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)
   Astronomy/Astrophysics
3. Title of the research project
   Calibration of 21cm intensity mapping data from HIRAX
4. Full names of supervisor and co-supervisor(s)
   Kavilan Moodley, Devin Crichton, Jon Sievers
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.

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 large quantity of 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 to be built 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 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. They 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.

Year 2:

- Extend and optimize the year 1 analysis results and pipeline to be suitable for the forthcoming HIRAX deployments of both an 8 element and 128 element array at the Karoo site. Apply to new 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 systematics review paper to be released by the HIRAX team.

Year 3:

- Apply new tools to 256-element array to calibrate science data
- Characterize the array and quantify how non-redundancy in the instrument affects the ability of HIRAX to measure dark energy
- Write up results into a PhD 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 6.1 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.