Section 0: Research project abstract/summary (max 250 words)

The Hydrogen Real-time Analysis eXperiment (HIRAX) will be a radio interferometer array purpose built to measure the HI power spectrum. It will eventually consist of 1024 6m dishes and will operate in the frequency range 400-800MHz. In order for HIRAX to achieve its goal of measuring the Baryon Acoustic Oscillations in the power spectrum of neutral hydrogen it will be critical to accurately characterise the spectral and angular response of the instrument. Since HIRAX is a drift scan telescope, point source transits through the beam will only provide 1d slices of the full 2d beam, which will not suffice for the calibration needs of the instrument. This necessitates the use of an artificial source that can be scanned through the beam to produce full 2d beam maps. In particular, this project will focus on the use of a drone with a noise source. The student will develop software pipelines and apply it to early data taken at the two element testbed array at Kleinfontein. Models will be fit to the beam maps, for use in forward modelling of the instrument, beam deconvolution, and weighting of the visibility data.

Section A: Overview of the Research Project Proposal

1. Academic level of research project (Masters or Doctoral)
   MSc
2. Broad field of research (Engineering or Astronomy/Astrophysics)
   Astronomy/Astrophysics
3. Title of the research project
   Analysis of drone beam mapping data from the HIRAX testbed array
4. Full names of supervisor and co-supervisor(s)
   Kavilan Moodley, Anthony Walters
5. University where postgraduate student would be registered
   University of KwaZulu-Natal

Section B: 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.

Ever since the discovery of the dimming of distant supernovae, and the associated accelerated expansion of the Universe, understanding the nature of the “dark energy” which is believed to cause this phase of acceleration has become one of the central pursuits of modern cosmology. Of the various known astronomical probes of dark energy, the Baryon Acoustic Oscillations (BAO) have particular appeal. Set up by competing forces in the early universe, these oscillations imprint a characteristic length scale in the distribution of matter, and have the potential to provide a strong constraint on the equation dark energy. The first detection of the BAO was seen in the distribution of galaxies in the Sloan Digital Sky Survey. Another place these BAOs are expected to be detectable is in the distribution of neutral hydrogen (HI). In particular, it is expected to impart its oscillations in the summary statistic referred to as the power spectrum. These were recently observed in cross-correlation by the Canadian Hydrogen Intensity Mapping Experiment (CHIME), which correlated its HI data with galaxy survey data. A detection of the BAOs in the auto- power spectrum of HI remains elusive, and a high priority goal in the field.

The Hydrogen Real-time Analysis eXperiment (HIRAX) will be a radio interferometer array purpose built to measure the HI power spectrum at the spatial scales of the BAO. It will be constructed in the Karoo near the MeerKAT/SKA site, eventually consist of 1024 6m dishes densely packed in a grid type array, and will operate in the frequency range 400-800 MHz. This corresponds to HI emissions at redshifts $0.8 < z < 2.5$, and will thus provide a strong constraint on the evolution of dark energy. However, one of the main challenges associated with making these measurements is overcoming the presence of strong galactic foreground emission, which is some 5(6?) orders of magnitude brighter than the hydrogen signal being targeted. While various techniques exist to remove / avoid these foregrounds, these approaches rely on the fact that the foregrounds are spectrally smooth compared to the HI signal. If the instrument imparts any unknown spectral features into the data, these smooth foregrounds will “leak” into the region of the HI signal containing the BAOs, thereby corrupting any possible measurement of it in the power spectrum. It is thus critical to the outcome of the experiment that one can precisely characterise and calibrate the spectral response of each element in the array. Moreover, it is also vital to have a good understanding of the angular response of each element in the array, as bright objects in the telescope sidelobes can also impact measurements.

Beam calibration for radio telescopes has traditionally been done using astronomical point sources. However, HIRAX will have the added limitation that its dishes are not mounted motorised assemblies, meaning that they cannot be easily pointed. This means that the dishes will not be able to scan point sources in the sky to build up a map of its beam response. The instrument will be limited to measuring source transits through its beam, which will only produce a single 1d slice through the 2d beam. This will be insufficient for the beam calibration needs of HIRAX, and so an alternative approach is needed. Since astronomical sources will not suffice, the only alternative is to use an artificial calibration source that can be easily manoeuvred through the beam. One such approach that the HIRAX project is actively investigating is the use of a drone equipped with a noise transmitter, which will allow for full 2d beam maps to be built up for each telescope in the array.

This project will focus on analysis of data produced by drone flights over the two-element testbed array in Kelerevontein. The student will develop code, and integrate it with existing software pipelines, to produce 2d beam maps for all frequency channels in the HIRAX band. The student will also partake in planning of the drone flight path for optional sampling of the beam. The data taken at the testbed array will be fed through the pipeline, producing 2d beam maps, to which models will be fit. The resulting model will be used in various aspects of the HIRAX project, including forward modelling of the instrument, beam deconvolution of the data, and optional weighting of the data.

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 HIRAX two element testbed array at Klerefontein is expected to be built by mid-2023. Shortly thereafter, once acquisition systems are in place, drone flights over the array will be planned and executed in conjunction with collaborators at McGill, Yale, and ETH-Zurich, who will each fly different drone systems over the testbed array, so we expect to have drone flight data in hand by the end of 2023, prior to the start of the project in January 2024. The analysis of the drone flight data will be carried out by the student, using the bespoke pipelines they have developed and tested. Data analysis will be performed using UKZN's 1000-core HPC cluster.

Timelines:

- Year 1 - first and second quarter: Develop the existing analysis pipeline to accept the data formats produced by the testbed array. Test on single dish data taken at Bleien Radio Observatory in 2022 (which has multiple acquisition setups, one of which is the same as the HIRAX testbed array) . Produce 2d beam maps. Compare with existing beam maps produced by the Callisto spectrometer at Bleien.
- Year 1 - third and fourth quarter: Extend the analysis pipeline for multiple dish configuration. Input data from drone flights over the testbed array taken in 2023, and produce 2d beam maps
- Year 2 - first quarter: Continue analysis of beam maps produced by the 2023 drone flight data over the testbed array, and critically assess any potential shortcomings from the experiment. Develop recommendations for future flights over the array.

- Year 2 - second and third quarter: Fit models to the beam maps produced by the pipeline.
- Year 2 - fourth quarter: Write up thesis and submit

3. Link the proposed project to at least one SARAO research priority areas (refer to Section 4 of the Application Guide), and explain in some detail how the proposed research will contribute to the priority area(s).

HIRAX will target the BAO signal using intensity mapping -- analysis of data on early versions of the array forms one of the SARAO research priority areas under Science (Topics exploiting data including early versions of HIRAX).

This project will also address the priority area of "Radio astronomy antennas and receiver systems" (topic 1 under Engineering) associated with the guest instrument HIRAX. HIRAX is one of the approved SARAO instruments specified in the call, and this work will directly contribute to its success, through work on the HIRAX dish/feed and its characterisation, and developing techniques to study interactions among closely packed antennas.

The characterisation of instrument performance also falls under the priority area of: "Hardware, software and data analytic systems associated with the control and monitoring of radio telescopes." (topic 4 under Engineering)

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 must have a background in basic radio astronomy, and python programming.

Section C: Supervisor(s) Details

1. Primary supervisor's details
    1. Title and full name: **Prof Kavilan Moodley**
    2. Name of South African or SKA Partner Country university at which the primary supervisor is a permanent academic staff member: **University of KwaZulu-Natal**
    3. 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**
    4. 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.

1. 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)
Ajith Sampath	India	July 2021	June 2024	Beam calibration and its impact on the 21cm power spectrum	Tony Walters
Sindhu Gaddam	India	June 2021	June 2024	Electromagnetic simulations of HIRAX dish and feed systems	
Warren Naidoo	South Africa	Jan 2020	Jan 2023	Cross-Correlation Science with HIRAX HI Intensity Mapping	
Sinenhlanhla Sikhosana	South Africa	Sept 2017	Jan 2021	Diffuse Radio Emission in ACTPol Clusters	Kenda Knowles, Matt Hilton
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-Rodriguez	Spain	Jan 2007	Dec 2008	SKA 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)

2. Masters Students

Name of Student	Nationality	Date started Masters Degree (Month and Year)	Date completed / will complete Masters Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Isibabale Qhoboshiyane	South Africa	May 2021	May 2023	System for monitoring temperature variation of Low noise amplifiers on the HIRAX active feed	Mugundhan Vijayaraghavan

Tsepo Shekoasha	South Africa	May 2022	May 2024	HIRAX dish inclination monitoring system	Mugundhan Vijayaraghavan
Keshav Bechoo	South Africa	Feb 2023	Dec 2024	Analysis of on-sky data from HIRAX dish prototype	Mugundhan Vijayaraghavan
Tasmiya Papiah	South Africa	Feb 2023	Dec 2024	Drone beam mapping of the HIRAX testbed array	Anthony Walters
Bismark Abeku Nyamekye Kushiator	Ghana	July 2018	Dec 2021	Design of House Keeping and Monitoring System for HIRAX	Mugundhan Vijayaraghavan
Denisha Pillay	South Africa	Jan 2020	Dec 2021	Statistical Pilot Study for MERGHERS	Kenda Knowles
Carla Pieterse	South Africa	Jan 2019	Jan 2021	Comparison of prime focus and offset Gregorian reflector antennas for 21 cm intensity mapping	Martin Bucher, Dirk de Villiers
Scott Eyono	Cameroon	Jan 2019	Dec 2020	HIRAX Data Architecture and RFI Flagging	
Dalian Sunder	South Africa	Jan 2019	Dec 2020	Instrument Characterisation for CMB and HI Intensity Mapping Experiments	

Zahra Kader	South Africa	Mar 2018	Sept 2019	HIRAX: 21 cm Cross-correlations and Calibration	Devin Crichton
Warren Naidoo	South Africa	Jan 2018	Dec 2019	HI Intensity Mapping and Cross-Correlation Science with HIRAX	
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: Reconstructing 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)
    1. Title and full name **Dr Anthony Walters**
    2. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member: **University of KwaZulu-Natal**
    3. 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) **wltrs.tony@gmail.com**
    4. Supervision of postgraduate students – please provide the details of all the postgraduate students supervised. Please provide the information in table format, as shown below.

Masters:

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

Tasmiya Papiah	South African	Feb 2023	Dec 2024	Analysis of external calibration data from the HIRAX testbed array	Kavilan Moodley (main supervisor)

Doctoral:

Name of Student	Nationality	Date started Masters Degree (Month and Year)	Date completed / will complete Masters Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Ajith Sampath	Indian	July 2021	June 2024	Beam calibration and its impact on the 21cm power spectrum	Kavilan Moodley (main supervisor)

Section D: Signatures

1. Signature of the primary supervisor, with date

Kavilan Moodley
21/02/2023

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

21/02/2023
Anthony Walters