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

HIRAX dish pointing accuracy measurements using a star camera

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 roughly 1024 6m stationary dishes placed in a compact, redundant configuration. An eight-element HIRAX prototype array is already in place at HartRAO. This project aims at developing a system to characterize pointing errors in the HIRAX dishes. Measuring the accuracy is important to build a good beam and pointing model for every observation, to ensure that this error does not propagate unmodelled in the data. The student will develop a basic system for doing this using star cameras, which are commonly used for attitude sensing in cube-sats. The work will involve hardware design, development and testing of the system with the existing prototype array and design guidelines for scaling up to the pathfinder and final arrays.

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
3. Title of the research project
   HIRAX dish pointing accuracy measurements using a star camera

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.

For achieving the precision dictated by the science goals, measuring the antenna pointing and offsets are vital, as they directly affect the gain and phase calibration of the array. These offsets are required to be monitored regularly - ideally for every integration time - so that this can be fed into the meta-data to account for these errors. This is conventionally done using an inclinometer or an inertial measurement unit (IMU). However, it still needs to be verified if these methods can satisfy the accuracy requirements. This project deals with exploring an alternative measurement method - using a star camera for this purpose. The work would involve simulating the star camera, identifying optical components and the camera required, assembling these and testing at the lab for validation and RFI compliance and eventually commissioning the system in the field and taking measurements to verify the approach.

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 quarter, the student will simulate the star camera system and try to identify the instrument parameters required to achieve sub-arcmin resolution in pointing accuracy. In parallel, the student would also identify the required optical and electronic components, and the camera required for the work.

The work in the second and third quarter would be to assemble the cameras, write software to interface and grab images from the camera, and carry-out lab tests to validate the system. The student will also cross verify the results obtained in the lab with simulations. The student will also build an auxiliary inclinometer based on IMUs to compare the results with the star camera.

In the fourth quarter, the student will try to observe the sky in a relatively dark place with two star cams, and try to achieve the same results obtained in previous quarters. In the fifth quarter, the student will characterize the system for EMI compliance and carry-out necessary modifications for the instrument's suitability in the field.

In the sixth and the first half of the seventh quarter, the system will be commissioned on available dishes at HartRAO and the position offsets measured from the camera system will be compared with interferometric data. Any coordinate transformation method, if required, to align the antenna and the star-cam axis will be developed. The student will complete the thesis in the final semester and publish the result obtained in a refereed journal.

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 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 (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 SARAO instruments specified in the call, and this work will directly contribute to its success.

This project targets building of test and measurement instrumentation required on-field to measure pointing offsets, an important parameter that affects gain and phase calibration. This work directly falls under development of "Hardware, software and data analytic systems associated with the control and monitoring of radio telescopes" (topic 5.2.4).

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 sufficient patience and tenacity to withstand the inefficiencies and bureaucratic hurdles associated with hardware procurement. Basic experience in working with electronic systems, instrumentation and some basic knowledge of some programming language will be an advantage, but not mandatory.

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)
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'dovic h Effect as a Probe of Cluster Physics and Cosmology	
Angel Torres-Rodrigue z	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)

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	Democrati c 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 SARAO 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 **Prof V Mugundhan**

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 SARAO 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**

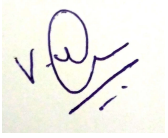
Section D: Signatures

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