Section A: Overview of the Research Project Proposal

1. Academic level of research project (Masters or Doctoral)
   Doctoral
2. Broad field of research (Engineering or Astronomy/Astrophysics)
   Astronomy/Astrophysics
3. Title of the research project
   Characterisation of instrumental systematics on foreground leakage in HIRAX data
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.

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 systematic effects in the instrument that could enhance foreground leakage. 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 instrument simulations to study anticipated systematic effects, such as beam and bandpass non-idealities arising e.g. from feed-dish reflections or feed cross-talk, baseline non-redundancy, and polarisation leakage on the simulated data. Use the mode mixing framework to develop filters and estimators to limit the foreground leakage -- this will involve a comparison of current state-of-the-art 21cm intensity mapping approaches, such as the delay spectrum analysis and the m-mode analysis, and relevant extensions of these approaches.

Year 2: Develop analysis tools on early calibrated data from the HIRAX-8 element prototype array at the Karoo Swartfontein site, which is expected to be commissioned in late 2020. Informed by the simulations done in the first year, identify relevant systematic effects observed in the data that would contribute to enhanced foreground leakage. Apply techniques from the mode mixing approach to mitigate the foreground leakage. 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 foreground mitigation 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 instrumental systematics. Based on these results derive power spectra from the pathfinder data and the level of contribution from systematics to these power spectra. Publish a paper on these results. Write up PhD thesis.

Data availability and 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. The HIRAX 8-element data will be available from the end of the first year, data from the 128-element pathfinder will be available in the second year, and data from the 256-element array will be available from the end of 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 6.1, 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 instrumental systematics to foreground leakage in the HIRAX interferometer data, which is a 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.