public Universities; SKA = the SKA, MeerKAT, KAT-7 and African VLBI network; SF = Science Facilities*
2. *The number of organisations included in each sub-group is indicated in brackets.*
3. *The numbers represent the mean weight for that category of network actor of relationships calculated as the product of the number of partnerships and their relative strengths, as reported in the network survey, in which partnerships were assessed using a scale of: 1 = Not at all; 2 = Isolated instances; 3 = Moderate scale; 4 = On a wide scale. The calculations do not take into account the number of organisations identified as partners. It is thus important to interpret the calculations in relation to the number indicated in brackets, which indicates the number of partners in each category.*

Case Study 1: EMSS Antennas – a high-tech SME working on receiver design

Firm overview

Our first case study firm is an SME based in the Stellenbosch Technopark that specialises in radio antennae technology. It is privately owned by its Directors and employees, and forms part of a group of firms. The other firms in this group specialise in simulation software development, electromagnetic field analysis and electromagnetic field compliance regulation for mobile network operators. More than 100 people are currently employed by the group, 20 of whom are in the antennae division.

The competences required by this group of 20 are focused on high-skills engineering. They do not employ technicians – the minimum requirement is a Bachelors degree in Engineering. Aside from engineers, there are three Directors and an Operating Officer (all also engineers) and the basic positions of cleaning and driving and a PA. It is thus a high-skills, high-technology firm occupying a small niche in the market.

The firm displays strong tacit and codified competences for interaction. It has successfully drawn on formal and informal networks to source skills, gain insider status within the SKA and position itself advantageously in the SKA's knowledge economy. Management of the firm sees itself as filling a skills gap in the SKA's set of requirements – specifically the skills in high-tech electro-magnetic engineering required to build the high-performance receivers required by the SKA's science objectives.

The firm designed and built receiver components for the KAT-7, and currently plays a role in the design phase of the MeerKAT and, through this, the SKA. (Specifically, the MeerKAT's L-band cryogenic receiver is being developed by EMSS Antennas.) These are small high-fidelity antenna systems, parts of which operate at 250 degrees below zero inside a vacuum vessel. To meet the SKA's requirements it recruited a specialist and, subsequently, a multidisciplinary engineering team. EMSS forms part of an engineering sub-network that includes the SKA and Stellenbosch University.

Its agreement with the SKA is based on the transfer of the resultant IP to the SKA, but the firm is hoping that its relationship will also ultimately also lead to a manufacturing contract for the SKA which, at 3 000 dishes, is a very large manufacturing contract compared to the precursor instruments. At the time of research, the firm was preparing to negotiate such a contract with the SKA.

The firm has a close contractual relationship with the SKA. The firm operates from within the SKA South Africa Project Office and forms part of the organisation's internal engineering team. The firm's directors report to the SKA's systems engineers and, in turn, to the SKA project manager. More specifically, within the division of research labour among 10 design consortiums – a type of horizontal division – there is, in each consortium, also a vertical, hierarchical system in which the telescope, as a full system, is designated Level 1, its major systems Level 2, their high-level operators Level 3, and its main sub-systems Level 4 – such as the dish and the optical fibre and ICT networks. The firm plays a leading role at Level 4, providing leadership in the area of receiver design under the auspices of the SKA.

Interaction with the SKA

The origins of this arrangement lie in a skills gap experienced by the SKA South Africa Project Office in 2005. At that point the SKA developed an internal engineering team, focused on system engineering, in order to begin working with international design consortia and plot the design process. At that stage, the SKA could not fill critical positions related to receiver design. EMSS was at that time a small SME employing only a few people, reportedly on the verge of disbanding, but they held the critical skills required by the SKA. As such the firm was brought into the organisation through a contract that allowed them a degree of insider status within the design process – they participate as agents within the SKA on matters related to receiver technology. This arrangement was underpinned by the firm's technological capabilities – the engineering staff all held postgraduate degrees, specifically in electromagnetic engineering.

An important factor in the origins and development of the firm are its location in the Stellenbosch technological cluster. The firm is based in the Stellenbosch Technopark, a local base for spin-off firms from the university. Most of its employees are graduates from the university, selected through informal networks that extend to the relevant academics at the university. This has allowed the firm to hand-pick top graduates in its specific niche field.

Moreover, the origins of the firm lie in the university's core role in the apartheid-era military–industrial complex, where Stellenbosch was a major knowledge partner. The firm was first formed in the late 1980s with a military technology orientation. At that time Stellenbosch hosted a strong group of electromagnetic engineers, with ample funding from the military. This provided the first cohort of electromagnetic engineers for the firm.

The orientation of the firm changed in 1995. At this time there were only two staff members, and the firm had an uncertain future. The direction chosen was one of software development, and they developed a number of software products. The firm that eventually evolved into our case study firm was originally a spin-off from one of these ventures, but retains ties to its parent firm. At this stage, two staff members wanted to gain traction in the market for military applications for electromagnetic technologies. This proved elusive but, by 2005, when the initial SKA bid was made, the firm was well positioned with the requisite capabilities to participate in SKA engineering. As such, a contemplated dissolution of the firm was cancelled and the process began that ended in the firm entering the SKA as an engineering partner.

This process evolved over time, beginning with a three-month contract, followed by a four month contract, then developing into a one-year contract for technology development for the KAT-7. Since then the partnership has deepened, driven by the successful outcome of the site allocation. One implication of this process was that both the Southern African and Australian project offices needed to show the capability for local technological development contributing to the telescope design and manufacture. In South Africa this needed to occur off a very limited knowledge base, so the firm was well positioned in that its intellectual capital was of high value to the SKA.

The engagement with the SKA organisation is mainly through the South African project office, rather than the international headquarters, and this includes occasional contact with the Human Capital Development Programme. The main channel of engagement is through the dish consortium, given the acronym SKADC. This entails research in the area of electromagnetics, providing input into the design of the receiver dish, R&D and prototyping of the receivers. These processes were completed for the KAT-7, for which the firm designed, produced and has maintained the receivers. For the MeerKAT and SKA dish design they are also working on the reflective properties of the dishes, playing a systems engineering role. This requires advanced interactive capabilities required to lead a global innovation network:

> We [are] doing the optics again, so we're participating through the offices of the SKA

> SA, the Pinelands system engineering. We are gonna do most of the optics analysis that will allow them to keep to their shape. Then on level 4 we're information leads, we have to co-ordinate all the receiver developments on the planet that's gonna be applicable to SKA 1. We have to control it, coordinate it, make sure it all comes together. (Management interview: EMSS)

Interactions thus take place with other firms, including both South African and multinational firms, primarily through their position within the SKA South Africa Project Office. In these relationships, the firm plays the role of design gatekeeper, acting to review the intellectual property provided by these firms to the SKA and ensuring that the interfaces between collaborating firms and SKA engineers within the SKADC are functioning smoothly.

Interactive capabilities for managing skills, knowledge and technology

Interestingly, the firm aims not simply to build a functioning telescope to meet specifications – it aims to build the world's most advanced receiver component. If this aim is met, it would place this firm at the global innovation frontier in its niche:

> We're trying to show the world we can do a really good telescope, the world's best, before the world's best come. This thing is to showcase the capabilities of the country, to put our name onto that. (Management interview: EMSS)

Despite this, the firm reports that it has never faced a significant skills gap. The reason given for this was that, as a small, well-connected firm, it has consistently been able to fill individual niche positions based on its knowledge of activities at universities and its connections to academic activity. To bring in the required skills they have relied on word of mouth, primarily through academic networks.

> We look around here, and there's a lot of those around in Stellenbosch. If we need an electronics expert, we find a couple of guys here. I would say, in general, that the number of people that universities produce at this level, at this PhD level, it's actually relatively easy to get somebody like that to come and work in Stellenbosch. And, because we're a small company, if we had a need for 5 000 people, it would be a problem of course, but because we're are a small company that grew from 2 to 20 people, I think the numbers are so small that we can find [the skills we need].

> [To find these skills we use] word of mouth, because we know people at the universities, so there's a number of people we employ because we know their lecturers at universities. (Management interview: EMSS)

Over time, the growth that the firm experienced through its involvement with the SKA necessitated a change in tactics for bringing appropriate skills into the firm. Moving beyond personal and academic networks, the growth forced the firm to use employment agencies and scan the CVs of applicants outside of their networks.

> When we started broadening, you know, the scope of the work that we do, [we changed] the way that we got people employed. When it was just electromagnetics we could count on the people at university that we know because we were there. Then when it started to become mechanical engineering, we had to rely on CVs that we'll get from employment agencies. (Management interview: EMSS)

Also, in a sense, the firm benefited from the hiring rigidities that characterised the SKA organisation (which has to adhere to the PFMA, amongst other restrictions). Thus, if demand for new knowledge or researchers grew, and the SKA couldn't take on new people, the firm could cherry-pick from applicants channelled through the SKA and absorb them into the comparably more flexible firm:

> It grows from five to 20 of which not all 15 were engineers so maybe 10 were engineers, only 10 engineers. Some present themselves because they applied at Pinelands [SKA headquarters] and they couldn't, the policy

> just didn't allow new appointments or vacancies and that got passed on to us we said, 'No, no, no, yes, thank you, we'll take you.' (Management interview: EMSS)

The SKA's Human Capital Development Programme's conference has played a role, serving as a networking opportunity for the firm to identify potential recruits.

> It's very small. We know all the lecturers in Stellenbosch, we're even part of the [SKA conference] for bursars and all the bursars that they put through in the astronomy field, and we go there, we look around, we present to them, we listen, we buy them beer … and find the good students and we okay them. So I would say a steady supply of two or three that might be interested and we don't have a vacancy, we just told them to 'keep at it. Call us in a month, if you don't come right.' (Management interview: EMSS)

This takes place in the context of a clear understanding of the broader role of the HCDP in the astronomy 'sector'. The firm sees itself as an indirect beneficiary of the skills development taking place through the HCDP, which involves training people for the SKA but also for the SKA's value chain in terms of research, manufacturing and maintenance.

Commercialisation

Commercialisation prospects for the firm are limited by the extreme technological parameters required by the SKA. For the receiver component, reducing the temperature cuts out 'noise' and thus improves the signal quality proportionally. For a project the size of the SKA, this creates an incentive to go to extreme lengths to reduce temperatures and improve reception quality – lengths that are generally not feasible in a commercial context. For example, reducing the temperature from 20 degrees above absolute zero to 19 degrees above absolute zero will improve the signal quality by one twentieth – 5%. Since the cost of a single dish is between 10 and 20 million rand, and 3 000 dishes are planned for the mid-frequency array alone, it makes financial sense to invest millions just to reduce the operating temperature of the receivers by single degree. There is, moreover, an ongoing incentive. Reducing the temperature from 19 degrees to 18 degrees above absolute zero leads to a greater improvement (6%), incentivising ongoing investment in this research. That is one reason why the firm has designed the coldest and, in that respect, the most advanced radio satellite receiver component in the world. This is, reportedly, technologically far more advanced than even military applications of radio receiver technology.

However, this can also make it difficult to identify possible spin-offs.

> We find it hard at the level where we're involved to find spin-offs, commercial world spin-offs, because it's extreme technology. So much money pouring into one box [the receiver] to make it as good as you can because you get more science from it. You know we're way past the point where you can really commercially spin off something or maybe we're too dumb to find it… People in the industry and the commerce will not pay that much for that little bit of extra performance, it's just that, it makes no sense. (Management interview: EMSS)

Benefits and costs of interaction with the SKA

The firm has grown along with the SKA, which has become the firm's main client. This creates risk for the firm:

> We have one client and they can drop us overnight … It's pretty risky, but great fun and we're allowed to play with extreme things. (Management interview – EMSS)

On the other hand, insider status within the SKA has allowed the firm access to the labs of international actors in their technological space and to networks that are oriented towards collaboration and the generation of new high-technology products. For example, along with the SKA staff, they were granted access to the labs of the US National Radio Astronomy Organisation.

> We've been there three or four times, a number of people, we toured all their labs, all the development labs in Charlottesville, we've seen most of their big telescopes. We learnt a lot there in the beginning and we follow some of the ongoing things that they are working with, we keep tabs on it.
>
> We've seen extreme things that you will never see in the industry … In the first world, you'll never see, won't even make it past the front door. In the commercial world, you might get access but you sign this stack of confidentiality papers and things. (Management interview – EMSS)

The firm has used conferences to build and maintain their networks, including SKA HCDP conferences, IAU conferences and NRAO conferences.

Relationships with universities are maintained via the SKA, for example a personal relationship with Justin Jonas, a senior SKA manager, and an associate professor at Rhodes. Through this relationship the firm can channel knowledge back into the university, particularly regarding new technologies and specifications developed for radio astronomy equipment.

Networking position within the astronomy SSI

A closer look at the firm's network analysis schedule reveals that it is highly networked, particularly for such a small firm. The firm shares substantial networking ties with most of the main actors in the astronomy sectoral system of innovation, including the:

- South African Astronomical Observatory (organisational links);
- HartRAO (staff and knowledge links);
- National Astronomy and Space Sciences Programme (source of graduates);
- International Astronomical Union (conferences, organisational links);
- African-European Radio Astronomy Platform (SKA partner, funder, technology partner);
- European Space Agency (technology development, SKA technology partner);
- US National Radio Astronomy Organisation (conferences, lab tours, technology partner, organisational links);
- Department of Science and Technology (funder);
- National Research Foundation (funder);
- CSIR (product testing); and
- Universities, including UCT, Rhodes, UWC, CPUT, Stellenbosch, North-West, and Pretoria.

From a science point of view, the firm is involved in the ROACH board, but they have largely focused on the engineering aspects. The locus of interaction with universities has a localised slant, favouring universities in the Cape Town metropole, and excluding universities such as Wits, UKZN and NMMU. There is no contact with FET colleges or private training providers.

Case study 2: Stratosat Datacom – a technology firm focusing on dish design and manufacture

Firm overview

Our second case study firm is a telecommunications company that produces antennas and related equipment. It is a market leader in Africa for the provision of satellite hardware and technology. It is 80% owned by a German multinational parent company, and it benefits from intellectual property flows from this parent company, which gives it an advantage in the domestic market. The firm employs 35 people, five of whom are dedicated to the MeerKAT project. The firm has subsidiary companies in South Africa, Nigeria and Kenya, and has positioned itself as the largest provider of satellite hardware in sub-Saharan Africa, ranging from small terminals to more complex in-orbit tracking systems for satellite operators and space agencies. In terms of radio satellite technologies, the firm provides commercial satellite infrastructure, ranging from smaller one- or two-metre dishes to large-aperture antenna infrastructure for space operations or ICT infrastructure. Other areas of expertise include in-orbit testing terminals for telemetry tracking and satellite control applications, a range of products and services for space agencies, logistical services, warehousing, satellite engineering and electronic repair. Examples of customers include Vodacom DRC (Democratic

Republic of Congo), MultiChoice Africa, Sentech (communications equipment for the 2010 football world cup), Telemedia, MTN Business and Internet Solutions (ISP).

Role in the astronomy SSI

Stratosat Datacom has has several links to the astronomy SSI. Through the MeerKAT the firm has previously worked on VLBI radio telescopes – specifically for a project to convert a mothballed 32-metre communications satellite dish in Ghana for use as a radio telescope. For this project they have been contracted by the SKA to provide project management and consultancy services. Prior to their engagement with the SKA, the firm had conducted repairs on the main telescope at HartRAO in 2008.

Based on its experience and expertise in radio astronomy, in July 2013 the firm was selected to design, build, install and commission the 64 antennas for the MeerKAT, with technical support from an international antenna manufacturer, General Dynamics SATCOM Technologies. The radio telescope dishes will be built especially for the Karoo environment, and SKA South Africa will own the intellectual property rights. Manufacturing will take place in South Africa with assistance from GD SATCOM. Together they have established a fabrication facility for the manufacturing of the antennae panels. The plant will manufacture 2 400 panels during the execution of MeerKAT.

This contract, in turn, has necessitated numerous sub-contracts for the many components and fabricated items that will make up each telescope. The backbone of the antenna positioner is a 25-ton backup structure that consists of 6 000 different components that have to be perfectly aligned to ensure the structure can accommodate the highly accurate and sensitive reflector panels for MeerKAT. Sub-contractors include:

- Tricom Structures as the primary fabricator of the positioner;
- Titanus Slew Rings (TSR) as the supplier of a high-precision, low-tolerance azimuth bearing (slew ring) which connects the pedestal and yoke; and
- Efficient Engineering as the supplier of the pedestal and yoke section of the antenna.

Skills and interactive capabilities

The skills required to achieve all of this include mechanical and structural engineering for the design phase, and for the installation phase this is extended to artisanal skills in the areas of mechanical engineering and electrical engineering. The main skills gap reported by the firm is in the areas of electrical and mechanical engineering, as well as artisanal skills such as electrical and mechanical artisans.

The firm does not engage with universities to fill these gaps, although they report that this is something they would like to change, and in future aim to interact more with universities so that they can identify young talent and nurture it through higher education and into the firm. Currently, however, the identification of talent takes place through recruitment agencies.

In terms of scanning for change in the external environment, the firm has no formal mechanisms in place, but it does operate on three-year and five-year strategies to align itself with the market, and this process entails a degree of external scanning and integration of this information with the firm's strategic direction.

The firm gave a clear indication as to which changes would be desirable in the higher education system. These related to career guidance:

> I think educational counselling is imperative because a lot of people, there's lots of industries, like the satellite industries for instance, where there's a real shortage of knowledgeable staff, and the shortage of people that come through the system with the required educational background, and I think from a career guidance point of view, more should be done in order to align the people with the right career path. Because there's lots of people go into directions where there's really no market for them. They finish their studies and there's no opportunities for them, and then there's other industries like

> satellite industries for instance, where there's a real shortage and a demand for good, capable, skilled people, but very few people know about it before engaging on this, in their studies. (Management interview: Stratosat Datacom)

The firm is networked with other actors in the SSI, but at a less intensive scale than the other case study firms, with fewer linkages to universities, intermediaries and science facilities. However, they do play a significant coordinating role within the SKA supply chain. For their role as dish designers for the MeerKAT, the firm also interfaces with second-tier suppliers that provide components, such as Efficient Engineering and TriCom. These interactions are described as very intense and ongoing, and contextualised by tight schedules that require a high level of coordination to meet. The firm also works with the case study 1 firm, in that the receiver technology is placed within the dish to form the basic structure of the telescope.

Case study 3: Tellumat – a diversified technology firm with a focus on electronics

Tellumat is a privately owned, medium-sized South African firm. It is a diversified firm, with a focus on contract electronic manufacturing. This includes television sets, medical products, military, avionics, electronics for vehicles, etc. The firm employs approximately 480 people. The origins of the firm lie in Plessey, a UK-based multinational that was established a presence in South Africa in the 1960s and was bought out by Dimension Data, a South African multinational, in 1998. Tellumat formed as an offshoot of this transaction, in which some Plessey business and staff broke away to form an independent firm. In 2013 the firm brought in over R300 million in revenue, split into about 40% in the defence area, 32% in manufacturing and 28% in telecommunications, into which the radio astronomy contracts fit.

Role in the astronomy SSI

Tellumat contributed to the KAT-7 design and manufacture, as well as an early prototype for the KAT-7 – namely the XDM dish erected in 2007 at HartRAO. This placed it at the core of the radio astronomy SSI at a key point in its history – the design of a prototype (XDM dish) for a precursor (the KAT-7) for the pathfinder (MeerKAT) for the SKA. Specifically, the firm worked in the feed cluster sub-assemblies for the KAT-7, which receive, amplify and begin to process data captured in the form of radio frequency (RF) emissions from celestial bodies. Tellumat was awarded the KAT-7 contract based on its RF expertise and involvement in the early demonstration prototype. The intellectual property from the design belongs to the SKA, and was handed over in the form of a 'data pack' that includes all relevant IP and specifications required to manufacture the product.

Its current contribution to the MeerKAT and SKA is largely related to participation in the collaborative design for upgrading the ROACH board, and the firm still manufactures the ROACH board for the SKA. The ROACH is a signal-processing board based on field-programmable gate array (FPGA) chips. FPGAs are reconfigurable processing chips that are particularly suited to doing many computations in parallel. The ROACH family is a high-end (and higher-cost) platform, while the related RHINO board is a lower-cost (but also lower-capability) one. The ROACH board is a primary building block for digital signal processing systems in many next-generation radio telescopes. It is a cutting-edge innovation that enables highly specialised and high-performance computing.

The ROACH was developed at MeerKAT by an international consortium of researchers, including scientists from the University of Cape Town, UC Berkeley – particularly the Center for Astronomy Signal Processing and Electronics Research (CASPER) – the NRAO and others. The firm partner in this collaboration is Tellumat, the South African company at which the boards are assembled.

About 300 of the ROACH-1 boards are already in use at high-tech facilities around the globe. Twenty boards will be funded by UCT for undergraduate training, and there is a growing international interest in this entry-level platform.

However, the firm no longer has design contracts for major telescope components. For reasons that have not become clear through interviews (perhaps confidential or controversial?), the firm has more recently been sidelined from some aspects of the MeerKAT. Interviews suggested that the firm had somehow been outmanoeuvred in the competition to participate in the SKA's technology development process and (related to this) its supply chain.

> The Meerkat, the receivers weren't even made available to us to offer a design solution for. It was made available to another entity, but it didn't come out on tender. (Management interview: Tellumat)

There appears to be a competitive relationship between Tellumat and EMSS. During the design process for the KAT-7, Tellumat collaborated with EMSS. Tellumat reported that they 'trained' EMSS on aspects of antenna design, and that subsequently EMSS used this knowledge to achieve a sort of *en passant* to capture the antenna design role for the MeerKAT, sidelining Tellumat in the process. Management interviews even implied a degree of intellectual property pilfering. At the same time, there was concern that EMSS did not go through a tender process, while Telllumant, and other firms, did.

Skills and interactive capabilities

Whatever the case, a substantial body of skills and capabilities has been a prerequisite for Tellumat's participation in the receiver design and the ROACH board. The skills required to achieve this are diverse, but concentrated within engineering. Systems Engineering is a critical skill, particularly for astronomy applications, where science parameters must first be translated into engineering parameters at the early stages of the process. Generally, systems engineering skills are accumulated over time – for example, by an electrical engineer with 10 years' experience. Systems engineering skills are defined not only by qualification, but by capabilities – the ability to execute and understand the development process, and specifically the process that has been established within the firm – for example, meeting milestones established for systems engineering and managing the various processes that are included in the design process, such as testing, reviews, etc.

Interviews did not report any significant skills gaps (in line with the other case study firms). The engineering niche most highly sought-after for Tellumat is in specialised electrical and electronic engineering. These are sourced from a range of universities – interviews did not highlight any special relationships with specific institutions. Technicians are employed at the level of S4 Electrical Engineering, largely from universities of technology, and are trained to work within the firms proprietary production method.

There is an intrinsic relationship between the firm's technological capabilities, its embedded skills and knowledge, and its interactive capabilities (both internal and external). Its large R&D budget, well-developed R&D process and history of training staff to use this process have built up these interrelated capabilities:

> Our company has historically been one that had a huge amount of its turnover set-aside for research and development. So we constantly do research and development on new products, which meant there is a certain skill set that we then had available to us that we could draw on. If we didn't have that historical diversification and capability, which defines the methodology of getting to a solution, we wouldn't have been in a position to offer those skill sets.
>
> For example, part of the solution was a cryogenic low noise amplifier. We hadn't designed low noise amplifiers before, but not cryogenic ones. So the way we responded was by investing and tackling it first at the Systems Engineering level, then at an engineering level and then try and understand what are the risks that this challenge imposes on us and then we go through a phased approach of reducing the high risk areas and saying, 'Right, we are able to offer a solution that could possibly work here.' So we've got a sort of a standard formula that will apply to any challenge that someone put on the table

> in the way we first have to have a full systems understanding of where the solution is going to be used. Then we break it down into the technology types that we know and what we don't know and once we understand what are the risks, the first elements that we tackle are in the solution of the high-risk elements, and then we try and integrate that into an overall project at the end of the day. (Management interview: Tellumat)

In terms of interactions with education institutions, the firm does not engage with FET colleges at all. However, it does interact with a range of universities, including universities of technology. Based on this engagement it has an intake of about 15 graduates per year, which it keeps in the firm at an intern level for that year. The internal selection mechanism is meritocratic, in that the top performers are offered ongoing positions while the remainder enter the labour market with enhanced skills and experience – experience at this particular firm is reportedly seen as valuable in the labour market in this sector:

> We've been very successful. We typically used to take on in the order of about 15 graduates from the Technikon environment, bring them into our system on a continuous basis for a year and then, if we are unable to offer them a position, they're then free to leave and find alternative positions. So we have always been in the market to provide industrial support, as well as industrial training, both benefit, while they come through our system, we can then cherry-pick who we believe we need to keep behind for other projects and also, we try to get them to become useful in that period of time and then we can see what is the benefit. So there is, it basically benefits both parties at the end of the day. (Management interview: Tellumat)

This internship process is linked to systematic internal training. Each intern has a mentor that assists him or her throughout his or her introduction to the firm's internal processes and engagements with the firm's knowledge base. This includes knowledge that is specific to radio frequency (RF) engineering, which contributed to the firm's design activities for the KAT-7 and its precursor prototype.

> Typically, they would have someone mentoring them, because they would be exposed to the production test processes. Secondly, then they also get exposed to our internal processes, which explains their knowledge base. It's not something that is going to be taught at any institution and then that allows them to be extremely saleable in the market. We do have a reputation that we are very good at training people in the RF domain. (Management interview: Tellumat)

The firm's capabilities in the RF domain have played a central role in their participation in the astronomy innovation system. RF design and engineering requires expensive equipment and highly specialised knowledge and, as such, only a few firms in South Africa have this capability at the level required by the SKA. It was this capability that placed the firm in the running to participate in the first KAT-7 prototype.

There are no formalised mechanisms for interaction with universities, but there are informal one-on-one interactions. Through these the firm scopes for information about course content, and lecturers receive input from the firm about their course content. Using this information the firm is better able to select students who are learning skills that are relevant to the firm. The main universities they interact with are CPUT, Stellenbosch and UCT.

Management commented that the education system on the whole has been maintaining its standards and that, in general, there is a good match between what the institutions are producing and what is required by the electrical engineering sector. However, in the RF domain there is a reported gap, brought about by the recent increase in demand from astronomy, as well as growing demand from the ICT sector:

> The skill shortage is in the RF domain. There's not many students that go in for that domain. So there's a huge demand from service providers like Vodacom, MTN, all the

> cellphone service providers, Telkom, all clamour for that type of technology capability. (Management interview: Tellumat)

Technological change has less of an effect on Tellumat in comparison to the other case study firms. Management reported that technology in their area is generally changing rapidly, but that there is variation from one technology domain to another. For example, radio frequency technology apparently doesn't change very rapidly, but processor technology does change rapidly. However, on the whole, the moderate pace of technological change is related to their broader customer base, largely parastatals and large corporates such as Eskom and Telkom. Their customers' business models do not require solutions that involve new cutting-edge technologies – instead they prefer tried and tested technologies that can last over time and provide value for money.

Tellumat has comparatively fewer network connections within the astronomy SSI compared to the more densely networked EMS and Stratosat. The firm only engaged with a few actors, mostly universities in the modes of graduate hiring and limited informal relationships with academics. The main interaction has been with the SKA itself, and with other firms in the SKA's value chain. Importantly, however, capabilities beyond the technical were required to gain access to the SKA value chain. These included capabilities in the areas of procurement and administration and financial management:

> At the time, there were quite a number of companies that got opportunities in different work packages and I think that was a tender process and we were allocated that. A lot of small companies fell by the wayside, because they couldn't cope with the payment cycles and administration that went with it and all sorts of other issues, cash flow issues that went with working with a fairly immature organisation at the time and we, of course, looked at it from a long-term investment and we invested a lot of effort and time to develop this whole process and alignment with them. Of course, then with time, they got to rely on us to do more and more engineering around the final solution. (Management interview: Tellumat)

Discussion

The three case studies illustrate the complexities of participation in the SKA's innovation network and the diversity of firms within the value chain, even within the much narrower band of engineering firms (as opposed to infrastructure or ICT firms). Each firm has a distinct historical trajectory, role in the innovation network, set of skills requirements, and skills strategies. All three firms need strong interactive capabilities in order to play their part in the SKA's innovation network. All the firms need to engage intensively with the SKA, with other firms involved in innovation activities, as well as with many sub-contractors. In the case of EMSS, which leads the dish consortium, this requires advanced capabilities for leading a semi-autonomous global innovation network.

The level of network density for each firm varies accordingly. EMSS is densely networked, reporting connections to many of the main actors in the SKA's innovation network. Stratosat and Tellumat are less densely networked. However, Stratosat does play a major role in the supply chain, reporting widespread and intensive relationships with a diverse supply base. Tellumat, on the other hand, plays a more restricted role, focusing on the ROACH board (although in the past its role was larger), and it is therefore less densely networked, reporting relationships primarily with universities, with the SKA itself and with some of the other firms in the SKA's value chain.

The capabilities and knowledge assets of each of the firms have played a critical role in their insertion into the SKA's innovation network. All three of the firms report that their niche capabilities were sufficiently rare in the South African context to provide them with a strategic advantage – in short, that the SKA needed them as much as they needed the SKA. All three firms require competences in the domains of highly skilled engineering. However, the specific skills domains required by each firm vary considerably and are, in each case, determined by the firm's narrow and highly specialised niche. EMSS requires mostly electromagnetic engineers, Stratosat requires mechanical and structural engineers, while Tellumat requires a range of electronic, electrical and systems engineers.

However, perhaps unexpectedly, two of the three firms report that they do not experience any critical skills gaps. The reasons for this differ among the firms, however. For EMSS, as a small, well-connected firm, management perceived their strategy of personal contacts, academic networks and word of mouth to be sufficient for meeting the firm's skills needs. However, it seems that the larger a firm becomes, the less effective this strategy is. EMSS reported that as the firm grew, it relied less on personal networks and more on external recruitment agencies. Tellumat reported that competences in their main area of skills requirement – electrical and electronic engineering – were sufficient, although there is a gap in the niche area of RF engineering due to the current rapid growth in demand for these skills at the national level. Stratosat Datacom reported skills gaps in the areas of electrical and mechanical engineering, as well as artisanal skills.

Two of the three firms show strong capabilities in terms of skills planning and sourcing, while the third reported limited capabilities. However, these capabilities were largely related to hiring skilled personnel, and did not include engagement with universities regarding curriculum content. EMSS, as the smallest of the three firms, relies more heavily on personal relationships with academics and word of mouth. This strategy is reportedly successful in identifying and recruiting the skilled individuals that the firm requires. Tellumat also engages with universities, also through informal networks and individual interactions. The firm draws on these networks to learn about course content at universities, and also to influence course content. Using this information, the firm draws on exiting graduates to enter their internship programme, which, through a meritocratic selection process, filters in the most suitable candidates. This system is in turn linked to a formalised internal training process, which aims to transform the raw competences emanating from the universities into functional capabilities that have value to the firm and that contribute to R&D and innovation capabilities. Stratosat, the largest of the three firms, reported a limited range of strategies for meeting skills needs. They reportedly do not interact directly with universities, preferring to rely on recruitment agencies.

Capability-building is also an internal process. This is best evidenced by Tellumat's R&D process, in which the firm's embedded, largely tacit, capabilities are intrinsically related to its internal training process, its formalised R&D process and its interactive capabilities.

Technological change has a pervasive effect on firms, although this varies across domains and affects firms differently. Tellumat reported a lower pace of technological change, as it services primarily parastatals and large corporates that require already proven technologies, not the cutting edge. On the other hand, EMSS is pushing the global technological frontier, and the intense knowledge and technical demands of operating in this space have a wide-ranging effect on the firm's skills strategies and overall market orientation.

5. THE SKILLS SUPPLY AND SKILLS DEMAND ROLES OF SCIENCE FACILITIES

In the astronomy sector, like other sectors, firms constitute a locus of employment, particularly with regards to engineering and manufacturing. However, in addition, in the astronomy sector science facilities (largely telescopes) constitute a major source of employment. This applies both to the science aspects of the system (astronomy and cosmology) and to engineering aspects. Science facilities make up a substantial proportion of skills demand in the sector. However, their role is not only on the demand side. Science facilities are vested with intermediary functions that co-ordinate innovation in the sector and also participate in capability-building mechanisms in collaboration with other actors. In the South African context, science facilities are key actors in the astronomy sectoral system of innovation. However, due to the functional split between optical and radio astronomy, most of South Africa's astronomy science facilities do not play a major part in the SKA's innovation network, with the exception of HartRAO and, to a smaller extent, the SAAO.

The main science facilities in South Africa's astronomy SSI are described below, with consideration given to their role in the astronomy SSI and their relationship with the SKA. This is followed by a brief overview of the various roles of science facilities, including their skills needs, skills strategies, position in the astronomy SSI and SKA innovation network, interactive capabilities and intermediary roles.

National Science Facilities

The NRF manages and funds South Africa's 'National Facilities', a term referring to the country's apex science facilities. These are grouped in clusters in relation to their area of knowledge production: 1) Astro/Space/Geo Sciences, 2) Biodiversity/Conservation and 3) Nuclear Sciences. These clusters are aligned with the science themes identified as critical in the national Research and Development Strategy and central to the national research and innovation agenda. Approximately 30% of the budget for these facilities has consistently been allocated to astronomy facilities, illustrating the priority level for astronomy in this domain (Paterson et al. 2005).

There are, in total, seven national facilities. Three of these are astronomy facilities, including:

- the Hartebeesthoek Radio Astronomy Observatory (HartRAO);
- the Hermanus Magnetic Observatory (HMO); and
- the South African Astronomical Observatory (SAAO).

Of these, the HMO is an outlier, as magnetic observations use different techniques and technologies to optical and radio astronomy. As such the HMO is not connected to the SKA's innovation network (no respondents reported links to this science facility) and is moreover only weakly linked to the broader astronomy SSI. However, it does represent an important facility in its own right, as part of a worldwide network of magnetic observatories that monitor and model variations of the earth's magnetic field.

These science facilities, as a whole, act as hubs for research – offering instruments that attract world class scientists and enable the development of local capabilities on the global stage. The facilities are used by students in their training programmes, and by South African astronomers in collaboration with global research teams. The existence of such infrastructure motivated for the location of the SKA in South Africa.

South African Astronomical Observatory
Established in Cape Town in 1820, and therefore nearly 200 years old, the South African Astronomical Observatory (SAAO) is both a science facility and an intermediary, acting as a coordinating body for a number of astronomical observatories in South Africa. The science focus of the SAAO is on furthering fundamental research in astronomy and astrophysics at both the national and international levels. It also plays an advocacy role in terms of furthering awareness and research of astronomy and astrophysics in southern Africa. The SAAO plays an intermediary role in the astronomy SSI, overseeing the activities of several of South Africa's major telescopes, including the SALT. It coordinates research activities through its involvement in a number of research projects and through its connections to universities.

SAAO also operates the existing suite of small telescopes at Sutherland, which include 0,5 m and 0,75 m telescopes redeployed for public outreach and student training; 1,9 m and 1 m telescopes used for competitive research projects; and six international specialist telescopes that conduct infrared surveys, and searches for exoplanets and near-Earth asteroids and oscillations on the sun. The majority of these facilities are robotic and remotely operated from international locations. These international remote stations are operated by the following groups.

The SAAO has workshop facilities at its Cape Town headquarters that are used for training interns – largely from universities of technology. Engineering students work on internships in the SAAO's mechanical and engineering departments, an also have the opportunity to spend time at science facilities such as SALT, which gains them valuable practical and tacit knowledge. The SAAO maintains close relationships with universities, particularly UCT, which is geographically close by and also has the only dedicated astronomy department in the country. Perhaps most importantly, the SAAO is the coordinator of the NASSP.

The SAAO hosts a critical mass of competences and interactive capabilities within the astronomy SSI. The organisation has a staff complement of approximately 130, of whom 30 are astronomers and the remainder are engineers, ICT staff and support staff. The Human Resources function within the SAAO plays a key role in capability-building and interaction within the astronomy SSI. With a complement of two full-time staff, the HR function is tasked with recruitment, engaging internally with management to align with the SAAO's strategy and vision and managing capability-building aspects such as internships, bursaries and R&D support.

> HR is not just about looking at the actual people, but it's looking at the organisation and how can we better improve the organisation specifically around human capital and manpower and those kinds of things. We play a role of both strategic player as well as somebody that assists the people. (Management interview: SAAO)

The SAAO is a main employer of astronomers and astronomy-related engineers in South Africa, and recruitment is a major challenge. The SAAO is, however, constrained in its options for recruitment. As an agency of the NRF, the SAAO needs to channel all of its recruitment through the NRF's online recruitment portal, Career Junction. However, this usually only applies to the recruitment of engineering, ICT and support staff, due to the severe shortage of astronomers in South Africa. Reportedly, 70% of the SAAO's astronomers are foreign.

> We don't do astronomy through that because we don't have South African astronomers. Any South African astronomer that does optical astronomy, which is specifically us, we will either know about them, or they would be employed by us. Most of the optical astronomers in South Africa, there aren't a

> range of them; it is a scarce field as you are aware. (Management interview: SAAO)

This reveals the extent of the mismatch between the supply and demand of optical astronomers in South Africa, as well as the globalised nature of the sector. Instead of advertising locally, the SAAO advertises on international platforms:

> It is noted as a scarce skill in South Africa, so we advertise all our astronomer positions via the AAS, the American Astronomical Society web page. Any astronomer, be it South African or be it European, will always look on that web page for positions because that is known to the astronomy environment, that is where you find jobs. (Management interview: SAAO)

Skills shortages also occur in the engineering domain, specifically in electrical, mechanical and software engineering, but this is only in relation to previously disadvantaged population groups, where other sectors offer more competitive salaries.

These skills shortage also underlies the SAAO's capability-building activities. The SAAO manages the NASSP, and NASSP students are co-supervised by SAAO astronomers. The SAAO is also a site for internships under the DST's Personal Development Programme (PDP). This provides up to R200 000 per student for postgraduate and postdoctoral internships at the SAAO. The PDP started in 2009 and, at the time of research, there were nine PDP interns at the SAAO.

The SAAO also manages vocational training activities apprenticeships, and in-service training for approximately four mechanical and electronic engineering students per year from universities of technology. The latter are placed in the SAAO's workshops, where and R&D function is employed to custom-build telescopes for South African national facilities. This is an important part of the SAAO – according to management, 60% of the SAAO's staff are placed in this engineering and R&D function. The best performing interns are retained within the SAAO.

The SAAO is a central actor in the astronomy SSI, but a peripheral actor in the SKA's innovation network. This is due to the functional division between optical and radio astronomy. The SAAO is responsible for optical astronomy, effectively forming an umbrella body for managing all of South Africa's optical astronomy facilities. However, non-optical facilities such as the HartRAO, the HMO and the SKA fall outside this portfolio. The primary relationship between the SAAO and the SKA is through the NASSP programme, which is administered by the SAAO.

South African Large Telescope (SALT)

The 10-metre diameter Southern African Large Telescope (SALT) was commissioned in 2005, and forms part of the growing complex of astronomy facilities in Sutherland. The SAAO is responsible for managing the operations of the SALT on behalf of an international consortium.

SALT as a global science network

South Africa is the leading partner in SALT with a shareholding of approximately 33%. Other partners include the USA, Germany, India, Poland, the United Kingdom and New Zealand. The eleven partners coordinated by the SALT Foundation at the SAAO are the National Research Foundation of South Africa, the Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences, the Hobby-Eberly Telescope Board, Rutgers, the State University of New Jersey, Georg-August-University Groningen, the University of Wisconsin-Madison, the University of Canterbury (New Zealand), the University of North Carolina – Chapel Hill, Dartmouth College, Carnegie Mellon University and the United Kingdom SALT Consortium (UKSC), comprising the Armagh Observatory, the University of Keele, the University of Central Lancashire, the University of Nottingham, the Open University and the University of Southampton.

SALT is currently the largest single optical telescope in the Southern hemisphere, and is equipped with state-of-the-art imaging and spectroscopic and polarimetric instruments. SALT is a good example of South African capability in astronomy. About 60% of the parts necessary for the construction of the telescope were contracted in South Africa, which partially addressed the goal of creating spin-off companies from this project. As an illustration of South Africa's capacity to manage and maintain large-scale international astronomy collaborations, the SALT played an important part in securing the SKA project's allocation to South Africa. However, SALT does not have strong ties to the SKA. Optical astronomy and radio astronomy use different instrumentation and methodologies, and occupy distinct niches within the field of astronomy.

Hartebeesthoek Radio Observatory (HartRAO)
HartRAO is based on satellite dishes that date back to the space race. The observatory was originally built in 1961 by NASA, and during that time operated as a Deep Space Station to monitor the southern skies, including communication with spacecraft, for example lunar missions, and continues to play a key role in global science networks. Until the construction of the KAT-7, HartRAO was the only major radio astronomy observatory in Africa. It undertakes research and training in radio astronomy, with a focus on radio wavelengths and their mapping. Like the HMO, it was also administered by the CSIR until 1991. It is arrayed through interferometry with telescopes on other continents, forming a set of 'super' telescopes.

HartRAO formed a part of the team to develop the bid to host the SKA in Africa. Its Radio Astronomy Programme includes radiometry, spectroscopy, pulsar timing and VLBI as observing techniques for astronomy. Its Space Geodesy Programme, forming part of a global network, uses applications of VLBI and the global positioning system, in order to conduct research in geodesy. HartRAO operates a satellite laser that provides data to NASA, together with the International Laser Ranging Service (ILRS) and the GPS base station network, which provides data to the International GPS Service. It is one of the five permanent space geodesy stations worldwide. HartRAO's position as the national leader in radio astronomy has led to a key role in the SKA, including a role in the bidding process, the development of the Research and Technology Collaboration Centre (RTCC), groundwork for design and engineering requirements, and participation in the development and construction of the KAT-7 and MeerKAT.

HartRAO has considerable interactive capabilities within the astronomy SSI, and is particularly relevant to the SKA, as it is also a radio astronomy facility. The competences and capabilities required to operate HartRAO therefore overlap with those required by the SKA. Many of the SKA's senior management and scientists originated from HartRAO, and the two organisations maintain close ties. HartRAO works with SKA South Africa on the African VLBI network, as well as the HCDP, where it provides in-service training for 10 interns (technical students) per year, and supervises postgraduate students funded by the HCDP. Moreover, HartRAO played a key role in the development of the KAT-7, including support for testing, technology development and science collaboration. HartRAO staff are also staff on several of the MeerKAT's science projects.

In terms of engagement with other actors in the astronomy SSI, HartRAO works primarily with academic and technical universities in supervising students doing BTech, MSc and PhD degrees in research, engineering and technical areas of radio astronomy and space geodesy. This is a successful and expanding area, and includes students from a variety of African countries, especially SKA partner countries. This transfers knowledge to the students and their supervisors at the universities. Each year HartRAO conducts in-service training for two cohorts of five technicians from technical universities, who are funded by the SKA HCDP.

HartRAO carried out training of SKA staff in the early years of the project, as very few had experience of radio astronomy or radio telescopes. In addition, they provided training for engineers from EMSS, Tellumat and BAE Systems, which led to the successful construction of the first prototype radio telescope for SKA in South Africa, the 15-m diameter eXperimental Development Model (XDM) built at HartRAO in 2007.

The environmental turbulence affecting the astronomy SSI, particularly in radio astronomy, has also affected HartRAO. Management indicated that increased demand for radio astronomy skills and knowledge has led to increased numbers of students and researchers from universities being attracted to the facility. However, management also reported that its capacity to respond to this growth in demand has been constrained, mostly due to a lack of funding from the NRF:

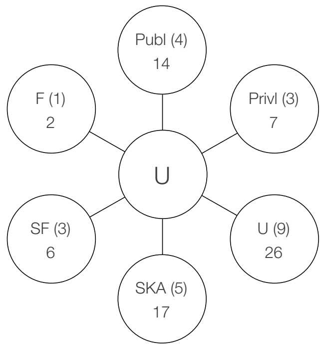
> The parliamentary grant for the HartRAO has not kept pace with demands and ambitions of the facility and this remains a bottleneck. In particular, the annual grant increase is much less than annual salary increases reached in settlements between the NRF (our parent organisation) and the unions in the NRF. This means we have not been able to expand our research and engineering staff as we should. (Management interview: HartRAO)

Management, however, expressed a hope that the development of more holistic and integrated astronomy strategies for South Africa, being undertaken by DST and the Astronomy Desk, would lead to a more integrated approach towards radio astronomy and reduce the funding differentials and gaps.

The network analysis schedule highlights HartRAO's role in the radio astronomy SSI, and its even more central role in the SKA's innovation network. The organisation is densely networked, being closely connected to many of the main actors in the SSI, including engagements with one firm, three private intermediaries, four public intermediaries, five components of the SKA and eight universities (see Figure 7).

The connection between HartRAO and the Ghanaian contingent of the African VLBI network is significant for the astronomy SSI in that HartRAO serves as a training ground for African astronomers and technicians. This bolsters the competences and capabilities available in African partner countries, thereby strengthening the position of the SKA African consortium in the global context. In Ghana, as in other countries involved in the African VLBI, mothballed telecommunications satellite dishes are being re-tooled as radio astronomy facilities. HartRAO staff are assisting the Ghanaian team with this effort. HartRAO astronomers and engineers visited the proposed facility in Ghana and, while there, conducted an assessment of the facility and also established networks with Ghanaian astronomers. A team from Ghana was located at HartRAO at the time of research (2013) for a six-month period in order to gain practical experience in radio astronomy. In future, HartRAO is expecting similar interaction with partners from Mozambique, Zambia, Mauritius, Namibia and Botswana.

Figure 7: HartRAO network connections



Notes:

1. *F = Firms; Publ = Public Intermediaries; Privl = Private Intermediaries; U = Public Universities; SKA = the SKA, MeerKAT, KAT-7 and African VLBI network; SF = Science Facilities*
2. *The number of organisations included in each sub-group is indicated in brackets.*
3. *The numbers represent the mean weight for that category of network actor of relationships calculated as the product of the number of partnerships and their relative strengths, as reported in the network survey. The calculations do not take into account the number of organisations identified as partners. It is thus important to interpret the calculations in relation to the number indicated in brackets.*

HartRAO also plays a key role in NASSP, particularly in the radio astronomy domain. As the only radio astronomy facility pre-dating the MeerKAT and SKA, HartRAO has traditionally been the training ground for postgraduate radio astronomers in South Africa. This role continues through the construction phase of the MeerKAT. NASSP students visit HartRAO for a week-long introduction to radio astronomy. Students specialising in space geodesy spend additional time at HartRAO gaining both codified and tacit knowledge in this area. For example, students run small experiments to construct a radiometer using a DStv satellite dish.

The link with DUT is also significant in the radio astronomy knowledge system in South Africa. DUT sends students, often funded by the SKA HCDP, as part of their technical training and work experience – at the time of research, six DUT students were placed at HartRAO for this purpose.

With respect to capability-building, the primary challenge for HartRAO is funding. Funding constraints mean that the facility is understaffed at all levels, including astronomers, engineers and artisans. It is also reportedly difficult to find the required skills in demographics that would meet employment equity targets. In addition, the salary differential between HartRAO and the SKA has incentivised moves away from the HartRAO, leaving it under-capacitated to some degree. For example, the SKA reportedly pays approximately double the salaries of HartRAO, which makes it difficult for HartRAO to attract top skills. Reportedly, SKA bursars can even earn more than HartRAO staff astronomers. The reasons for this are well understood by HartRAO management: that NRF salaries are benchmarked across the science system, while SKA salaries are set to achieve the extreme demands that the project makes in terms of skills and milestones that have been committed to on the international stage.

Within the context of high levels of interaction, there is also a history of division. Radio astronomy was once seen as a minor component of South Africa's astronomy landscape, and there was limited interaction between radio astronomy and optical astronomy. Recently this balance has shifted, but the embedded sense of separation may take longer to recede:

> Radio astronomy and optical astronomy have never really communicated. Optical astronomy always felt that they were it. We used to have annual astronomy meetings where we all got together and talked about our research. As soon as we became acceptable in the international community, then SAAO hosted international conferences to which you never would be expected to pitch up, and the funny thing is that when we have those meetings they would always host them at SAAO which is lovely, because it gave us Vaalies a chance to go down to Cape Town. It was held in February and good weather and you could take a weekend in Cape Town afterward. I think we did try to organise a meet up in the north, with the Kruger Park as an attraction, but no astronomers of SAAO thought it was worth attending … (Management interview: HartRAO)

Discussion

Science facilities play a central role in South Africa's astronomy SSI, but only HartRAO and, to some extent, the SAAO play a role in the SKA's innovation network. The SAAO plays a minor role, primary as the facilitator of the NASSP.

The interactive capabilities reported by HartRAO are advanced, enabling participation in multiple global research projects. The competences and capabilities vested in HartRAO allowed the facility to play a central role in the bid to host the SKA in Africa. This also allowed HartRAO to play a central role in technology development aspects of the SKA, as well as an ongoing role in capability-building in the domain of radio astronomy, including aspects of research, postgraduate training and technical internships. This extends to the SKA's African partner countries. HartRAO also plays a role in the NASSP, thereby shaping the radio astronomy curriculum at the postgraduate level. Interaction between HartRAO and SKA staff is intensive, including formal and informal engagements at the senior strategic level and at the levels of science and engineering. HartRAO has also played a broader role in the SKA's innovation network, providing a training ground for firms in the SKA's supply chain and knowledge network.

However, dynamic interactive capabilities are constrained by a funding differential, in which the SKA acts as competition to the HartRAO – which thus finds itself under-resourced and less competitive in the race for skills. This is in the context of its role as a publicly funded science facility that is focused on providing instrumentation for astronomy research but not on intermediary roles or skills development.

6. THE ROLES OF PUBLIC AND PRIVATE INTERMEDIARY ORGANISATIONS IN BUILDING NETWORK ALIGNMENT AROUND SKILLS DEVELOPMENT

In this section, the main research question is: *What are the roles of public and private sectoral intermediary organisations in building network alignment and addressing misalignment in relation to skills development in the SSI*? Due to the heavily networked nature of astronomy, intermediaries play an important role in the SSI, both at the international and the domestic levels. This includes both public and private sector intermediaries, and both South African and international intermediaries. Several of these intermediaries have also played roles in the SKA's innovation network.

The functions of intermediaries active in the SKA's innovation network are in contrast to the distinction made by Interramakund (2012; 2013), which suggests that private intermediaries focus on responding to industry and firm-specific issues and that public sector intermediaries focus on public good objectives. The nature of astronomy as fundamentally driven by basic science rather than either private profit or public good in the narrow sense means that intermediaries play a different set of roles. Private intermediaries largely play roles of international networking, while public intermediaries are largely occupied with funding and strategic direction. However, intermediary functions are not vested solely in intermediary actors. Many non-intermediary actors host such functions. For example, the SKA organisation itself plays intermediary roles. It acts as a network facilitator, for example through conferences and meetings, and also integrates networks through the many sub-projects that are subsumed into the overarching projects of the KAT-7, the MeerKAT and the SKA. Another key programme that takes on intermediary functions, particularly with respect to skills, is the National Astrophysics and Space Science Programme (NASSP). This is a collaboration of universities and the NRF, the DST, the SKA, the SAAO and other partners that coordinates skills development activities across South Africa's universities. However, the NASSP is based at the University of Cape Town, and is therefore examined in further detail together with other higher education actors.

The roles and strategies of the main public intermediary organisations in the SKA

Increased support for astronomy at the top levels of government has galvanised increased public support through the main agencies of the DST, NRF and DHET.

> President Thabo Mbeki took a personal interest in astronomy, and I think that simply raised the level ... and various government departments had to take attention. Presently President Zuma has set up the team within government where 20 national activities, projects, etcetera are looked at on a regular basis by ministers, and astronomy [is on this list of 20 things]. I think it's just simply the overall attention paid to astronomy and SKA at a national level that's lifted the entire profile, there hasn't been a change in legislation, it's just attention has been focused on it. That leads to more funds, it leads to more people entering it, and a greater attention to detail. (Academic interview: UKZN)

Table 8: DST expenditure 2009–2016

R Million	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	
	Outcomes			Revised estimate	Medium-term estimates			MTEF Average annual growth
National departments	3 507	3 360	3 691	4 067	4 616	4 716	5 565	11.0%
	7 712	9 291	10 021	11 030	11 679	12 678	13 361	6.6%
Total	**11 220**	**12 651**	**13 713**	**15 096**	**16 294**	**17 394**	**18 926**	**7.8%**
Of which:								
Square Kilometre Array	502	13	11	231	641	661	715	45.8%
Human capital and science platfroms	1 119	1 244	1 408	1 434	1 707	1 858	2 346	17.8%
Research and infrastructure	449	485	531	603	738	792	1 036	19.8%

Department of Science and Technology

The DST is the central public sector intermediary in terms of funding and overall strategic direction. The priority enjoyed by astronomy is reflected in the budget allocations made by the DST. Expenditure on astronomy, specifically that related to the SKA, has risen sharply over recent years and is expected to increase dramatically over the medium term, according to the Medium Term Expenditure Framework (MTEF) (see Figure 8).

Astronomy Desk

The Astronomy Desk was established by the DST in 2010 to advise the Minister of Science and Technology on the development of a long-term astronomy strategic plan for the country and human capacity development for astronomy. This represents another aspect of the South African government's active coordination of actors in the NSI, in this case focusing on astronomy – for which the Astronomy Desk provided intelligence and strategic guidance. At that time, advice related to South Africa's bid to host the SKA was critical. The Desk was established with a reference team of five senior scientists: Professors George Ellis (UCT), Renee Kraan-Korteweg (UCT), Sunil Maharaj (UKZN), George Miley (Leiden University and VP, International Astronomical Union) and Harm Moraal (North-West).

The Desk was tasked with providing advice about how South Africa could obtain maximum advantage and return on the significant investment being made in astronomy; the appropriate relationship between South African national research facilities and internationally funded projects; the appropriate structural, organisational and management relationship between optical and radio astronomy and the High-Energy Stereoscopic System in Namibia; and the most appropriate governance model for astronomy facilities in South Africa. The focus of the desk was thus largely on questions of network alignment. The desk recommended that astronomy be organised in an independent structure. This advice was only partially taken up by the government in that a dedicated astronomy function was established within the NRF but not outside the NRF as recommended by the Desk.

Another function of the Desk was to develop short-term capacity-development interventions for astronomy (including optical and radio astronomy), which have contributed insights to the various forums in which this is a focus. Furthermore, the Desk developed a Decadal Plan for astronomy in South Africa, which has helped guide the strategic decisions of the DST and the NRF (Bharuth-Ram 2011). However, once these functions were completed, the purpose of the Desk was also complete and in 2013 the Desk was dissolved. The network alignment focus of the desk has, however, paid off – as a result of its research and strategic guidance, dedicated institutional mechanisms to govern and coordinate astronomy at a national level have been created through policy and optimised through interaction with sector specialists.

National Research Foundation (NRF)

The NRF is mandated to promote and support research in all fields of humanities, the social and natural sciences, engineering and technology, and indigenous knowledge. The foundation provides research funding and research platforms through national facilities and science awareness activities. It also performs an agency function on behalf of the Department of Science and Technology, and is a service provider to several other government departments. The NRF is a key intermediary in the astronomy SSI and, conversely, astronomy plays a significant and unique role in the overall mandate and activities of the NRF. The NRF employs a range of interactive capabilities for skills development in the astronomy SSI, primarily through its funding and coordinating role in oversight of the national astronomy science facilities.

The NRF funds the South African Research Chairs (SARCHIs), which are designed to support world-class research and teaching at universities across the country (the SKA SARCHI chairs are discussed in Chapter 3).

Following up on the recommendations of the Astronomy Desk, in 2013 the DST established an astronomy sub-agency within the NRF as an interim measure aimed managing the growing field of astronomy in South Africa. Previously, there had been no single public institution overseeing the country's astronomy activities. This required the NRF to create the post of Deputy CEO: Astronomy, which is now part of the NRF corporate executive and the 'NRF anchor point' for liaison with actors in the astronomy SSI – in particular, the DST. The sub-agency makes use of the NRF's shared corporate services, such as finance, governance and human resources. Astronomy is the only scientific field – of the approximately 200 disciplines managed by the NRF – that has such a position. It is significant that a single discipline of science is being elevated to the level of Deputy CEO in the organisation – a reflection of public support, political priority and rapid growth in the scale and complexity of the sector.

The organisational relationships between the DST, the NRF and the SKA are complex, requiring strong interactive capabilities to maintain. The coordination capabilities required to achieve this are substantial.

The astronomy sub-agency oversees all the astronomy facilities, including the SKA. The role of the DST is largely constrained to policy and funding. The DST does not directly employ any person in the astronomy sector, does not approve the budgets of science facilities, and does not have a fiduciary responsibility for any of the science facilities. Rather, these functions are vested in the NRF. Strategic direction is given by the DST, and funds are channelled from Treasury through the DST to the NRF based on policy decisions. The NRF is then responsible for the disposal of these funds. With regards to the SKA, management of expenditure is guided by the strategic directions given by the SKA steering committee. Thus, from a public management point of view, the NRF is operationally responsible for the SKA project in South Africa.

The NRF also plays a role in the interactions that take place around curriculum content and structure in the astronomy SSI. This role is constrained, however, in that the NRF does not have a mandate to intervene within universities, particularly with regards to issues of curriculum (this is a DHET mandate). Therefore, the instruments and activities of the NRF do not have a direct bearing on this area. However, the NRF is the funder of the NASSP, which is a central intermediary body established within the higher education system and based within UCT, although the NASSP is coordinated by the SAAO and funding from the NRF is channelled through the SAAO to the universities.

Department of Higher Education and Training
The Department of Higher Education and Training plays two main intermediary roles in the Astronomy SSI. The first is in its capacity of oversight and management of the higher education system, which includes the various university faculties and departments that play important roles in the SSI. As such, the skills planning process, at a national level, has an impact on the Astronomy SSI. At the branch level, this takes place through the universities branch of the DHET.

The second role is through a Special Projects Unit dedicated to servicing the requirements of the National Infrastructure Plan, which includes eighteen Strategic Integrated Projects (SIPs). The SKA is one of these SIPs. The SIPs themselves are apex projects, serving as umbrellas for approximately 700 small projects. The DHET plays an intermediary role in that it is mandated to develop skills development plans that will generate the skills and knowledge required for the SIPs to be realised. For this purpose, the DHET has developed a systematic methodology.

To aid analysis for skills planning, the DHET has clustered these 700 projects across the eighteen SIPs into sectors – for example, projects related to railways, or ports, or water, or construction, etc. Within these sectors, sub-sectors have been identified through a methodology of case study research and upscaling. For example, experts would be consulted about the skills that would typically be required for a single coal-fired power station, and these requirements would then be scaled up to assess the requirements for multiple power stations.

This methodology, however, is not a simplistic arithmetic exercise – due consideration is given to the nature of the upscaling. For example, if the scale is to be doubled, the size of teams at the lower skills levels might need to doubled, but you might not need to double the size of the management stratum or the engineering stratum – these might increase by a smaller factor. From this exercise, which is conducted in detail to the level of occupations (OFO level 6), a list of scarce skills is also produced based on consultations with experts in the field.

This research is communicated within the DHET to the universities branch, where it enters consideration in the enrolment planning function. This informs the DHET's position when it meets with the senior management of each of the 23 universities to discuss institutional planning. The DHET has the responsibility of signing off on the plans of these institutions, which allows them space to comment on their plans with a view towards taking greater account of the SIPs.

This methodology has been applied to the SKA, with some modifications. The DHET has worked closely with the SKA organisation in order to assess its skills requirements. In particular, the DHET has engaged with the manager of the HCDP – indicating a strong and direct networking and knowledge-sharing link between these two actors. This is reported by both SKA and DHET management. The two parties meet monthly to discuss skills requirements and how these could be communicated to educational institutions.

However, the DHET's engagement with the Astronomy SSI is largely restricted to post-school education institutions and the SKA organisation itself. Management interviews reported that there are no connections with intermediaries and science facilities that fall under the portfolio of the DST and the NRF, for example the SAAO. However, management interviews did report sporadic interaction between the DST and the DHET – which is something of a departure from the norm. For example, representatives from the DST, the DHET university branch and the DHET Special Projects Unit, as well as management of the SKA HCDP, have previously met to discuss and coordinate skills development across the institutions. This represents a tangible network link among these core actors in the SSI, made possible by the interactive capabilities vested in each. Interestingly, however, this particular meeting was called by the SKA organisation, suggesting that it might have played a catalytic role in fostering communication between the DST and DHET.

Political support and the policy environment

South Africa's democratic government has offered strong support for the astronomy sector. Astronomy and space science are seen as large-scale, broad-scope, new technology platforms that will be directly coordinated and led by the DST as a priority area. The main form of policy support has been through the Astronomy Geographic Advantage Act (2007). The aim of the Act is to ensure that the geographic areas that are suitable due to atmospheric transparency, low levels of light pollution, low population density and minimal radio frequency interferences, are protected. In 2010 the Minister of Science and Technology declared all land in the Northern Cape Province situated 250 kilometres from the centre of the South African Large Telescope dome as an astronomy advantage area for optical astronomy purposes and the whole of the territory of the Northern Cape province, excluding Kimberley, as an astronomy advantage area for radio astronomy purposes. Furthermore, those parts of the Northern Cape which are to contain the SALT dome, the MeerKAT radio telescope and the multi-billion rand SKA have been declared as core astronomy advantage areas (see Figure 8).

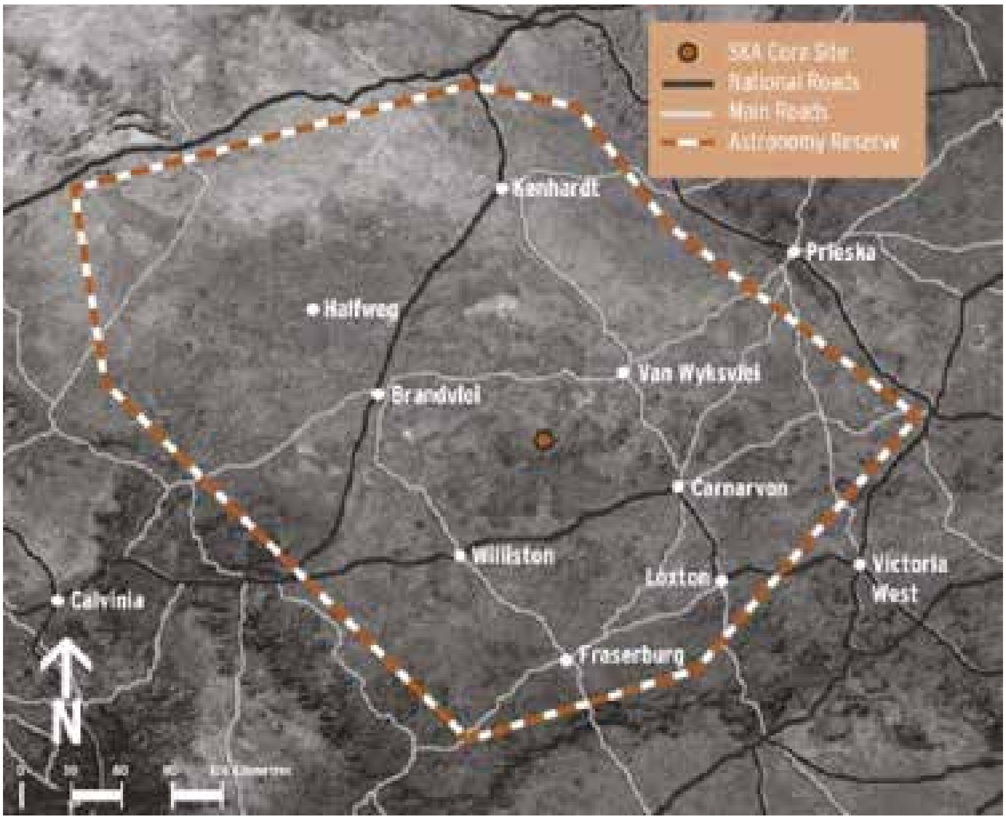
Restricted activities in core astronomy advantage areas include prospecting and mining activities; harmful industrial process; the construction and development of new business or residential premises or recreational facilities; the operation, construction or expansion of facilities for the generation, transmission or distribution of electricity; or any other activity which might detrimentally impact on astronomy and related scientific endeavours. This includes a restriction of any activity that may cause light pollution or interfere with the radio frequency spectrum of 9 kHz to 3000 GHz in these areas. These restrictions could severely limit shale gas fracking within astronomy advantage areas.

Beyond the explicit legislation, the tacit political support for the SKA should not be underestimated. From the early stages of its conception, the SKA bid was seen as a flagship national project with enormous potential, not just for science, technology, skills and economic development, but also as a national symbol of world-class scientific and technological achievement (Gottschalk 2007).

The roles and strategies of the main private intermediary organisations for addressing *routine* skills needs

Private sector intermediary organisations play a limited role in the SKA's innovation system, and are primarily focused on building networks to connect the SKA with other actors in the local and international astronomy sectors. This is partially a result of the SKA's status as a publicly funded project, which entails closer relationships with public than with private intermediaries.

Figure 8: Core Astronomy Advantage Area



Source: http://eepublishers.co.za/article/hans-05-how-will-the-ska-affect-people-in-the-astronomy-advantage-area.html

The International Astronomical Union (IAU) and the Global Office of Astronomy for Development (OAD)

The International Astronomical Union is an international coordination body for astronomy, with a membership body of professional astronomers (http://www.iau.org/about/). Intermediary activities include hosting international symposia and hosting discussions about large-scale facilities such as the SKA. The IAU also works to promote astronomical education and research in developing countries.

The Office of Astronomy for Development (OAD) operates under the auspices of the IAU. Its headquarters have been located in at the South African Astronomical Observatory (SAAO) in Cape Town, in recognition of the role that astronomy can play in development in Africa. This office coordinates between the IAU and South Africa's NRF with a focus on the use of astronomy as a tool for education and development. The OAD is co-funded, at approximately a 50/50 ratio, by the IAU and the NRF, and thus represents a network link between local and international intermediary actors. The OAD manages astronomy education projects around the world, some of which are located in South Africa. In South Africa, the OAD has played an intermediary role, facilitating interaction between historically black universities and the previously white research universities. In 2013 they ran two workshops with groups of academics from these two sets of institutions. This networking role appears to be quite distinct, and reportedly is highly beneficial in helping historically black institutions to make the most of their own competences and capabilities by linking them with expertise and knowledge at the research universities.

The African-European Radio Astronomy Platform (AERAP)

The African-European Radio Astronomy Platform (AERAP) is a stakeholder forum of industry, academia and the public sector established to define and implement priorities for radio astronomy cooperation between Africa and Europe. It was launched in 2012 in response to calls from the European Parliament and the African Union for radio astronomy to be a priority focus area for Africa–EU cooperation. The overall goals of AERAP are to promote scientific discovery in the field of radio astronomy and to improve knowledge transfer and competitiveness across Europe and Africa. The platform aims to 'enable effective dialogue to build a shared vision for international cooperation in radio astronomy.' (http://www.aerap.org/news.php?id=79). For example, AERAP has held workshops focused on assisting researchers in finding partners and preparing funding proposals. The workshops have focused on funding opportunities for training networks, partnerships and international exchanges.

The AERAP platform has been instrumental in raising the profile of African radio astronomy in the EU. It has contributed to the explicit inclusion of this focus area in the EU Horizons 2020 funding programme of €81 billion, which is set to replace the FP system as Europe's main public funding stream for science and technology.

USA National Radio Astronomy Observatory (NRAO)

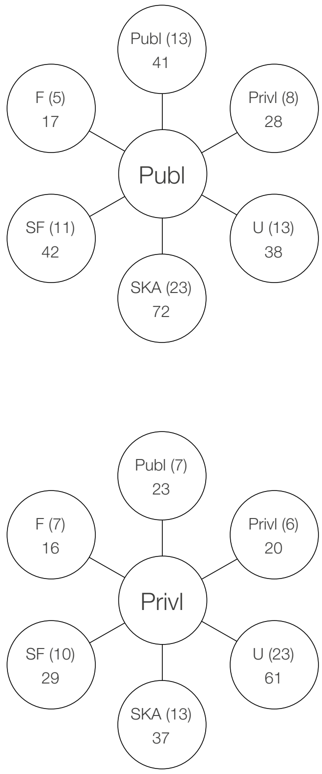
Beginning in 2008, and extended in 2010, the South African SKA Project Office signed a formal collaboration agreement with the USA National Radio Astronomy Observatory (NRAO) with the shared goal of collaborating and cooperating to develop radio astronomy projects of common interest, including software development, data-processing capabilities and joint scientific research, as well as a student and staff exchange programme. Hardware development collaboration includes that related to the ROACH board. Software collaboration includes software needed for the MeerKAT and NRAO radio telescopes. The NRAO has sent astronomers and engineers to help with the commissioning of the KAT-7 and MeerKAT telescopes and NRAO scientists and engineers have participated in MeerKAT review panels, including the Science Advisory Committee, the Time Allocation Committee, and the Concept Design Review panel.

Sensing, learning and coordinating capabilities for addressing *changing* skills needs

The public and private intermediary organisations in the SKA's innovation network are, for the most part, not primarily concerned with skills development or addressing changing skills needs, but rather focus on a range of other roles which, in some cases, impact indirectly on skills development. The DST is primary a source of funding and a strategic partner; the NRF plays a more operational role as it acts as a funding conduit and managing agency for the SKA. A narrower role is played by the DHET through the SIPs, where it has undertaken extensive research to assess the skills requirements of the SKA. Private intermediaries play comparatively limited roles. The OAD has hosted workshops that bring together historically disadvantaged universities and research universities, but otherwise has not played any intermediary roles. On the international front, the AERAP has primarily been responsible for opening up funding opportunities. However, the NRAO has played a more substantial intermediary role, establishing opportunities for SKA researchers to collaborate with international groups in the areas of hardware development, software development and telescope design and fabrication.

The roles of intermediary organisations are summarised and their interactions depicted in Table 9. This illustrates the clear distinction between the funding, strategy and planning roles of public sector intermediaries, and the network-building and knowledge-transfer roles of private sector intermediaries. For comparative purposes, the intermediary functions vested in non-intermediary actors are also included in the table. This highlights the complex and distributed nature of intermediary roles related to the SKA and to astronomy more broadly. Organisations each occupy distinct niches in the system, with most of the actors in the system playing some intermediary roles in addition to their primary roles of knowledge generation, skills development, or science.

Figure 9: Average interaction with public and private intermediary organisations



Notes: See Figure 6

The nature of interactions illustrated in Figure 9 was described in detail in this section. However, this illustrates that, at the broadest level, the interactions of the public and private intermediaries are broadly in line with their functions. Public intermediaries have higher levels of engagement with the SKA and other public sector intermediaries, while private sector intermediaries engage more with universities and firms, but in both cases there is broad-based engagement with all types of actors – underlining their intermediary and bridging functions within the SKA's innovation system.

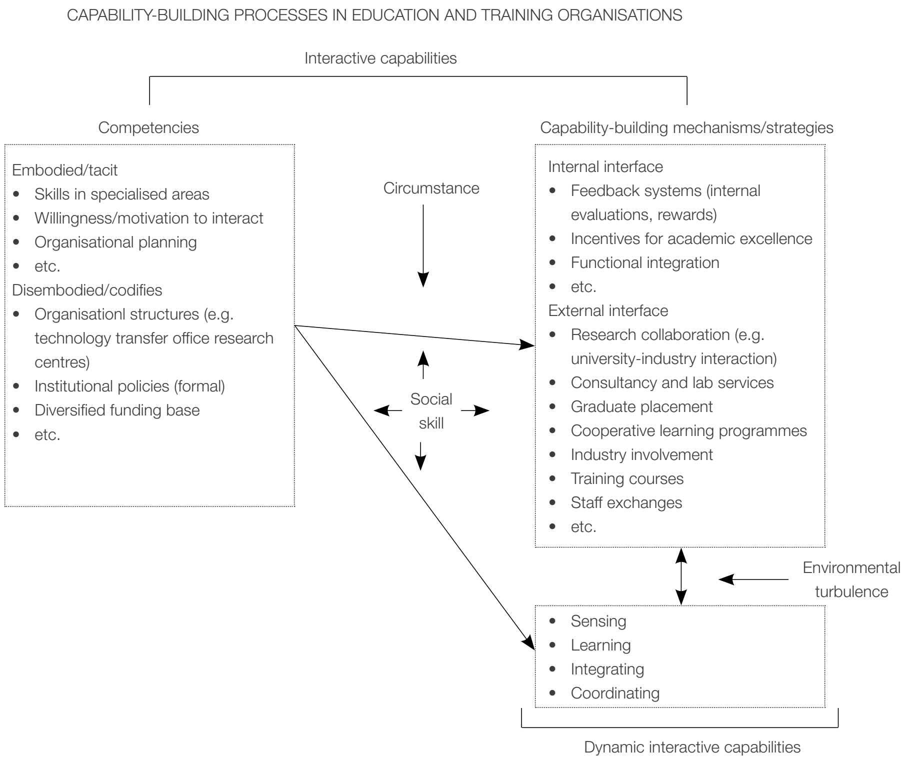
Table 9: Summary of the roles played by intermediary organisations and other actors

Main function	Public	Private	Other actors
Funding and resources	DST, NRF	AERAP	SKA
Strategic direction	DST, Astronomy Desk		SKA
Skills planning	DHET		SKA, NASSP, universities
Network building		IAU/OAD, AERAP, NRAO	SKA, NASSP, universities, firms, science facilities
Knowledge transfer and diffusion		IAU/OAD, AERAP, NRAO	SKA, universities, firms, science facilities

7. INTERACTIVE CAPABILITIES AND DYNAMIC INTERACTIVE CAPABILITIES OF UNIVERSITIES

Universities are central actors in the astronomy SSI, being the primary locus of skills development and major partners in knowledge production and technology development. Each university, to a greater or lesser extent, hosts capabilities for interacting with the SKA, science facilities, firms and intermediaries. This section of the report investigates these capabilities. This forms the heart of the report, as the main argument of the research is that the extent to which education and training (E&T) organisations address skills needs of SSIs depends on their interactive and dynamic interactive capabilities. In other words, the extent to which they are responsive to skills needs depends on their capacity for learning and accumulation of new knowledge, and the effectiveness of their responses to changes in the business and education environments. The analysis thus focuses on identifying the competencies and strategies/mechanisms that each university uses to respond to the routine and changing skills needs of the SKA. Figure 10 illustrates the key dimensions investigated within E&T organisations, with possible features of each for illustrative purposes.

Figure 10: Capability-building processes in education and training organisations – a generic framework



Historical links to the astronomy sector

Of all the universities in South Africa, **UCT** has the longest history in astronomy. UCT is one of only two universities in South Africa offering undergraduate programmes in astrophysics; the other is UNISA which, according to fieldwork and desktop research, plays no notable role in either the Astronomy SSI or the SKA's innovation network. Although other universities are in the process of establishing undergraduate programmes in astronomy, these are administered by other departments – in most cases, physics.

The UCT astronomy department has thus, over time, developed close ties with the SAAO, the SKA and the other main astronomy actors. The long-standing historical relationship between the UCT Department of Astronomy and the SAAO has evolved to include both tacit and codified partnership agreements and a tradition of collaboration on astronomy projects. This has maintained UCT's leadership in astronomy among South African universities and also established an institutional foundation for playing a leading role in radio astronomy (which falls outside the SAAO's mandate) and the SKA. The head of department described this relationship as symbiotic – the SAAO acting as the de facto science facility of the astronomy department, and the department acting as the main (South African) source of astronomy skills for the SAAO.

The relationship between UCT and the SAAO is supported by their close geographical proximity. More recently, the SKA headquarters in South Africa have been established within a similar geographical locus – within a five-kilometre radius of both the SAAO and UCT. These organisations therefore form a tight-knit and effective geographical and organisational cluster that represents a core network within the broader astronomy SSI.

Another key actor is **Rhodes** University, which has historically maintained a close relationship with HartRAO, and has thus developed unique capabilities in the area of radio astronomy. HartRAO has formed a training ground and science facility for astronomy students and researchers, while at the same time drawing on Rhodes graduates as an employer. This, again, is premised on informal relationships that have evolved over time.

Stellenbosch is a more recent entrant to the Astronomy SSI – but in the domain of engineering rather than science. This follows a historical trajectory of engineering excellence, characterised by close relationships with firms, the military, the space science sector and the engineering professional body. This has positioned the university to play a leading role in technology development in collaboration with the SKA and technology-oriented firms in its value chain.

The University of Stellenbosch was a core actor in the apartheid-era military–industrial complex, and a main site for military R&D. One of our key informants reflected on the role of skills drawn from this set of capabilities in the SKA. Essentially, it seems that the SKA has absorbed a share of South Africa's engineering capabilities that were previously directed at military applications. In a sense, one could speculate that this aspect informed the strategic decision by government to invest funds in radio astronomy and the SKA bid – in order to harness capabilities that needed a new direction following cuts to military R&D expenditure post-democracy.

The structure of military R&D bears more similarity to the SKA's R&D requirements than the usual requirements of engineering firms. This is essentially due to the one-off nature of the SKA, compared to the mass-production orientation of most firm-level R&D projects.

> The type of projects that the military go for are very high-tech things, normally with quite a big budget, so they have what they call development budgets. They pay you to develop a project, not to produce it really. So what you get paid for development is a lot more than what the actual component costs are, that's the typical military model. Because the stuff they want is normally sensitive and often not obtainable anywhere else, they go for new products and so it's low volume, very high-tech … and you're not going to sell

hundreds of this. The SKA is very similar, the technology is pushing the limits to such an extent that for some parts the technology doesn't even exist yet. They are banking on technology to be developed in the next five years that will be able to do the signal processing. It's very high-tech, it's very low-volume. In the end they're talking about a few thousand units. There's a lot of overlap essentially between the typical military project and the SKA. Also it's government-funded, which the military also was.

> In contrast to that you have commercial things, which are normal, the company makes money by selling high numbers of units, which is typically the non-military market. So there the design process is completely different. The technical level should be just high enough that you actually can do what you're supposed to do, but it has to be cheap, and possible to manufacture in high volumes. I think it's one of the reasons there's quite a bit overlap between the two. Also, most of the engineering in the country was very involved in the military market, up until about the early 90s, so there's a lot of skills which were developed then, which are still present in the country. (Academic interview: University of Stellenbosch)

At the other universities, participation in the Astronomy SSI has historically taken place through pockets of excellence that exist in domains relevant to astronomy. Here SARCHI chairs have played a key role in building up critical mass. At **Wits** astronomy is still an emerging field. Growth here appears to be driven by university's context in the Gauteng metropole. The university has little historical role in the Astronomy SSI, which has been largely based in Cape Town. **UWC** and **UKZN** have only developed astronomy competences in recent years. At the level of vocational and technical skills, **DUT** has more recently emerged as a capability development partner, and this university of technology has formalised agreements with the SKA HCDP to be the main partner institution for the development of technical skills.

Current links to the astronomy sector and the SKA

The competences available at universities outside the traditional institutions of UCT and Rhodes have grown rapidly over the last few years, with escalating staff numbers in the areas relevant to astronomy, as well as escalating numbers of postgraduate students and postdoctoral fellows. Several universities are currently establishing undergraduate programmes in astronomy (based in other departments, mostly in physics), including Wits, UKZN, Rhodes and UWC. This has partially been a result of the influx of funding, as well as the attraction that a large project such as the SKA offers to prospective students and academics. This is also an indicator of the responsiveness of these universities to changes in their external environment – assessing that demand for skills in the area of radio astronomy will increase in the medium term, and adjusting teaching, learning and research accordingly. This has been one of the key successes of the South African higher education system's dynamic interactive capabilities with respect to radio astronomy.

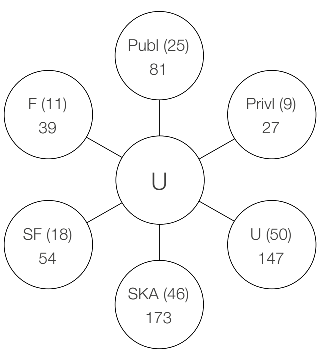
Detailed information about the competences and interactive capabilities vested in South Africa's universities is included in Bharuth-Ram (2011) – the Decadal Strategy – which provides a starting point for this discussion. A useful comparator is Paterson et al. (2005), who provide similar data for an earlier point, thus making it possible to identify trends (see Table 4). These overviews informed the sample selection for this study, which includes most of the major partner universities for the SKA as well as some minor partners that occupy distinct systemic roles and can therefore contribute to a broader picture of interaction. Of course, many other institutions play a role, but the sample requires constraint or it would extend to include most of South Africa's universities. The sample thus consists of:

- UCT – the main partner university for the SKA in terms of astronomy;
- University of Stellenbosch – the main partner university for the SKA in terms of engineering;

- UWC – a leader among previously disadvantaged universities, and recent entry into the astronomy domain, supported by an influx of public funding;
- Wits – a locus for SKA-related activity in the Gauteng region that has experienced rapid growth in astronomy and SKA-related teaching and research;
- Rhodes University – historically the leading university in radio astronomy, a key astronomy partner for the SKA;
- UKZN – a critical mass of research excellence has evolved in the area of cosmology. As a leader in terms of transformation the university has received increased public funding for astronomy; and
- DUT – the only university of technology with a formalised partnership with the SKA. It plays a small but systemically important role.

The sample reported extensive links to other actors in the astronomy sector. In addition to a multitude of links to various aspects of the SKA, the universities interact frequently with other universities. Interaction with public intermediaries is more common than with private sector intermediaries, and firms make up only a small proportion of interactions – largely related to engineering rather than science. Overall this illustrates that astronomy within universities is, like the Astronomy SSI more generally, an intensely connected system. This requires strong interactive capabilities and dynamic interactive capabilities – these are explored in more detail in the sections below.

Figure 11: Interaction with universities



Notes: See Figure 6

Interactive capabilities

Universities' roles in the Astronomy SSI and the SKA

Institutional overview

The SKA's innovation network includes a range of institutions with distinctive sets of competences and capabilities, but the emphasis is overwhelmingly on South Africa's top research universities, with very few roles for previously disadvantaged universities. The only and notable exception here is the University of the Western Cape, which has developed a critical mass in physics and astronomy and has also been awarded two SARCHI SKA chairs. Universities of technology also play a marginal role, with the only formal relationship here being with the Durban University of Technology, and this is itself only in a minor capacity. The sample of universities was also largely unaffected by the mergers that took place circa 2005, with only the relatively minor partners, UKZN and DUT, being affected.

From one point of view, this paints a picture of an elitist activity, pursued by previously advantaged, well-resourced urban universities. From another point of view, this reveals the necessity faced by the SKA to engage with the knowledge partners that hold the most advanced competences and capabilities in astronomy – thus responding to the SKA's science and technology mandate rather than its social mandate. This also suggests that the SKA remains largely unaffected by the challenges and constraints faced by rural universities and previously disadvantaged universities and by the long-term consequences of merger activity that are still being felt.

The six research universities are largely undergraduate universities with postgraduate components ranging from 23% to 37%. However, all of these are more postgraduate-intensive than the national average of 16% (HEMIS database, 2012). The outlier is the Durban University of Technology, with only 3% of its enrolments at the postgraduate level.

Table 10: Basic profile of SKA higher education partners

	Students (+/-)	Academic staff	Other descriptions		
UCT	26 000	961	Not merged	Research	Urban (non-HDI)
RU	7 600	317	Not merged	Research	Rural-Urban (non-HDI)
US	28 000	886	Not merged	Research	Urban (non-HDI)
UWC	19 500	517	Not merged	Research	Urban (HDI)
UKZN	44 000	1 444	Merged	Research	Urban
WITS	30 500	985	Not merged	Research	Urban (non-HDI)
DUT	25 000	562	Merged	U. of Technology	Urban (non-HDI)

Table 11: Student numbers disaggregated by level

	Undergraduate students	Postgraduate students
UCT	69%	31%
RU	70%	30%
US	63%	37%
UWC	77%	23%
UKZN	75%	25%
WITS	63%	37%
DUT	97%	3%
National average	84%	16%

Source: DHET and institutional data

As might be expected, the SKA's partner universities have substantially higher proportions of SET enrolments than the national average, with the exception of Rhodes University, which has a larger humanities focus.

University of Cape Town

The University of Cape Town is by far the most active university in the Astronomy SSI and in the SKA's innovation network, and has the highest concentration of astronomy competences in the country. It has the country's only autonomous astronomy department, having offered postgraduate degrees and an undergraduate major in astrophysics since 2006. In 2010 there were 45 undergraduates enrolled in astronomy as a major, with many more taking the course as a non-major. There were also 13 postdocs, 15 PhD students and 23 MSc students, of which 30% are funded by the SKA. In 2010 the department established of a Research Centre for Astrophysics, Cosmology and Gravity (ACGC), bringing together researchers from the Departments of Astronomy and Mathematics and Applied Mathematics. This research centre (in 2010) included 17 academic staff, three emeritus professors and a SARCHI chair in radio astronomy, and a second SARCHI chair was added in 2011. A joint UCT/UWC SKA Research Chair was taken up in 2014 by Prof. Russ Taylor, one of the founding international SKA project scientists and co-author of the first SKA science case. He currently represents Canada as one of the national members on the SKA Organisation Board. He has also served as the founding Executive Secretary of the International SKA Steering Committee, the predecessor to the International SKA Science and Engineering Committee.

The department has a particularly strong link with the SKA. Of the 10 major science projects for the MeerKAT, four are led by UCT astronomers. The first science paper published using the SKA precursor (KAT-7) was published by UCT astronomers in one of the leading journals in the field (the *Astronomical Journal*). UCT is also home to one of the SKA's funded research programmes, namely the MeerKAT Digital Signal Processing (DSP) research programme. This project supports four master's students and a research officer who assists with coordination and provides training on DSP development tools in other South African universities.

Rhodes University

While Rhodes does not play central role in optical astronomy, it is a key actor in the domain of radio astronomy due to its long-standing partnership with HartRAO and its close institutional ties with the SKA. The radio astronomy unit at Rhodes University, based within the physics department, played a role in developing the KAT-7 and the MeerKAT precursor instruments. The lead scientist in South Africa's SKA project, Justin Jonas, and the site manager, Adrian Tiplady, are Rhodes alumni. Rhodes academics sit on the HCDP panel, the Universities Working Group of the SKA and the NASSP committee. In 2012 Rhodes was awarded the SARCHI chair in Radio

Table 12: Student numbers disaggregated by programme area

	Science, engineering and technology	Business and management	Education and humanities
UCT	41%	25%	3% + 32%
RU	24%	16%	10% + 51%
US	45%	19%	5% + 30%
UWC	36%	14%	12% + 38%
UKZN	36%	16%	16% + 32%
WITS	49%	14%	13% + 25%
DUT	50%	33%	5% + 12%
National average	28%	31%	17% + 24%

Source: DHET and institutional data

Astronomy Techniques and Technologies (RATT), which focuses on algorithm development for working with big data. This centre includes postgraduate students in mathematics, statistics, computer science, physics and electronics who focus on the challenge of processing bulk data, including radio astronomy calibration, imaging, data analysis algorithms and software.

University of Stellenbosch

The University of Stellenbosch does not play a significant role in optical astronomy, but does play a central role in the SKA's innovation network, specifically in the area of engineering. Stellenbosch is the largest source of high-end engineering skills for the SKA, building on its historical trajectory of close ties with the military establishment, space science and engineering firms. This focus is also a result of a considered strategy, which looks at an overview of the roles that each of the universities play in the SKA and focuses on the university's strength without establishing unproductive competition:

> In South Africa you will find universities essentially have fields of expertise which don't put them into conflict with each other, so everyone's got his own niche area which is developed over the years. So for instance UCT has got a Master's Degree in Astrophysics, which is very closely related to the astronomy side, and then Rhodes has got a very big astronomy side, and I think Wits as well. So it didn't really make sense for Stellenbosch to start something up as well. In terms of serving the country I don't really see a point in that. Whereas on the engineering side we're very involved. Astronomy in South Africa is not big enough to support all the universities being involved in that. (Academic interview: University of Stellenbosch)

The university hosts a SARCHI SKA chair in Electromagnetic Systems and Electromagnetic Interference Mitigation in the Department of Electrical and Electronic Engineering, headed by Prof. David Davidson. This group has assisted with the civil, mechanical and electrical teams of the SKA Project Office with the building of KAT-7 and MeerKAT. Prof. Davidson is involved in the placement of the dishes in the array, and in the engineering of the telescope and the antenna dishes. Another SARCHI chair is held by Prof. Howard Reader, head of the EMC and Metrology research team at the Electrical and Electronic Engineering Department. Reader's research team contributed to the EMC (electromagnetic compatibility) and RFI (radio frequency interference) mitigation modelling and measurement of the KAT-7 and MeerKAT, in collaboration with the mechanical and civil engineering project teams. This chair plays an important gatekeeping role in the SKA technology development process. Since the entire SKA project is dependent on radio silence at the infrastructure site, the prevention of RFI is critical – a single exposed wire in a single building could emit enough RFI to interfere with the entire project. Prof. Reader's chair acts as a gatekeeper on all design reviews for all technology designs for the SKA, with the aim of avoiding any RFI. This includes informal engagement with firms and formal oversight on internal SKA structures, namely the RFI Working Group, which meets monthly, and all the technology systems being developed for the SKA.

Other key academics conducting SKA-related teaching and research include Prof. Petrie Meyer, who is conducting research on the simulation and design of SKA antennas, and Dr Dirk de Villiers, who is working with EMSS Antennas and the SKA South Africa office to optimise the design of the antenna for MeerKAT.

University of the Western Cape

The University of the Western Cape is the only historically disadvantaged university to play an important role in the SKA's innovation system. This has been, in part, spurred by significant funding allocations to the university from both the DST and the SKA. The astronomy group at UWC was started in 2008 when the SKA project funded a SARCHI research chair in astrophysics. UWC astronomers are also working on the Large Survey Projects on South Africa's MeerKAT array. By 2010 UWC hosted eight academic staff working in astronomy, along with four postdoctoral researchers and eight postgraduate students.

At the UWC, the primary driver of the growth of astronomy has been the university's status as a leader among the previously disadvantaged universities. This has attracted public funding for astronomy, both from the DST and from the SKA, in the context of confidence in the quality of teaching and research at the university. Prior to the advent of the MeerKAT and the SKA site bid, there was no astronomy activity at UWC. However, the SKA bid acted as a catalyst, again, driven by informal relationships and processes. This led to astronomy being included in the activities of the physics department, where it later became a major focus. The status of UWC as a previously disadvantaged university, with a high throughput of graduates from previously disadvantaged population groups and partnerships with other previously disadvantaged institutions, has positioned it positively to receive public funding. The interaction that has facilitated this process has taken place at the top levels of the university, in which senior management and senior academics interact, both formally and informally, with government actors, thus establishing the basis for financial support.

The allocation of a SARCHI chair in astronomy to UWC acted as an attractor for further activity in the area.

> In practice, one thing happens or you get one person and things get driven by that. In this case, what happened was somebody applied for a job here, who was very good, he was an astronomer, which was not the sort of normal thing, and since we didn't have an astronomy section, we didn't appoint her. But it made us think, 'Well maybe we should do that.' Then, through serendipity rather than planning, we got involved in astronomy …
>
> By chance, the then Head of Department, Danny Adams, spoke to somebody at DST one day at a conference and told him about this programme and this person at the DST, who's called Tshepo Seeko [DST Chief Director: Radio Astronomy], his job was to try and boost radio astronomy in the country, and he was amazed at how many postgrad students we had. And, of course, that most of them are black South Africans. He then said, 'Why don't you get into astronomy?' And because we had been talking about that, we then met with Bernie Fanaroff at a couple of meetings, where I was Head of Department at the time. I just gave him half-an-hour PowerPoint presentation about what we do and said 'that we were interested in getting more involved in astronomy'. And it looked as if radio astronomy was a real niche area for us or could be a niche area for us because UCT was the only university in the Western Cape involved in astronomy, and they were not very strongly radio astronomy. This led to many discussions with Patricia Whitelock at the SAAO and more with Tshepo Seekoe and Bernie.
>
> We got on the bandwagon at exactly the right time. We got an astronomer, decided we were going to concentrate on that section, to

some extent, and then there was this South African Research Chair initiative, so we applied for a SARCHI chair in astronomy. Through the fact that we had already had a quite successful postgraduate programme, which attracted many black South Africans in physics, we worked with the University of Zululand … And because of that success, when we spoke to people, they said, 'Wow, you are training black South Africans. Don't you want to get involved in astronomy because there's a real lack of black South Africans in astronomy?' Through that sort of goodwill, we got one of these SARCHI chairs, and now we have two and we have more people in the physics department as well, who are astronomy researchers. So it has been a major change to the department. From zero astronomy 10 years ago, we now have two SARCHI chairs in astronomy plus two on the lecturing staff who are astronomers and then several postdocs and we've now introduced undergraduate courses in astronomy as well. (Academic interview: UWC)

I saw one of the proposals for boosting astronomy in the country and it mentioned paying for a researcher at a historically black university. And I immediately thought, 'Well, UWC is in Cape Town, so we should be well positioned for that.' But when I spoke to one or two people, it was clear they had in mind, 'No, we must really broaden things, so this person should be in Venda or Mafikeng or somewhere. And that maybe UWC would not be in a good position to get such a person.' But, subsequently, I think it certainly works out much better. (Academic interview: UWC)

University of KwaZulu-Natal

Although the UKZN does not host a department of astronomy, it does host an interdisciplinary research group focused on astrophysics and cosmology. As such, it plays a relatively small but systemically significant part in the Astronomy SSI and the SKA's innovation network. In both cases, this role is focused on science rather than engineering. The Astrophysics and Cosmology Research Unit (ACRU) at was established in 2004, based in the School of Mathematics, Statistics and Computer Science and the School of Chemistry and Physics. In 2010 it had five academic staff and three postdoctoral researchers working in astrophysics, relativity and cosmology – including a SARCHI chair in Gravitating Systems – and 11 postgraduate students and six undergraduate students in astrophysics and cosmology.

Researchers at ACRU have been working with the SKA in South Africa since the early stages of the project. The the university has multiple links with the SKA, including undergraduate and postgraduate bursaries and SKA-funded academic positions, and now hosts a node of the SKA astronomy undergraduate bursary programme. Academics from the ACRU have collaborated on the KAT-7 as well as several science projects of the MeerKAT, including the MIGHTEE, MALS, PTS and LADUMA projects. Astronomy students have worked with KAT-7 data. They have recently appointed a specialist in instrumentation in order to expand from their core expertise in astronomy, and they have recently employed a specialist in high-performance computing and the analysis of large data sets. Academics from the ACRU sit on the SKA Universities Working Group, which they report as being highly effective in developing coordination between the SKA and the university.

University of the Witwatersrand

Wits University is the main SKA higher education partner outside the Western Cape, hosting a critical mass of relevant competences and capabilities in Gauteng, South Africa's economic hub. Wits employs about 20 academics working in astronomy, including two SARCHI chairs in Radio Astronomy – the SKA Chair in Radio Astronomy, held by Prof. Sergio Colafrancesco, and the Chair in Theoretical Particle Cosmology, held by Prof. Vishnu Jejjala. Staff also include a number of astronomers and theoretical physicists who work in related areas. Wits does not host a dedicated astronomy department, and its academics and postgraduate students conducting astronomy-related research are dispersed throughout several departments within the faculty of science, primarily physics, applied mathematics and computer science.

Postgraduate students at the School of Applied Mathematics conduct mathematical modelling with application to astronomy – for example, two honours students are undertaking mathematical models of star formation. Prof. Erwin Block offers an honours-level course in galaxy morphology. Staff members are involved in the SKA's Universities Working Group, the NASSP and the DST's Astronomy Desk.

Wit's involvement in the SKA innovation network is almost entirely focused on astronomy, rather than engineering. There was no reported interaction with firms in the SKA value chain or innovation network, with the possible exception of reported interaction with ICT firms in the department of computers science. This again underlines the sharp distinction between astronomy-focused universities and engineering-focused universities in the SKA's innovation network.

Durban University of Technology

The Durban University of Technology is the only higher education institution that has a close relationship with the SKA in terms of technical skills. The university has established a Radio Astronomy Telescope (RAT) group, based in the Department of Electronic Engineering. The group is small, including only two teaching staff, but it plays a systemically important role in capability-building for the SKA. The students are in three main streams of study, these being communication engineering, instrumentation and computer assistance. Although there are no specific astronomy programmes, astronomy-related project work begins at the final semester level of the diploma and continues into the BTech and Masters levels.

In 2006 one of the lecturers in engineering decided to build a platform for student practical work in radio astronomy. Together with the current leader of RAT, they built a five-meter parabolic reflector radio telescope, the Indlebe Radio Telescope (IRT). Although the rise of radio astronomy in South Africa played a role in this decision, the primary motivation was one of cost – that information at radio frequencies is free, and the technology low-cost, which makes it suitable for student projects on a tight budget:

> Basically because it's all free, you know, what's out there is free. You can just put the dish up and, and play around with different files and small signals and so on and that is the area of specialisation. (Academic interview: DUT)

News about this development reached the SKA and shortly thereafter the university was visited by a delegation from the SKA, including the Justin Jonas and the manager of the HCDP. From that point they formed an agreement with the SKA to link bursaries to in-service training. The SKA offered internships to students from the department, and in 2009 the first group of interns spent time at HartRAO, at the MeerKAT/SKA site in the Northern Cape and at the Cape Town offices of the SKA. These internships led to a positive working relationship that is ongoing. At the time of research there were 12 students in this stream.

To support these activities there has been a mobilisation of funding support. Although there is no internal university funding for astronomy or the RAT, they have received funding from the DST (for their collaboration with Mauritius) and student bursaries from the SKA via the NRF.

Dynamic interactive capabilities

The self-rating of dynamic interactive capabilities at the sample universities reveal some aspects of how universities perceive their own capabilities. In some cases, these are in line with the other available data; in other cases, these diverge. For example, the engineering faculty at the University of Stellenbosch evidently has high dynamic interactive capabilities, and this is reflected in its self-perceptions. On the other hand, Wits management rated its own learning capabilities as low, which is in contrast to other evidence that suggests substantial learning capabilities.

More detailed information about the dynamic interactive capabilities vested in universities can be found in their specific responses to changes in technology and, more importantly, to the rapid growth in astronomy in South Africa over the last decade and the emerging skills needs of the SKA. These dynamic interactive capabilities are examined

Table 13: Dynamic interactive capability scale (average scores)

University	Faculy/ Department	Sensing capability	Learning capability	Integrating capability	Coordinating capability	Dynamic Interactive Capability (overall)
Rhodes	Computer Science	2,5	3,33	3,4	3,6	3,21
Rhodes	Science	2,75	2,67	2,40	3,20	2,75
Rhodes	(overall)	2,63	3,00	2,90	3,40	2,98
UCT	Astronomy	3,50	3,33	3,80	3,40	3,51
UWC	Physics	2,25	2,00	3,20	3,60	2,76
Stellenbosch University	Computer Science	3,25	3,33	3,40	3,00	3,25
Stellenbosch University	Engineering	4,00	4,00	3,40	3,60	3,75
Stellenbosch University	(overall)	3,63	3,67	3,40	3,30	3,50
Wits	Physics	3,25	3,00	3,80	4,00	3,51
Wits	Management	2,00	1,00	2,80	3,00	2,20
Wits	(overall)	2,63	2,00	3,30	3,50	2,86
Overall scores		2,94	2,83	3,28	3,43	3,12

Scale: 1 = Not effective; 2 = Somewhat effective; 3 = Effective; 4 = Very effective

in more detail in the following analysis of universities' organisational competences and strategies to respond.

Organisational competences and strategies to respond

Strategic orientation

The strategic orientations of the sample universities are, to some degree, a reflection of their historical trajectories. The strategic plan for the **University of Cape Town** includes six strategic goals, including 1) internationalising UCT via an 'afropolitan niche'; 2) transformation, including redress, diversity and inclusiveness; 3) working towards a desired size and shape for UCT; 4) achieving greater impact and greater engagement through research; 5) enhancing the quality and profile of graduates; and 6) contributing to South Africa's development challenges. These strategic imperatives require the cultivation of interactive capabilities in several places. The notion of an 'afropolitan niche' positions UCT at a crossroads of African and international influences and imperatives, supporting interaction between local and international academics and partners. Research that achieves greater impact and greater engagement also requires stronger interactive capabilities. This is particularly the case in relation to UCT's guiding notion of 'institutional responsiveness', which serves as an umbrella term referring to responsiveness towards communities, industry, academic partners, national imperatives and any other external partner or drivers. This positions UCT as a university that is more responsive, in general, to its external environment. Other strategic goals, related to the quality of graduates and contribution to national objectives, also inherently require improved interactive capabilities.

Rhodes has a more holistic strategic orientation, emphasising a commitment to the local community and region. Community engagement is a critical pillar of the university's strategy, with the aim of enhancing scholarship, development, social cohesion and social transformation. At the time of research the university was developing an institutional development plan, which draws strongly on a transformation and social justice agenda. The emphasis is on the growth of critical citizens, rather than on specific skills for industry.

The strategic plan for the **University of Stellenbosch** includes five goals falling under three main aims: broadening access, growing research excellence and growing social impact. These goals are: 1) increasing access to new knowledge markets; 2) increasing diversity of students and staff; 3) positioning itself as the leading research institution in Africa; 4) maintaining a success rate in research excellence; and 5) establishing committed, visionary leadership for social impact. These goals to not explicitly refer to interactive capabilities. However, the need for interactive capabilities is implied in each of them. In light of the strong interactive capabilities that are evident at the university, it seems that at Stellenbosch the need to interact, internally and externally, is an internalised value rather than one expressed at the highest strategic level.

The **UWC** has a five-year strategic plan focused on the identification and prioritisation of niche areas or focus areas in terms of innovation and industry relevance. This places a strong emphasis on various modes of interactive capability, with key roles for the university's technology transfer office and their business innovation centre. In addition, the university has a research strategy with five main goals: 1) excellence in research; 2) research capacity development; 3) strategic research partnerships; 4) a research incentive scheme; and 5) an internal research funding scheme. This strategy positions interaction as a central feature, particularly in the area of 'strategic research partnerships'.

Since forming through a merger in 2005, **UKZN** has had two phases of strategic 're-engineering'. The first was to consolidate and embed the new institutional structures following the merger. The second, current, stage (2007–2016 strategic plan) focuses on the value of various programmes, thus revisiting curricula, looking for redundancy, aiming to consolidate programmes and creating flexibility to develop new modules. Through this it aims to become the 'premier university of African scholarship' and achieve a higher ranking in the QS World University Rankings. This strategic orientation suggests that there will be more flexibility to introduce new and more contextually relevant curricula.

Wits' strategic institutional policy, drawn from its 'vision 2022', states that the university 'aspires to be a leading research-intensive university, firmly embedded in the top 100 world universities by 2022'. The strategy positions Wits as a leading research university, and also explicitly positions it with the South African National Innovation System, indicating that an innovation systems approach has influenced the university's strategic orientation. The notion of the 'triple helix' has also entered this strategic document, in which the university sees itself has operating dynamically with industry and government. This position has also been put forward in management interviews, and has influenced the manner in which research decisions are taken – for example, aiming to increase publication rates and taking on projects that are less complex, and more tailored towards individuals, and thus more orientated towards producing research papers.

The **DUT** does not make an institutional strategy available, and interviews did not reveal a clear institutional strategy. However, the university does express statements of its vision and its mission, which strives to 'develop leadership in technology' through excellence in teaching and learning, technology transfer and applied research, and external engagement that 'promotes innovation and entrepreneurship through collaboration and partnership' (www.dut.ac.za). Senior management (the Vice Chancellor and Chancellor) have undertaken to participate in industry engagement. In his inauguration speech in 2011, the Vice Chancellor remarked: 'Universities are constructed in a local space from which they reach out into global spaces ... There is a specific responsibility that rests with our universities to produce knowledge that is contextually defined ... DUT will be an institution embedded in its context but able to reach beyond it.'

Institutional planning

Institutional planning functions do not have much direct relevance to niche areas such as astronomy or the SKA – where planning and coordination tend to take place at a more devolved level of the organisation. However, these are important drivers of the overall effectiveness of universities to cultivate interactive capabilities, and thus indirectly impact on astronomy and the SKA. As such, the main features of the institutional planning competences and mechanisms are presented here. As might be expected, the larger and better-resourced universities have stronger centralised institutional planning functions.

UCT's Institutional Planning Department shows strong competences and capabilities for institutional planning and coordination. The functions of the department include:

- enrolment planning;
- overall strategic planning for the institution;
- academic planning, particularly with respect to any proposals for new qualifications that need to be offered;
- issues related to the curriculum and the extent to which the curriculum is geared towards meeting the aspirations and goals of the university's strategic plan. This represents clear articulation between the university's strategic outlook and its planning and coordination function;
- institutional research, including an annual graduate exit survey and, in 2012, a regional study with three other universities in the region on graduate pathways from the university; and
- quality assurance.

Within the department is the Social Responsiveness Unit, which focuses on how the university responds to the needs of society, broadly defined.

The **University of Stellenbosch** has strong institutional planning capabilities, with a centralised office responsible for institutional research, enrolment planning, academic planning, liaison with government departments and the approval of curricula. Enrolment planning includes planning for the size and 'shape' of the student body, looking at demographics and the composition of academic programmes. Academic planning includes planning for new programmes and fields of study and the approval of curriculum changes. Liaison with government departments includes close relationships with DHET, HESA and CHE. The institutional planning function also approves research projects, provides access to university databases and is responsible for institutional reporting – for example, to the DHET.

At **Rhodes University** this function is somewhat weaker. An Institutional Planning Committee assesses possible new programmes, but there is no Institutional Planning department – at the time of research this position had remained empty for some time. There is, however, an institutional data analyst.

At the **UWC** the institutional planning and strategy function is nested within the broader 'institutional advancement' function, which reports to the Rector. However, a major component of institutional planning is, in practice, conducted by the academic planning and curriculum unit, which is responsible for:

- managing the academic planning committee of the university – requires liason with the seven faculties and the collation of planning documents;
- reviewing all academic departments as well as all centres and institutes within the university and recommendations for improvement and change;
- managing institutional information, for example throughputs, results, etc.; and
- responding to requests from management for institutional information.

The tasks required to support these functions are devolved to academic planning committees within each faculty.

At **UKZN** the functions associated with institutional planning are somewhat dispersed. The information and data management functions are grouped within the Institutional Intelligence office, which falls within the Information and Communication Services (ICS) function. Activities include:

- maintaining and providing information to support the decision-making processes within the institution, including information about qualifications, modules and curriculum details; and
- the preparation and submission of statutory data (HEMIS) in the areas of students, staff and space to the Department of Higher Education and Training. This is recorded and maintained on ITS.

However, the strategic aspects of institutional planning are not co-located with these data functions and are, instead, dispersed throughout the leadership structures and support structures such as the Teaching and Learning Office. This suggests a lower level of functional integration of institutional planning activities.

At **DUT** there are no centralised institutional planning functions. The registrar is responsible for the collection and management of institutional data, but the strategic use of this data is a senior management function.

Teaching and learning: Policy, strategy and structures
Top research universities have higher proportions of academics with doctorates and a higher rate of publication for academics and for academics with doctorates. UWC, a previously disadvantaged university, has lower publication rates than the other research universities. DUT has the lowest publication rate of the sample and the lowest proportion of academics with doctorates. What this illustrates is the locus of SKA partnerships within the best resourced universities with the highest levels of competences and capabilities required by the project.

The research universities have strong teaching and learning policies, although the mechanisms by which these are implemented differ. DUT has less substantial and complex systems in place. On the whole the range of policies and mechanisms employed by each institution provide forums for staff development, institutional research, curriculum review, the rewarding of teaching excellence and pedagogical support. Similarly to the role of institutional planning, teaching and learning policies and mechanisms at the institutional level have little direct relevant to a niche area such as astronomy. Instead, teaching and learning strategies and mechanisms that are of relevance are to the faculty level, the departmental level, or to individual academics. As such, the analysis pays separate attention to the institutional aspect as well as the more devolved aspects of teaching and learning at each university.

UCT hosts highly integrated and comprehensive mechanisms and structures that support teaching and learning. In 2009 the portfolios of the university's deputy vice chancellors (DVCs) were reviewed, and oversight of teaching and learning was consolidated into one portfolio (included in this study's fieldwork sample). A Teaching and Learning Committee reports to this DVC and is tasked with developing and promoting strategies for the development of teaching and learning, including matters related to:

- teaching and learning with a focus on undergraduate and all taught postgraduate programmes;
- measuring the quality of teaching and learning;
- student progression;
- promoting improvements in teaching, curriculum and assessment;
- enhancing and improving students' learning experiences; and
- national, institutional and regional challenges, possibilities and policies that have implications for teaching and learning and academic planning.

In 2011 the senate also approved the establishment of a Quality Assurance Committee (QAC) to monitor the implementation of the institution's policies and strategies and to manage the core functions of

Table 14: Characteristics of academic staff by institution

	Permanent academics		Research publication units		
	Total	Total with doctorates	Publication units produced	Units per total permanent academics	Publications per permanent academic with doctorate
UCT	961	563	1 166	1,2	2,1
UKZN	1 444	515	1 057	0,7	2,1
RU	317	168	323	1,0	1,9
US	886	491	1 014	1,1	2,1
UWC	517	336	262	0,5	0,8
WITS	985	508	911	0,9	1,8
DUT	562	56	43	0,1	0,8

Source: CHET open data (2008–2010)

teaching and learning, research and social responsiveness.

The department has shown strong capabilities in terms of adapting its teaching and learning activities to the changing requirements of the astronomy sector, both in terms of scale and scope. Historically, the UCT Astronomy department has mostly focused on postgraduate qualifications, with the exception of a few years during the 1990s when there was an undergraduate programme on offer. However, this was shut down due to low enrolment levels. However, subsequent to the construction of SALT, the SKA bid and the initiation of MeerKAT, this was reviewed, and in 2006 an undergraduate programme was reinstated in response to increased demand. This requires majors in astrophysics and physics, as well as components of cosmology and mathematics. The escalating demand for radio astronomers has been responded to by growth in staff and student intake:

> When I was here before as a PhD student and postdoc, we had two permanent staff, one or two postdocs and a handful of postgrads, not just for PhDs. Nowadays, we have nine staff. We've got 15 postdocs and we've got 35 postgraduate students. So that's a complete change. In the past, 10 years ago, there was maybe one PhD student in astronomy in the entire country, and nowadays we are at a stage where we have about three or four just at UCT each year. So that's made a big impact. (Academic interview: UCT)

The department also introduced a new undergraduate course in 2013 on radio astronomy observational techniques, including a practical component. Another response has been the establishment of a learning path for students interested in astronomy engineering – called 'astro-technology'. This is a cross-faculty offering that includes the basic components of astronomy and physics, combined with the relevant engineering courses such as signal processing.

However, in terms of curriculum responsiveness, undergraduate curricula do not change rapidly. On the contrary, they consist of a standardised canon that forms the foundation for more responsive curricula and research at the postgraduate level. This is not unique to UCT or South Africa – it is reportedly standard practice at the global level, with global reliance on a small set of textbooks for undergraduate astrophysics. This does not mean that classroom content is static. New practical components are introduced, and engagement with the newest observations and facilities provides variation and excitement for students:

> In good teaching practices you bring in some research aspects to excite the students who are doing the course – this was found recently by the telescope, like MeerKAT or the space telescope. You bring in aspects of research into the classroom, not just to excite, but also to raise the curiosity of the students and teach them how to do research at an early age. So in the third year classes they go to Sutherland to have a hands-on experience. We've now updated our teaching observatory on the roof of this building and there is an active component where the students in groups of two and three, work with that, and the new course that we've introduced this year, second-year level, is very, it's very much practical work. (Academic interview: UCT)

One of the key roles played by UCT is in its administration of and leadership in the NASSP programme. Although the NASSP is funded by the NRF and managed by the SAAO, it is based at UCT and is administered by the university through the Astrophysics, Cosmology and Gravity Research Centre (ACGC). It thus represents a true confluence of actors collaborating in the area of skills development for astronomy, and is made possible by UCT's strong organisational and interactive capabilities. The NASSP is currently considering expanding the programme to include additional hosting sites at UKZN and at North-West University. The NASSP students (who come from both South Africa and abroad) work towards honours, masters and PhD programmes in astrophysics and space science. Coursework covers most areas of modern astronomy, astrophysics and cosmology. Practical components involve field trips to some of southern Africa's space science and astronomy research facilities.

The idea for NASSP originated in 2000 during an NRF strategic planning exercise, and the programme was launched in 2003. This was in response to a shortage of astronomers, particularly black astronomers, in South Africa. This has since proved to be useful, in that it established a pipeline of astronomy skills that supported the bid for the SKA. This also represents a crucial mechanism for articulating the skills demand and skills supply organisations through long-term planning and institution-building.

Outcomes of the masters programme include:

- 134 students registered between 2003 and 2011;
- 16 students registered for 2012; and
- 85 graduated, eight PhD upgrades, 27 are currently completing thesis, nine completed coursework only.

An analysis of pathways for NASSP graduates indicates that the 85 masters graduates have had the following destinations:

- 25 PhD graduates;
- 45 currently studying for a PhD;
- two permanent faculty in SA (UCT, UKZN);
- postdoctoral fellows (including Caltech, Princeton, Yale, ICRAR and Oxford);
- SANSA;
- the SKA office; and
- industry.

The NASSP has thus been highly effective in meeting the skills demands of the space and astronomy sectors in South Africa. Bharuth-Ram (2011) reports a rapid increase in applications to the NASSP programme in the years leading up to 2011. This is attributed to the introduction of an undergraduate astronomy programme at UCT and the initiation of outreach programmes in astronomy around the country. Since the advent of the SKA this trend has escalated.

The NASSP employs strong interactive capabilities in the process it follows to determine its curriculum. The NASSP has an executive committee, which maintains executive control, as well as a management committee, which manages the day-to-day activities. Informing both of these is a steering committee. The steering committee includes academics as well as practising astronomers, and is therefore an important forum for these actors to exchange views and information to inform the curriculum development for the NASSP. Approximately 30 people sit on the steering committee, including representatives of the SKA. This is a key forum for interaction between the SKA and the NASSP, as there are several students on SKA HCDP bursaries that are on the NASSP programme. So, communication between these two actors, with a view to optimising the curriculum, is vital.

The NASSP, structurally, aims to make the most of South Africa's uneven and fragmented competences and capabilities in the space science and astronomy domains. But achieving this requires interactive capabilities to manage the sometimes competing interests of different universities:

> NASSP is saying the following: it's very inefficient for 20 different honours programmes in South Africa to launch an astronomy programme, so the physics department with the UKZN, the physics department at Rhodes, the physics department of Johannesburg, would normally maybe just have one, maybe two, modules in astronomy. To have a fully fledged programme in the entire year being astronomy related, it's not cost effective at all for these departments who do it. So it's much more cost effective to locate those few students located at these institutions who wish to pursue astronomy, locate them at a single institution and then bring in the expertise from around the country to the same institution and let the teaching happen. Easier said than done, because there's all sorts of complications that come with that, you know there are students that are

> registered at UCT who get the subsidy credits, who gain the registration fees, and should other universities willingly give up their students to such a programme and so on and so on.
>
> So those are some of the challenges and tensions that have developed that need careful management and that's part of the ongoing engagement that I have with the universities, trying to find a more credible arrangement to ensure that this happens. Nobody disagrees that this is the most efficient way to make it happen, but then when you start looking at the mechanism around it does become a little difficult. (Management interview: NRF)

One key forum for interaction at the NASSP is its Curriculum Workshop, at which all main stakeholders meet to discuss and determine the future curriculum. Several key informants reported that they participated in this workshop, which included discussions about the future skills and research requirements of the various employers in the Astronomy SSI over the short, medium and long term. This forum is critical in terms of aligning the NASSP with current and future skills requirements.

The **University of Stellenbosch** hosts comprehensive and integrated teaching and learning policies and mechanisms. This is led by the Vice Rector: Learning and Teaching, who is responsible for seven broad areas:

- learning and teaching management;
- education policy development;
- education quality assurance;
- student enrolment management;
- student affairs;
- support to student governance structures; and
- language management, especially the implementation of multilingualism.

Overall, the evidence indicates that the university has strong institutional competences in the area of teaching and learning. However, the locus of interactive capabilities relevant to the Astronomy SSI is at the faculty level, specifically within the engineering faculty. Here, teaching and learning have been highly responsive to changes in the astronomy sector, particularly to changes in the demand for radio astronomy engineers for the SKA. In 2012 the faculty started up a one-semester postgraduate course on radio astronomy that is targeted at SKA bursary-holders. This is in the context of much more rapid responsiveness at the postgraduate level compared to the undergraduate level (as is the case at all the universities in the sample). The primary aim of the course is to bridge the gap between astronomy and engineering – primary to position engineers to play a role in astronomy:

> The moment SKA started we immediately saw that these are two groups of people where the interaction is almost zero. The way they talk about the same thing, the terminology and the concepts, while the concepts may be very similar, the terminology is completely different. The one is from a physics point of view, the other is from an engineering point of view. So there was a big need for people to be able to talk to each other, which is where exactly this course fits in – to teach engineers astronomy from an engineering perspective. (Academic interview: Stellenbosch)

At **UKZN** there is a DVC for Teaching and Learning, responsible for the University Teaching and Learning Office (UTLO), which supports and funds across the university in support of teaching and learning. Each college also has a Dean for Teaching and Learning, indicating the centrality of this function. In addition there is a teaching and learning strategy group at the institutional level, comprised of the college deans. Within each school there is a teaching and learning leader reporting to the college dean, as well as a teaching and learning committee within each school. Research and guidance are provided by the Curriculum Development Centre. The College Academic Affairs Board is the final approval stage for curriculum review. Other formal structures that support teaching and learning include the Senate Teaching and Learning Committee, the Quality Assurance Committee and the Programme Accreditation and Approval Committee. The evidence thus suggests a comprehensive range of institutional competences for teaching and learning.

Again, the teaching and learning interactive capabilities relevant to astronomy are devolved – in this case, to the ACRU – within the physics department. The ACRU has been purposefully responsive to the recent growth in astronomy, and particularly responsive to the prospect of further growth through the SKA, which has been enabled by increased public funding through the NRF and the SKA:

> We're gearing up for training a large number of students in astronomy, at the undergraduate level, and also the postgraduate level. Those have been in response to the government investment in astronomy. (Academic interview: UKZN)

The establishment of an undergraduate major in astronomy has involved both internal and external interactive capabilities. Firstly, the content of the course was shaped by a series of meetings of academics in the research unit, which took into account the nature of skills demand, what would 'link in with the South African astronomy community'. At the undergraduate level, as with all of the other universities, a standard curriculum is being established in line with global practice. At the postgraduate level, engagement between students and astronomy employers is encouraged through research projects that are conducted at most of South Africa's astronomy science facilities, including the SKA and its precursors.

The NASSP has approved the establishment of an additional node at the university, which will make it a hub for postgraduate teaching and research. However this is dependent on the approval of funding by the DST, which had not yet occurred at the time of research. At the time of research they were in the process of establishing an undergraduate major in astronomy, including a component for radio astronomy, to bolster the future prospects for its postgraduate students further. However, key informants highlighted that the rapid growth in demand would nonetheless outstrip growth in supply:

> The one medium-term concern would be that there's massive development, and there's been a need for a great number of highly skilled people, and we don't have that on the ground, so there is a shortage of people, and the present endeavour to get more graduates out who will help a little bit, but I don't think it will fill the gap completely. (Academic interview: UKZN)

Wits has a formal teaching and learning policy, which lays out a strategy for strengthening the quality of education at the university. This is informed internally by a research programme, the 'sociology of work project'. There is an Academic Planning and Development Unit and a Centre for Teaching and Learning Development, which reports to the Director of Strategic Planning, who in turn reports to the DVC: Academic. A Science Teaching and Learning Centre plays a key role in putting together curriculum documents for approval, including aspects of both content and pedagogy. In addition, five-year reviews of curricula are managed by the Academic Planning function, which are presented to the Academic Planning and Development Committee and the Senate.

Within departments of computer science, applied mathematics and physics, there is evidence of considerable interactive capabilities in terms of adapting teaching and learning to the evolving needs of the astronomy sector. The establishment of astronomy-related undergraduate and postgraduate programmes has occurred as a strategic reaction to the growth of the field in South Africa and in anticipation of further growth through the SKA. In this context, the supply of, and demand for, skills within the geographical locus of Gauteng are concentrated at Wits. Together, these two drivers have resulted in significant growth of astronomy and related fields at Wits. The interaction that has facilitated this growth has primarily been that of 1) internal strategic choices by Wits management; and 2) formal and informal interaction with the SKA and DST to establish a rationale and basis for funding and administering astronomy-related activities at the university.

Prof. Carlo Francesco has been leading the establishment of a new undergraduate programme in astronomy, to be based in the physics department. This has required substantial internal interactive capabilities, as it requires coordination between various departments within the faculty of science. The main forum for this is the faculty executive meetings, which are attended by all heads of departments, schools and research units. The honours programme has recently been streamlined to accommodate changes in external demand, including from the SKA:

> We've streamlined our honours programme in computer science toward big data … They've realigned their honours programme, they've taken out topics they feel they don't really need any more in computer science, and they've reintroduced things like machine learning, IT machine intelligence, big data, and robotics … We've essentially shifted the computer science away from the more theoretical computer science to the more applied, so that the students who come through the programme, those who want to go in this direction, will be able to do so almost immediately … It's actually a response to a national demand, being a response of … it's SKA, there's also demand from industry, in fact, if you have students who understand how to manage big data. The university's establishing a centre for big data. (Academic interview: Wits)

Programmes within computer science are being restructured to increase attention to image processing and big data – for example, a project on hyper-spectral data funded by the CSIR, which includes eight postgraduate students, some of whom are also SKA-funded.

Changing the curriculum is easier in the computer science departments than in other departments. A particularly high rate of change is experienced in computer science, driven by Moore's Law, which has, for decades, accurately predicted a doubling in processing speed for computers every eighteen months. Thus, the technical parameters for computer science are constantly changing, and curricula must change accordingly. Generally, however, undergraduate curricula can be somewhat flexible – it is possible to change up to 30% of an undergraduate course without significant administrative impediments. If a change is greater than this, the process take approximately three years.

Overall, the evidence shows that Wits has been strategically and operationally responsive to the changing needs of the astronomy sector on the basis of its capabilities to engage with other actors in the sector, assess their needs and modify their programmes and curricula accordingly.

Rhodes, at the institutional level, has a policy to guide curriculum review and a teaching and learning committee. Teaching excellence is rewarded through the VC's distinguished teaching award. However the emphasis at Rhodes is more on academic autonomy and the prerogative to determine teaching and learning styles and content.

In terms of astronomy, Rhodes has not implemented the type of substantive changes that have occurred at other universities – since radio astronomy was already a niche area of expertise prior to the advent of the MeerKAT and SKA. Although there has been growth and change in the domain of astronomy at the research level – for example, the awarding of a SARCHI chair – teaching and learning have expanded in scale, but the undergraduate curriculum remains the 'standard' astronomy course that is widely drawn upon globally. This raises the question of whether the university has taken sufficient advantage of its initial lead in the domain of radio astronomy to position itself strategically as a leading teaching and learning centre in the field.

At **UWC**, on the basis of institution-wide research across all faculties conducted in 2008 surveying both student and staff needs relating to teaching and learning, the Directorate of Teaching and Learning developed a Strategic Plan for Teaching and Learning, a charter of Graduate Attributes, and an Implementation Plan on Teaching and Learning. Each faculty has developed its own implementation plan in alignment with the university plan. In this context, the following strategies were highlighted:

- Enhance and promote the status of teaching and learning;
- Develop and promote the scholarship of teaching and learning;
- Professionalise teaching through formal and informal education for academics;
- Infuse technology into teaching and learning and promote the use of e-pedagogy;
- Develop an infrastructure for teaching and learning;
- Embed graduate attributes into an aligned curriculum and plan, revision, establish and align;
- Develop a responsive teaching and learning environment, including improved virtual; and
- Enhance epistemological access through responsive teaching and learning programmes.

Teaching and learning at UWC have evidently been highly responsive to changes in the astronomy sector, and have been managed strategically on the basis of sufficiently strong interactive capabilities. An undergraduate programme, based in the Department of Physics, has been developed that allows students to enrol for formal courses in astronomy in their second and third years and to participate in an additional research training programme. Enrolment in the second-year course reached 60 in 2010. Again, following the pattern of universities focusing on either the science or the engineering aspect of the SKA, at UWC there is involvement in astronomy but no involvement in engineering – the university does not have an engineering faculty or department.

In terms of teaching, the physics department has responded to increased demand for radio astronomy skills. A second-year and a third-year semester course have been initiated and at the time of research an honours-level course was under consideration. As with other universities, these new courses have been organised through intra-departmental meetings of the relevant academics.

At **DUT** there are few formal policies and structures for teaching and learning. However, the Centre for Excellence in Learning and Teaching (CELT) provides guidance on issues of teaching, assessment, e-learning, student access and support, and multimedia. Teaching excellence is rewarded through the VC's Teaching Excellence awards. Again, the interactive capabilities that impact on teaching and learning for astronomy are more devolved, in this case to the level of a single individual who is driving the growth of radio astronomy related teaching and research.

In sum, the assessment of interactive capabilities for teaching and learning makes it clear that competences at the institutional level are generally strong, but have, at most, an indirect significance for astronomy. Instead, structures and interactive capabilities at lower levels of the institution – the faculty, the department, or the individual academic – are the main platforms for interaction and for responsiveness. These platforms have achieved results. All the universities in the sample have responded to the changing needs of astronomy through expanding their teaching and learning offerings and modifying their curricula accordingly, with the possible exception of Rhodes University, where radio astronomy was already a niche area of expertise.

Research, innovation, and technology transfer: Policy, strategy and structures

Interactive capabilities and dynamic interactive capabilities relevant to research, innovation and technology transfer form the core of the engagement between universities and the astronomy sector. This is both a priori evident – since astronomy is a scientific activity – and supported by empirical evidence. Interactive capabilities that support the cultivation of research collaboration and innovation networks are critical to the engagement between universities and astronomy actors, and form one of the main channels of interaction and communication. Again, institutional competences are only indirectly relevant – rather, capabilities at the faculty, department and individual level are responsible for mediating between universities and the sector. There is also a clear distinction between the types of interactive capabilities that are relevant for science (astronomy) and for engineering. The universities that engage with astronomy primarily through science display a typical pattern of interaction and interactive capabilities, focused on the cultivation of formal and informal collaborative research networks. In contrast, research and innovation in the domain of engineering takes place though a highly structured set of formal competences and on the basis of a range of advanced interactive capabilities. This, again, underlines the inherent differences between the interactive capabilities required for science and those required for engineering.

The interactive capabilities relevant to research and innovation are strong across all the sample institutions, perhaps reflecting the highly interactive nature of astronomy as a discipline. For example, UCT hosts strong interactive capabilities for cultivating and maintaining research collaboration. The UCT astronomy department is guided by a policy that encourages linkages with other actors in the astronomy SSI. This has resulted in the evolution of a highly connected department with strong capabilities for interaction.

> From a department point of view, it's been our policy to actively link out to the national facilities, the other stakeholders in this and that is exemplified by the fact that we have a number of joint positions at this university. We've got two joint positions with the Southern African Astronomical Observatory, the SAAO. They have, they are close to us geographically, but that also enhances interaction. We've got joint students in position at postgraduate level, with people at the Observatory, or any other facility. So people supervising students at the national facilities, because the national facilities don't offer a degree, have to go through university and UCT has been and is the natural link for people at the observatory, supervising students. So, an academic from UCT co-supervises their student and the student graduates through UCT, or through UWC. We have an SKA-funded lecturer in our department and we've got an SKA visiting professor in our department. So there are cross-linkages. (Academic interview: UCT)

Wits also appears to have strong interactive capabilities related to research and innovation. At the time of research the School of Applied Mathematics had submitted a proposal to the NRF to establish a Centre of Excellence focusing on big data, which would have significant application for the SKA. This is part of a broader responsiveness of the computer science department to the requirements of employers and research partners. The engagement of the School of Applied Mathematics with external partners draws on interactive capabilities that extend to a variety of economic sectors and fields of study. In this sense, astronomy and the SKA represent only one area of application for mathematical tools that form the core knowledge domain of the school. The school maintains extensive interaction with industry, and particularly with the financial sector, which requires skills and research in the area of advanced financial mathematics. Examples of interactive structures and mechanisms here include weekly seminars with invited speakers from industry and an alumni network. In addition, firms contact the faculty or its departments directly with requests related to recruitment.

At Wits, as with the other universities that focus on astronomy rather than engineering, the engagement with the SKA is primarily related to research collaboration and mediated by informal relationships, particularly through the SARCHI chairs, who are key contact points between the university and the SKA. Wits has strategically developed its research orientation to respond to the emerging needs of the SKA. For example, Wits' role in research oriented towards the analysis of big data is seen as a core competency by one key informant, who expressed the central role of this research area for the SKA, particularly in terms of developing these research capabilities in South Africa to prevent the research from being conducted abroad instead.

> It's no use having things collecting all this information and you don't know what to do with it, and at the end of the day that's all that SKA is, it's just one big piece of equipment that's collecting a whole lot of information. Astronomers have all the models, yes, they have thousands of models. I am co-supervising one such model. Models need verification, they need new models, you're

going to see a blip, what does the blip mean, they're going to see thousands of blips, some are going to be noise, some are going to be significant, some will win you a Nobel prize, some will make you look like an idiot. Somebody's going to have to be able to distinguish those things, and it's no use sending all that data overseas, it's just pointless, it's like I also have started, not collaborating, but we've started putting things together with the people in public health. Public health has tons of data related to Aids and HIV which they send overseas for people to analyse, because we can't do it in South Africa. So the only way you know there's a shortage in HIV drugs is if you analyse the data and see what's happening, not if you go to a hospital, you don't see it. So we have that as a major problem in South Africa, where we cannot analyse our own data. It's like the problems they had with census data, we cannot analyse, I mean those problems should not have been problems, it's just ... it's that skill that's missing, going from an almost masters to PhD level, we had people at the one level, but it's that next level, that next step that's just not there, and that's the challenge posed by SKA. You will have all this data, but so what? (Academic interview: Wits)

The School of Applied Mathematics is thus sensitive to changes in technology and how these impact on what is required on the demand side of the knowledge economy. These changes are strategically worked into the school's teaching and research:

> The kind of research that's being done in astronomy has changed materially because of the data that's available from satellites, and we have these telescopes, so even if you look at the kind of research Prof. Block is doing now, it's all based on data he gets from various satellites and telescopes around the world, and all of that is immediately accessible, whereas in the past you had to physically go to a telescope and measure things. So a lot of what we do, what is being done now, is based on being able to get data from collaborators across the world. So my research that's based, for example, on modelling of stellar phenomena, say, is verified by experiments that people report on almost immediately, from data obtained from Hubble and various other telescopes. So data is so accessible, that's the biggest significant change in the past five years from a research perspective, and we've had to filter that down to our students, whereas it's not you who's sitting in a lab doing an experiment, it's you downloading data and analysing data to verify your mathematical model, and that's what's changed. It's how we train our students to model things, to analyse things, to compare things, to discuss things, to compare results. That's been the biggest significant change for us. So even our mathematical modelling courses have changed, because there's just so much biological data available, there's so much astronomical data, there's just so much financial data, because we have advanced maths of financing our department as well. So all of it is related to data. So a student doing finance can easily go and work in the SKA because the tools are the same. If you know how to analyse financial data you can analyse data from SKA. It's a big amount of data that's just been thrown at you, how are you going to analyse it? So we've tried to get our students to look at it as – you have all this information, what can you extract from it? What model do you have of these phenomena? Does your data support that? How are you going to think about this? So we've tried to, over the past five years, adjust our courses as we've gone along, that's why you'll see we've introduced new courses, made fundamental changes to our curriculum across our faculty, introduced now new courses in astronomy, because there actually is a need for that now, and I think going forward we'll probably see more and more heavily computer-based postgraduate courses. We're also going to introduce, in 2015, masters course work for the first time, because we're finding more and more people

> want to come and do postgraduate studies with us, but they just don't have the background. They actually just cannot cope with the level of computing that we expect, so we're going to introduce masters course work in computer science, in applied maths, statistics does have some course work, we're not sure yet how they're going to do it, and, yes, we'll take it from there. (Academic interview: Wits)

With respect to adapting to the presence of the SKA, key informant interviews described an organic adaptive process through which students and staff, over time, become increasingly influenced to take up research relevant to the SKA:

> We had a student who did the control theory for the mirrors, you know the mirrors were not aligned properly, so one of our students did a control theory for that to get the mirrors to work together properly, so that's how we got involved almost immediately, because we worked out the algorithms to do the control, because it's all control theory, so, yes, if it wasn't there we wouldn't it, we wouldn't have had that project, so our students wouldn't have had some of their masters projects in terms of data analysis in physics, to go over to physics, so, yes, that's had a big impact on us already in terms of the project our students are exposed to. Not so much on staff yet, because many of us, as staff members, have fixed research projects that have got a long way to go still, but people are going to seminars and things, and learning, so, yes, I imagine over the next five to ten years we will see a steady shift, especially with the young researchers coming in. I think we'll see a lot more interest. (Academic interview: Wits)

UKZN, **Rhodes** and **UWC** reflect similar patterns in their research and innovation engagements, which have generally been highly responsive to the needs of the astronomy sector and the emerging needs of the SKA. These strong interactive capabilities are reflected in their results – for example, at UKZN the ACRU has attracted research projects and student funding from the SKA and Rhodes has attracted a SARCHI chair that conducts research that is of a high value to the SKA, namely algorithm development for working with big data.

UWC has attracted two SARCHI chairs and a rapidly expanded astronomy research profile for its physics department.

DUT, which generally shows lower levels of interactive capabilities compared to research universities, has in this case also successfully engaged with the astronomy sector in the domain of research and innovation. DUT's involvement in the SKA's innovation network has facilitated the development of strong relationships with multiple actors, including several international partnerships, that have led to improved technical capacities and facilities and an increasing role in astronomy research and innovation:

> We have a very good relationship [with the SKA]. Of course we've broadened out a lot since then. We now have four radio telescopes and we're about to acquire another pair of dishes from Telkom. We got a lot since those early days, and we have contracts now with HartRAO and the SKA. We also are collaborating with UKZN just down the road from us, and we have collaborated with the University of Western Kentucky in the US, supplying them with data from our first telescope. We also visited Caltech last year at their invitation, and are trying to set up a programme under the Lewis Centre for Educational Research, where they are very much involved with Goldstone Apple Valley radio telescope … There is one other strong international cooperation that we do and that's with the University of Mauritius. We are building an instrument together with them, and the idea is that we build an element here, they build an element there, and a long term goal is to try and do interferometry with students. (Academic interview: DUT)

The University of **Stellenbosch** provides the best example of strong interactive capabilities in the areas of research, innovation and technology transfer relevant to astronomy. The nature of participation in the SKA's innovation network is distinct in that it is focused on engineering rather than astronomy and primarily driven by a set of institutional mechanisms and structures that facilitate engagement. The Engineering faculty plays a central role in facilitating interaction with industry through a variety of formal and informal interface structures, including advisory boards, a five-year review process, academic time allocations for working with industry, contract R&D for industry, funding for equipment, close engagement with the engineering professional body, invited speakers from firms, strategic interaction with government and strong interactive capabilities among individual academics. Such mechanisms are reportedly not all unique to the university – rather, this reflects the status of the engineering profession's close relationships with universities in South Africa. Interactive capabilities at the faculty are strategic, and aim to be empirically informed. At the time of research the faculty was planning to implement a survey for employers and ex-graduates to gather data about the alignment between graduate attributes and the requirements of firms.

However, the success of this mechanism is premised on Stellenbosch's reputation for excellence in the field of engineering, which is a reflection of its strong competences and capabilities in this domain. Industry appears to have confidence in the university's capacity to deliver engineering innovation based on this strong performance. This has placed the university in a strong position to participate in the engineering aspects of the SKA, either through direct involvement with the SKA or, more commonly, through SKA-related firms.

The faculty has an advisory board of about 30 members, which is itself comprised of five advisory boards – one for each department in the faculty, each of which consists of between five and eight representatives from industry. They meet annually. These meetings are critical interfaces between industry and academia:

> We use that as one of the main sound boards to actually find out what the latest trends are, what the industry needs, do they see anything that we actually need to add to our graduates, and attributes in order to actually meet the needs of industry. That is very important to us. (Management interview: Stellenbosch)

Industry members on advisory boards are chosen to maximise the quality of their input on firm needs. They usually have fairly senior positions in industry, but are still involved with engineering work. They include some alumni and some non-alumni. They should be in a position in which they can judge the Stellenbosch graduates – that is, in a managerial position with a number of engineers supporting them. Another aim of the advisory boards is to build relationships with industry, so members should also be at a level of seniority where they can facilitate access to people in companies to showcase the faculty's research and possibly obtain funding, particularly contract funding.

There are, moreover, medium-term structures for shaping discussion on the faculty advisory board. Every year there is a 'focus topic' for discussion – chosen every second year by the faculty and on alternating years by one of the departments. For instance, in 2013 the topic was what firms see as things that need to change in the undergraduate curriculum – an excellent example of responsiveness at the faculty level. Questions that may be asked of firms are:

> What are the latest trends in a certain branch of engineering that they feel we don't actually give enough attention to, or are there certain attributes of our graduates that they think can actually improve? Are their communication skills okay? Must they be able to write better reports or whatever the case might be? (Academic interview: Stellenbosch)

The engineering faculty also undergoes a review process every five years. At least 50% of the review team must be from industry, and they impose outcomes that are aligned with the needs of industry.

Another important mechanism for interaction is that of contract research. The faculty has partnerships with a wide range of firms, ranging from parastatals such as Telkom and Eskom to the military and military contractors to SMMEs and start-ups, many of which are based in the Technopark. Engineering academics have a positive reputation within industry, and often hold key capabilities that are rare in the national and even the global context – to the extent that industry often initiates relationships. Contract research is largely conducted in the 'research centres' – there is one in each department, and one (the Centre for Sustainable and Renewable Energy Studies) which is allocated to the faculty and not a department. This is perhaps the most important mechanism for interaction with industry, at least from a financial point of view. To achieve this, these centres cultivate close relationships with industry:

> In order to get contracts we need to listen to industry and actually make sure that we deliver. The interaction with industry is important in two ways. The first one is the funding for research, but secondly also through that actually [to] find out what the industry needs are because you build relationships with people and through that you know what the needs of industry are … (Management interview: Stellenbosch)

Of the total budget of the faculty, only 40% comes from the university budget, and more than 50% comes from contract income. This is not unique to the Engineering faculty – it is aligned to the total budget of the university as a whole. To maintain such a high level of contract income, the university requires sustained, good relationships with firms based on an understanding of their needs and a reputation for performance:

> If you don't have a good relationship with industry and actually deliver on what their needs are, that won't be possible. (Academic interview: Stellenbosch)

The income derived from external contracts is used strategically to build internal capabilities. This establishes a virtuous cycle of growing capabilities and extended engagement with firms:

> The bulk of that money is to sponsor postgrad students for masters or PhD work, but a trend that we have started, which we encourage, is also to appoint researchers from that funding in order to build capacity, because some of the academics, they just have too many postgrad students to supervise themselves. If you can get a company to sponsor half a senior researcher's post as part of a contract, you try and do that, or actually get them to sponsor a postdoc or two in order to build more capacity. (Management interview: Stellenbosch)

Informal modes of interaction are also important. The faculty often invites guest speakers from industry to inform final-year students about the needs of industry – with a focus on the largest firms and largest employers. The faculty also engages through alumni functions twice a year, and invites a ten-year graduate group through which it builds relationships with firms. These functions serve as catalyst for networking:

> The faculty management, the deans and the vice deans and the heads of departments would interact with the people and quite often afterwards we get emails from people saying it was good to hear about that. Our company has this problem, is there someone that can help, and in that way you start new relations with some new companies. (Management interview: Stellenbosch)

Another mechanism for interaction exists to foster engagement between the engineering faculty and its corresponding faculty at UCT. They host combined management meetings annually – an unusually close relationship. On the agenda are common problems that engineering faculties face, funding issues and desired changes in the curriculum. This bilateral forum takes place in the context of a generally close relationship – in times when either faculty is short-staffed, lecturers from the other faculty have taught there, and both faculties have absorbed former staff and alumni from the other, leading to multiple linkages.

A critical role is played by the Engineering Council of South Africa (ECSA), the statutory professional body. The engineering council has a specification for the BEng degree with generic outcomes that are approved by the council – this directly shapes the curriculum at Stellenbosch and other universities. In this case, therefore, the balance of power in terms of determining curricula lies with the professional council. On one hand, this makes curricula strongly responsive to the needs of industry. On the other hand, this undermines the autonomy of universities.

One of the most powerful catalysts for interaction is the allocation of time for external engagement. Academics are allocated 400 hours per year to conduct work external to the faculty – largely as consultants in the private sector. This plays a major role in fostering engagement, building networks between academics and firms and aligning the research activities of academics and postgraduate students with the requirements of industry in a highly responsive manner. This has applied directly to interaction with the SKA, with members of the engineering faculty consulting to firms in the SKA's supply chain and innovation network, or forming their own start-ups:

> In the faculty what we try and encourage is that people use that and integrate that with their research. In other words if you are a specialist in a certain field and you need a number of postgrad students in that field, you will probably find that the companies that sponsor you would also want you to help them with certain projects and then you do it that way. Quite often I think this consulting work, a company actually phones and says, we have got this problem, I want someone to look into it and an academic would do a bit of consulting for that company and then we need to put a project student on it next year, a masters student. At the same time we start to build a relationship with that company. (Management interview: Stellenbosch)

One of the academic key informants described the process through which the allocation of this time for external engagement led to his establishment of an external consulting company that works directly with the SKA:

> In 2002, because of my work in [confidentiality constraint], I found that many companies in south Africa were coming to me both for educational training requests and also for specific jobs. What I found was that I couldn't handle it as an academic. It was too onerous, as people have to meet deadlines in industry. So what I did then was I carved out a day a week with the Engineering Faculty with university's support, as many of my colleagues have. I worked on it professionally, and then I got a couple of my postdoctoral students involved, and in fact now my company has got two former SKA postdoc students who now are associates in the company. (Academic interview: Stellenbosch)

There are many benefits to this mechanism, which has emerged as one of the most powerful mechanisms for supporting interactive capabilities. Firstly, academics benefit from additional income. Secondly, engagement with industry provides a source of ideas for research directions that are up to date and responsive to industry requirements. For these reasons, such engagement with industry is supported by ECSA:

> Well for an individual there are two main aims I think. It's an added income for lecturers, which is useful, and from the personal perspective you become aware of and involved in the problems that are faced by South African industry, which is important. You get a lot of research ideas from the problems that industry faces. Then from the perspective of the institution, which is the faculty, there's a lot of gain to be had by lecturers who actually are engineers as well … ECSA prefer lecturers to be professional engineers as well, not just lecturers. So engineering is slightly different from a lot of other academic sections of the university, and there's a very strong focus on interacting with

> industry. And it's not just a nice to have, we actually encourage it very strongly from the faculty side. (Academic interview: Stellenbosch)

Informants described this mechanism as the most important facilitating factor in their relationships with firms:

> Well the main facilitator is easy, that's the option that we have of working [with firms]… if you only can work on stuff like this in the evenings, it makes it difficult. If you have a formal message from your employer which says this is encouraged, it's a big facilitator. (Academic interview: Stellenbosch)

Capabilities for interaction with government are also strong. The faculty has several government partnerships, including on some of its largest projects and funding for research centres. This requires responsiveness to government requirements. It also creates a virtuous cycle in which funding from private industry acts as a catalyst for increased funding from the dti:

> There is quite a bit of input from certain government departments, and some of this research funding, a substantial proportion of that, does come from government departments, but not from the department of Higher Education and Training, from other government departments. The more funding you get from private industry, the more funding you can also get from the Department of Trade and Industry, so there is a substantial amount of government money. In order to get access to that money, you need to align yourself with the government policies. (Management interview: Stellenbosch)

Interactive capabilities at the level of individual academics are also important. One key informant is a specialist in the field of high-frequency engineering, leading a group of nine academics as well as 18 postgraduate students. He has cultivated extensive engagements with the SKA, particularly in the niche area of engineering high-frequency receivers. He operates in a loose collaboration with academic colleagues who are working on antennae design, dish design, RFI mitigation and the radio spectrum, amongst other fields. His specific role has been to supervise postgraduate students funded by the SKA, well as to subcontract work for firms involved in receiver design, including Tellumat, EMSS and ETSE. The origins of these relationships with firms lie in informal interactive mechanisms:

> We don't market, so essentially it's word of mouth probably, so people know other people who know other people. South Africa is fairly small, so in general we all know who the people at the universities are, and what they're doing. In terms of what I do, there's only about three people in the country who do that. So most of the engineering companies know me and what I do. Yes, so that's the way it starts, they have a specific requirement, and then they contact me and say, can I do this for them … At this stage most of the people working in high frequency in South Africa [were] taught by myself or one of my close colleagues. So I know most of them, and most of them know me. (Academic interview: Stellenbosch)

This highlights how critical informal processes are to the interactive capabilities of academics. The nature of the engagement varies according to the nature of the firm:

> In terms of the official relationship, it changes, depending on how big the company normally is. Small companies, we have a fairly informal relationship, mostly, typically it would be selling consultation hours, for instance, to a company. For bigger companies they normally like people to quote for delivery of a specific product. So it's like a business, they say we want this … [these are] the specs, please give us a quote. (Academic interview: Stellenbosch)

The various interactive capabilities support a key capability-building mechanism – the acquisition of expensive and specialised equipment. Partnerships with external actors have facilitated a high level of funding in this area, which provides the faculty with a competitive edge. The importance of this is high. As reported by a key informant, 'for us it's absolutely non-negotiable, we can't survive without it'.

> We're very well equipped. In high frequencies, in all the sectors in our department, we're very well equipped … There's a lot of different funding mechanisms which change over the years. Sometimes there's funding by the university itself, with special projects, then there's even funding by the NRF, or government, then in our department we have a lot of industry funding, most of our funding comes directly from industry. And it's quite a lot. It's about double the rest of our complete budget. Most of the equipment that we have was bought with industry money. (Academic interview: Stellenbosch)

The university's science park, the nearby Stellenbosch Technopark, acts as an attractor for start-ups and SMMEs that partner with the Engineering faculty – these are often destinations for PhD graduates. Several firms in the Technopark have links to the SKA, including one of the firms in this study's sample. EMMS Antennas was formed as a spin-off in the Stellenbosch Technopark by University of Stellenbosch alumni – illustrating the clustering effect that has formed in the Western Cape, with collaboration between SKA scientists, University of Stellenbosch scientists, and CapeTown-based firms to develop SKA technologies.

In sum, across the sample of universities, interactive capabilities and dynamic interactive capabilities relevant to research and innovation are strong. At the universities focusing on astronomy, this is largely manifested in collaborative research networks that entail close institutional relationships with other astronomy actors. Universities have been responsive to the knowledge needs of the astronomy sector and adjusted their research foci accordingly. The mechanisms at work are, however, quite different for engineering. At the University of Stellenbosch a highly organised and structured set of interface mechanisms successfully links the engineering faculty to other actors, thus providing an exemplar for successful engagement between actors on the supply side and the demand side of the sectoral system of innovation.

Professional support and development: Policy, strategy and structures

The research universities have a fairly comprehensive range of internal capability-building mechanisms. DUT has some internal capability-building mechanisms, but to a lesser extent and at a lower level of complexity. In all cases, with the exception of Wits, most of these mechanisms are managed by the internal Human Resources function and, in addition, some activities are outsourced to external service providers, for example CHEC, which runs specialised courses for higher education middle management. However, in all cases these policies, strategies and mechanisms have at most an indirect effect on engagement with the astronomy sector or the SKA specifically.

At **UCT**, the Human Resources Development function coordinates and facilitates internal capability-building mechanisms. This includes the provision of an on-campus annual learning and development programme. In addition, other 'centres of learning' at UCT contribute towards capability-building. These include the Centre for Higher Education Development (CHED), Information and Communication Technology Services (ICTS), the Research Office and Health and Safety. Human Resources Development publishes a 'Staff Learning and Development Resource Guide', which provides a detailed description of a wide range of capability-building mechanisms made available to staff, including dozens of individual courses. These are aimed at the full spectrum of employees, ranging from basic literacy to advanced leadership and strategic skills development.

At the **University of Stellenbosch**, internal capability-building mechanisms, managed by the Human Resources function, including training in the following areas:

- Leadership Development Programme for Academic Leaders;

- Mentor training and mentee orientation programme;
- Effective recruitment and selection practices;
- Managing team resilience;
- Building effective relationships;
- Performance management;
- Stress management; and
- Positive leadership, positive change (related to HIV, gender and disability).

Staff are also encouraged to attend the courses provided by the Cape Higher Education Consortium (CHEC) regional management development programme, which is aimed at middle management of higher education institutions.

At **UWC** internal capability-building mechanisms are also managed by the Human Resources function. These include training for administrative support staff and capacity-building initiatives for academic staff in the areas of teaching and learning, research and publication.

Wits has well-developed internal capability-building mechanisms, although these are organised in a manner distinct from the other universities. Rather than being centrally organised by the Human Resources function, capability-building mechanisms are dispersed throughout the organisation, with the majority of these being located within research support and innovation support functions – for example, the university research office provides a notification service for research funding opportunities. The DVD: Academic, through the Deans of Faculties, is responsible for the implementation of academic support within the faculties and the professionalisation of lecturers in terms of pedagogy. This includes capacity development activities such as short courses, seminars, workshops and peer mentoring, and the formal qualification of the postgraduate diploma in higher education teaching.

At **Rhodes**, aside from the diploma in higher education teaching, no formal internal capability-building mechanisms were reported. A proposed staff management and leadership development programme was under consideration at the time of research, but the implementation of this will be dependent on whether funding is made available by the relevant SETA.

At **UKZN** the University Teaching and Learning Office (UTLO) is also responsible for internal capability-building. Other formal structures include a research office and innovation centre, which provide support for academic departments for the commercialisation of their intellectual property. The university also has a performance management system that rewards teaching and learning.

At **DUT** each faculty has a skills budget drawn from the Skills Levy, which funds professional development activities for staff. The Centre for Excellence in Learning and Teaching (CELT) plays a central role in internal capability-building as well as teaching and learning. This includes the management of a range of programmes for academic staff, including elements of curriculum renewal, teaching and learning methodologies, and ICT integration into teaching and learning.

Transference into the workplace: Policy, strategy and structures

Key aspects of employability promotion for graduates include the definition of graduate attributes, career and placement services, and work-integrated learning. Again, however, these policies, strategies and structures are only of indirect relevance to astronomy and the SKA.

The existence and nature of a graduate attributes framework at the universities varies widely. UKZN has no formally stated graduate attributes framework. Rhodes has no predetermined 'list' of attributes required of graduates. There is, however, a clear sense of 'cultivating humanity' – producing graduates that use their agency to transform South Africa and contribute to democracy, education and citizenship. All the other universities have extensive and well-defined lists of graduate attributes included in their policies.

All the universities have career and placement services, but the capabilities vested in these services vary widely. Careers centres, in various forms, provide one or more of the following: graduate recruitment handbooks that outline employers and profiles of their skills requirements; counselling for students with walk-in queries; career assessments; workshops; interview preparation; mock interviews; CV-writing workshops; career success workshops; career fairs; and so on. The research universities have strong capabilities in this area. UCT has the largest careers service of any university in the country by an order of magnitude, employing 12 staff against a usual staffing of between one and three. This places the university in a strong position in terms of engaging with employers. However, the SKA organisation does not engage with these offices and they have not played a part in the Astronomy SSI or the SKA's innovation network.

Work-integrated learning, in South Africa, is primarily active in universities of technology and comprehensive universities, playing a minor or zero role in research universities. This is indeed the case in the sample, with no work-integrated learning being reported at the research universities. On the other hand, DUT has well-developed work-integrated learning policies and mechanisms in which all departments have a Liaison Committee composed primarily of stakeholders from industry. The committee facilitates work-integrated learning for each department.

Informal and tacit interactive capabilities and mechanisms

In the tight-knit astronomy community, informal and tacit interactive capabilities are critical to successful and responsive interaction between educational institutions and employers. These capabilities appear to be strong at all the sample institutions, perhaps pointing to a characteristic of the astronomy sector more broadly.

The astronomy department at **UCT** clearly hosts strong tacit interactive capabilities, having proven its capacity to mobilise resources and alliances both internally (within UCT) and externally. One example reported by an astronomer illustrates this:

> I've met with the Vice Chancellor and the Dean and there has been so much collaboration. There's very good interaction between the science faculty and the university in general … We had the opportunity, for example, the SKA person in Canada – someone I knew well because we worked postdoc together in Holland, in our young days – and I convinced him to come here, but there was no position, no chair available. And UCT, and UWC because it's a joint chair, just worked very hard with the other departments. Renee [the HoD of UCT's Astronomy department] she's fantastic – they worked very hard to try to find everything needed to put the chair together … if that guy was ready to come here it was very important to work with me at this stage, someone with that kind of background that could really help us to get the project … The university was very responsive. At the beginning there was no possibility, there was no chair available … but UCT pulled the necessary money; UWC, DST, the SKA put some money for postdoc. Everybody poured in together and we got together something that was interesting for him to come. (Academic interview: UCT)

At **Rhodes**, internal interaction between academics within the various fields relevant to astronomy, with a view towards coordination and a focus on the skills necessary for astronomy, is undertaken informally. Rhodes is a small university, and the academics find it easy to operate through loose and informal networks:

> There is cooperation but it seems to be more informal than formal. We are a very small university, the smallest in the country, so we know all the physicists, they know all of us, and it is kind of known to be [on an] informal ad hoc basis. Justin Jonas, who is one of the main movers and shakers in the SKA, I tend to bump into him at Pick n Pay in town more often than on campus, and he stops in the aisle and has a chat to find out what is happening. So there is no formal structure in place. (Interview: Wells)

Informal interactive capabilities are similarly important at the other research universities. For example, at **Wits**, SARCHI chairs engage with colleagues within the SKA and bring that information back into the university where it is discussed internally and, where possible, reacted to:

> We collaborate with other scientists, but we don't really have formal agreements, as such, but we tend to work with people who we meet at a conference, or … someone's interested in your research, you work with that person.
>
> We discuss curriculum changes fairly often. For example, if there's something urgent John just phones me, he says, look, Carlo Francesco came back from this SKA meeting, we found this is where we see the SKA going, can we have a chat with you, you're the expert in this field, and then we went for the meeting, and then he said, okay, we've identified this as something, let's accept this one. (Academic interview: Wits)

At **DUT**, participation in the Astronomy SSI and the SKA has largely been driven by a single individual, who has acted as a champion of the RATT programme. This individual academic has engaged over several years with the SKA, making a case for the DUT's role in the technical training required by the SKA. This engagement would not have been successful without strong informal interactive capabilities being held by this individual.

Even in the domain of engineering, informal capabilities and mechanisms are critical. At **Stellenbosch**, informal mechanisms and networks play a central role in terms of accessing this funding, although when partnering with large firms, more formalised mechanisms play a larger role:

> It's not managed at all, strangely enough it consists of numerous individual links. Each lecturer, or two or three together, have a little group which works on something, they have a connection with a few industry partners, and that's the level of the management. Of course there are contracts and stuff which are managed by university, but the interaction is not managed on a higher level. It also varies a bit, if you go to chemical engineering, they have a few very big players in South Africa, like Sasol and Anglo and so on, so there the funding is often slightly more managed on a higher level, because it's a lot of money and there's quite a number of people involved. (Academic interview: Stellenbosch)

Overall, the evidence shows that informal mechanisms and tacit interactive capabilities must complement their formalised and codified counterparts in order for universities to be fully responsive to the requirements of the astronomy sector.

Discussion

Astronomy is a high-skills and high-technology niche area in a country with a small skills pool, characterised by different types of interaction compared to other sectors. An important driver of interaction is the availability of domain competences and capabilities. When making decisions about interaction with universities, astronomy actors – including the SKA – are primarily attracted to key competences in the domains of astronomy, engineering, mathematics and ICTs. In this sense, astronomy is similar to other sectors. However, in terms of interactive capabilities the sector is somewhat different.

Astronomy and the SKA operate within a dense network of organisations within which individuals have cultivated valuable relationships that underpin the coordination of the system, through the establishment of formal interactions and partnerships and through the establishment and maintenance of informal interactions that allow individuals and organisations to 'short-cut' interactive processes. This increases the efficiency and efficacy of interaction. The coordination of skills supply and demand thus takes place in parallel through several systems (see Table 15). The first is a set of formalised forums external to the universities, including the SKA's Universities Working Group, the SKA's Human Capital Development Programme, the DST's Astronomy Desk and the NASSP, each of which provide opportunities for astronomy employers, including the SKA, to interact with universities. These formalised forums have been highly effective in aligning skills supply and skills demand and, in the broader knowledge economy, research supply and research demand.

Another set of interactive mechanisms is based within the university. At the institutional level there is very little place for interactive mechanisms. Generally, of course, the overall efficacy of functions – such as institutional planning, teaching and learning, internal capability-building, student support and external engagement mechanisms – all impact on the overall quality and quantity of graduates emerging from a university and on the university's research capabilities and reputation. Hence these aspects are indirect and background drivers of excellence, capability-building, and interactive capabilities.

However, with regards to astronomy and the SKA, the specific mechanisms that have facilitated interaction, particularly in relation to capability-building, have not been directly related to these broader institutional functions. Instead, they are largely based within faculty or department structures. At this level, interactive capabilities in the domains of teaching and learning, and research and innovation, emerge as the primary points of articulation with the astronomy sector. In both of these areas, universities have adapted the scale and scope of the teaching, learning and research to the changing needs of the astronomy sector in general and the SKA in particular.

However, there is a clear distinction between the profile of interactive capabilities for science and for engineering. Interaction in the domain of engineering occurs through a more formalised, complex and structured set of mechanisms, including advisory boards, a five-year review process, academic time allocations for working with industry, contract R&D for industry, funding for equipment, close engagement with the engineering professional body, invited speakers from firms and strategic strategic interaction with government.

Table 15: Overview of interactive capabilities at universities relevant to the Astronomy SSI

Interactive capabilities	Astronomy science	Astronomy engineering
Interactive mechanisms outside the university	SKA Human Capital Development Programme DST Astronomy Desk SKA Universities Working Group NASSP	SKA Human Capital Development Programme DST Astronomy Desk SKA Universities Working Group
Institutional level	Weak/indirect relevance: institutional planning, professional support and development, transference into the workplace	Weak/indirect relevance: institutional planning, professional support and development, transference into the workplace
Faculty level		Highly responsive teaching and learning Highly responsive research and innovation Research and innovation networks Collaborative research projects with external actors Academic networks Advisory boards Five-year review process, academic time allocations for working with industry Contract R&D for industry Funding of equipment Close engagement with the engineering professional body Invited speakers from firms Strategic interaction with government
Departmental level	Highly responsive teaching and learning Highly responsive research Research networks Collaborative research projects with external actors	
Individual academics	Important role for personal relationships and networks, tacit interactive capabilities	Important role for personal relationships and networks, tacit interactive capabilities
Informal/tacit	Relationships and resource mobilisation underpinned by strong tacit interactive capabilities and informal mechanisms	Relationships and resource mobilisation underpinned by strong tacit interactive capabilities and informal mechanisms

In parallel to the formal interactions, a rich and complex system of informal interactions coordinates and governs the matching of the supply of and demand for skills in the sector. This is as a consequence of the knowledge and technology structure of the Astronomy SSI. As a highly specialised niche area, skills in astronomy are rare and cannot successfully be treated as skills 'commodities', where large numbers of graduates with standardised qualifications enter a labour market consisting of a multitude of potential employers. On the contrary, in the case of astronomy, a handful of astronomers and highly specialised engineers enter a labour market consisting of only a few employers – universities, astronomy facilities and engineering firms. Moreover, each employer requires such narrow skills bands that employers are largely aware of who the specific individuals within the system are that hold, or are developing, these skills. Likewise, postgraduate students or employed astronomers and engineers largely have an awareness of who the small group of actors are who require their specific skills.

Informal mechanisms for interaction, such as personal relationships and 'behind-the-scenes' discussions, play a greater role than formalised institutional mechanisms. The main capabilities that have had a tangible effect on interaction between the SKA and universities are the existence of personal and professional relationships between SKA management and scientists and university-based scientists, and the role of SARCHI chairs in establishing critical mass in knowledge and technology domains required by the SKA. Importantly, relationships evolve over time – thus historical trajectories have a tangible effect on the structure of interaction. Relationships built on the basis of previous collaborations endure, and continue to structure new projects and partnerships. This is not to say that the past will devour the future – in the South African context the shifting structure of the SSI is also influences by the dynamic role of the transformation imperative, which motivates for the establishment of new relationships, partnerships and resource allocations.

8. A CASE STUDY OF THE SKA'S FET COLLEGE PARTNER

FET colleges, vocational training and astronomy

In principle, there appears to be a strong rationale for increasing the role of FET colleges in the Astronomy SSI. The Department of Science and Technology's Deputy Director General, Thomas Auf der Heyde, has emphasised the importance of mid-level and artisan skills for the SKA:

> It is obvious to me that the key bottleneck in the more effective use of the infrastructure is not that we don't have enough scientists, we don't have enough artisans, engineers and technicians to enable [us] to adapt the instruments from time to time. Now, with 2 500 radio telescopes to be build from 2016 until 2034, we have got a need for vocational artisan training in the country that is unprecedented. We have a strong rationale to ensure that the human capital development takes place. (Quoted in http://www.southafrica.info/news/business/ska-090712.htm)

However, in practice, only one FET college plays any role in astronomy – the Kimberley FET college. This is due to is relative proximity to the SKA core site in the Karoo. As a consequence of this proximity, the college was chosen by the SKA as a partner institution for vocational skills development. The relationship between the SKA and the Kimberley FET college was initiated in 2011 and two cohorts of SKA-funded students have passed though the college. The SKA Human Capital Development Programme has provided bursaries for technicians to train at the college, focusing on electricians, plumbers, bricklayers, mechanics, welders and carpenters.

The relationship between the SKA and the college has, at times, been problematic. Students achieved low throughput rates and there were reportedly disciplinary problems. The college sees this as a result of poor student selection by the SKA. The SKA sees this as a result of limited capabilities within the college.

In terms of competences, capabilities and dynamic interactive capabilities, the college is perhaps at an average level for an FET college. Several competences are in place, but many of these have not developed into fully operational capabilities. However, providing a comprehensive assessment is difficult. The main challenge in the analysis of the college's interactive capabilities has been an embargo on all college strategy documents, policy documents, annual reports, or any other documentation, enforced by the principal. This inexplicable position (in contravention of DHET policy) has resulted in a research approach that relies mostly on key informant interviews, which, in terms of detailed and formal policy and strategy positions, necessary remain incomplete and at times contradictory.

Nonetheless, since there is only one FET college involved in the Astronomy SSI, the analysis of this college is in-depth, seeking to understand the systemic issues that impact on the role of the college in the Astronomy SSI and the SKA innovation network, focusing on competences and interactive capabilities.

The Kimberley FET College

Kimberly FET college is one of two FET colleges located in the Northern Cape province, the other being in Upington. This illustrates both the relative shortage of colleges in the province, and the relative importance of this college in its context. The college has two campuses, one in Kimberley central (City Campus) and one in an adjacent township of Galeshwe (Moromogolo Campus). The college employs 209 staff, of which 100 are lecturing staff and 106 are support staff. The principal and two deputy principals are classified by the college as management staff – although several of the lecturer and support staff occupy managerial positions too. The college is oriented towards local employers – primarily the diamond mining sector, government departments and parastatals.

Tacit competences

Teaching competences

In terms of lecturer competences, the college is challenged by under-qualified staff. Many of the lecturers do not have pedagogical training – instead, they are recruited from the trades in which they now teach. Thus the technical domain knowledge might be in place, but the pedagogical skills may be lacking. However, there does appear to be ongoing training of lecturers with the aim of keeping up to date with regards to new technologies through a partnership with the EDTP Seta. At the time of research, 16 lecturers and two management staff were undergoing this training. However, staff attrition and vacancies undermine the capabilities of the lecturing function. The primary driver of this is the availability of higher remuneration elsewhere.

Leadership skills

Leadership skills are variable. Some of the respondents provided narratives of leadership – seeking to improve the skills outcomes of the college, actively engaging with external actors and trying to improve college policies and structures. Others did not provide such narratives – placing responsibility for interaction, student performance and change management with external actors.

One weakness in this area was that of the principal, who maintained a defensive attitude towards the LMIP as a research project and endeavoured to minimise the information that the college made available to researchers. He also indicated that he did not favour participation in research or value the outcomes thereof, as his own knowledge and understanding of the FET college system was greater than that of academic researchers. This reluctance to engage with knowledge production and external actors may be described as a weakness in terms of tacit interactive competences and may constrain interactive capabilities at the leadership level of the organisation.

Organisational planning

In terms of organisational planning, there appear to be moderate competences held at the college. There was a degree of consensus among respondents about which internal and external organisational mechanisms existed at the college, indicating at least an awareness of the outlines of the planning process. There were, however, some gaps, in which respondents showed limited cognisance of how organisational planning in the college operated and the details of the process. Overall, however, assessment of tacit organisational competences is limited in that they cannot be placed within the context of detailed policy and strategy information.

Codified competences

Formal policies and mechanisms

One issue of concern with regards to the Kimberley FET college is the embargo that is enforced on the college's formal documentation, including policy and strategy documents and annual reports. During interviews, management indicated that they were not allowed to provide strategy or policy documents to researchers or anyone else on instructions from the principal, and were uncomfortable even discussing the reasons for this. This was the case even though it was made clear that the research was being conducted for the DHET and towards the public good. The principal maintained a defensive attitude in this regard. When the request for policy and strategy documents was made in writing, the following response was obtained:

From: Dr. CF Barnes [mailto:cbarnes@ncufetcollege.edu.za]
Sent: Friday, November 08, 2013 7:50 AM
To: Michael Gastrow
Subject: RE: Request for documentation

Dear Michael,

It is college policy not to make our policies available to the public except in cases where it is required by legislation.

Kind regards
Dr. CFBarnes

From: Michael Gastrow [mailto:mgastrow@hsrc.ac.za]
Sent: 06 November 2013 03:19 PM
To: cbarnes@ncufetcollege.edu.za
Cc: aysha@ncufetcollege.edu.za; mbaden@ncufetcollege.edu.za
Subject: Request for documentation

Dear Dr. Barnes

On behalf of the Department of Higher Education and Training and the Human Sciences Research Council I would like to thank you for participating in research for the Labour Market Intelligence Partnership.

In follow up, I would like to request access to the relevant documentation - institutional policies and strategies, annual reports, and any other report outputs documenting your structures and activities. This will form an important part of the evidence base for our research.

I hope that such documentation is indeed available so that we can meet the expectations of DHET.

I look forward to future co-operation and will be in touch regarding the progress of this research project.

Kind regards,
Michael Gastrow

Without access to the these documents, it is not possible to conduct an informed analysis of the college's policies, strategies, structures, mechanisms and strategic orientation. The evidence base is restricted to management interview transcripts, which are, in places contradictory and, as a whole, less reliable and comprehensive than formal documentation. Interviews suggested that there may, in fact, be a gap in the area of policies relevant to interactive capabilities:

> Participant: We don't really have very many policies in place with regard to the work-integrated learning or job placement as such or making linkages with firms.
>
> Interviewer: In terms of these interactions, workplace learning and so on, are there policies in the college that exist to govern these kind of interactions to ensure that graduates match the skills needs of companies? Are there policies here or is it more of practices of what you do?
>
> Participant: It was, actually, driven by the higher education department that we should, actually, have this industry-based experience. But we don't have any policies that guide that. (Management interview: Kimblerley FET college)

Within this constraint, and on the basis of interviews with management staff, the following mechanisms were reportedly in place:

- MoUs with firms;
- MoUs with provincial government; and
- MoUs with SETAs.

Organisational structures

The following organisational structures were reportedly in place:

- Student support services unit;
- Teaching and learning unit;
- Placement unit;
- Careers advisory office;
- Alumni engagement;
- Support for bursaries/financial aid;
- Local firms serving on college council;
- Involvement in SACPO committees;
- Industry members' active role in council;
- Internship programme;
- Learnership programmes;
- Career exhibitions;
- Firm bursary or scholarship programmes with a work requirement;

- Internship programmes based in firms;
- Student placement activities (e.g. employment agency); and
- A student CV database for employers.

Internal interface structures

The following internal interface structures were reported:

- A performance management system that rewards teaching and learning;
- Awards for distinguished teaching;
- Specialised funds for promoting interaction with firms;
- Graduate tracer surveys or exit polls;
- A quality assurance committee;
- Staff employed from industry to update teaching; and
- Staff training to keep up with new technology.

The following internal interface structures were not reported:

- Promotion criteria that reward interaction or engagement with firms.

External interface structures

The following external interface structures were reported:

- Local firms serving on college council;
- Involvement in SACPO committees;
- Industry members playing an active role on the council;
- Internship programme;
- Learnership programmes;
- Career exhibitions;
- Firm bursary or scholarship programmes with a work requirement;
- Internship programmes based in firms;
- A student CV database for employers; and
- Student placement activities (e.g. employment agency).

The following external interface structures were not reported:

- Industry liaison events;
- Apprenticeship programme;
- Open days for firms; and
- An Industry Advisory Committee.

Diversified funding base

The college has a staff member devoted to external fundraising – i.e. income that is not from the DHET. This includes searching for donations and bursaries for students, and cultivating relationships with firms. This position lies outside the regular management structure of the college, and reports directly to the principal. Unfortunately we have been unable to determine any further details about this position as members of the management team were unable to provide details. However, bursaries are not a strong mechanism for interaction. Firm bursaries do not usually lead to interaction beyond that of employing the student.

Interactive capabilities: Internal interface structures

With respect to internal interface structures, the evidence base is limited, with interviews indicating that certain structures were in place, but not offering much detail.

- *Performance management system that rewards teaching and learning:* This was indicated as being in place, but no details were made available.
- *Awards for distinguished teaching:* There is an award for distinguished teaching, but it is 'only in a letter', and does not offer any financial reward or promotion opportunities.
- *Specialised funds for promoting interaction with firms:* It was suggested that the corporate services office might have a small budget for such activity, but no details were made available.
- *Graduate tracer surveys and exit polls:* The Quality Manager undertakes some surveys of this nature.
- *Quality assurance committee:* This is in place, but no details were made available.
- *Staff employed from industry to update teaching:* This is a well-entrenched feature of the college, where most of the lecturing staff are drawn from the trades that they are teaching, rather than having a pedagogical background.

This keeps the lecturing staff up to date on industry trends and requirements.

- *Staff training to keep up with new technology*: The DHET reportedly arranges for staff to undergo subject-specific training.

Interactive capabilities: External interface structures

Career services and job placement

The career services and job placement functions are limited in capacity, being staffed by one person referred to as a job placement officer. This officer engages with firms to place students into learnerships and internships for the work-integrated learning and work exposure components of coursework. She places graduates in their experiential learning training, which occurs 18 months into their studies. This function also includes workshops for exiting students to assist them with skills such as CV writing and interview skills. However, staff retention creates a challenge within this function, as job placement officers frequently leave the college, which erodes institutional memory and efficacy.

Graduate placement in the public sector occurs within the framework of MoUs with the Department of Public Works and the premier's office. This relationship is contextualised by institutional pressure from the Department of Higher Education and Training to place graduates.

Career services seem to play a key part in the interaction between the college and firms. Firms contact the job placement officer, who then connects them with the appropriate students. The officer can also take a proactive approach by scanning vacancies for which college students might be suitable.

> Look, we do get feedback from companies. Okay, they will contact the college if they need specific people, you know, in their expected volumes. Some of those who contacted us would be referred to our job placement, especially the small companies. You know they would call the collage and ask if we do have some electricians or boilermakers, or any training, then we will refer them to our placement or we send some couple of CVs to them. Big companies are, our job official liaison with them, and then she goes out and asks them to place some of our students. We also know the websites of all these companies. Or she goes to the companies' websites. And if there are adverts in the paper of apprentices, she will probably know and [liaise] with them. (Management interview: Kimberley FET college)

However, the notion of job placement and career services is not deeply entrenched in the institution:

> If you think where we come from we were not part and parcel of providing jobs to our students. We deliver the teaching and learning part but with the new change in the country this extra add-on came and it's new to colleges. So it's a mind shift and it's changing slowly to take on that responsibility of not only teaching and learning to take place but also the placement of the student in the industry. (Management interview: Kimberley FET college)

> The cost to train an artisan varies between R300 000 and R500 000 to get them qualified. So as far as I'm concerned one cannot have people dropping out of the process if that's not what they want to do. So for me the selection process and career guidance is vital. Now that scope unfortunately does not fall entirely on the FET sector cause there is no funding for it. It falls under the SETAs and for them to actually do adequate career guidance under those guidelines. (Management interview: Kimberley FET college)

Workplace learning

Workplace learning appears to take several forms. Firstly, work-integrated learning refers to students who are undertaking a three-year programme, who are placed for five days every year in the work environment relevant to their field. Experiential training takes place after the theoretical component of the programme is completed, and is required in order for the diploma to be issued. This experiential training can lead to 're-employment', in which the student is retained in the firm in which he or she was placed. The exact mechanism for workplace learning was difficult to establish in management interviews, as it appears to be an informal process:

> It was, actually, driven by the higher education department that we should, actually, have this industry-based experience. But we don't have any policies that guide that. (Management interview: Kimberley FET college)

It was clear that in some instances students received experiential learning or 'work exposure', but under which framework conditions is not clear. It seem that in some cases the relationship with the employer is informal, and in others it is formalised. For example, the college has established MoUs with the Department of Public Works and the premier's office of the Northern Cape to receive students for workplace learning. The latter is an overarching MoU, in which the premier's office in turn places students in a range of departments in the province. This mechanism could be described as one of the more advanced interactive capabilities in the college, and it has reportedly placed over 100 students and is engaging with a student database of over 350 students.

Modes of interaction with employers

Local firms serve on the college council, providing one of the few formalised mechanisms through which to engage with firms. At the time of research, these included PricewaterhouseCoopers and a range of government departments. Interaction with these firms does not influence the curriculum (as this is fixed by the DHET), but it does provide a channel for communication with some potential employers.

Interaction with firms and other employers is focused on local industries – such as mining, utilities and manufacturing – and government departments. Examples of specific sectors mentioned in interviews include construction (e.g. Murray and Roberts), electrical engineering, automotive repair (e.g. Mercedes-Benz), mining (including De Beers and Kumba), Eskom, the defence force, and the Department of Public Works. The scale of intake varies considerably, with over 100 students from a particular year going to provincial government departments, about 20 going to a Kumba and three going to Murray and Roberts. In some cases it appears that MoUs are signed with firms to govern interaction with students and lecturers. These MoUs reportedly govern longer-term interaction that includes elements of experiential learning. However, in the absence of policy documents, the specifics of this mechanism are difficult to identify. One particular instance was discussed in an interview, detailing the process of the establishment of an MoU with Mercedes-Benz. In this case, the lecturer had existing informal contacts in the firm. He approached the firm with the intention of establishing experiential learning there. The contents of the MoU and the details of the interaction would then be formalised and signed off by the CEO of the college. In some cases, more substantial agreements are reached, for example a relationship with Eskom that entailed funding for new equipment for an electrical workshop.

Interviews indicated that lecturers largely do not have interaction with firms – this is seen as a management function. In particular, firm interaction is not seen to be part of the lecturer's job description. Interaction with firms is thus ad hoc and variable, depending on the individual lecturer, the structure of the course and the demand of firms.

Interactions with firms are perhaps mediated by a 'business unit' that was reported by one respondent. However in the absence of documentation we are unable to verify the existence or functionality of this unit.

> Participant: We have developed a special unit we call it the business unit which falls partially on the, Mr Michaels and that unit is working specifically on that responsiveness to businesses to the industry and they develop some programmes but as I explained to you it's a very lengthy process.
>
> Interviewer: What are the kinds of activities at that unit? The kinds of things.

> Participant: They deliver learnerships, they deliver skills programmes, as I said they were involved with the SKA project, they [are] involved now with the solar energy project.
>
> Interviewer: And how many people are working with that unit?
>
> Participant: From the top of my head about five. (Management interview: Kimberley FET college)

One challenge with the interaction with firms is a mismatch of expectations. Firms are often reportedly disappointed with the students they receive from the college. On the other hand, college management perceives firms' expectations as unrealistic:

> I don't think that they have a real understanding that when they form a partnership with the college they getting a raw student … they think they are going to get this perfect individual who has completed her two-year whatever course or three-year course and they should know everything and when the student gets there they don't realise that there's extensive training still to be done with that learner and so complaints come back that you know, we don't train a proper student, our qualifications are not really valuable, or it doesn't match the working environment as such, so that to me is the difficulty with partnerships, with companies that they might not have an understanding as to the type of partnership that they might have with us and with the student. I think their expectations might be too high. (Management interview: Kimberley FET college)

At the same time, perceptions of the college appear to be low:

> I think there's still a stigma attached to an FET college student that might not be the best candidate for the position. (Management interview: Kimberley FET college)

Environmental change and dynamic interactive capabilities

Environmental turbulence

The college is confronted by several distinct sources of change. Changes in technology require new skills and knowledge from lecturers. Changes in demand for certain skills domains lead to changes in the distribution of required teaching skills and knowledge. Changes in curricula, which are largely set by the DHET, lead to changes in the skills and knowledge required for teaching. Increased government oversight and administrative obligations have provided a challenge for some staff too. High levels of staff turnover also result in turbulence, which requires management. The college has several mechanisms in place to cope with such change, which are functional to different degrees and are mostly small and informal efforts.

Environmental scanning

Management interviews highlighted that academic staff undertake informal scanning of the external environment, demonstrating a limited sensitivity to changes – for example, picking up that the automotive industry is looking for more skills in diesel engines as opposed to petrol engines. However, there is no formalised function to undertake such environmental scanning.

Feedback from firms

Lecturers occasionally approach firms to obtain feedback about the performance of the students placed there – but only in an informal capacity. Some of the lecturing staff devise their own feedback mechanism – for example, one respondent reported that for all workplace exposures he receives written feedback from both the firm and the students. However, this was his own initiative and not in response to college policy.

There does not seem to be a formal policy or structure to this effect:

> We don't have the formal method of tracking those students to see how long they remain there, what is the feedback from the employer and so on so we need to put

> maybe a more formal process in place to monitor those students. (Management interview: Kimberley FET college)

Responding to change: Teacher capabilities

Teacher capabilities can be stretched in response to change. Sudden changes in demand for teaching staff can result in recruiting lecturers on short contracts, which undermines overall capabilities. This is contextualised by uncompetitive salaries at the college.

> Participant: You see for example our full-time staff is employed full time and they deliver the formal courses. Now when you've got a project coming up and you need to deliver the courses you need to find additional people. Now you can't get the best people off the street at any time and then you have them for a contract and that makes it very difficult to attract for example artisans to deliver that programmes for us because it's maybe a three-month period and then it's over, so to get the quality staff to deliver that.
>
> Interviewer: Okay, so it's a challenge to get the right people?
>
> Participant: Yes it is.
>
> Interviewer: Okay, that's kind of ...
>
> Participant: And especially for, yeah, especially for the monies that they do get paid at the mines in this area in Northern Cape. (Management interview: Kimberley FET college)

Responding to change: Curricula

On the whole, the curriculum of the college is determined by the DHET, and only minor supplementation to this is permitted. The responsiveness of the curriculum towards changes in the external environment is thus limited, as curriculum changes need to be achieved through DHET approval and SETA accreditation channels, which have very long turnaround times. Speeding up the accreditation process would thus appear to be beneficial in terms of increased responsiveness, as would allowing some leeway for the college to modify curricula within limited parameters.

The flexibility of the curriculum, in terms of the lecturers' ability to adapt it rapidly to firm requirements, is low – core curricula remain fixed, but there is scope for staff to 'enrich' these curricula in a responsive way.

However, where there are external changes to curriculum – i.e. those occurring in a top-down manner driven by the DHET – they are described as sudden and rapid. These changes to the curriculum can be challenging, particularly in the context of limited teaching competences and capabilities. Lecturers are not adequately trained and, therefore, sometimes struggle to adapt to such changes:

> The curriculum has changed so rapidly and I think that our lecturers were not really equipped to handle those changes. You must remember that historically our lecturers, the majority of them don't have a teacher's qualification, as such. A lot of them come from the workplace environment, a lot of them are people who have a trade, we've taken out of the trade industry and who have come into the teaching environment, so with the new curriculum has come lot of teaching practices which I don't think they were well equipped to do. (Management interview: Kimberley FET college)

However, it appears that some measures are being taken by the DHET to mitigate these problems. The DHET has intervened to arrange subject-specific training for lecturers. However, there has, to date, not been any pedagogic training for lecturers – this is being discussed with the University of the Free State, and the DHET is apparently working on a new FET teaching qualification, but neither of these had been actualised at the time of research.

Responding to change: Government oversight

Increasing levels of government oversight and scrutiny have also created challenges, as staff focus on administration at the cost of teaching. This refers particularly to the Department of Higher Education and Training and Umalusi, the relevant qualifications framework authority.

> The paperwork has just spiralled out of control. I don't think they've been handling it very well, and I think as a result of all that the student throughput and certification rates have really suffered because a lot of what is happening at the moment is that the lecturers are concentrating more on administrative duties, for example getting portfolios together, because we always getting visits from Umalusi or DHET to come and check if the portfolios are being done. (Management interview: Kimberley FET college)

Suggestions for improvement

Management interviews indicated that there are policy and strategy gaps with regards to addressing the main challenges facing the college. Suggestions included the development of specifications for student referrals for absenteeism and academic support, and increased 'soft skills' development. The latter is particularly in response to feedback from firms that students lack the soft skills required at their jobs, even if they have some of the technical skills.

> Three main strategies – lecturer qualification, student absenteeism and academic support for the learner – I think in those three areas we really need to up our game. And obviously those have to be fed into our policies. I think what has been missing, is that we don't have a definite policy with regard to academic support. How do we refer a student that is for example not doing so well in the class to our student support you know, there's no fixed policy to say but at what, you know, when do you send the child? After how many days absent do you refer a child? When do you call the parents etcetera, etcetera, so those are the things I'm currently working on and I think that's how we need to improve it …
>
> Similarly for, if we find that he is not doing well in class he needs mathematics support etcetera you know at what stage do you refer the child? So we don't have any policies in place with regard to that, and I think that's important.
>
> With regard to employability I've just recently figured out … that when we placed a student in the work environment the employers always come back to us and say that they [are] not really suitable yet or they [are] not really mature enough for the job environment, so I think for us also we need to look at courses like developing the students' soft skills to make them more employable. I know they've complained about things that might impact the job environment to a big extent but we might see as not very major things like telephone etiquette, speaking to customers, spelling, the little things like that that, I think we need to train our learners. I think that's a student support function but again I mean it can be a policy, we can formulate a policy with regard to all our exit-level students going through a soft skill course, for example. (Management interview: Kimberley FET college)

Kimberley FET college and the SKA

Overview

The relationship between the SKA and the college was reportedly initiated by the SKA. An SKA scientist contacted the college in 2011 to request information about the scope of the college's training activities. The broad agreement that was reached was that the SKA would fund students' tuition and hostel fees. The college sourced additional funding for their 'theoretical component' from the IDC, although there is no further detail about this arrangement. The first cohort of SKA students was in 2011, and the second in 2012. There was no intake in 2013 or 2014, reportedly because of low performance: a low pass rate accompanied by widespread disciplinary problems. The college thus appears to have fallen out of the Astronomy sectoral system of innovation fairly rapidly.

Information about the first cohort of SKA students in 2011 is conflicting, with one informant reporting a cohort size of 11, another reporting nine and another reporting 20. However, they agreed that the main subject areas were electrical, carpentry, welding and plumbing. The pass rate for this group was low. Of the original (reported) 20, three dropped out in the first year, 11 dropped out in the second year and six graduated.

The second cohort, in 2012, reportedly consisted of 15 students, covering a similar range of skills domains. Due to conflicting reports, a conclusive assessment of the throughput rate cannot be made, but all respondents indicated that the rate was low.

Responsiveness and interactive capabilities

The responsiveness of the college towards the requirements of the SKA has been mixed. On one hand, there appears to have been willingness to engage with the SKA organisation around what their skills requirements would be. Discussions about the skills requirements of the SKA focused on the operational demands of the SKA and the vocational skills that would be required in those areas.

The SKA had reportedly also undertaken research about its vocational skills requirements, and passed these on to the CEO of the college. In response to SKA requirements, the college principal requested that management look into the establishment of an accredited course for radio astronomy technicians. At the time of research, management was still investigating this – looking for where this could be accredited and how it could be outsourced, as the knowledge did not reside in the college.

The main contact point at the SKA has been the manager in charge of human resources development. However, there appears to be a communication gap between the SKA and the college, with no reported interaction about the quality or appropriateness of the skills that emerged.

Challenges and obstacles

The main challenges to the relationship between the SKA and the college were seen by college staff was as being a consequence of an inadequate selection process. In practice, the SKA organisation itself undertook the process of student selection, focusing on the town of Carnarvon and other areas close to the SKA core site. These students were then given options, listing first, second and third choices from among the various skill sets required by the SKA. By using this information about student preferences, the SKA organisation assigned students to specific subjects and career paths.

> The ones that were more committed are more mature students and selected the right careers. You know I think they were given various options, you can do this this and this … and if maybe one was full they were told okay this as an option … you can either do B or C. Whereas maybe their preference was A. So I think that was part of it … (Management interview: Kimberley FET college)

However, several of the college staff felt that this selection process was flawed. Firstly, the selection process resulted in a lack of maths and science skills in the incoming students. This undermined their ability to engage with their coursework and achieve higher throughput rates. A lack of sufficient career guidance for the group was also seen as a weakness.

> The first group that came, and it was a big failure, a big failure … The reason, in my view, is that most of that students are long out of school. They don't have maths, they don't have science. (Management interview: Kimberley FET college)

> I think that is where the shortfall was in maybe not doing adequate career guidance and selection at the start. (Management interview: Kimberley FET college)

Another significant challenge resulting, reportedly, from the selection process was one of social setting and discipline. The SKA students resided at a hostel and were paid a monthly stipend. This context lead to disciplinary problems such as alcohol abuse and class absenteeism. This was particularly the case at the end of the month, when students received their stipends. College staff saw the cause of this as being the selection of more mature students, rather than students exiting school.

> You see the students that come, normally, if they come out of the school system, they are

> 17, 18. Most of them were three years, two years already out of school, sitting at home, doing nothing. Have lost interest in education, now this opportunity come[s]. I can get away from my place so I take it and come into Kimberley, study. So, I just accept the first opportunity coming to me. (Management interview: Kimberley FET college)

> It starts at the selection process. Who did they send. I think it started there. Because we were struggling with a lot of social issues, alcohol misuse, all of that, because it's older group. I don't want to obey by rules and so when they get their stipends, on the 25th, the 26th, the 27th they are not at class. They are drinking. (Management interview: Kimberley FET college)

Of course, these views by college staff need to be seen in context. Blaming poor student selection and unruly students for poor performance may not be a view shared by the SKA and skirts around the manifest weaknesses of the college. Taken a step further, the reluctance to introspect and assess internal causes for this poor performance suggests a lack of self-reflection and adjustment.

Discussion

Despite the clear need for vocational skills within the expanding astronomy sector, efforts by the SKA to engage with FET colleges have so far proved to only partially effective. The Kimberley FET college, as a result of its geographical location, has been the test-bed for this engagement, but it seems that limited competences and interactive capabilities, and opaque leadership, have constrained the efficacy of the interaction and the production of outputs.

Like many other colleges, the Kimberley FET college is challenged by underqualified staff, particularly in the area of pedagogy. Many of the basic competences required for interaction are in place at the college, but the capabilities drawing on the competences are in almost all cases limited, with internal interface structures having limited scale, application, funding and formality. The exception to this was the practice of employing staff from industry. This common practice plays an important role in keeping the knowledge base of the teaching staff current.

The primary external interface structures at the college are those of career services, workplace learning and various modes of interaction with employers, ranging from informal personal relationships to larger-scale multi-department MoUs. These structures appear to be moderately effective in facilitating interaction between the college and employers. Career services and workplace learning play a particularly important role in articulating the college and (predominantly local) firms. However, the formality, or lack thereof, of workplace learning structures was difficult to establish on the basis of interview data. Local firms also serve on the college council, thus influencing management decisions, but not the curriculum, which is largely determined by the DHET.

Dynamic interactive capabilities are stretched as the college responds to several sources of change, primarily emanating from changes in technology (requiring new teaching skills and knowledge), changes in curricula determined by the DHET and increasing government oversight requiring new administration procedures. To cope with these changes, teaching staff undertake some degree of environmental scanning and seek a limited degree of feedback from firms, both in an informal manner.

The college's engagement with the SKA has seen mixed success amidst a number of challenges. The interactive capabilities, in relation to the SKA, are moderate at best. The main contact point within the SKA has been the manager of the Human Capital Development Programme. College management reported that it engaged with the SKA to discuss what their skills requirements were, and were seeking to formalise these skills into an accredited course for radio astronomy technicians. However, evidence for a broader engagement, seeking to identify the causes of poor performance and low outputs and thus look for ways to improve, is lacking. Instead, management blamed poor performance on the actions of the SKA, citing poor student selection as the main cause. It thus seems that the capacity to engage with the SKA at a deeper level is constrained.

9. CONCLUSION

The SKA in South Africa is largely a success story. It tells of a sequence of events that would have been thought unlikely, if not impossible, a decade ago, but which have since propelled South Africa onto the global stage of science. The challenges have been great, but the constraints and threats to growth have largely been overcome through ample public funding, strategic risk-taking and highly coordinated, highly interactive, strategic skills planning. The lessons that can be drawn from this are related to overcoming challenges and achieving success in a sectoral system of innovation at the apex of the knowledge economy.

The starting point for South Africa's success in astronomy is its geographical advantage, which has been successfully leveraged by long-term policy support, including legislated protection through the Astronomy Geographic Advantage Act. However, it became clear to strategic movers, from the early stages of the SKA bid, that this geographic advantage would have to be complemented by hugely increased capabilities in terms of astronomy and engineering in order to tilt the odds of success sufficiently in South Africa's favour to justify the large investments that would have to be made. Thus, backed by high levels of public, political and financial support, highly coordinated skills development efforts were rolled out that required intensive interaction between actors on the skills demand and skills supply sides of the sectoral system of innovation. This has rapidly grown the competences available to employers, and greatly increased South Africa's capabilities and competitiveness in the international arena. The gamble paid off, and now that the SKA infrastructure will mostly be built in South Africa, this initial growth in capabilities represents only the first stage of a long period of growth in South African astronomy.

In conclusion, we return to the main research questions:

1. *What is the nature and strength of interaction and network alignment in the SSI?*

The Astronomy SSI benefits from strong network alignment amongst its key actors, and this is reflected in the network alignment specific to the SKA. There are several forums, both formal and informal, in which the main employers in the sector engage with the main skills development institutions in order to align curricula, research and funding. These include forums based within universities, such as the National Astrophysics and Space Sciences Programme, as well as those based within science facilities, such as the SKA's Human Capital Development Programme and Universities Working Group. Among public sector intermediaries, the DST, the NRF and the DHET have conducted evidence-based research and deployed interactive capabilities to develop strategic approaches to the planning and funding of skills development in the sector. This has included dedicated funding for South African research chairs and for the SKA's Human Capital Development Programme. More importantly, perhaps, strong informal linkages exist between individuals and organisations in the SSI, generating widespread awareness of skills demand and skills supply issues among all the major actors.

The SKA provides a locus for local and global innovation networks. From an innovation systems point of view the SKA is structured as a very large global innovation network that has a high level of network density at multiple scales, which together form a set of 'stacked and overlapping global innovation networks'. This global innovation network is characterised by a high level of alignment and strong interactive capabilities vested within the SKA as well as in its innovation partners.

The SKA in South Africa has adopted of an array of tactics to build and absorb capabilities into a rapidly growing organisation, including intensive and widespread interaction with external stakeholders in the process of skills planning and resource allocation through the Universities Working Group and the HCDP. Tacit competences for personal interaction with senior university management are also strong, and this has enabled rapid and responsive interaction at the strategic level. The SKA has developed strong capabilities for interacting with firms, including aspects of research management, business development and supply chain management. HartRAO also plays an important part in the SKA's innovation network. The interactive capabilities reported by HartRAO are advanced, enabling participation in multiple global research projects.

2. *What are the main components in the sectoral system of innovation (SSI) addressing skills needs?*

Skills needs in the sector are primarily addressed by South Africa's research universities. Within research universities, departments of physics, mathematics, computer science and engineering are the most relevant to the skills needs of the sector. Only UCT hosts a systemically significant Department of Astronomy, and this has been a key actor in the sector. Despite attempts to draw an FET college into the skills development system, there has been a very limited role played by this actor, with an apparently low return on investment due to limited competences and capabilities.

Each university has a distinct role in the SKA's innovation network, and each exercises a distinct set of interactive competences, capabilities and dynamic interactive capabilities. At the university of Stellenbosch an exceptionally high level of interactive capabilities within the engineering faculty has played a major role in articulating the university and the SKA. UCT and Rhodes both continue along historical trajectories of partnership with astronomy science facilities, UCT with the SAAO and Rhodes with HartRAO, which has positioned them as key actors in radio astronomy and hence the SKA. On the other hand, UWC has developed astronomy capabilities over the last decade without any prior role in the Astronomy SSI – primary driven by public funding mandated by its status as a leading previously disadvantaged institution. Wits provides a locus for astronomy-related activity in Gauteng, and has followed a strategic path towards growth in response to the expansion of the astronomy sector in South Africa. At DUT, the emergence of capabilities for technical training in astronomy has emerged largely out of the efforts of a single individual who had, over the five years prior to the time of writing, led engagement with other astronomy actors to position DUT as the SKA's primary technical training partner.

Astronomy is a highly globalised activity, and astronomy actors in South Africa also draw on international sources to meet their skills needs. In this area, the main constraint is that of gaining entry for international employees – the process is slow, expensive and unpredictable, which acts as a bottleneck on skills supply.

3. *What are the routine skills needs and non-routine changes in the business environment related to skills development, of firms in the sector? What are the strategies they use to address these needs?*

Firms in the astronomy sector, as well as science facilities (which also constitute a large source of demand for skills) have a range of skills needs. Amongst firms, routine skills needs include demand for a wide range of engineering specialists and technicians. Among science facilities, both astronomy skills and engineering skills are required. However, given the rapid rate of growth in the sector over the five years prior to the time of writing – and anticipating even more rapid growth over the next decade – the ability of firms and science facilities (including the SKA) to adapt to non-routine changes in the environment is critical. Many the skills required by firms in the SKA's value chain are non-routine, in that they find application in the unfolding SKA project and are thus unique at any point and are constantly changing.

Strong interactive capabilities within the SKA are matched with strong interactive capabilities within its partner firms. However, due to the wide variety of firms in its innovation network and value chain, the structure of these capabilities varies considerably. Partner firms reported that their niche capabilities were sufficiently rare in the South African context so as to establish a symbiotic relationship with the SKA based on mutual dependency. Against expectations, the case study firms did not report significant skills gaps – suggesting that despite skills gaps that are prevalent across the general economy, South Africa produces sufficient high-level niche engineering skills to meet their demand. This may be the result of the high level of inequality in the South African higher education system, with pockets of excellence occurring where resources and capabilities are concentrated and systemic weakness occurring where they are not.

For firms, as for the other actors, informal and tacit interactive capabilities are critical for matching skills demand and skills supply. Firms rely heavily on personal contacts, academic networks and word of mouth to identify and incorporate the skills and knowledge they need, particularly specialist knowledge-intensive technical skills. However, it seems that the larger a firm becomes, the less effective this strategy is, and larger firms rely more heavily on formal mechanisms such as recruitment agencies. As with universities, the formality of interactive capabilities is inversely related to knowledge intensity and the size of the relevant pool of skills.

4. *What are the roles of public and private sector intermediary organisations in building network alignment and addressing misalignment in relation to skills development in the sectoral system of innovation?*

Intermediaries in the Astronomy SSI are diverse and play a variety of roles, although public intermediaries play a far more significant role than private intermediaries. The DST is primarily a source of funding and a strategic partner, and the NRF plays a governing operational role. The DHET plays a less prominent, but nonetheless important, role, firstly in the broader sense of being responsible for the management of the public higher education system and in narrower sense through the SIPs, where it has undertaken extensive research to assess the skills requirements of the SKA.

The DST has played a central strategic role in building network alignment, establishing the Astronomy Desk with the purpose of providing strategic direction and coherent governance to the sector. This entailed research about the competences and capabilities vested in the various actors in the SSI, and the Desk provided a forum for representatives from these actors to engage over the key challenges and issues facing the sector. Similarly, astronomy functions within the NRF have been grouped together and are represented at a high level in the organisation. Since the NRF funds a substantial proportion of astronomy in South Africa, it provides a contact point for universities, science facilities and even firms to interact. Finally, The DHET has played a smaller role, but has reportedly facilitated some degree of interaction between the DST, the DHET and the SKA.

5. *What are the interactive capabilities of universities/universities of technology/FET colleges/private HET organisations/private FET colleges/SETAs to address the routine, and changes in, skills needs of firms in the sectoral system of innovation?*

Astronomy is at the apex of the science and engineering knowledge economy. The sector thus moves away from some of the structures and mechanisms that coordinate skills supply and demand at lower levels of the knowledge economy, which operate more like a traditional market for skills, whereas in astronomy the mechanisms operate more like a network than a market. As a consequence, the interaction in astronomy is less influenced by formal institutional mechanisms and more influenced by tacit and informal capabilities and networks.

There is, however, a clear distinction between astronomy *science* and astronomy *engineering*. Engineering departments and faculties utilise a suite of formalised interactive mechanisms that are not in evidence in astronomy science departments or units. These include advisory boards, academic time allocations for working with industry, contract R&D for industry, funding for equipment, close engagement with the engineering professional body, invited speakers from firms, and strategic interaction with government.

Within engineering, the more specialised and knowledge-intensive the skills and research in question, the more the interactive drivers and mechanisms depart from those that apply more generally, and they become increasingly informal and devolved. Thus, formality in interactive capabilities is inversely related to knowledge intensity, and inversely related to the size of the pool of skills in question. In a small world, word of mouth can be better heard.

Changes in the skills needs of firms occur along two vectors – technological change and organic growth in the astronomy sector. Sensitivity to the effects of technological change on firms' skills demand is largely achieved through the various interactive mechanisms, such as those employed by the University of Stellenbosch's Faculty of Engineering.

Responding to growth in the sector has been taken up as a strategic priority by all the universities in the sample. One common response has been the establishment of undergraduate majors in astronomy. Growth at the undergraduate level is seen as a major driver of future capabilities. Several universities, including Wits, UWC and UKZN, are in the process of establishing undergraduate majors in astronomy. Accelerating this process has emerged as one of the key policy imperatives for capability-building in astronomy.

In contrast to the universities, the SKA's relationship with FET colleges has not been successful. Despite the need for vocational skills within the expanding astronomy sector, efforts by the SKA to engage with FET colleges have so far proved to only partially effective – limited competences and interactive capabilities have constrained the efficacy of the interaction and the production of outputs.

6. *What is the nature of mis/alignment between dynamic skills supply and demand in the sectoral system of innovation to address skills needs and promote economic development? What are the challenges/constraints/threats to growth and skills development in the sectoral sector of innovation?*

The various challenges and constraints to growth have not played a major role in holding back the development of the sector. Of course, there have been substantial challenges. Only five years ago, the skills pool available for astronomy in South Africa was much smaller than it is currently, and Afro-pessimism prevented some actors from looking ahead to the upcoming growth prospects. However, strategic action and conscious efforts to facilitate interaction have largely overcome these challenges, even within the constrained South African skills landscape. Niche areas of skills have been strategically developed over time to meet the needs of the sector.

Some challenges remain. Procurement processes within the SKA are immensely complex and present a challenge. The FET system appears to have insufficient competences and capabilities to meet the SKA's requirements. The possibility of shale gas fracking presents a risk for the SKA project as a whole. Interference by the NRF in the SKA's HCDP has reportedly caused problems in its implementation. Undergraduate curricula in science and technology reportedly change slowly, making it difficult to adapt to rapid and radical change. However, none of these problems have been critical, and all of them are topics for mitigation for various actors in the sector.

Overall, the SKA provides a success story, showing how a South African organisation in the higher strata of the knowledge economy can meet demanding mandates and achieve excellence on the international stage. This has required 1) ample public funding; 2) a long series of high-stakes, calculated, strategic risks that turned out to have very large net returns; 3) strong support at the top political levels; 4) well-organised and strategically oriented interactive capabilities required to manage the complex skills, knowledge and technology to deliver on the SKA mandate; and 5) long-term, well-funded, well-informed, well-organised skills planning that has been responsive to the skills demands of the SKA.

ENDNOTES

1. This section was authored by Il-haam Petersen and Glenda Kruss to set the conceptual framework for the project as a whole.

REFERENCES

Bharuth-Ram K (2011) *A decadal strategy for human capacity development in astronomy and astrophysics in South Africa*. National Research Foundation

Chabalala AH (2012) African indigenous cosmology and development of astronomy. The re-emergence of astronomy in Africa: A transdisciplinary interface of knowledge systems. Maropeng Conference Centre, Cradle of Humankind, 10–11 September 2012

Chaminade C (2009) *On the concept of global innovation networks*. CIRCLE Electronic Working paper 2009/05

Dalziel, M (2010) Why do intermediaries exist? DRUID Conference 'Opening up innovation: Strategy, organization and technology'. Available at: http://www2.druid.dk/conferences/viewpaper.php?id=500976&cf=43

DHET (2013) *Statistics on Post-School Education and Training in South Africa: 2011*. Pretoria: DHET

Gottschalk K (2007) *The Political Uses of Astronomy*. African Skies. Proceedings of the African Astronomical History Symposium held in Cape Town, 8–9 November 2005

Holbrook JC (2007) *African Cultural Astronomy – Current Activities*. African Skies/Cieux Africains. No. 11. Working Group on Space Sciences in Africa

Iammarino S, Piva M, Vivarelli M & Von Tunzelmann N (2009) Technological capabilities and patterns of cooperation of UK firms: A regional investigation. IZA Discussion Paper, No. 4129

Intarakumnerd P & Chaoroenporn P (2013) The roles of intermediaries in sectoral innovation system in developing countries: Public organizations versus private organizations. *Asian Journal of Technology Innovation* 21(1): 108–119

Kruss G, Visser M, Aphane M & Haupt G (2012) *Academic Interaction with Social Partners: Investigating the Contribution of Universities to Economic and Social Development*. Cape Town: HSRC Press

Lall S (1992) Technological capabilities and industrialization. *World Development* 20(2): 165–186

Malerba F (2002) Sectoral systems of innovation and production. *Research Policy* 31(2): 247–264.

Malerba F (2005) Sectoral systems of innovation: A framework for linking innovation to the knowledge base, structure and dynamics of sectors. *Economics of Innovation and New Technology* 14(1–2): 63–82

McGrath S (2004) Reviewing the development of the South African further education and training college sector ten years after the end of apartheid. *Journal of Vocational Education and Training* 56(1): 137–160

National Treasury (2013) *Estimates of National Expenditure 2013*. Pretoria: National Treasury

Paterson A, Kruss G & Wildschut A (2005) *Support for Astronomy and the SKA Facility.* Report commissioned by the SKA Bid Committee

Snedegar K (1999) *Sub-Saharan Africa: Cultural Astronomy's Heart of Darkness*. Essays from *Archaeoastronomy and Ethnoastronomy News*, The Quarterly Bulletin of the Centre for Archaeoastronomy. *Archaeoastronomy & Ethnoastronomy News* Archive. Number 32. Center for Archaeoastronomy

Snedegar K (2007) *Problems and Prospects in the Cultural History of South African Astronomy*. African Skies. Proceedings of the African Astronomical History Symposium held in Cape Town, 8–9 November 2007

Vavus F & Bartlett L (2006) Comparative Knowing: Making a Case for the Vertican Case Study. *Current Issues in Comparative Education* 8(2):95–103

Von Tunzelmann N & Wang Q (2003) An evolutionary view of dynamic capabilities. *Economie Appliquée* 56(3): 33–64

Von Tunzelmann N & Wang Q (2007) Capabilities and production theory. *Structural Change and Economic Dynamics* 18(2): 192–211

Von Tunzelmann N (2010) Alignment, misalignment and dynamic network-based capabilities. In DA Dyker (ed) *Network Dynamics in Emerging Regions of Europe.* London: Imperial College Press, pp. 3–22

Wild S (2012) *Searching African Skies: The Square Kilometre Array and South Africa's quest to hear the songs of the stars*. Cape Town: Jacana

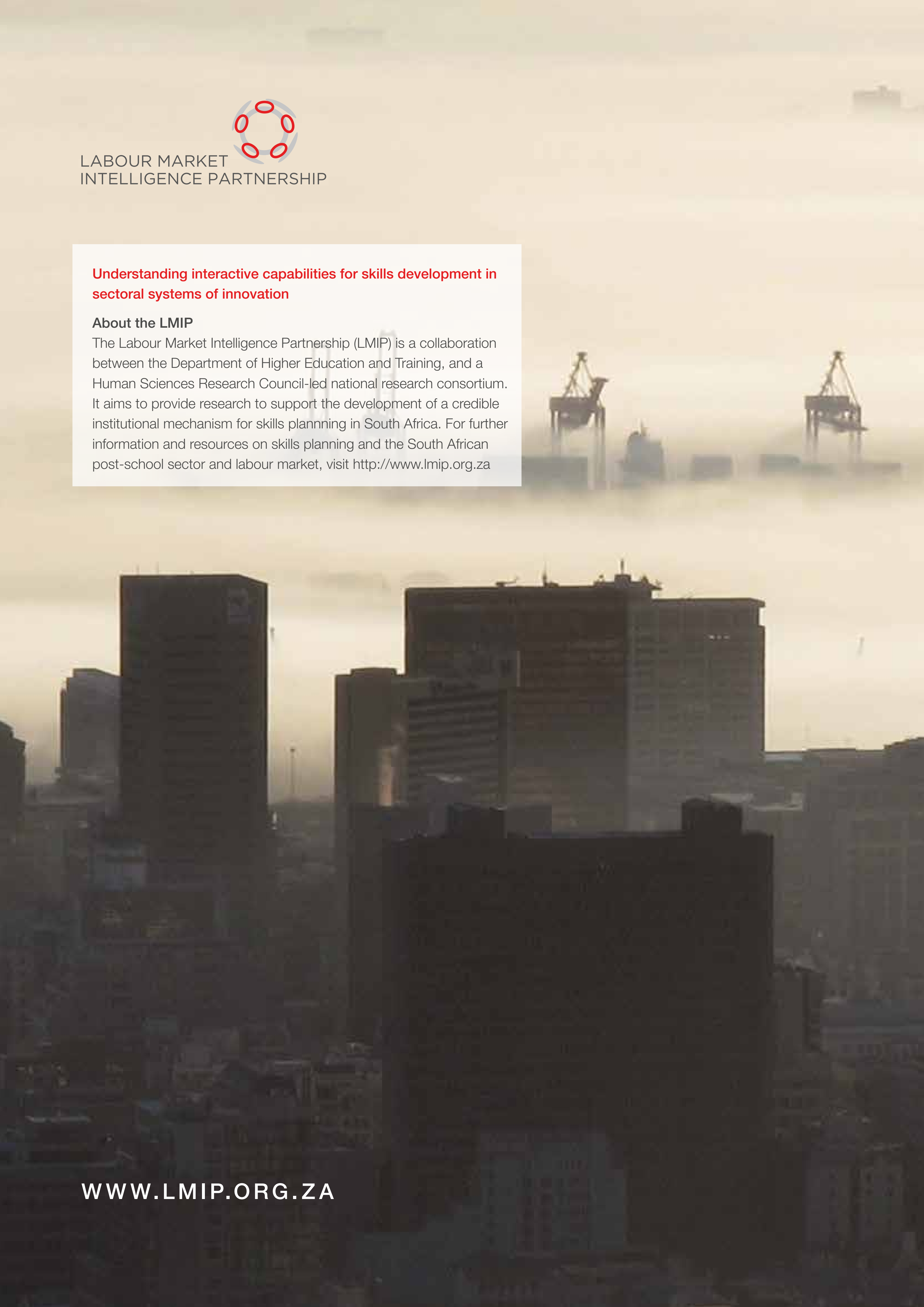
LMIP – Labour Market Intelligence Partnership

Cutting-edge LMIP research on skills planning, labour markets, the economy, the post-school sector, artisan training and more, may be found on the project website www.lmip.org.za, where a specialised research repository holds all emerging research, including research reports, working papers, presentations and policy briefs as well as 'grey' literature on a range of topics relevant to skills planning.

LMIP Reports:

- Report 1: Occupational Shifts and Shortages: Skills challenges facing the South African economy. By Haroon Bhorat, Sumayya Goga and Benjamin Stanwix (2014)
- Report 2: Towards Understanding the Distinctive Nature of Artisan Training: Implications for skills planning in South Africa. By Nhlanhla Mbatha, Angelique Wildschut, Bongiwe Mncwango, Xolani Ngazimbi and Thembinkosi Twalo (2014)
- Report 3: Growth, Employment and Skills: The New Growth Path revisited. By Haroon Bhorat and Nan Tian (2014)
- Report 4: Responding to Shifting Demand for Skills: How do we get firms and post-school education and training organisations to work together? By Glenda Kruss, Il-haam Petersen, Simon McGrath and Michael Gastrow (2014)
- Report 5: Higher Education, Employment and Economic Growth: Exploring the interactions. By Haroon Bhorat, Aalia Cassim and David Tseng (2014)
- Report 6: Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation: A case study of astronomy and the Square Kilometre Array telescope. By Michael Gastrow (2015)
- Report 7: Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation: A case study of the Tier 1 automotive component sector in the Eastern Cape. By Simon McGrath (2015)
- Report 8: Understanding Interactive Capabilities for Skills Development in Sectoral Systems of Innovation: A case study of the sugarcane growing and milling sector in KwaZulu-Natal. By Il-haam Petersen (2015)

LABOUR MARKET
INTELLIGENCE PARTNERSHIP



Understanding interactive capabilities for skills development in sectoral systems of innovation

About the LMIP

The Labour Market Intelligence Partnership (LMIP) is a collaboration between the Department of Higher Education and Training, and a Human Sciences Research Council-led national research consortium. It aims to provide research to support the development of a credible institutional mechanism for skills planning in South Africa. For further information and resources on skills planning and the South African post-school sector and labour market, visit http://www.lmip.org.za

WWW.LMIP.ORG.ZA