MeerKAT L-Band Primary Beams: Effects of HI Intensity Mapping

Theo Narh
Ghana Atomic Energy Commission

- Operational instrument is situated in the Karoo of South Africa.
- It is made up of 64 offset Gregorian dishes.
- The diameter of the main dish is 13.5 m.
- Secondary reflector is 3.8 m.
- The interferometer has a maximum baseline of 8 km.
- There are four feeds on each receptor with the L-band having a frequency range of $0.9 - 1.67\,\mathrm{GHz}$.

- The offset design of MeerKAT provides a better aperture efficiency, a symmetric beam pattern with a decrease in the side-lobes and an increase in the antenna gain.

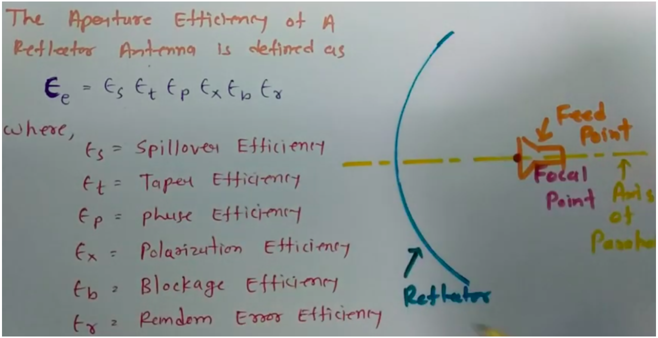

Figure: Aperture efficiency. *Source*: Engineering Funda Lecture, 2018

- Almost 70 % of the receptors are found in the core area of 1 km in diameter.

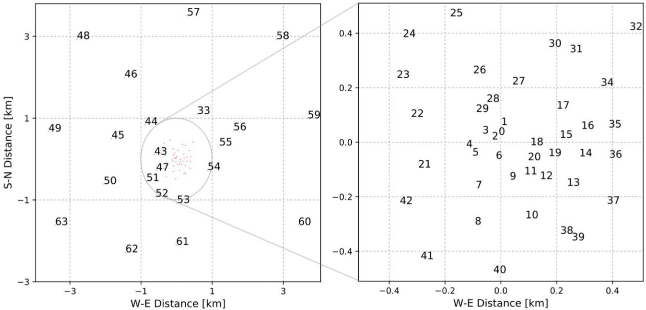

Figure: Distribution of the 64 antennas of MeerKAT.

MeerKAT: Holographic observation

- In radio interferometry, holographic observation is used to measure the complex beam pattern of an antenna.
- The technique cuts out the need for slew scans in the traditional way, and hence reduces the tracking period.

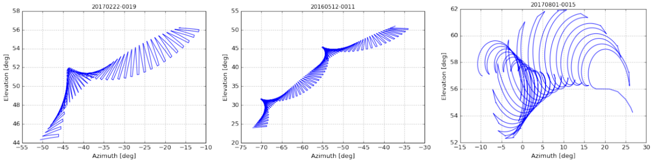

Figure: Raster scanning patterns of three of the astro-holographic observations of MeerKAT.

- Undesirable RFI corrupts many frequency channels in a holographic observation.
- The source of RFI can be resolving satellites and other terrestrial radio emissions.
- Therefore, it is important to introduce a mathematical model to reconstruct these perturbed holography measured beams.

MeerKAT: Holographic observation

- In the paper, we demonstrated three different semi-analytic techniques, namely, Principal Component Analysis (PCA), Spherical Harmonics (SH) and Zernike polynomials (ZP) to model the measured beams.

Astrophysics > Instrumentation and Methods for Astrophysics

Primary beam effects of radio astronomy antennas - II. Modelling the MeerKAT L-band beam

K. M. B. Asad (1, 2, 3), J. N. Girard (4), M. de Villers (3), R. Lehmensiek (5, 6), T. Ansah-Narh (1), K. Iheanetu (1), O. Smirnov (1, 3), M. G. Santos (2, 3), J. Jonas (3, 1), D. I. L. de Villiers (7), K. Thorat (1, 3), B. Hugo (1, 3), S. Makhathini (1), F. Camilo (3), G. I. G. Jozsa (1, 3, 8), S. K. Sirothia (1, 3) ((1) Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa, (2) Department of Physics and Astronomy, University of the Western Cape, Bellville, Cape Town, South Africa, (3) South African Radio Astronomy Observatory, Cape Town, South Africa, (4) AIM, UMR CEA-CNRS-Paris 7, Irfu, Service d'Astrophysique, France, (5) EMSS Antennas, Stellenbosch, South Africa, (6) Cape Peninsula University of Technology, South Africa, (7) Department of Electrical and Electronic Engineering, Stellenbosch University, Stellenbosch, South Africa and (8) Argelander-Institut für Astronomie, Germany)

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After a decade of design and construction, South Africa's SKA-MID precursor MeerKAT has begun its science operations. To make full use of the widefield capability of the array, it is imperative that we have an accurate model of the primary beam of its antennas. We have used an available L-band full-polarization astro-holographic observation and electromagnetic simulation to create sparse representations of the beam using principal components and Zernike polynomials. The spectral behaviour of the spatial coefficients has been modelled using discrete cosine transform. We have provided the Zernike-based model over a diameter of 10 degrees in an associated software tool that can be useful for direction dependent calibration and imaging. The model is more accurate for the diagonal elements of the beam Jones matrix and at lower frequencies. As we get more accurate beam measurements and simulations in the future, especially for the cross-polarization patterns, our pipeline can be used to create more accurate sparse representations of MeerKAT beam.

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Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**
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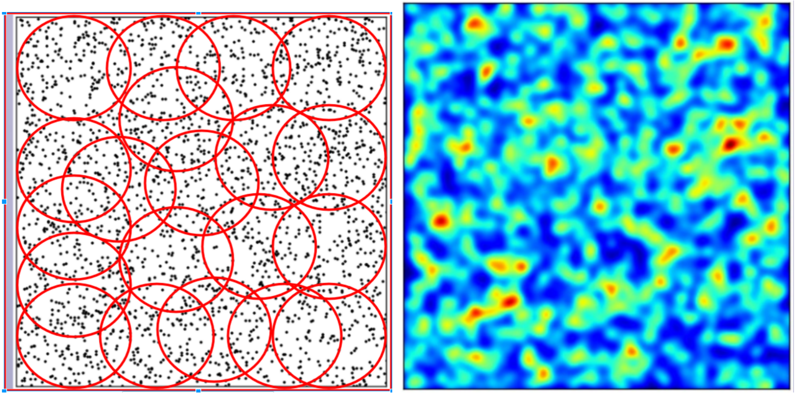
(or arXiv:1904.07155v1 [astro-ph.IM] for this version)

Figure: https://arxiv.org/abs/1904.07155.

How corrupt PBs affect Intensity mapping



(a) (b)

Figure: Simulated variations in the 21 cm emission brightness temperature. The red rings in (a) show how to perform IM experiment by observing multiple patches in the sky with the radio telescope in order to measure the 21 cm emission to produce (b).

- Dutch physicist and winner of the Nobel Prize for physics in 1953.
- image classification
- image reconstruction
- image retrieval

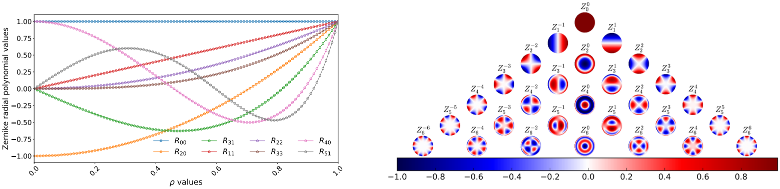
- The polynomials $Z_\beta^\alpha(\rho,\theta)$ are a set of complete orthogonal functions over a unit disc.

$$\Phi_w(\rho,\theta) = \sum_{\beta,\alpha}^{M} C_\beta^\alpha Z_\beta^\alpha(\rho,\theta) \tag{1}$$

where the basis function or ZM $Z_\beta^\alpha(\rho,\theta)$

$$Z_\beta^\alpha(\rho,\theta) = \begin{cases} \Lambda_\beta^\alpha R_\beta^{|\alpha|}(\rho)\cos(\rho\alpha\theta), & \alpha \geq 0 \\ -\Lambda_\beta^\alpha R_\beta^{|\alpha|}(\rho)\sin(\rho\alpha\theta), & \alpha < 0 \end{cases} \tag{2}$$

How corrupt PBs affect Intensity mapping



(a) (b)

Figure: (a)Expansion of eight orthogonal radial polynomial $R^{|\alpha|}(\rho)$ plots. (b) Basis patterns of Zernike moments

MeerKAT: Complex beams

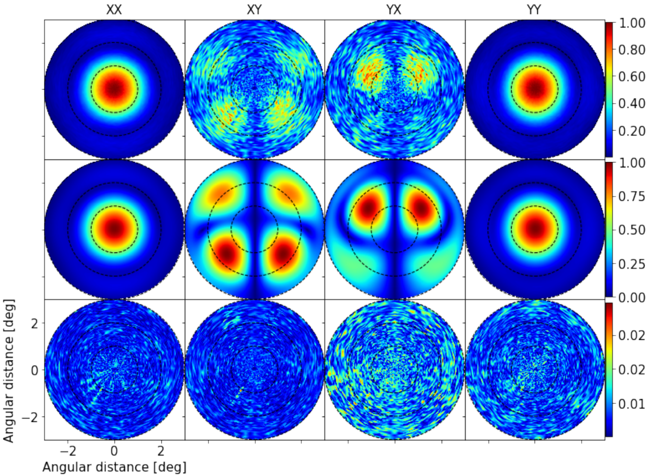
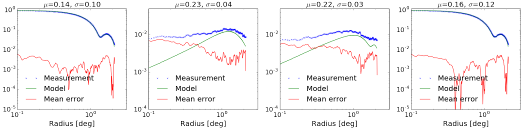
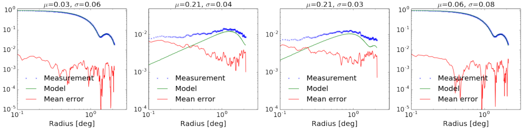


Figure: Amplitude representation of MeerKAT beam model at 990 MHz.

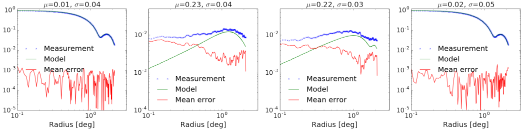
MeerKAT: Radial representation



(a)



(b)



(c)

Results: Convolved foregrounds

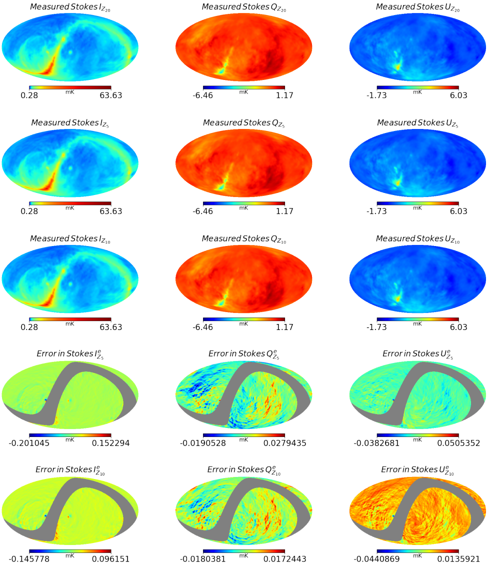


Figure: Measured Stokes I, Q and U convolved with reconstructed MeerKAT els

Results: Convolved power spectra

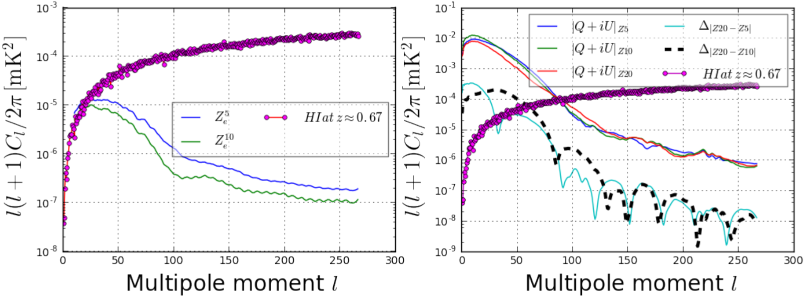


Figure: The distribution of angular power plots showing the effect of recovering the cosmological 21 cm signal when we correct for the beam errors in Stokes I to when there is no beam correction at all.

Conclusion

- The observed beams were reconstructed with 20 strongest Zernike coefficients for the gain terms of the Jones matrix (XX and YY) and 5 strongest coefficients for the cross terms of the Jones matrix (XY and YX). The maximum rms residual obtained from the reconstruction is $\backsimeq 0.05$.
- A set of corrupted beam models were generated using 5 strongest coefficients for all the Jones matrix terms (XX, XY, YX and YY). A second set of corrupted beams were created using 10 strongest coefficients for all the Jones matrix terms (XX, XY, YX and YY). The maximum rms residual obtained are 0.12 (for using 10 strongest coefficients) and 0.08 (for using 10 strongest coefficients).
- The astigmatism and coma Zernike functions turn out to have the strongest coefficients to model the cloverleaf nature for the cross terms (XY, YX) of MeerKAT beams while the piston and spherical basis functions prove to be the best model for the gain terms (XX, YY).
- If MeerKAT IM observations are corrected using a beam model where only 5 or 10 strongest Zernike coefficients are used, even then the HI signal remains higher than the residual errors at $l \geq 25$.
- If polarization leakage is not removed from MeerKAT IM observations, the HI signal will still be above the leakage above $l \sim 100$. If the leakage is removed using a perturbed model created from 5 or 10 Zernike coefficients, then the signal becomes higher than the remaining residual leakage above $l \sim 50$.