# Section A: Overview of the Research Project Proposal

1. Title of the research project:
   **Calibration of 21cm intensity mapping data from HIRAX**
2. Broad area of research (Engineering or Science)
   **Science**
3. Academic level of research project (Masters or Doctoral)
   **Masters**
4. Abstract of research project:
   Post-reionisation hydrogen intensity mapping projects provide an exciting avenue for probing the evolution of large-scale structures over a large fraction of the universe's history. In particular, by measuring the angular scale Baryon Acoustic Oscillation (BAO) feature in the distribution of matter over cosmic times the geometric expansion of the universe can be studied, constraining the nature and evolution of dark energy - the unknown substance causing this expansion to accelerate. The Hydrogen Intensity and Real-time Analysis eXperiment is one such project, aiming to map the distribution of matter as traced by neutral hydrogen emission from redshifts 0.8-2.5. HIRAX will make use of an array of 1024 antennas in a compact grid, sensitive to frequencies in the range of 400-800 MHz. While HIRAX's design is optimised to measure the BAO signal, significant challenges for this and other intensity mapping projects are present in controlling measurement errors and systematic uncertainties. Probing cosmology with 21cm intensity mapping involves accurately separating signals which vary greatly in terms of on-sky brightness and their spectral characteristics. It is therefore critical to be able to understand and measure the instrument's response to signals in the sky with high precision such that meaningful information may be extracted from the data products. Calibrating the response of the instrument is therefore a crucial step in the analysis of intensity mapping data. This research project will focus on testing and adapting different calibration techniques to HIRAX and integrating them into the data analysis pipeline for the early stage deployments of HIRAX up to the 256 element Phase 1 array.
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**
   a. Full name of co-supervisor/research supervisor: **Jonathan Sievers**
   b. University where co-supervisor/research supervisor is employed: **McGill University**

# 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.*

The nature of Dark Energy, the dominant component of the energy density of the universe that drives its accelerated expansion, remains one of the greatest mysteries of modern cosmology. The most natural theoretical explanation for its origin is discrepant with observations by over a 100 orders of magnitude. As such, the Dark Energy Task Force (DETF) motivated an empirical approach to understanding the evolution of Dark Energy's impact on the universe's expansion rate. HIRAX's goal is to observe the baryon acoustic oscillation (BAO) feature imprinted on the distribution of matter which forms a so-called standard ruler. Through this, HIRAX will probe the geometric expansion the universe over a redshift range beyond the reach of current optical galaxy surveys and will therefore play an important role in measuring the nature of Dark Energy's impact on the expansion of the universe.

To do this, instead of studying the BAO feature by detecting individual galaxies, HIRAX aims to map the distribution of matter through observations of the neutral hydrogen gas that lies in the gravitational potentials occupied by these systems. By observing the 1.4GHz (21 cm) hydrogen line redshifted to between 400-800 MHz, HIRAX will construct a tomographic map of the universe extending from 7-11 Gyr ago, at a key time when Dark Energy begun to dominate the expansion rate of the universe. However, major challenges arise in separating out this cosmological signal from the much brighter foregrounds signals in these frequencies, including that from our own galaxy. To be able to achieve these science goals, the instrument must be well calibrated and its spectral response well understood.

The overarching goal of the project will be to work with the HIRAX team to develop and extend calibration tools to aid in the characterisation of the instrument beginning initially with the existing data and ongoing data collected from the HIRAX-8 prototype array at HartRAO. The student will also work to extend these approaches and methods so they are relevant to the 8 element prototype and 128 element pathfinder at the Karoo site. The calibration techniques will be based on correlation calibration, a framework that extends redundant calibration by allowing for deviations from exact redundancy in hardware, while also naturally taking advantage of partial knowledge of the sky (such as the locations of bright point sources while not needing to know their fluxes).

*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 student will be able to immediately begin analysing the large quantity of HartRAO prototype data that has been accumulated using the preliminary analysis tools that have been developed. The student will right away be able to characterize redundancy in the prototype data and extend the framework to carry out bandpass calibration. This effort will be expanded as data from the Karoo 8-element prototype is collected in the first year. The

student will work together with the team to extend these tools focusing on the following key areas which have been separated into an approximate timeline for the project:

Year 1:

- Perform simple calibration routines on transiting sources, over time monitoring gain stability and testing the receivers on-sky performance in terms of their frequency dependent response and noise performance

- Characterize the redundancy of the prototype data, including antenna-based beam profiles and UV coordinates. Compare correlation calibration solution to traditional techniques

- Begin developing corrcal-based bandpass calibration tools. This will rely on spectral smoothness of the sky forward-modelled into cross-frequency correlations.

- The above methods will be applied to data from the HartRAO and Karoo HIRAX 8-element arrays.

Year 2:

- Extend and optimize the year 1 analysis results and pipeline to be suitable for the HIRAX deployment of the 128-element array at the Karoo site, which will happen at the end of the first year. Apply to new HIRAX 128-element data as it arrives.

- Demonstrate in simulations how well corrcal recovers bandpass calibrations.

- Develop tools to automatically measure array properties such as primary beams, antenna *uvw* coordinates, pointing errors and the like.

- Contribute to the planned detailed calibration and systematics review paper to be released by the HIRAX team.

- Write up results into a Masters thesis.

Data Availability/Access to Resources:

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.

*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 research proposed here relates directly to SARAO priority area 5.1 as the bulk of the research will involve developing calibration tools for the HIRAX project and applying this to early stage HIRAX data. The tools developed will also generally be applicable to redundant interferometer arrays such as HERA.

*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.