Section A: Overview of the Research Project Proposal

1. Title of the research project:
   Beam calibration and power spectrum estimation
   with HIRAX 21cm intensity mapping data
2. Broad area of research (Engineering or Science)
   Science
3. Academic level of research project (Masters or Doctoral)
   Doctoral
4. Abstract of research project:
   A central goal of current cosmological surveys is to uncover the nature of dark energy. The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) project will eventually comprise a compact array of around 1,000 small (6m) dishes operating at 400-800 MHz. The primary aim of HIRAX is to map baryon acoustic oscillations (BAOs) in the cosmological 21cm intensity distribution over a significant fraction of the sky between redshifts 0.8-2.5, and thereby place strong constraints on the dark energy equation of state. The first stage of the project comprising 256 dishes has been fully funded. 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 in the measurement of the 21cm power spectrum. The large contrast in amplitude of the 21cm BAO signal relative to foregrounds such as galactic synchrotron emission and extragalactic point sources, combined with chromaticity of the instrument make disentangling these two signals a challenging data analysis problem. In this project we propose for a PhD student to work with the HIRAX team on characterising one important source of instrument chromaticity, the instrument beam, and understanding its effect on power spectrum estimation through the analysis of HIRAX stage 1 data. The student will be involved in quantifying the effect of the HIRAX beams on power spectrum estimation and developing power spectrum estimators that mitigate the beam chromaticity. Based on this work beam calibration and power spectrum techniques will be developed and applied to HIRAX data with the goal of extracting the 21cm BAO signal.
5. Primary supervisor's details:
   a. Full name of primary supervisor: **Kavilan Moodley**
   b. Primary supervisor's email address: **kavilan.moodley@gmail.com**
   c. University where primary supervisor is employed: **University of KwaZulu-Natal**
6. Co-supervisor/Research supervisor's details (if relevant):
   a. Full name of co-supervisor/research supervisor: **Devin Crichton**
   b. University where co-supervisor/research supervisor is employed: **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.

Since the first observational evidence of the accelerated expansion of the universe, cosmologists have sought a theoretical understanding of the so-called dark energy driving this acceleration. While measurements of the expansion rate of the universe have become increasingly precise over the past few decades, the nature of dark energy remains one of the most perplexing unsolved problems in modern cosmology. One of the most promising methods for constraining the nature of dark energy relies on the baryon acoustic oscillation (BAO) feature in the large-scale structure of the universe. This feature, imprinted on the initial distribution of matter before the onset of large-scale structure formation, provides a standard ruler -- a constant comoving length scale -- that can be used to map the geometric expansion history of the universe over cosmic timescales. By making measurements of this standard ruler during epoch which the dark energy comes to dominate the expansion, the dynamics of dark energy may be constrained.

The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) project aims to use an alternative technique to optical redshift surveys, known as 21cm intensity mapping, to measure the BAO signal. Specifically, HIRAX will conduct a spectroscopic radio survey which will capture the aggregate emission of hundreds of galaxies in a volume element, without detecting galaxies individually. Observing the 1.4 GHz (21 cm) hydrogen line redshifted to between 400-800 MHz, HIRAX will extend the range of BAO-based distance measurements into the key redshift range $0.8 < z < 2.5$ when the expansion rate transitioned from decelerating to accelerating. Measurements of the BAO scale across this wide redshift range can be combined with those from lower and higher redshift to yield tight constraints on dynamical dark energy.

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 on early data from the HIRAX-8 element prototype array at the Karoo Swartfontein site to aid in the characterisation of the instrument beam to mitigate systematics that could enhance foreground leakage, and to study its effect on the estimation of the 21cm power spectrum. The student will work with the HIRAX team to extend these methods and tools to the staged 128-element pathfinder and 256-element arrays.

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 methods to be used in the project are outlined below for each year.

Year 1: Prepare the analysis framework and associated tools. Use realistic sky and beam simulations to study beam systematic effects, e.g. from feed-dish reflections or feed cross-talk on the simulated data. Develop analysis tools to process beam calibration data, in addition to early data from the HIRAX-8 element prototype array at the Karoo Swartfontein site, which is expected to be commissioned in early 2021.

Year 2:
Continue developing analysis tools and apply to early calibrated data from the HIRAX-8 element prototype array. Use the mode mixing framework to characterise the effect of beam systematics on the estimated power spectrum, which will involve incorporating and extending the existing delay spectrum and m-mode approaches. Informed by this framework and the simulations, identify relevant beam systematic observed in the data that would contribute to enhanced foreground leakage. Apply techniques from the mode mixing approach to mitigate the foreground leakage and improve power spectrum estimation. Publish a paper on this work based on analysis of the HIRAX-8 element Karoo prototype data. Continue this study on the 128-element pathfinder data and start to develop tools for foreground removal and power spectrum estimation.

Year 3: Apply the methods and tools developed for beam calibration and power spectrum estimation foreground to the 128-element pathfinder data and early data from the 256-element array. Using these larger datasets, quantify the amount of foreground leakage from beam systematics. Based on these results derive power spectra from the pathfinder data and the level of contribution from beam systematics to these power spectra. Publish a paper on these results. Write up PhD thesis.

<u>Data availability and access to resources:</u>

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. The HIRAX 8-element data will be available from the middle of the first year, data from the 128-element pathfinder will be available at the end of the first year, and data from the 256-element array will be available from the second year onwards.

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 proposed here relates directly to the SARAO research priority area 5.1, specifically exploiting data from early versions of HIRAX, which is a key existing radio astronomy instrument located in South Africa. The project will develop key data analysis techniques to quantify the effect of beam systematics on foreground leakage and methods for 21cm power spectrum estimation in the HIRAX interferometer data. These are key challenge facing experiments in the area of 21cm intensity mapping.

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.