Section A: Overview of the Research Project Proposal

1. Academic level of research project (Masters or Doctoral) :
   Masters
2. Broad field of research (Engineering or Astronomy/Astrophysics)
   Engineering (but interdisciplinary)
3. Title of the research project
   Electromagnetic Simulations and Antenna Optimization for HIRAX
4. Research project abstract/summary (max 250 words)

The University of KwaZulu-Natal is leading the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) project, which will comprise a compact array of around 1000 small (~6m) dishes operating between 400 and 800 MHz. The primary scientific objective of HIRAX is to map baryon acoustic oscillations (BAOs) in the cosmological 21cm intensity distribution over a significant fraction of the sky between redshifts of 0.8 and 2.5, and thereby to place strong constraints on the Dark Energy. Several prototype dishes will be deployed in the next few months at HARTRAO near Johannesburg in order to test and finalise the dish design. Early next year an eight-dish prototype will be deployed at the RFI-quiet SKA SA Losberg site in the Karoo with a view toward converging on an end-to-end design for the 128-dish pathfinder, and subsequently for the full circa 1000 dish deployment. It is of great interest to optimize the telescope and feed design to maximize the science return from HIRAX and simultaneously minimize risk. At present some initial electromagnetic simulations of the current design have been carried out, but further investigation is required before converging on the final design. In particular, interactions between the dishes and with the ground need to be investigated, and better performance metrics must be devised. This work is necessary so that the optimizations carried out indeed serve to maximize the science return.

Section B: Supervisor(s) Details

1. Primary supervisor's details
   a. Title and full name

Professor Kavilan Moodley

   b. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member

University of KwaZulu-Natal, Westville Campus, Durban, South Africa

   c. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

kavilan.moodley@gmail.com, 072 447 5499

d. Supervision of postgraduate students – please provide the details of all the postgraduate students supervised. Please provide the information in table format, as shown below.

i. Doctoral Students

Name of Student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Kenda Knowles	South Africa	Jan 2013	Dec 2015	Observational Probes Of Merging Galaxy Clusters	Matt Hilton Mathilde Jauzac
Susan Wilson	South Africa	Jan 2013	Aug 2017	Evolution of Galaxy Cluster Scaling Relations Over Half a Hubble Time	Matt Hilton (main supervisor) Nadeem Oozeer
Darell Moodley	South Africa	Jan 2010	Dec 2014	Optimisation Of The Population Monte Carlo Algorithm: Application To Cosmology	
Simon Muya Kasanda	Democratic Republic of Congo	Jan 2007	Dec 2011	Initial Conditions of the Universe: Signatures in the Cosmic Microwave Background and Baryon Acoustic Oscillations	
Ryan Warne	South Africa	Jan 2006	Dec 2010	The Thermal Sunyaev-Zel'dovich Effect as a Probe of Cluster Physics and Cosmology	
Angel Torres-	Spain	Jan 2007	Dec 2008	SKA	

Rodriguez				simulations and cosmological constraints from large HI surveys	
Khadija El Bouchefry	Morocco	Jan 2004	Dec 2008	Multi-wavelength study of radio sources in the universe	Jon Rash (main supervisor)

ii. Masters Students

Name of Student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Sinenhlanhla Sikhosana	South Africa	Jan 2015	Dec 2016	Giant Radio Halos and Relics in ACTPol Clusters	
Heather Prince	South Africa	Jan 2014	Dec 2015	Gravitational Lensing Of The Cosmic Microwave Background: Techniques And Applications	
Jethro Ridl	South Africa	Jan 2010	Dec 2012	Weak Gravitational Lensing In The Cosmic Microwave Background: Reconstructin g The Lensing Convergence	
Devin Crichton	South Africa	Jan 2010	Dec 2011	Probing Missing Baryons Using High Resolution	

				Measurements Of The Cosmic Microwave Background	
Darell Moodley	South Africa	Jan 2007	Dec 2010	Bayesian Analysis Of Cosmological Models	
Mokhantso Phoolo	Lesotho	Jan 2006	Dec 2007	Optimal polarization measurements for constraining isocurvature modes	
Simon Muya Kasanda	Democratic Republic of Congo	Jan 2005	Dec 2007	Cosmic Microwave Background Anisotropies in Neutrino Isocurvature Models	
Ryan Warne	South Africa	Jan 2005	Dec 2005	Optical Observations Of Galaxy Clusters: Photometric Calibration Of Imaging Data From The Southern African Large Telescope	

2. Co-supervisor / Research Supervisor's details (if relevant)

This project has two co-supervisors: Prof. Martin Bucher (Fractional Research Professor, Mathematics, UKZN) and Prof. Dirk De Villiers (Electrical Engineering, University of Stellenbosch). In addition to his Fractional Time Research Professorship Appointment at UKZN,
Bucher is CNRS Directeur de recherche première classe (in South Africa equivalent to a Research Professorship at the Full Professor level). Bucher will be the de facto main supervisor and spend approximately 3 months per year at UKZN. He will also interact with the student recruited and co-supervisors by means of at least weekly telecons. Moodley will ensure that there is continuous local support and De Villiers in addition to participating very actively will provide invaluable guidance and expertise acquired from the MeerKAT design. The student recruited will spend some time at Stellenbosch working with De Villiers during this project.

Details regarding Professor Martin Bucher:

a. Professor Martin Bucher
b. University of KwaZulu-Natal, Westville Campus, Durban, South Africa & Université Paris 7/Centre National de Recherche Scientifique, Paris, France (France is now an SKA partner country.)
c. Email address and/or contact telephone number : m.aaron.bucher@gmail.com,

Supervision of postgraduate students – please provide the details of all the previous and current postgraduate students supervised. Please provide the information in table format, as shown below.

i. Doctoral Students

Name of Student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Mathieu Remazeilles	France	2005	2008	Topics in Braneworld Cosmology	None
Carla Carvalho	Portugal	2001	2005	Braneworld Perturbation Theory	None
Kavilan Moodley	South Africa	1998	2001	Isocurvature Modes and the CMB	Neil Turok
Yong Zhu	China	1991	1996	CMB Non-Gaussianity	Neil Turok

ii. Masters Students

Name of Student	Nationality	Date started Mastersl Degree (Month and Year)	Date completed / will complete Mastersl Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Heather Prince	South Africa	Jan 2014	Dec 2015	Gravitational Lensing Reconstructio n with Polarization	Kavilan Moodley (main supervisor)
Anne-Sylvie Deutsch	Belgium	2011	2012	B-mode Estimators for a Cut Sky	None
Thibaut Louis	France	2011	2012	Constrained Gaussian Realizations	None
Jem Pearson	United Kingdom	2000	2001	Braneworld Cosmology	None
Frederic Glanois	France	2000	2001	Simulations of Colliding Bubbles	None

Details regarding Professor De Villiers

3. Title and full name

Professor Dirk De Villiers

4. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member

University of Stellenbosch, Stellenbosch, South Africa

5. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

ddv@sun.ac.za

6. Supervision of postgraduate students – please provide the details of all the postgraduate students supervised. Please provide the information in table format, as shown below.

i. Doctoral Students

Name of Student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree	Title of Research Project / Thesis	Co-Supervisor (if relevant)

			(Month and Year)		
Ryno Beyers	South African	Jan 2013	Dec 2015	Circuit Model Design of Conical Transmission Line Power Combiners and Isolation of Reactive Combiners	N/A
Ngoy Mutonkole	DRC	Jan 2014	Dec 2016	Modelling of Antenna Responses	N/A
Brandt Klopper	South African	Jan 2016	Dec 2018	Antenna elements for sparse-regular aperture arrays	N/A
Fahmi Mokhupuki	Botswana	Jan 2017	Dec 2019	Surrogate-based Design and Optimisation of Wideband Feeds for the SKA	N/A

ii. Masters Students

Name of Student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Sunnelle Otto	South African	Jan 2009	Dec 2010	A study of radio astronomy principles and SKA pathfinder system designs with pulsar science	Prof. Petrie Meyer
Karla Schoeman	South African	Jan 2009	Dec 2010	Waveguide Antenna Feed for the Square Kilometre Array	Prof. Petrie Meyer
Phillip Terblanche	South African	Jan 2010	Dec 2011	Electronically Adjustable Bandpass Filter	Prof. Petrie Meyer
David VdM. Prinsloo	South African	Jan 2010	Dec 2011	Characterisation of L-band Differential Low Noise Amplifiers	Prof. Petrie Meyer
Shamim O. Nassar	Kenya	Jan 2010	Dec 2011	An Investigation of the Equivalence Between Combline and Evanescent Mode Waveguide Filters & of Aspects Related to Reduction of	Prof. Petrie Meyer

				Manufacturing Costs for Combline Filters	
Stephanie Alphonse	Madagascar	Jan 2010	Dec 2012	Fast Analysis of a Compound Large Reflector Antenna	Prof. Keith Palmer
Alex Ibbotson	South Africa	Jan 2011	Dec 2012	The Design and Analysis of a Rotman Lens with Reduced Conjugate Port Coupling	Prof. Keith Palmer
Dewald Schoeman	South Africa	Jan 2011	Mar 2013	Full Scale Low-Cost Ultra Wide Band Antenna for SKA Low Frequency Array	N/A
Ngoy Mutonkole	DRC	Jan 2012	Dec 2013	Study of a Wideband Sinuous Feed for Reflector Antenna Applications	N/A
Lukas M. van Vuuren	South Africa	Jan 2013	Dec 2014	Design of a Receiver System for Use in Radio Astronomy	N/A
Brandt Klopper	South Africa	Jan 2014	Dec 2015	Fast Design and Optimisation of One-Dimensional Microstrip Patch Antenna Arrays	N/A
Alex A. Vermeulen	South Africa	Jan 2014	Dec 2015	The design of a dual reflector feed using surrogate modeling techniques	N/A
Nicol Steenkamp	South Africa	Jan 2015	Dec 2017	Design of a Wideband Sinuous Antenna for Radio Telescope Applications	N/A
Malan A.X. Ruppert	South Africa	Jan 2016	Dec 2017	Study on Phased Array Feeds for Paraboloidal Reflector Antennas	Dr Ryno Byers

Ridalise Louw	South Africa	Jan 2016	Dec 2017	Surrogate Modelling of Performance Metrics of a Wideband Feed for the SKA Reflector Antenna	N/A
Cifford Sibanda	Zimbabwe	Jan 2016	Marc 2018	Design and Optimization of Gap Waveguide Components through Space Mapping	N/A
David Wolsky	South Africa	Jan 2015	Dec 2018 (part-time student)	A Space Mapping Code for Microwave Optimization	N/A
Jako du Toit	South Africa	Jan 2016	Dec 2018	Partially Filled Radial Power Combiner	Dr Ryno Byers
Channel Hannah	South Africa	Jan 2016	Dec 2018	Antenna Noise Temperature Measurements and Modelling	N/A
William J. Cerfonteyn	South Africa	Jan 2017	Dec 2018	A Multi-beam Reflector Antenna for Water Vapour Radiometry	N/A
Shane Moyce	South African	Jan 2017	Dec 2018	Practical Implementation Issues of Null-steering Anti-jamming GPS Arrays	N/A

Hein Swart	South African	Jan 2017	Dec 2019 (part-time student)	A Short-step Axially Symmetric Power Combiner	N/A
Michael Johnston	South Africa	Jan 2017	Dec 2018	Wideband Marchend Baluns for Radio Astronomy Antennas	Dr. Carlo van Niekerk
Scott Kriel	South Africa	Jan 2018	Dec 2019	Antenna Array Calibration using a UAV	N/A
Zain de Toit	South Africa	Jan 2018	Dec 2019	Manufacturing wideband sinuous antenna reflector feeds	Dr. Carlo van Niekerk
Jackline Koech	Kenya	Jan 2018	Dec 2019	Hyperband directional EMC antenna design	Dr Gideon Ward
Ben van der Merwe	South Africa	Jan 2018	Dec 2020 (part-time student)	H1 Galactic Drift Scan Using a 4.5m Reflector	N/A

Section C: Full Research Project Proposal

Maximum of three A4 pages, written for a professional who is not necessarily an expert in the relevant subfield

1. Scientific merit: describe the objectives of the research project, placing them in the context of the current key questions and understanding of the field.

Understanding the nature of the Dark Energy constitutes one of the most important science objectives of contemporary Observational Cosmology. This objective is now being pursued by means of diverse techniques using the Baryon Acoustic Oscillations (BAO) as a Standard Ruler. Optical surveys including redshift information, either through spectroscopic redshifts or through less accurate photometric redshifts, are one option. However, it is difficult to go beyond z=0.8 because spectral features needed for redshift determination become redshifted into IR bands that are difficult to access from the ground. Identifying galaxies in the radio through their 21 cm emission has already been demonstrated by means of cross-correlations, but to date a direct detection of the extragalactic 21cm signal has remained elusive because a number of technical challenges must first be overcome.

Compared to other science objectives for the next generations of radio telescopes, mapping the BAO introduces a unique set of new instrumental requirements for which traditional performance metrics, tailored to other science targets, are not necessarily applicable. A major challenge is removing the much more intense galactic foreground emission from the much weaker signal, and this requires simple primary beams with as little variation with frequency as possible. Almost all feasibility studies and forecast papers to date have assumed extremely simple beams that are very much unlike the actual simulated beams.

The HIRAX team is in the process of optimizing their dish/feed design, which has already undergone several iterations, and a prototype is about to be deployed at the Karoo site. Moreover, end-to-end simulations going from the time-ordered data to scientific results are being developed. The primary goals of this project are: (1) to develop new performance metrics relevant to optimizing the HIRAX instrument for BAO science, and (2) to optimize the antenna/feed design in order to optimize the instrument for BAO science (as well as other the other science objectives). This work is extremely important for optimizing the HIRAX science return and reducing risk.

2. Feasibility: outline the methods that will be used to achieve the objectives. Provide details on the availability of required data / access to required equipment / availability of research facilities and other resources required. Include any relevant expected intermediate milestones and associated timeframes towards attaining the overall objectives of the project.

Workplan:

Year One:

* Define optimization criteria relevant to the BAO science objectives. Current optimization metrics (e.g., aperture efficiency) are well suited to communications applications rather than radio astronomy science, and other metrics such as survey mapping speed do not fully reflect the complexity of BAO science, for which simple beams with low side-lobes are more important.

* Define feed/dish designs to be studied and optimized. The current on-axis feeds require optimization of the dish illumination as well as minimization of reflections between the feed and the dish.

* Carry out electromagnetic simulations using CST of beam patterns for ideal CAD designs (as opposed to "as built" beam patterns). Interactions with other dishes and with the ground are to be explored.

Year Two:

* Carry out more extensive end-to-end simulations in collaboration with other members of the HIRAX team in order to explore the impact on the final science outputs. A validation of the design will require end-to-end simulations, which are being developed using a cosmology simulations code from CHIME as a starting point, adapted for HIRAX.

* Carry out sensitivity analyses to determine tolerances and other requirements for dish/feed fabrication. The dishes as built will not necessarily correspond to the ideal CAD design and requirements must be defined based on simulation and comparison to actual beam measurements.

* Write up MSc thesis.

Data Availability/Access to Resources:

The student will have access to a high-end workstation dedicated to running CST and other simulation software, and to the full HIRAX data products as part of the HIRAX collaboration team.

3. Link the proposed project to at least one SARAO research priority areas (refer to Annexure 1 of the Application Guide), and explain in some detail how the proposed research will contribute to the priority area(s).

Area 3. Radio Astronomy antennas and receivers
Area 7. Epoch of Reionization and Intensity Mapping data reduction and analysis.
Area 8. Interferometric Data Processing and Analysis, including calibration and imaging.

4. If relevant, describe any particular qualifications, academic abilities, skills and/or experience that a student should have in order to successfully deliver on the objectives of the research proposed.

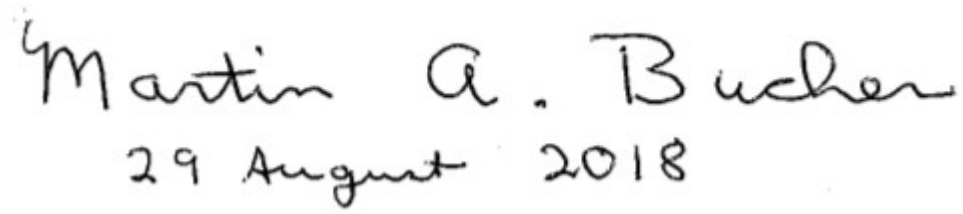
Knowledge of classical electromagnetism and methods of applied mathematics. Some familiarity with radio astronomy highly desirable.

Section D: Signatures

1. Signature of the primary supervisor, with date

29 August 2018
Kavilan Moodley

2. If relevant, signature of the co-supervisor/research supervisor, with date



Martin A Bucher

28 August 2018
Dirk de Villiers