Section A. Overview of Research Project

1. **Title:** Towards all-sky surveys at milli-arcsecond angular resolutions with wide-field VLBI

2. **Area of research:** Science

3. **Academic level:** Doctoral

4. **Abstract:** Understanding the astrophysical processes associated with star-formation and black hole activity, and testing models for dark matter and dark energy, requires observing the radio sky on extremely small spatial-scales. This is best achieved using the technique of Very Long Baseline Interferometry (VLBI), where radio telescopes separated by great distances are combined to produce sensitive images of the sky at milli-arcsecond (mas) angular resolutions. Unfortunately, the number of radio sources observed at such resolutions, and to a good sensitivity, are extremely limited. For example, data from single pointed observations and some well-studied "famous" fields have provided only a few hundred detections. However, any VLBI experiment has within it the signals from several hundreds of detectable radio sources (on 5 to 200 mas-scales). In this project, a PhD student will develop calibration and imaging algorithms that can be applied to wide-field VLBI experiments involving HartRAO and European VLBI Network stations (and eventually MeerKAT), with the goal of increasing sample sizes to the level where various applications of VLBI can reach their full scientific potential. The methods developed here will be directly applicable to all-sky surveys with SKA-VLBI in the future.

5. **Primary supervisor:**

   a. Prof. John McKean
   b. john.mckean@up.ac.za
   c. South African Radio Astronomy Observatory (SARAO) / University of Pretoria

6. **Co-supervisor / Research Supervisor:**
   a.
   b.
   c.

Section B. Details of Research Project

1. **Scientific merit:**

In recent years, several pathfinder instruments (ASKAP, LOFAR and MeerKAT) have identified millions of new radio sources, laying the ground work for the deep surveys to be carried out with the SKA. These surveys have investigated the co-evolution of supermassive black holes and the triggering of star-formation in the distant Universe through forming large statistical samples (including sub-samples based on morphology, luminosity and host galaxy properties). These large population studies have resulted in many important results and contributed greatly to our understanding of galaxy formation and evolution. However, the vast majority of the detected radio sources remain unresolved in these data, and so, understanding the astrophysical processes at play and testing various models remains challenging. In the age of the SKA, observations from a few arcsecond to around 300 milli-arcsecond will be possible (with SKA-MID at 1-2 GHz). However, given that the median size of a radio source is ~7 kpc (~1 arcsec; Muxlow et al. 2020), many radio sources will be marginally resolved, or only limited information about their structure will come from such data. To overcome this, astronomers can use a process called Very Long Baseline Interferometry (VLBI), which connects radio telescopes over vast distances to improve the angular resolution. This comes at the cost of losing information on the large-scale properties of the radio emission and significantly decreasing the area of sky that can be imaged. However, recent improvements in signal-processing and computing has led to the development of wide-field VLBI techniques that can allow several hundred radio sources per observation to be imaged. Thus far, this technique has been best applied to deep data from a few “famous” fields, yielding a handful of detections. To increase the statistics and to find rare types of compact radio sources, it is important to develop an all-sky survey mode for wide-field VLBI experiments that can be routinely applied to any part of the sky.

In this PhD project, the student will build upon work pioneered at the University of Pretoria (e.g. Radcliffe et al. 2021) to develop a generic wide-field VLBI pipeline that can be applied to any part of the radio sky. Currently, most VLBI experiments target a single object, even though the signals from 100s of sources are in the data. This represents a significant waste of resources, but also provides an opportunity to increase sample sizes by several orders of magnitude. Therefore, this project will develop a commensal VLBI observing programme that works hand-in-hand with regular experiments. This will involve efficiently identifying the locations of radio sources in low resolution data (either from existing catalogues, or from the short-baseline data in the VLBI observations; aka “on-the-fly” selection) and then selecting these targets for VLBI analysis. This will require the student to work closely with other members of the team at UP, who are developing techniques for efficiently creating multiple VLBI datasets from a single observation. Here, the student will develop the initial imaging and target selection for correlation, and build an automated pipeline so that the datasets can be efficiently analysed. This work will have an immediate impact through increasing the number of VLBI detected radio sources by up to 2500 per year, which will be informative for the work being done at lower angular resolution with MeerKAT, but will also show the importance of having 5 to 200 mas resolution imaging, demonstrating the feasibility and scientific merit of developing an SKA-VLBI array. From these data, the student can potentially investigate the astrophysical processes associated with star-formation, black hole activity, and high-energy phenomena, but they can also test models for dark matter and dark energy using gravitational lensing. The science focus will be left to the interests of the student.

2. Feasibility:

The data for this project will come, in the first instance, from single-target e-MERLIN+EVN (including HartRAO) experiments that are led by the PI and members of their team. These data are typically extremely sensitive (~5 to 10 μJy / beam) and have baselines sensitive to structure on 700 to 5 mas-scales, with an average beam-size of around 15 mas. These datasets are ideal for probing galaxy structure and formation given the wide-range of angular-scales that they probe. Once the methodology has been demonstrated, it will be applied to a commensal wide-field VLBI programme that runs in parallel to standard EVN experiments; this will provide the large number of detections needed for the science goals of the project.

In recent years, wide-field VLBI techniques have matured to the point that shallow/wide and deep/narrow surveys have been carried out (Deller & Middleberg 2014; Radcliffe et al. 2021). The basic model of creating multiple-phase centres exists, but this has been reliant on having pre-existing imaging to determine the phase centres and has been limited by the prohibitive processing time at the correlator. The pipelines developed during these surveys already exist, but will need to be modified to take into account the "on-the-fly" source selection proposed here. This should be rather straightforward as pipelines for analysing the e-MERLIN component of the data exist.

The project will also be intensive in terms of the required computing. In the first instance, we will use the facilities provided by IDIA for testing and producing initial results, before using a new compute cluster being procured at the University of Pretoria for joint correlation and data analysis of the large-scale wide-field VLBI commensal project. We are in the process of acquiring 150 TB of disk space for local data processing at UP. However, we already have funds (~R 1M) to purchase ~1.5 PB of disk space to store the VLBI data from 1 year of observations. Over the last year (2023), the group at UP has started correlating EVN data on-site and will start testing on National HPC facilities in 2024.

3. SARAO research priority areas:

The project directly ties in with the following main SARAO postgraduate research focus areas in 2025:

> *Topics exploiting data projected to be available by 2024 from key existing radio astronomy instruments located in South Africa.*

In particular, this project will use data that involves HartRAO as part of a VLBI array, in the first instance, and then MeerKAT when it becomes available for VLBI.

4. Qualifications, academic abilities, skills and/or experience:

The PhD student should have a background in radio astronomy techniques with an interest in imaging/calibration and pipeline development in Python.

Section C. Curriculum Vitae

Personal Details

Name: Prof. John McKean
Position: National Facilities SARChI in Very Long Baseline Interferometry (VLBI)
Institution: SARAO / University of Pretoria
Email: john.mckean@up.ac.za

Education

- PhD Radio Astronomy, 2004, University of Manchester
- MSci (Hons) Physics and Astronomy, 1999, University of Glasgow

Awards, Distinctions, Fellowships

- Marie Cure Research Fellowship (2005–2007), Max Planck Institute for Radio Astronomy
- Postdoctoral Scholarship (2003–2005), University of California, Davis
- PPARC (UK) PhD Studentship (1999–2002), University of Manchester

Leadership Positions

- National Facilities (SARAO) SARChI Chair Holder in VLBI, *"Probing the Nature of Dark Matter with Very Long Baseline Interferometry",* (R 11M)
- NWO-CAS, "*Testing galaxy formation on the smallest sales with gravitational lensing",* (R 9M)

Employment History

- Professor, University of Pretoria, 2023—present
- Associated Professor, University of Groningen, 2013—present
- Associated Scientist, Netherlands Institute of Radio Astronomy, 2013—2023
- Institute Fellow, Netherlands Institute of Radio Astronomy, 2009—2013
- Institute Fellow, Max Planck Institute for Radio Astronomy, 2005—2008
- Postdoctoral Scholar, University of California

Teaching

- *Introduction to Radio Astronomy,* University of Groningen, BSc Astronomy, 2014—present

Research Interests

- Continuum studies (LOFAR, VLBI)
- Active Galactic Nuclei and star-formation activity (triggering, feedback)
- Gravitational lensing (surveys, dark matter, high redshift Universe)
- Machine learning (source detection and characterisation)

Supervision

- 3 Postdoctoral Fellows (since 2018)
- 11 PhD Students (since 2008)
- 15 MSc Students (since 2016)
- 31 BSc Students (since 2015)

Publication Metrics

- 133 refereed papers (4 in *Nature*, 1 in *Science*)
- 8818 citations
- *h*-index = 47

Select Publications

1. *"A machine learning based approach to gravitational lens identification with the International LOFAR Telescope"*, Rezaei et al., 2021, MNRAS, 517, 1156
2. *"Gravitational lensing in LoTSS DR2: extremely faint 144-MHz radio emission from two highly magnified quasars"*, McKean et al., 2021, MNRAS, 505, L36
3. *"LOFAR imaging of Cygnus A - direct detection of a turnover in the hotspot radio spectra"*, McKean et al., 2016, MNRAS, 463, 3143
4. "*LOFAR: The LOw-Frequency ARray"*, van Haarlem et al., 2013, A&A, 556, A2
5. *"Gravitational detection of a low-mass dark satellite galaxy at cosmological distance"*, Vegetti et al., 2012, Nature, 7381, 341
6. *"High-resolution imaging of the anomalous flux ratio gravitational lens system CLASS B2045+265: dark or luminous satellites?",* McKean et al., 2007, MNRAS, 378, 109
7. *"The Cosmic Lens All-Sky Survey - II. Gravitational lens candidate selection and follow-up",* Browne et al., 2003, MNRAS, 341, 13