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)
   Astronomy/Astrophysics
3. Title of the research project
   Instrument Characterisation and Analysis Pipeline for HIRAX Prototype Data
4. Research project abstract/summary (max 250 words)

Post-reionisation hydrogen intensity mapping projects provide an exciting avenue for probing the evolution of large-scale structures over a large fraction of the universe's history. In particular, by measuring the angular scale Baryon Acoustic Oscillation (BAO) feature in the distribution of matter over cosmic times the, geometric expansion of the universe can be studied, constraining the nature and evolution of dark energy - the unknown substance causing this expansion to accelerate. The Hydrogen Intensity and Real-time Analysis eXperiment is one such project, aiming to map the distribution of matter as traced by neutral hydrogen emission from redshifts 0.8-2.5. HIRAX will make use of an array of 1024 antennas in a compact grid, sensitive to frequencies in the range of 400-800 MHz. While HIRAX's design is optimised to measure the BAO signal, a significant challenge for this and other intensity mapping projects is the mitigation of foregrounds. While the characteristics of galactic synchrotron emission and the BAO signal are quite different on the sky, the large contrast in signal strengths combined with chromaticity of the instrument make disentangling these two signals a challenging data analysis problem, particularly when including systematic uncertainties inherent in the instrument hardware. In this project we propose for a student to work with the HIRAX team on characterising the instrument performance through the analysis of data from the HIRAX prototype array. As such they will assist in building a thorough understanding of these systematics which can then be applied to the full HIRAX array.

Section B: Supervisor(s) Details

1. Primary supervisor's details
   a. Title and full name: **Prof Kavilan Moodley**
   b. Name of South African or SKA Partner Country university at which the primary supervisor is a permanent academic staff member: **University of KwaZulu-Natal**
   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 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)
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	Sinenhlanhla Sikhosana
Heather Prince	South Africa	Jan 2014	Dec 2015	Gravitational Lensing Of The Cosmic Microwave Background: Techniques And Applications	Heather Prince
Jethro Ridl	South Africa	Jan 2010	Dec 2012	Weak Gravitational Lensing In The Cosmic Microwave Background: Reconstructing The Lensing Convergence	Jethro Ridl
Devin Crichton	South Africa	Jan 2010	Dec 2011	Probing Missing Baryons Using High Resolution	Devin Crichton

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

2. Co-supervisor / Research Supervisor's details (if relevant)
    a. Title and full name **Dr Devin Crichton**
    b. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member **University of KwaZulu-Natal**
    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) **crichtond@ukzn.ac.za , 066 173 5092**

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)
N/A	N/A	N/A	N/A	N/A	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)
N/A	N/A	N/A	N/A	N/A	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.

The nature of Dark Energy, the dominant component of the energy density of the universe that drives its accelerated expansion, remains one of the greatest mysteries of modern cosmology. The most natural theoretical explanation for its origin is discrepant with observations by over a 100 orders of magnitude. As such, the Dark Energy Task Force (DETF) motivated an empirical approach to understanding the evolution of Dark Energy's impact on the universe's expansion rate. HIRAX's goal is to observe the baryon acoustic oscillation (BAO) feature imprinted on the distribution of matter which forms a so-called, standard ruler. Through this, HIRAX will probe the geometric expansion the universe over a redshift range beyond the reach of current optical galaxy surveys and will therefore play an important role in measuring the nature of Dark Energy's impact on the expansion of the universe.

To do this, instead of studying the BAO feature by detecting individual galaxies, HIRAX aims to map the distribution of matter through observations of the neutral hydrogen gas that lies in the gravitational potentials occupied by these systems. By observing the 1.4GHz (21 cm) hydrogen line redshifted to between 400-800 MHz, HIRAX will construct a tomographic map of the universe extending from 7-11 Gyr ago, at a key time when Dark Energy begun to dominate the expansion rate of the universe. However, a major obstacle to this approach lies in removing the other foreground signals that are significantly brighter than the cosmological signal at these frequencies. While the characteristics of the cosmological signal and the foregrounds are quite distinct in their frequency and spatial dependence, the chromaticity (and other factors) in the response of the instrument to the on-sky signal can mix them in complicated ways in the observed data. This is the primary limitation of 21 cm cosmology and overcoming this necessitates a detailed understanding of the instrument in order to make unbiased measurements of the BAO signal.

The overarching goal of the project will be to work with the HIRAX team to develop and extend data analysis tools to aid in the characterisation of the instrument beginning initially with the large quantity of existing data and ongoing data collected from the HIRAX-8 prototype array at HartRAO. The student will also work to extend these approaches and methods so they are relevant to the 8 element prototype array at the Losberg site and the 128 element pathfinder array at the Swartfontein site.

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.

The student will be able to immediately begin analysing the large quantity of prototype data that has been accumulated using the preliminary analysis tools that have been developed. They will work together with the team to extend these tools focusing on the following key areas which have been separated into an approximate timeline for the project:

Year 1:

- Develop RFI mitigation techniques to aid in unbiased instrument characterisation tests
- Perform simple calibration routines on transiting sources, over time monitoring gain stability and testing the receivers on-sky performance in terms of their frequency dependent response and noise performance
- Investigate chromaticity effects in the radio frequency (RF) hardware through their effects on the prototype data using a comprehensive study of feed autocorrelations
- Contribute to the planned detailed systematics review paper to be released by the HIRAX team.

Year 2:

- Extend and optimize the year 1 analysis results and pipeline to be suitable for the forthcoming HIRAX deployments of both an 8 element and 128 element array at the Karoo site.
- Incorporate instrument characterisation and data quality analyses and results into the full HIRAX simulations and analysis pipeline.
- Write up the results in an MSc thesis.

Data Availability/Access to Resources:

The student will have access to a high-end computing cluster on which to set up, test and run the data analysis pipeline, and to the full HIRAX dataset 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).

The proposed research falls primarily within topic 7 and topic 8:
“7. Epoch of Reionization and Intensity Mapping data reduction and analysis.”
“8. Interferometric Data Processing and Analysis, including calibration and imaging.“
The student will be directly involved in hands on data analysis of HIRAX’s interferometric data that will be used for HI intensity mapping. They will be extracting information about the instrument performance, including calibration tasks, as well as evaluating the effect of instrumental uncertainties and characteristics on the final data products.

Additionally by working closely with HIRAX’s digital backend in the data pipeline, the student’s work will also fall within topic 2:
“Real-time Signal Processing instrumentation for Radio Astronomy, specifically using FPGA and GPU platforms.”

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.

The student will require pre-existing coding skills preferentially with python. Hands-on data analysis experience as well as basic knowledge of radio astronomy and interferometry fundamentals are also preferred.

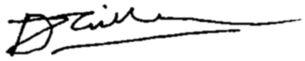
The student will additionally require a strong applied mathematical ability and experience in conducting collaborative research.

Section D: Signatures

1. Signature of the primary supervisor, with date

30 August 2018
Kavilan Moodley

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



30 August 2018
Devin Crichton