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

A new frontier of radio astronomy is using the redshifted 21-cm emission line of neutral hydrogen to reconstruct a three-dimensional map of large-scale structure in the universe. These measurements encode a faint imprint, known as baryon acoustic oscillations (BAOs), that correspond to remnant ripples left behind by sound waves echoing through the plasma of the early universe. Measurements from upcoming experiments will constrain BAOs with exquisite precision, opening new views into structure formation and the universe's expansion history, and shedding light on the mystery of dark energy. The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) is a new radio telescope array that has the goals of measuring BAOs, searching for pulsars, detecting fast radio bursts and other transients, finding neutral hydrogen absorbers, and other auxiliary science. HIRAX will be sited in South Africa and will map most of the southern sky (in a declination range of -60 deg to 0 deg) over a frequency range of 400–800 MHz. The array will eventually consist of 1024 6m stationary dishes placed in a compact, redundant configuration.

Knowing the beam shape, its chromaticity and receiver gain is important for an array like HIRAX as systematic errors in the aforementioned parameters cause leakage of power into the region where the cosmological signal is expected to reside. Therefore, it is essential to make exhaustive study of possible causes of systematics through extensive simulations and observations. This Masters project, commencing in January 2024, focuses on the latter. At this stage, HIRAX has a prototype 6m dish at HartRAO, and construction of the 2-element dish verification array is underway at Klerefontein, and is expected to be completed by mid-2023. The student will analyze data from these arrays to gain insight into the receiver temperature, gain, and its variation with time. The student will first study the beam shape of the MMS dish at HartRAO from source transits, using data that is already in hand, and obtain upper limits on coupling between the 6m dish and other reflective elements around the dish. The student will also work on studying the long term gain and noise-temperature stability of the receiver system at HartRAO, and its variation with ambient temperature on site, using data that is already in hand. The effect of strong and weak RFI on the estimates of the system gain, and how these signals couple between the dishes will also be studied.

The student will then take an active role in analyzing first light observational data from the dish verification array at Klerefontein to characterise the array's sensitivity, system temperature and study the RF system stability, where much reduced RFI will will lead to a more accurate characterisation. This study also has the scope to be extended to the 8-element array at Swartfontein, when data from the array becomes available by early 2025, where there will be an added focus to extensively study the mutual coupling and its impact on the power spectrum from observational data.

This work will be crucial for HIRAX as it will lead to a better understanding of systematics and its sources, and the impact on the power spectrum measurement.

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

On-sky characterisation and analysis of HIRAX prototype and dish verification arrays

4. Full names of supervisor and co-supervisor(s)
   Kavilan Moodley, V. Mugundhan
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.

An exciting frontier of radio astronomy is using the redshifted 21-cm emission of neutral hydrogen to reconstruct a three-dimensional map of large-scale structure in the universe. These maps encode a faint imprint, known as baryon acoustic oscillations (BAOs), that correspond to remnant ripples left behind by sound waves echoing through the plasma of the early universe. Measurements from upcoming experiments will constrain BAOs with exquisite precision, opening new views into structure formation and the universe's expansion history, and shedding light on the mystery of dark energy.

We are in the initial stages of building a new radio telescope array called the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX). HIRAX will measure BAOs by mapping the entire southern sky over a frequency range of 400–800 MHz, and the experiment will be sited in South Africa. The project is complementary to the Canadian Hydrogen Intensity Mapping Experiment (CHIME), which has recently begun surveying the northern sky. HIRAX has received funding to build a 256-element array, and an eight-element prototype array is already in place at HartRAO.

The student who takes on this project will play a key role in the continued characterisation of HIRAX instrumentation through low-level data analysis. The work will include coming up with techniques to measure the properties of the HIRAX dish and feed elements. In particular, the student will develop passive measurement techniques via observations of celestial sources, and satellites. The student will work on analyzing the data from HIRAX arrays at HartRAO, Klerefontein and Swartfontein. The results obtained from the analysis here will be an important verification of the on-sky noise temperature, gain and the stability of the receiver system in general. The student will gain knowledge in both single dish and interferometric data analysis techniques and learn methods to calibrate data using sky/source models, flagging RFI, estimating antenna and receiver performances using observational data. The techniques learned can be universally applied to characterise any radio telescope.

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 project has been granted funding for constructing a 256-element array in its first phase. This work will focus on the early staged deployments of the HIRAX array. Data storage and analysis will be performed using UKZN's 1000-core HPC cluster.

The data analysis methods listed below will be applied for all early-stage (prototype, 2-element, 8-element) arrays:

1. Preliminary data quality check by using metadata from the F-engine
2. Apply RFI mitigation
3. Calibrate data using known sky models and sources
4. Estimate system noise temperature and gain by using on/off source measurements over a single day, repeating for multiple days to study stability
5. Fold data over LST to study the presence of low-level RFI and its impact

Timeline:

Year 1 (first half, 2024) - Use pre-existing data from HartRAO to develop a pipeline to apply the aforementioned steps and study the fiducial single dish system

Year 1 (second half, 2024) Extend the analysis pipeline to work with the interferometric data from the 2-element array at Klerefontein; Examine source transits and compare results obtained using complementary methods (drone based beam mapping, noise temperature measurements from anechoic chamber and conducted Y factor measurements)

Year 2 (fourth half, 2025) Summarise results obtained from HartRAO and Klerefontein in the first year and feedback into design of the larger array

Year 2 (second half, 2025; if time permits) Extend the pipeline to include analysis of data from the 8-element prototype array at Swartfontein to characterise the system noise temperature and gain stability and analyze the Swartfontein 8-element data for mutual coupling and provide constraints on systematic effects

Year 2 (second half, 2025) Write up and submit thesis

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).

The project specifically deals with analyzing data from early versions of the HIRAX array, which is a guest instrument of SARAO, and is expected to provide useful feedback for the implementation/commissioning of the final 256-element pathfinder array. This falls under the SARAO research priority area of Science as it exploits data from early versions of the HIRAX array. 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 and monitoring 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'dovi ch 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 Mugundhan Vijayaraghavan**
    2. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member: **Onsala Space Observatory, Chalmers University of Technology, Sweden**
    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) **mugundhaniia@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. **N/A**

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)
Bismark Abeku Nyamekye Kushiator	Ghana	July 2018	Dec 2021	Design of House Keeping and Monitoring System for HIRAX	Kavilan Moodley (main supervisor)

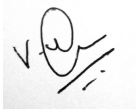
Isibabale Qhoboshiyane	South Africa	May 2021	May 2023	System for monitoring temperature variation of Low noise amplifiers on the HIRAX active feed	Kavilan Moodley (main supervisor)
Tsepo Shekoasha	South Africa	May 2022	May 2024	HIRAX dish inclination monitoring system	Kavilan Moodley (main supervisor)
Keshav Bechoo	South Africa	Feb 2023	Dec 2024	Analysis of on-sky data from HIRAX dish prototype	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



15/02/2023
V. Mugundhan