(PhD) Sparsity-based methods for multi-frequency, rotation measure synthesis deconvolution

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Dr Julien N. Girard (RATT/Rhodes & AIM/CEA-Saclay) (jgirard@ska.ac.za / julien.girard@cea.fr)

Recent progress in compressive sensing (CS) methods has yielded a number of deconvolution algorithms based on the sparsity assumption of the sky that seem far better at recovering extended emission than CLEAN and its multiscale variations. For example, the MORESANE (Dabbech et al. 2015, arXiv:1412.5387) algorithm as implemented and released by J. Kenyon (Rhodes PhD student, see http://github.com/ratt-ru/PyMORESANE) has already given us the deepest-ever images of Cyg A in S-band (using JVLA data). Other promising algorithms include PURIFY (Carrillo et al. 2014) and LOFAR-CS (Garsden at al. 2015, arXiv:1406.7242 -- one of the key developers of the latter did a postdoc at Rhodes/SKA SA and remains a collaborator of the project). New work by Ferrari et al. (2015, arXiv:1504.06847, same team as MORESANE) has extended this work into the multi-frequency regime (and other teams are working on similar extension). We propose to develop, jointly with the Ferrari et al. team (and possibly other teams, e.g. using Morphological Component Analysis at AIM), a sparsity-based deconvolution method for full-polarization multi-frequency rotation measure (RM) synthesis.
Relevance to MeerKAT and the SKA. MeerKAT and SKA1 will enable wide-band radio observations to unprecedented sensitivity. A lot more faint extended and polarized emission will be detectable, but the wide frequency band makes it crucial to incorporate the frequency and polarization axis into the deconvolution process if the full potential of these instruments is to be realized.

(MSc/PhD) Bayesian Inference for Polarimetric Calibration

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Prof. R. Taylor (UCT/UWC) (russ@ast.uct.ac.za)

Recent work on BIRO (Bayesian Inference for Radio Observations) by Lochner at al. (2015) and Natarajan et al. (in prep.) has demonstrated the promise of Bayesian inference techniques in the domain of radio interferometric calibration. We now propose to apply BIRO to polarization calibration. Accurate polarization calibration in radio interferometry is a difficult problem, as the instrumental polarization leakage terms interact with the time-variable gain terms, and also need to be disentangled from intrinsic source polarization. The matrix-based radio interferometry measurement equation (RIME) provides a complete mathematical model for forward modelling of this process; inverting the model to go from observed visibilities back to polarization properties is a different matter. The Bayesian approach seems ideally suited to this, its particular strength being the ability to map out correlations between instrumental and scientific parameters while imposing prior constraints.
Relevance to MeerKAT and the SKA. A number of key MeerKAT and SKA1 surveys will rely on accurate polarimetric calibration to achieve their science goals. The problem is especially severe with the linearly polarized feeds employed by KAT-7, MeerKAT and SKA1. Urgent progress on this problem is required.

(PhD) Understanding the Limits of Interferometric Techniques for Epoch of Reionisation Detection

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Prof F.B. Abdalla (UCL/Rhodes) (fba@star.ucl.ac.uk)

The Epoch of Reionisation (EoR) is the next frontier for the cosmologist. The faint signal arising from this epoch can be measured by radio interferometers at low frequencies capturing the redshifted signal from the 21cm line. However, an outstanding issue not clearly resolved by any current EoR experiment is that calibration issues could plague this signal and prevent a clear detection from taking place. In particular, it is possible that direction dependent effects (DDEs) will change the nature of this signal and smear any possible detection. We propose to investigate how DDEs affect this cosmological signal, and whether the statistical properties of this signal are maintained after DDEs are calibrated out, and more specifically if the magnitude of the fluctuations is maintained. The student would obtain simulations of the 21cm signal, pass them through a radio interferometry simulator, and obtain visibilities which would be corrupted with a direction dependent signal. This signal would be calibrated with DD-solution algorithms such as SAGECAL or StefCal, and the signal would be remeasured and compared to the original input. The result of this research would place clear constrains on our ability to measure the EoR signal using current and future interferometers, and inform the calibration strategy of future EoR experiments, and

(PhD/MSc) Analyzing The Impact Of Ghosts On Future Cosmological Radio Surveys

Supervisors: Prof O. Smirnov (osmirnov@gmail.com),
Prof F.B. Abdalla (UCL/Rhodes) (fba@star.ucl.ac.uk)

Ghosts are calibration artefacts that are always present in radio maps (even if only below the noise) that are calibrated with incomplete sky models, as would be the case for any blind survey. While the presence of ghosts and the mechanism by which they form has been conclusively established (see recent work by Grobler, Smirnov et al.), their impact on the science performance of future deep surveys needs to be studied. Ghosts show up in specific configurations determined by the interferometer layout, and In principle affect the statistical distribution of galaxies in an image. The aim of this project is to obtain a scientific measure of how much ghosts affect the power spectrum in the intensity mapping of galaxies and to determine if they are serious enough to put a show-stopper in cosmological measurements of the galaxy distribution. The student would attempt to calibrate radio data with incomplete models and hence obtain images with ghosts and obtain a measurement of the n-point correlation functions to measure cosmological parameters. These measurements would be biased due to the presence of calibration ghosts. The magnitude of the measurements would yield information about how well calibration needs to be done (i.e. how deep the sky models need to be) in order to obtain correlations of galaxies which are not corrupted by the

presence of ghosts. Other related observational techniques such as intensity mapping. this is directly relevant to SKA1 and SKA2. The results of this work will inform the calibration strategies for the next generation of deep radio surveys with JVLA,
MeerKAT and SKA1.

(PhD) TiRiFiK - better than TiRiFiC II

Supervisors: Dr G. I. G. Józsa (gigjozsast@gmail.com)
Prof O. Smirnov (osmirnov@gmail.com)
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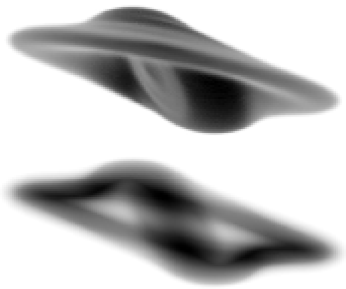
Prof K. Spekkens (Kristine.Spekkens@rmc.ca)



TiRiFiC model of a warped galaxy, opaque (top) and translucent (bottom)

In this project, the student will participate in the (re-)development of an astronomical toolkit to simulate spatially resolved spectroscopic observations of neutral hydrogen (HI) and other species in galaxies. In addition, a set of methods to automatically adjust the model parameters to optimally fit the simulation to existing observations will be investigated (including Bayesian approaches). Finally, an automated heavy-duty analysis pipeline for use in large volume galaxy surveys will be developed and implemented.

While pilot studies have demonstrated the success of the technique, the challenge is to create a comprehensive, flexible, and fast set of software components that can be combined quickly by any user at a high level. One goal is to optimally serve a large number of use cases, already providing the most important application, the automated parametrisation of large survey data. At the same time, shortcomings of existing software packages will be addressed, and the scope of existing software will be widened, including additional and alternative parametrisations.

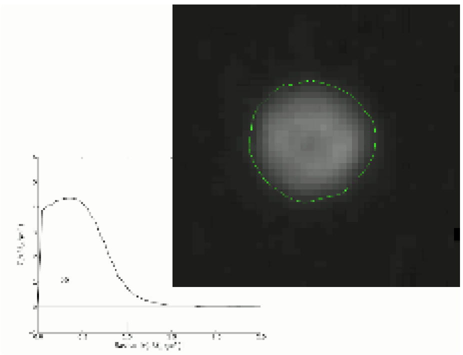
The basic concept has been investigated and prototype software is available (TiRiFiC/FAT, 3D-BAROLO). Briefly, a galactic disk is simulated according to the (tilted-ring) input parameters, projected onto a 3d spectroscopic data cube, artificially observed via a convolution, and the result compared to an input data cube to return a goodness-of-fit measure. This procedure is repeated with the goal of changing the parametrisation to optimally fit the observation.

TiRiFiK aims at an improved implementation of this concept. The toolkit will consist of low- and high level modules (e.g. written in C and Python or Cython) that can be accessed as objects of a higher-level language (Python), all accessible to the average astronomer. Based on the success and availability of time, the student will work on the implementation of the software in data processing pipelines.

(PhD) 3d stacking of neutral hydrogen in galaxies

Supervisors: Dr G. I. G. Józsa (gigjozsast@gmail.com)
Prof O. Smirnov (osmirnov@gmail.com)
Dr K. Geréb (kgereb@swin.edu.au)

We will investigate the possibility to stack (add) spatially resolved neutral-hydrogen (HI) line profiles of galaxies, as observed with radio interferometers, to enhance the average signal.

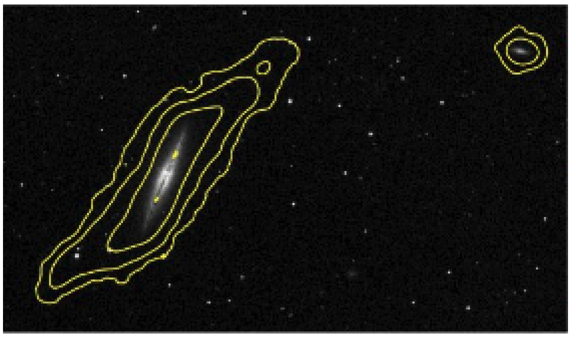


Averaged profile of 56 suitable galaxies in the WHISP survey, pilot study by Johansson et al.

Doing so, the we will study in detail the effects of calibration errors and deconvolution residuals by means of simulations. Working with existent H I data, first archive data from the WSRT, then with MeerKAT and ASKAP data, the student will provide resolved average observations of galaxies down to a column density normally not available in HI studies.
Stacking techniques make it possible to study average galaxy properties to much greater depth than an individual observation would allow. In the best case the noise shrinks proportionally to the number of added profiles or pixels. Stacking global line profiles of individual galaxies is a well-tested method and has been applied using unresolved H I observations to e.g. derive the average H I content of early-type galaxies.
However, with the SKA and its progenitors, e.g. MeerKAT, a large amount of galaxy observations will become available, in which the H I is spatially resolved. By averaging the signal of resolved targets to radial profiles (e.g. column density profile and rotation curve), and adding the individual observations, their (average) gas physics can be explored at much lower H I column densities. At least two questions highly relevant to galaxy evolution theory may be answered when analysing H I in emission in the reachable low column-density regime of $10^{17} - 10^{19}$ atoms cm^{-2} . Do spiral galaxies show a photoionisation edge in their H I component and what is the average slope of the rotation curve in the outskirts of galaxies? Making use of stacking it is in principle straightforward to reach the goal of detecting H I below the column densities of $0.5 \cdot 10^{19} - 1.0 \cdot 10^{19}$ atoms cm^{-2} , which are the limits of today's deepest extragalactic H I surveys (e.g. HALOGAS) targeting objects outside the local group. However, it is not clear whether systematic effects will indeed allow us to push below these limits. The main goal of this work is hence to thoroughly investigate the systematic effects occurring in the stacking process. Only if we can show that we have those under control, we will indeed attempt to coadd H I profiles in spatially resolved galaxies. In any case, the student will gain a detailed knowledge of interferometric data reduction and extragalactic H I science. The project comprises research in the context of galaxy evolution and the development of analysis tools for interferometric data.

(PhD) Intrinsic and external spin alignment of disk galaxies - a pilot

study



The spiral galaxy NGC 4013, optical DSS image overlaid with HI contours. The spin axis of the galaxy changes with increasing radius, it shows a typical "warp".

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In this pilot study, the spin orientation of the neutral hydrogen (HI) disks of a sample of gas-rich galaxies will be determined using interferometric spectroscopy and 3d tilted-ring modelling. The goal is to develop the technical ability to search for systematics in the HI spin alignment.

Disk galaxies acquire their star forming material continuously. Larger galaxies appear to grow inside-out with the largest-angular-momentum material being accreted most recently. Observations suggest that direct accretion of cool gas along cosmic filaments, settling at larger and larger radii, probably plays a significant role in the gas budget of galaxies. If this mechnism is indeed dominant, one would expect a preferred orientation of the spin vector at large radii, pointing into cosmic voids. However, torquing by the inner galactic disks, by interacting galaxies, by the Dark Matter halo, by winds, etc. might wash out this effect.

One would hence naively expect that the outer disks of galaxies would be better aligned with the cosmic structure than is already observed for the inner, stellar component of galaxies.

Galaxy disks are expected - and commonly observed - to be bent, or "warped". The effect of outer disks of galaxies preferrably bending with their angular momentum vector pointing into cosmic voids has been investigated using optical data, and cannot be excluded. However, since warps become most prominent beyond the bright optical disks and can be much better quantified using spectroscopy (tilted-ring modelling), future HI surveys with the SKA and its progenitors will mean a quantum leap for this kind of study.

This study will make use of small surveys (WHISP and Bluedisk), and a detection of the described effect cannot be guaranteed. But it will provide an invaluable input to this or similar future analyses of HI surveys.

(PhD) Blue Early Type Galaxies with MeerKAT and other telescopes

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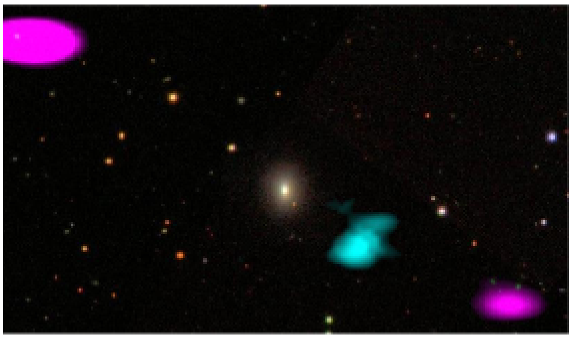
Dr O. I. Wong (ivy.wong@uwa.edu.au)



The galaxy J0836+30 in the optical, HI (cyan), and 21cm radio continuum. The gas in this object is displaced with respect to the galaxy in the direction of potential hot spots, indicating a possible connection of the HI displacement with the presence of radio jets.

In this study, we will embark on a multi-wavelength campaign to study the nature of Blue Early Type Galaxies.

Normally, galaxy either belongs to the population of blue, gas-rich spiral galaxies or it is a red, gas-poor elliptical galaxy. To understand cosmic evolution it is crucial to understand the evolution into this bimodal distribution, and to understand whether and how transitions from one type to the other take place. A clue might be provided by (rare) intermediate or mixed types.

Blue Early Type Galaxies (BETGs) appear blue, which is a signature of star formation, either ongoing or very recent, and yet their optical shape is that of an elliptical galaxy. We have argued that they are a fast transition type from spiral to elliptical. In that picture star formation is shut down rapidly, potentially induced by nuclear activity. This is supported by interferometric observations showing that with increasing stellar age the cool neutral gas is found further away from the galaxies as if being pushed out. Other studies claim that BETGs would have recently acquired gas and re-start (some) star formation.

To solve the question what BETGs are, multiwavelength studies of a larger sample are required. We hence propose a PhD project to conduct a targeted survey of a moderate number of (~35) Blue Early Type Galaxies with MeerKAT, other radio telescopes (HI and continuum to study HI structure and kinematics and nuclear activity), and optical telescopes (deep photometry to identify past interactions and the star formation history, spectroscopy to characterise nuclear and star forming activity), starting with the definition of the sample, to perform observations, data reduction, and analysis. Such a study has the potential to strongly support or disprove the hypothesis of gas-removal by kinetic feedback or gas accretion by gas capture.

(PhD) Gravitationally lensed HI with MeerKAT and the SKA

Supervisors: Dr Roger Deane (r.deane@ru.ac.za)
Dr Ian Heywood (ian.heywood@csiro.au)

Strong gravitational lensing provides the deepest views of the Universe through its magnification of the solid angle of distant galaxies combined with the conservation of surface brightness. It enables studies of high-redshift galaxies only possible with next-generation facilities without the lensing phenomenon. To date, HI has only been detected directly out to redshifts of ~0.2, limited by the sensitivity and frequency range of current radio telescopes.

MeerKAT and SKA1-MID will dramatically change this picture, pushing out to redshifts of z~1 for the several thousand hour surveys proposed.

However, what has not been considered in the MeerKAT science case, is the ability to detect gravitationally lensed HI emission in high-redshift galaxies. The instantaneous bandwidth and sensitivity of MeerKAT will yield the potential to produce high-impact early science. In our recently published MNRAS Letter (Deane, Obreschkow & Heywood, 2015), we demonstrate that SKA precursors have the potential to make the highest redshift HI detections to date within a fraction of the total duration of the deep HI surveys, provided the appropriate targeted lensed surveys are designed.

The primary objectives of this PhD project are fourfold:

1) design and optimise a MeerKAT lensing survey on known lensed systems

2) use current instruments (including MeerKAT-16/32) to make the highest redshift HI detections to date

3) use our large-scale HI simulation (SAX-Lens) in combination with machine learning techniques to determine source prioritisation best practices for multi-wavelength followup of the expected >10,000 lens candidates in SKA1-MID surveys

4) investigate the ability of SKA1-LOW to detect the highest redshift HI galaxies

This ambitious programme is enabled by the significant hardware and software successes within the MeerKAT programme and Rhodes University, providing an opportunity to lead this scientific field into the SKA era.

(PhD/MSc) Wide-field cm-VLBI surveys in the MeerKAT era

Supervisors: Dr Roger Deane (r.deane@ru.ac.za)

While MeerKAT's high sensitivity and wide field-of-view will enable deep surveys over large area, these will be limited to >5 arcsec angular resolution (at 1.4 GHz), which is not sufficient to discern radio jets from star formation in galaxies beyond the local Universe. This is of key importance for a number of MIGHTEE science objectives, particularly tracing the star formation rate history of the Universe and understanding the role of mechanical feedback in galaxy evolution. VLBI will also play an important role in HI emission and absorption components of MIGHTEE, contributing unique morphological insights to the interpretation of gas inflows and outflows in particular (e.g. Morganti et al. 2013). VLBI polarimetry will not only provide detailed information on sub-kpc magnetic fields and jet physics, but also enable comparison with (and separation from) the larger scale polarisation properties to be probed by MeerKAT (e.g. Agudo et al. 2015). Finally, wide field VLBI surveys will enable the discovery of exotic objects such as binary supermassive black holes and strong gravitational lenses.

Many MeerKAT extragalactic large survey programmes would therefore be significantly enhanced by matched sensitivity VLBI observations across a significant fraction of the selected fields. This student project forms part of the MIGHTEE-VLBI working group (chairs: Deane and Agudo) and perform deep VLBI surveys over the relevant extragalactic fields. Additional survey objectives will include multi-epoch VLBI imaging in order to select sources based on their milli-arcsecond flux variability; and to incorporate e-MERLIN observations where possible to bridge the L-band uv-coverage between the MeerKAT and VLBI components, enhancing the interpretation of both. The student will actively incorporate the wide range of cutting-edge interferometric calibration and imaging algorithms in development within the RATT group.

The wide FoV requirement naturally places an emphasis on MIGHTEE-VLBI observations in the L-band, which will have highest priority. However, we expect to perform multi-band VLBI on selected subsamples, the focus of which may be on S-band to combine with the corresponding MIGHTEE component. In this regard, this project will also monitor the status and capabilities of the African VLBI Network (currently with no L-band receiver plans), which would provide important uv-coverage between the intra-European and European-MeerKAT baselines.

(PhD/MSc) Studying the Epoch of Reionization with HERA

Supervisors: Dr. Gianni Bernardi (giannibernardi75@gmail.com)
Dr. Trienko Grobler (trienkog@gmail.com)

Our current understanding of the cosmic evolution from the epoch of Hydrogen recombination (300000 years after the Big Bang) till the first billion years is very poorly known from an observational perspective, although it must have seen the growth of the initial density perturbations via gravitational attraction into the first stars and galaxies.
The 21cm transition from neutral Hydrogen promises to be the best observational probe of such cosmic time and has driven the construction of the new generation of low frequency radio arrays. The HI Epoch of Reionization Array (HERA) is the next generation of such low frequency arrays and is a partnership between several US, UK and South African institutions. The first 19 HERA dishes have now been built, with 37 elements expected to be completed by September 2016 and 240 elements by 2019, becoming, by then, the most sensitive 21cm telescope in the pre-SKA era.
We are seeking for an ambitious PhD candidate who is willing to become an observational 21cm cosmologist and is ready to face the many challenges that such field presents. The candidate will be able to participate in the HERA commissioning activities as well as its data analysis towards measurements of the 21cm signal. In particular, the candidate is expected to work on the crucial topic of foreground subtraction and 21cm power spectrum estimation. As HERA is a collaborative effort, the candidate is expected to work together with the US and UK partners.
An ideal candidate will have a good background in physics and mathematics, the willingness to learn about advanced radio interferometry, statistics, signal processing techniques and cosmology, but, mostly, the desire to contribute to the 21cm cosmology revolution

(MSc) Observations of diffuse radio emission in galaxy clusters

Supervisors: Dr. Gianni Bernardi (giannibernardi75@gmail.com)

Prof. Oleg Smirnov (osmirnov@gmail.com)
Dr. Trienko Grobler (trienkog@gmail.com)

Galaxy clusters are the largest gravitationally bound structures and emit electromagnetic radiation at almost all wavelength. In particular, some of them host diffuse, Mpc scale, low surface brightness radio emission that has been the subject of intense investigation over the last two decades. Developments in recent observations and theoretical models suggest that such structures are created by merging events, when magnetic fields are amplified and particles re-accelerated to relativistic energies but additional observations are required to further test models.
The candidate will have the opportunity to work on Westerbork observations of clusters (A773, A781 or the Perseus) that are particularly interesting as they have been selected for their active dynamical state. He/she will be reducing the data, carrying out the scientific analysis and interpretation of the results. Observations of diffuse emission from galaxy clusters are ideal laboratories to test advanced calibration (i.e. direction dependent calibration) and imaging techniques (PyMORESANE, DDfacet, WSClean) as they require a careful analysis to extract the low brightness surface structures.
An ideal candidate will have the interest in developing an radio observational expertise, familiarizing/developing calibration and imaging pipelines and the desire to work on a prominent field (galaxy clusters) that will be relevant for MeerKAT observations.

(PhD) Development of new calibration techniques for variable sources using the MeerKAT/KAT7 observations

Supervisors: Dr. S.K. Sirothia (sirothia@gmail.com)
Prof. Oleg Smirnov (osmirnov@gmail.com)

The project is divided into multiple parts
(i) Develop a method to identify variable sources while mapping using the existing multi-epoch data of MeerKAT AR1. Example of Extragalactic variable sources are blazars and galactic variable sources are pulsars .
(ii) Study the impact of these variability on calibration solutions and dynamic range of the map. These sources will directly affect direction dependent solving techniques, whereby the source variability will get attributed to instrumental and beam related errors, thereby also spoiling flux density measurements of sources in their vicinity.
(iii) Subsequently, develop new calibration techniques taking into account the variability of such sources and improve dynamic range of map.

During first year method will be developed to identify variable sources. Flux density, time series related study of extragalactic variable sources, like blazars and galactic variable sources like pulsars using the existing multi-epoch data of MeerKAT AR1 to establish and quantify the effect. During second year we study the impact of these variability on calibration

solutions and dynamic range of the map and develop new calibration techniques.
During third year special emphasis will on
(a) develop new calibration techniques taking into account the variability of such sources
(b) subsequently, high dynamic range images will be made taking into account the variability of such sources.

Multi epoch data of selected fields from MeerKAT AR1/KAT7 archive will be used. Some of the datasets have specifically been obtained by proposer for such studies. No new observations and proposals are being required for this purpose.

Relevance of the research to the research priority areas of MeerKAT and SKA: Presence of variable sources in any field impact calibration solutions and dynamic range of map. In addition, the direction dependent solving techniques gives undesired results, whereby the source variability will get attributed to instrumental and beam related errors, and even result in spoiling the flux density of sources in the immediate vicinity of such variable sources. The project attempts to address issues so that the flux density accuracy and dynamic range of the images from MeerKAT and SKA can be improved.

(MSc) Developing advanced beam models of MeerKAT antennas using interferometer data

Supervisors: Dr. S.K. Sirothia (sirothia@gmail.com)
Prof. Oleg Smirnov (osmirnov@gmail.com)

The image is obtained by combining visibilities from various antennas having varied beams. A nominal primary beam correction is applied to the image, to get the true image. However, the interferometric image beam could be widely different from individual antenna beams. Techniques will be developed to measure the combined interferometer beam using the data used for mapping, and errors will be quantified as compared to individual antenna beams.

During the first year the candidate will learn the analysis techniques for making MeerKAT AR1 images. Also a framework will be developed to determine beam using the data, using sources and noise maps of the field of view. During second year the analysis technique developed for determination of beam will applied on actual cases and results compared with those obtained from the conventional methods of beam measurements.

Test observations using MeerKAT AR1 will be used for the purpose of determination of primary beams of individual antennas and the combined interferometer beam, simultaneously with the observations.

Relevance of the research to the research priority areas of MeerKAT and SKA: Accurate primary beam correction is essential for making wide field maps and surveys. Conventionally, individual antenna beams are separately measured and their models are used for primary beam corrections while mapping. The project aims to determine the primary beams of individual antennas using the visibility data during the observation in interest. The method could improve flux density accuracy from interferometric arrays like MeerKAT.