Exploring Intensity Mapping Techniques Via Simulations

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Outline

Introduction: *Intensity mapping* (IM)

- “Cheap“ way to observe large volumes of the Universe.
- Joint emission from multiple galaxies instead of resolving them.
- Smaller & "cheaper“ telescopes (eg. KAT-7) can be used.

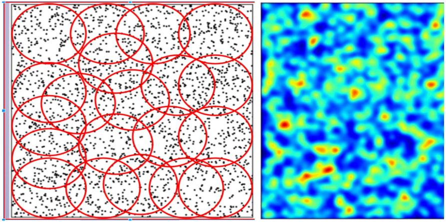


Figure: *Simulated fluctuations in the brightness temperature of 21 cm emission from galaxies. Red indicates over-density and blue under-density*

Introduction: *Challenges & Goal in IM Experiments*

- **Challenges:**
  1. Subject to DDEs (i.e. ionosphere and beam response): make telescope pointings vary with time.
  2. Due to imperfect feeds: signals tend to leak into another.

- **Goal**: Measure the amount of foregrounds that have leaked from intensity to polarisation.
  1. Produce a fully polarised beams of KAT-7.
  2. Introduce errors to distort these beams.
  3. Simulate these beams with the foregrounds of the sky to measure the leakage terms.

Notional Beam Simulation: *KAT-7 Dish Model*

- Consider KAT-7 single dish as a collection of dipoles.
- Dipole Orientation $\longrightarrow \phi \sim U(0, 2\pi)$
  1. $x_d = R\cos(\phi)$
  2. $y_d = R\sin(\phi)$
- For realistic aperture illumination: Radial distribution of dipoles is modeled as *inverse transform sampling* approach:
  1. Find the quantile function F_X^{-1}.
  2. Generate a uniform random number $u \sim U(0, 1)$.
  3. Return the random number $R_x = F_X^{-1}(u)$.

Notional Beam Simulation: *KAT-7 Dish Model*

- Consider the dipoles are drawn from the Generalized Normal distribution:

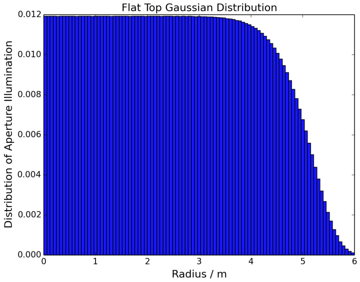
$$f_X(x) = \frac{\sqrt{s}}{2\sigma\Gamma(\frac{1}{s})} \exp\left(-\left|\frac{x-\mu}{\sigma\sqrt{2}}\right|^s\right) \qquad (1)$$

- Produces a CDF $F(x) = \int_{-\infty}^{x} f(t)dt$:

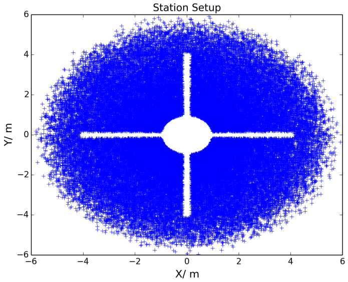
$$F_s(x) = \begin{cases} \frac{\Gamma\left(\frac{1}{s}, \{\frac{x-\mu}{\sigma\sqrt{2}}\}^s\right)}{2\Gamma(\frac{1}{s})}, & \text{if} \quad x \leq \mu \\ 1 - \frac{\Gamma\left(\frac{1}{s}, \{\frac{x-\mu}{\sigma\sqrt{2}}\}^s\right)}{2\Gamma(\frac{1}{s})}, & \text{if} \quad x > \mu \end{cases} \qquad (2)$$

- Choosing the random numbers generated to be: $0 < x < 1$, $\mu = 0$, $\sigma = 0.82$ and $s = 12.0$.

Notional Beam Simulation: *KAT-7 Dish Model*



(a) *Radial Distribution of Dipoles*



(b) *Station Layout of KAT-7 Dish*

Notional Beam Simulation: *OSKAR Beam Model*

- Beam response (in Jones terms) represents the horizontal and vertical polarization states of the signal.

$$\mathbf{J} = \begin{pmatrix} J_{00}(\nu, t, l, m, \ldots) & J_{01}(\nu, t, l, m, \ldots) \\ J_{10}(\nu, t, l, m, \ldots) & J_{11}(\nu, t, l, m, \ldots) \end{pmatrix} \tag{3}$$

- Stokes Mueller matrix representation of the primary beam.

$$M_{ij} = U\,(J \otimes J^*)\,U^{-1} \tag{4}$$

$$U = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -i & i & 0 \end{pmatrix}, \quad M_{ij} = \begin{pmatrix} I \to I & Q \to I & U \to I & V \to I \\ I \to Q & Q \to Q & U \to Q & V \to Q \\ I \to U & Q \to U & U \to U & V \to U \\ I \to V & Q \to V & U \to V & V \to V \end{pmatrix}$$

Notional Beam Simulation: *True Beam Model*

- We produce the gains and leakage terms of the beams.

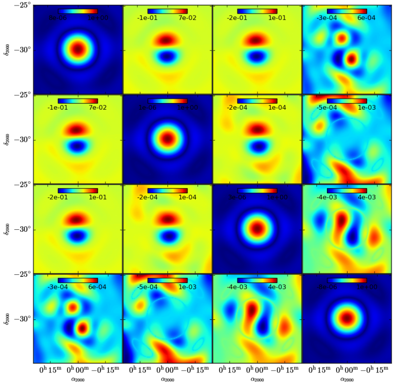


Figure: *Fully polarised non-distorted primary beams*

Notional Beam Simulation: *Corrupt True Beam Model*

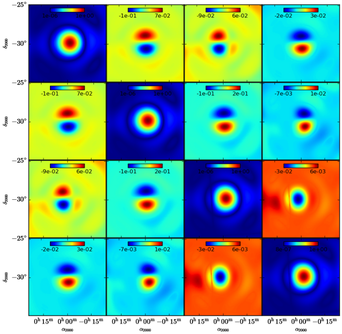
- Introduce **Gain and Phase (GP) Errors.**

$$B^w(u) = B^w_{geometric}(u)(G_0 + G_{error})\exp(i\,[\phi_0 + \phi_{error}]) \quad (5)$$

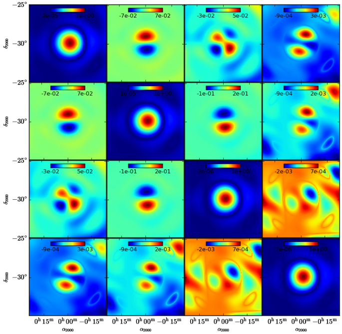
where $u = (\theta_{bm}, \phi_{bm}, x, y, z, t)$, G_{error} and ϕ_{error} are pseudo-random values at each time-step t using a Gaussian distribution with standard deviations G_{std} and ϕ_{std} respectively. We introduced 5° phase error and 10% gain error to distort the beams.

- Change the x and y - **orientation of the dipoles** to create systematic error feed angle displacement. We distorted the x and y - orientation of the dipoles by introducing $\simeq 0^\circ$ and $\simeq 1^\circ$ respectively.

Notional Beam Simulation: *Distorted Beam Model*



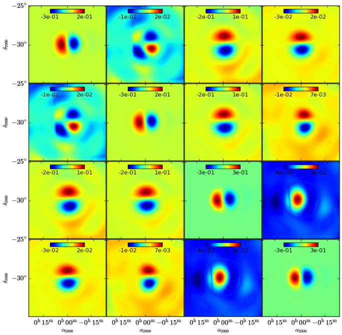
(a) Intro. gain and phase errors.



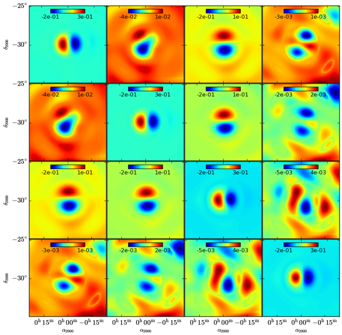
(b) Intro. dipole orientation errors.

Notional Beam Simulation: *Beam Errors*

- The diagonals are the residual leakages and the off-diagonals are the residual systematic leakages.

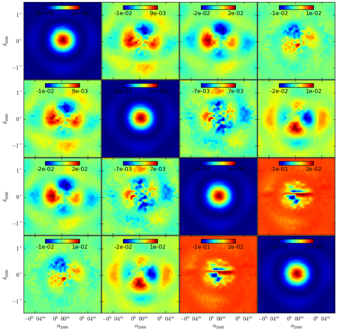


(a) Due to gain and phase errors.

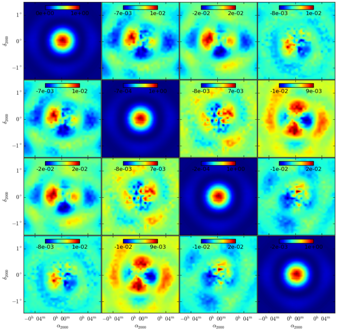


(b) Due to dipole orientation errors.

Holography Measured Beams: *VLA*



(a) *Using Antenna 5 Beams.*



(b) *Using Antenna 6 Beams.*

Holography Measured Beams: *VLA*

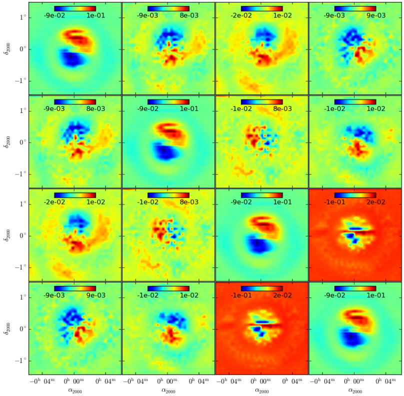


Figure: *VLA Beam Errors*

Full-sky Convolution: *convolution technique*

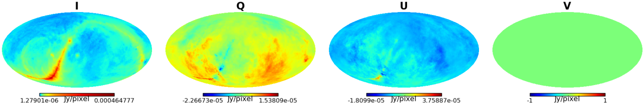
- Using **convolution technique**, we measure the overall intensity emerging from these patches:

$$
\begin{aligned}
F^{conv}(\theta,\phi) &= B_{fully}(\theta,\phi) \otimes f_{sky}(\theta,\phi) \\
&= \sum_{(\theta',\phi')=\lfloor(\theta,\phi)\rceil} B_{fully}(\theta'-\theta,\phi'-\phi).f_{sky}(\theta',\phi')
\end{aligned} \tag{6}
$$

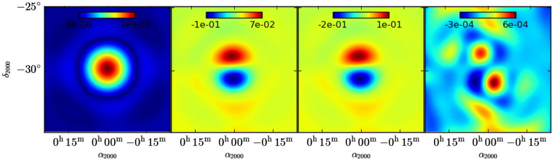
where, $(\theta',\phi') \leq npix$ and the symbol $\lfloor\,\rceil$ denotes the nearest pixels.

Full-sky Convolution: *Full-sky maps*

- The scheme used to generate the full-sky polarisation maps is described by (Shaw et al. 2015).



(a) *1000 MHz full-sky synchrotron maps simulated by using m-mode formalism.*



(b) *1st row of true polarised beams.*

Full-sky Convolution: *Using Notional Beams*

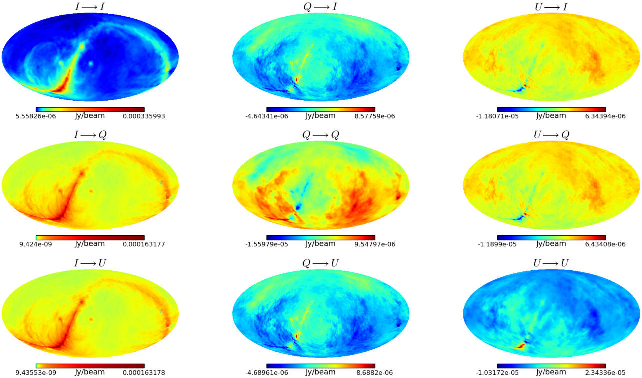


Figure: *Conv. with Uncorrupted Notional Beams*

Full-sky Convolution: *Using Notional Beams*

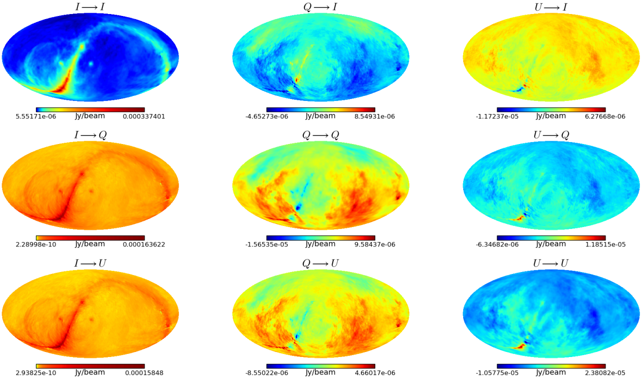


Figure: *Conv. with corrupted with gain and phase error beams*

Results: *Measured Stokes Using Notional Beams*

- Summing the convolved foreground maps across, we get the measured Stokes.

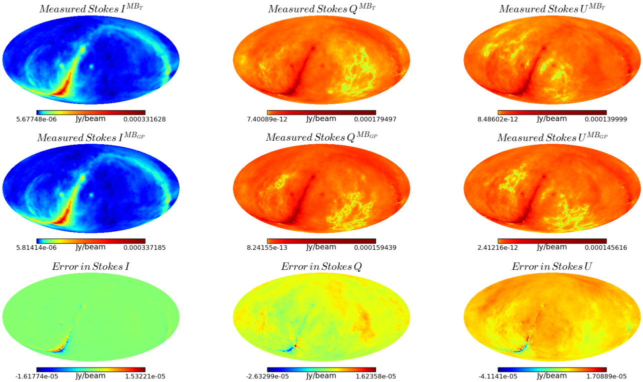
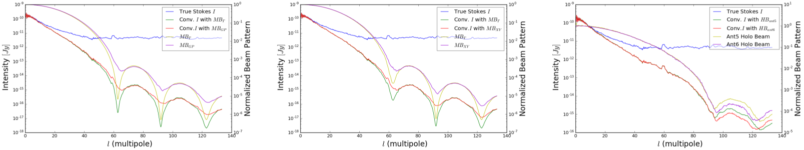


Figure: *Measured Stokes with corresponding error terms due to GP errors*

Results: *Conv. Power Spectrum in Spherical Harmonics*

- The convolved power spectrum for Stokes I for using notional and VLA beams:



(a) *True vrs GP Er. Beams.* (b) *True vrs XY Er. Beams.* (c) *VLA Holo. Beams.*

- This justifies the use of smaller and 'cheaper' telescopes for IM.

Results: *Power Spectrum of Leakage terms in SH*

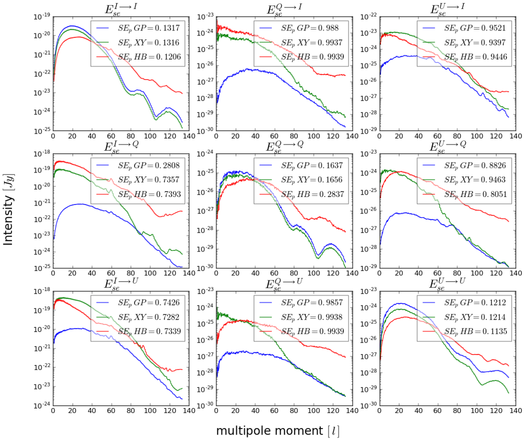


Figure: *Systematic leakage terms*

Results: *Using Notional Beams*

Table: Error in power spectrum estimation

	I **[%]**	**Q** **[%]**	**U** **[%]**
I	0.092	0.0002	0.007
Q	0.004	0.120	0.090
U	0.012	0.001	0.070

Current Research: *Raster Scan with KAT-7*

Observation parameters:

- **Number of antennas** $= 4$
- **Minimum elevation** $> 20^\circ$
- **Central frequency** $= 1328\ MHz$
- **Bandwidth** $= 400\ MHz$
- **Gain calibration** $-- > noise - injection$
- **Target(s)** $-- > 10^\circ \times 10^\circ$
- **phase centre** $-- > RA = 05h19m49.7s,\ DEC = -45d46m44s$
- **Total time on target** $-- > 4\ nights$
- **dump-period** $\approx 1.0\ sec$

Current Research: *Raster Scan with KAT-7*

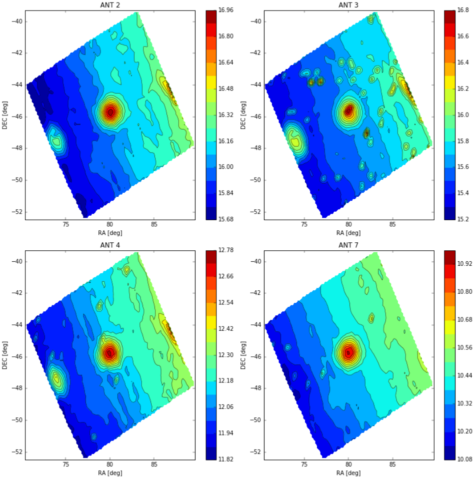


Figure: *HI source at the phase centre*

Current Research: *Raster Scan with KAT-7*

Simulation aspect:

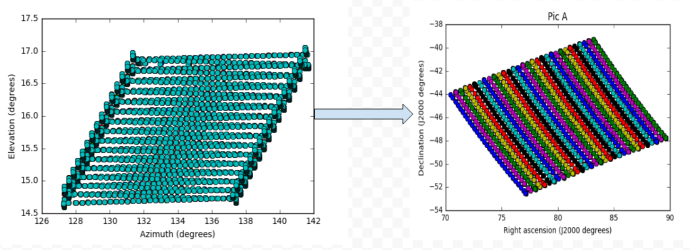


Figure: *KAT-7 raster scan Observation*

- **Working together with** : Prof. Mario G. Santos & Dr. Prina Patel

Conclusion

- We can effectively measure the polarization leakage of a signal with the presence of these fully polarised beams.

THANK YOU !!!