Simulating the Antenna Response of Radio Interferometers

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Introduction

- Transition from aligned to anti-aligned spin state in neutral hydrogen releases a 21-cm wave.
- The early universe was composed of neutral hydrogen so observing this transition gives us a hint in understanding the beginning of the universe. This is referred as 21-cm cosmology.
- Challenge: In order to clearly understand the early universe, it is crucial to collect pure 21-cm waves. However, while collecting pure 21cm wave data, the foreground noise contaminates our results.
- Understanding the antenna responses in a 21cm array is crucial to removing these foreground contaminants.

Background

- Our code is primarily concerned about the visibility equation, the correlation of signals measured by telescopes (see equation below).

$$V_{ij}^{sim} = \sum A(\nu) * I(\nu, s) * e^{-2\pi \frac{i\nu}{c} \vec{b} \cdot \hat{s}}$$

Where I is flux measured, A is the beam shape, and the exponential factor is the phase factor, depending on antenna position and pointing direction. The combination of beam weight and the phase factor captures the amount of flux detected by the antenna baseline, visibilities.

- Phase factor relates to a dot product between the unit vector directing toward the source and a baseline vector between two antennas divided by the wavelength. This geometrically represents path difference between the two received rays.
- We focus on simulating different beam models and study differences on visibilities. Two models we focused on are:
  - Airy Beam with Bessel function of the first kind of the first order
  - Airy Beam with Bessel function of the first kind of the second order
  - More realistic Beam Model
    - Perturbations to beam shape and positioning to model a realistic beam

$$A(\nu) = \left[\frac{2J_1\left(k\sqrt{a_x^2(x-x_{pc})^2 + a_y^2(y-y_{pc})^2}\right)}{k\sqrt{a_x^2(x-x_{pc})^2 + a_y^2(y-y_{pc})}} \right]^2$$

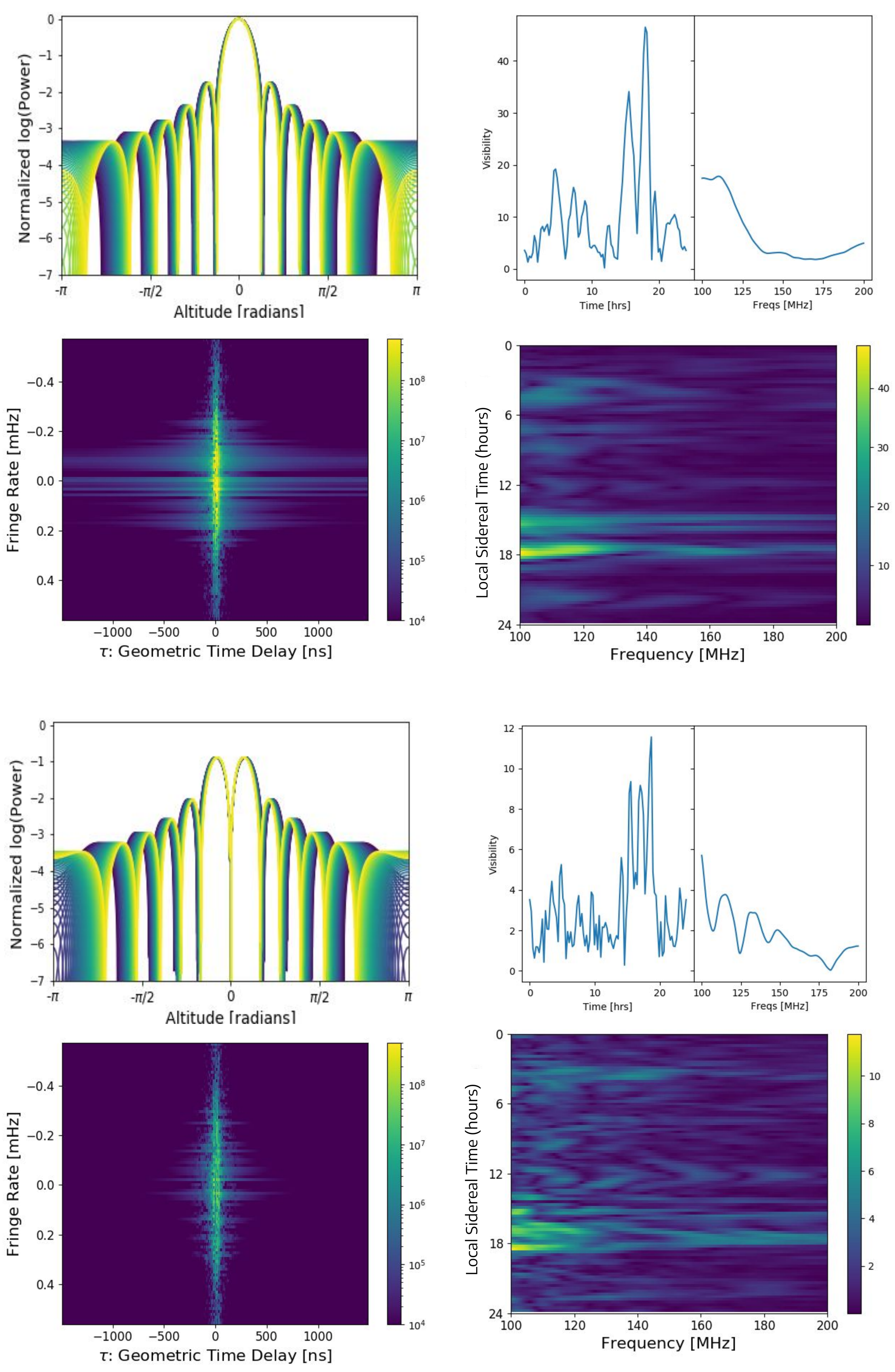
Methods (Algorithm)

- Data-MWA-GLEAM Catalog
  - For each source, create a corresponding position vector in the sky using right ascension and declination angle
  - Generalize flux for all possible frequencies in a given range using power law (see equation below, F, v denotes flux and frequency respectively and k, a are constant).

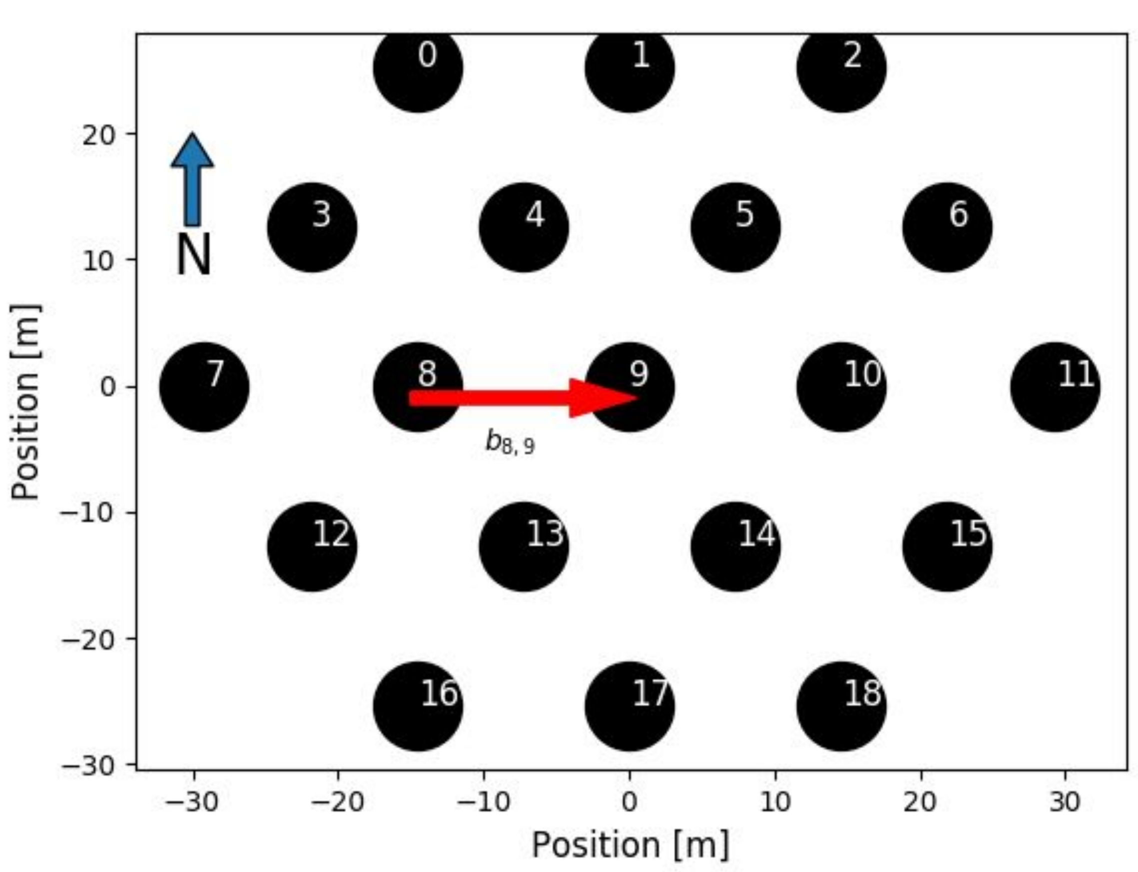
$$F = k\nu^{\alpha}$$

- Antenna Placement:
  - Hexagon array of antennas (see **Antenna Array**)
  - Find the baselines/distance to the other antennas (see the red arrow)
  - Introduce randomness to simulate error in physical setting. (x_{pc} and y_{pc})
- Beam Model, we focus on the following two:
  - Airy Beam (with Bessel function of first kind of first order)
  - Airy Beam (with Bessel function of first kind of second order)
- Everything together
  - Calculate the beam-weighted-flux by interpolating flux at the specified frequency and position with the beam model
  - Obtain visibibily by multiplying beam-weighted flux with a phase factor, an exponential function of the dot product of baseline and position in the sky.

Results



Antenna Array



Analysis

- We believe the spectral and temporal smoothness of the airy beam of order one implies it is a better model of foreground visibility.
- The airy beam of order one has a compact representation of sources where as the airy beam of order two disperses power because of its extended sidelobes.
- This leads to differences in visibility which supports our prediction that the airy beam of first order is the better model for visibility
- We see that the north-south baseline contain smaller maximum delay rates than east-west baseline, as we would predict.

Limitations of Simulation

- Due to limited computing power, we only tested a small portion of the data set. It is difficult to analyze the result without a larger, more complete catalog of known sources and flux to find pattern at this point.
- We focus on only two models, more models are needed for more detailed optimization work.
- Our simulation only accounts for xx-polarization. It may be helpful to stimulate for the yy-polarization.
- These limitations as well as the lack of calibration prevent us from performing a detailed comparison between models.

Future Work

- Simulate with different beam models such as spherical model and Nicholas Fagnoni beam model.
- Perform redundant baseline calibration on our models to match HERA
- Run the simulator on a larger data set and on a different data set such as Global Sky Map.
- Using the results of antennas reponse, develop and optimize calibration solution.

References

- Liu, A. and J. R. Shaw 2019. DAta Analysis for precision 21cm Cosmology. arXiiv e-prints, P. arXiv:1907.08211
- DeBoer, D. R., A. R. Parsons, J. E. Aguirre, P. Alexander, Z. S. Ali, A. P. Beardsley, G. Bernardi, J. D. Bowman, R. F. Bradley, C. L. Carilli, C. Cheng, E. de Lera Acedo, J. S. Dillon, A. Ewall-Wice, G. Fadana, N. Fagnoni, R. Fritz, S. R. Furlanetto, B. Glen- denning, B. Greig, J. Grobbelaar, B. J. Hazelton, J. N. Hewitt, J. Hickish, D. C. Jacobs, A. Julius, M. Kariseb, S. A. Kohn, T. Lekalake, A. Liu, A. Loots, D. MacMahon, L. Malan, C. Malgas, M. Maree, Z. Martinot, N. Mathison, E. Matsetela, A. Mesinger, M. F. Morales, A. R. Neben, N. Patra, S. Pieterse, J. C. Pober, N. Razavi-Ghods, J. Ringuette, J. Rob- nett, K. Rosie, R. Sell, C. Smith, A. Syce, M. Tegmark, N. Thyagarajan, P. K. G. Williams, and H. Zheng 2017. 2017. Hydrogen Epoch of Reionization Array (HERA). , 129(974):045001.
- Dillon, J. S., S. A. Kohn, A. R. Parsons, J. E. Aguirre, Z. S. Ali, G. Bernardi, N. S. Kern, W. Li, A. Liu, C. D. Nunhokee, and J. C. Pobe 2018. Polarized redundant-baseline calibration for 21 cm cosmology without adding spectral structure. , 477(4):5670–5681.
- Ewall-Wice, A., J. S. Dillon, A. Liu, and J. Hewitt 2017. The impact of modelling errors on interferometer calibration for 21 cm power spectra. , 470(2):1849–1870.
- Fagnoni, N., E. de Lera Acedo, D. R. DeBoer, Z. Abdurashidova, J. E. Aguirre, P. Alexander, Z. S. Ali, Y. Balfour, A. P. Beardsley, G. Bernardi, T. S. Billings, J. D. Bowman, R. F. Bradley, P. Bull, J. Burba, C. L. Carilli, C. Cheng, M. Dexter, J. S. Dillon, A. Ewall- Wice, R. Fritz, S. R. Furlanetto, K. Gale-Sides, B. Glendenning, D. Gorthi, B. Greig, J. Grobbelaar, Z. Halday, B. J. Hazelton, J. N. Hewitt, J. Hickish, D. C. Jacobs, A. Jo- saitis, A. Julius, N. S. Kern, J. Kerrigan, H. Kim, P. Kittiwisit, S. A. Kohn, M. Kolopanis, A. Lanman, P. La Plante, T. Lekalake, A. Liu, D. MacMahon, L. Malan, C. Malgas, M. Maree, Z. E. Martinot, E. Matsetela, J. Mena Parra, A. Mesinger, M. Molewa, M. F. Morales, T. Mosiane, A. R. Neben, B. Nikolic, A. R. Parsons, N. Patra, S. Pieterse, J. C. Pober, N. Razavi-Ghods, J. Robnett, K. Rosie, P. Sims, C. Smith, A. Syce, N. Thyagara- jan, P. K. G. Williams, and H. Zheng 2019.
  Electrical and electromagnetic co-simulations of the HERA Phase I receiver system including the effects of mutual coupling, and impact on the EoR window. arXiv e-prints, P. arXiv:1908.02383.
- Kern, N. S., A. R. Parsons, J. S. Dillon, A. E. Lanman, A. Liu, P. Bull, A. Ewall-Wice, Z. Abdurashidova, J. E. Aguirre, P. Alexander, Z. S. Ali, Y. Balfour, A. P. Beardsley, G. Bernardi, J. D. Bowman, R. F. Bradley, J. Burba, C. L. Carilli, C. Cheng, D. R. DeBoer, M. Dexter, E. de Lera Acedo, N. Fagnoni, R. Fritz, S. R. Furlanetto, B. Glendenning, D. Gorthi, B. Greig, J. Grobbelaar, Z. Halday, B. J. Hazelton, J. N. Hewitt, J. Hickish, D. C. Jacobs, A. Julius, J. Kerrigan, P. Kittiwisit, S. A. Kohn, M. Kolopanis, P. La Plante, T. Lekalake, D. MacMahon, L. Malan, C. Malgas, M. Maree, Z. E. Martinot, E. Matsetela, A. Mesinger, M. Molewa, M. F. Morales, T. Mosiane, S. G. Murray, A. R. Neben, A. R. Parsons, N. Patra, S. Pieterse, J. C. Pober, N. Razavi-Ghods, J. Ringuette, J. Robnett, K. Rosie, P. Sims, C. Smith, A. Syce, N. Thyagarajan, P. K. G. Williams, and H. Zheng 2019. Mitigating Internal Instrument Coupling II: A Method Demonstration with the Hydrogen Epoch of Reionization Array. arXiv e-prints, P. arXiv:1909.11733.
- Orosz, N., J. S. Dillon, A. Ewall-Wice, A. R. Parsons, and N. Thyagarajan 2019. Mitigating the effects of antenna-to-antenna variation on redundant-baseline calibration for 21 cm cosmology. , 487(1):537–549.
- Parsons, A. R., A. Liu, Z. S. Ali, and C. Cheng 2016. Optimized Beam Sculpting with Generalized Fringe-rate Filters. , 820(1):51.

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https://github.com/kgb0255/ULAB_21cm_cosmology