

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

Measurement of HIRAX feed and dish properties

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. An eight-element HIRAX prototype array is already in place at HartRAO. The student working in this project will play a role in developing techniques to characterize the HIRAX active feed and dish, and also observationally verify it. The installation of the first science-grade HIRAX telescopes in the Karoo will commence in 2021, and the student will begin by testing the 2 qualification dishes which will be built at Klerefontein, and based on this experience, characterize the first science-grade dishes at Swartfontein.

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)
Engineering
3. Title of the research project
Measurement of HIRAX feed and dish properties
4. Full names of supervisor and co-supervisor(s)
Kavilan Moodley, Cynthia Chiang, 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 design and testing of HIRAX instrumentation. 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 viz. observations of celestial sources, and satellites. The student will also work on algorithms to identify various factors that lead to change in beam shapes and estimate the degree to which these would affect the cosmology measurements. The work will use the ten HIRAX prototype dishes at HartRAO and the qualification dishes at Klerefontein and provide valuable inputs for subsystem refinement in preparation for the deployment of the 128-element pathfinder at the SKA Karoo site. These stages are critical milestones along the path to constructing the full science array, which at the first stage will consist of 256 funded elements but will eventually build up to 1024 elements. The student

will work closely with local and international team members throughout the duration of the project, and will assist in commissioning and data analysis.

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.

In the first year of the project the student will use the existing HIRAX dishes at HartRAO in combination with the 15m XDM dish to carry-out holography of the former. Holography is an interferometric technique using a reference (XDM) and test antenna (AUT, HIRAX) to observe a source, where the former would scan the source, while the latter would track it; the resulting visibility data is then reduced to derive the properties of the AUT. The student will take part in verifying the proper working of the dishes provided by the manufacturer and commissioning of the feeds. The work will also include scheduling observations with the prototype dishes, measuring the characteristics of the feed in the lab and on-field at HartRAO, and also try to understand the construction and working of the 15m XDM dish, which will be a crucial element in the holography measurements. The student will acquire data from the holography observations in HartRAO and try to do a first level analysis, and explore other data driven analysis techniques. The student will interact with other working groups, share results and work on developing techniques to integrate the holography results into the data analysis pipeline.

In the second year of the project, the student will work with data from the verification array at Klerefontein, and quantify the interaction between the dishes in a multi-antenna, closely packed environment. The results obtained with the prototype array and the verification array will be published in an engineering/astronomy journal. The student will extend the work done thus far to the 128 element array and work on techniques to measure antenna and feed performance from the visibility data itself. The inputs from here will be used in refining the design of the final 1024 element array. Halfway through year two, the student will start writing the thesis and summarize the results in a publication.

The HIRAX project has been granted funding for constructing a 256-element array in its first phase, and the installation of the eight-element prototype is complete. We have a well established radio instrumentation laboratory with all the necessary equipment for subsystem development and characterization. Data analysis will be performed using UKZN's 1000-core HPC cluster.

3. Link the proposed project to at least one SARA0 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 SARA0 research priority areas (topic 5.1).

This project will also address the priority area of "Radio astronomy antennas and receiver systems" associated with the guest instrument HIRAX (topic 5.2.1). HIRAX is one of the approved SARA0 instruments specified in the call, and this work will directly contribute to its success, through work on the HIRAX dish/feed and its characterization, and developing techniques to study interactions among closely packed antennas.

The characterization and monitoring of instrument performance also falls under topic 5.2.4: “Hardware, software and data analytic systems associated with the control and monitoring of radio telescopes.”

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 RF & microwave systems, basic knowledge on antennas and programming for data analysis.

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 SARA0 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)
Warren Naidoo	South Africa	Jan 2020	Dec 2022	Characterisation of instrument systematics on foreground leakage in HIRAX data	
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)
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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 **Prof Cynthia Chiang**
2. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member **McGill University**
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 SRAO postgraduate bursaries) **hsin.chiang@mcgill.ca**
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.
 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)
Liju Philip	India	1/2016	12/2018	The Design, Construction and Deployment of PRIZM	Jonathan Sievers
Heiko Heilgendorff	RSA	9/2013	12/2017	The C-Band All Sky Survey Commissioning and Data Analysis	Jonathan Sievers

2. 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)
Bismark Kushiator	Ghana	7/2018	7/2020	HIRAX instrumentation and prototype characterisation	
Nivek Ghazi	RSA	1/2018	12/2019	Exploring cosmic dawn from the sub-Antarctic with PRIZM	
Austin Gumba	Kenya	1/2018	12/2019	Radio Astronomy Receiver Design and Commissioning	Jonathan Sievers
Kabelo Kesebonye	Botswana	1/2017	12/2018	HIRAX commissioning and instrument characterisation	
Johannes Allotey	Ghana	8/2014	12/2016	Commissioning and Characterisation of the C-Band All-Sky Survey Southern Telescope	

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

5. Title and full name **Dr Mugundhan Vijayaraghavan**
6. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member **Raman Research Institute (moving to UKZN in mid-2021)**
7. 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 SRAO postgraduate bursaries) **mugundhaniia@gmail.com**
8. 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**

Section D: Signatures

1. Signature of the primary supervisor, with date



24 February 2021
Kavilan Moodley

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



24 February 2021
Cynthia Chiang



24 February 2021
V. Mugundhan