Precision Antenna Beam Modelling for Radio Cosmology from the Lunar Far Side

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ABSTRACT

The far side of the Moon offers unique opportunities to study the origin and evolution of the Universe through radio observations of the redshifted 21cm signal. However, the ability of Lunar experiments to detect the cosmological signal is dependent on subtracting bright astronomical radio foregrounds from the observations. Foreground subtraction is limited by frequency-dependent coupling of radiation into the instrument due to chromaticity in antenna beam patterns. Chromatic beams couple angular structures in Galactic foreground emission to spectral structures that may not be removed easily by existing foreground subtraction techniques. Changes of the order of even 0.1% in the primary beam of the antenna across the observation band can introduce spectral features that would limit the cosmological signal detection sensitivity. Here, we present recent work to cross-validate dipole antenna beam simulations using multiple EM solvers.

We have simulated the ground-based Experiment to Detect the Global EoR Signature (EDGES) blade antenna using three different EM solvers. To simulate the real ground for a more practical scenario, we are presently limited to only one EM technique - Method of Moments (MOM). Important details in simulated beam responses that are critical to the planned cosmology measurements are found to depend on choice of solver and configuration, such as meshing and boundary conditions, as well as ground plane and antenna configurations, suggesting the importance of careful antenna design and modelling.

BEAM CHROMATICITY

The spectral signature is broadband between 50 and 200MHz with a peak absolute amplitude between 10 and 200mK. Galactic and extragalactic continuum foregrounds from synchrotron and free-free emission are approximately four orders of magnitude larger, with typical sky temperatures of 250K at 150MHz away from the Galactic Center. The foregrounds generally exhibit smooth, power-law-like spectra that must be subtracted from observations to reveal the 21 cm signal. Antenna beam variation can couple angular variations in galactic foregrounds into spectral structures.

- *Objective*: To subtract Galactic foreground by smooth functional terms.
- *Required*: A directivity pattern that varies smoothly in frequency.

Considerations:

- Antenna Model – EDGES has a blade dipole antenna over a large ground plane as it satisfied the low beam chromaticity requirement.
- EM Solver Type – Simulation of the blade dipole is carried out in different solvers to gain confidence in the beam patterns.
- Ground Plane Effects – In low frequency antenna designs, as in EDGES, the currents at the edge of the ground plane affect the beam patterns.

EDGES BLADE DIPOLE: aims to detect the global 21 cm signal through full sky observations using a single dipole over a ground plane.

Figure1: Photograph of the EDGES high band blade dipole antenna placed over the ground plane.

Features	Value
3 dB Beam width ($\phi = 0^o$)	72
3 dB Beam width ($\phi = 90^o$)	110
Height (from the ground)	52.0 * scale cm
Panel length	62.6 *scale cm
Panel Width	48.2 *scale cm
Ground Plane	5 X 5 *scale m
3dB Bandwidth	100 – 190 *1/scale MHz

The above table summarizes the features of the EDGES antennas. The value of the variable scale is 1 and 2 for Highband and Lowband antennas respectively.

REFERENCES

[1] T.J. Mozdzen, J.D. Bowman, R.A. Monsalve, A.E.E.Rogers, MNRAS 455,2016

[2] http://loco.lab.asu.edu/memos/

[3]http://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/EdgesMemo.html

ANALYSING DIFFERENT EM SOLVERS

We modelled the antenna with its exact dimensions and the ground plane as an infinite PEC using three different EM solver techniques:

- FDTD – CST Time Domain Solver (T-Solver)
- MOM – FEKO, CST Integral solver (I-solver) & HFSS-Integral Equation Solver (IE)
- FEM – HFSS & CST Frequency Domain solver (F-Solver)

A.) Spectral Derivative of Beam Directivity

The beam chromaticity has to be inspected at an order of 0.1-1% thus we plot the derivative of the directivity with respect to frequency at every 1MHz.

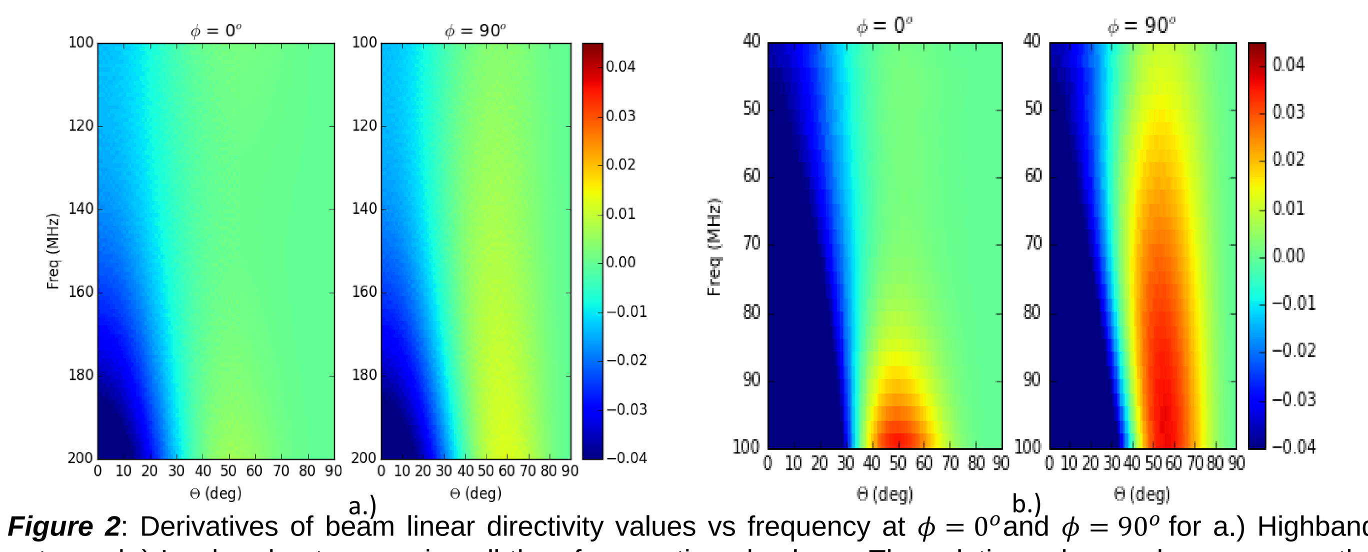

Figure 2: Derivatives of beam linear directivity values vs frequency at $\phi = 0^o$ and $\phi = 90^o$ for a.) Highband antenna b.) Lowband antenna using all the aforementioned solvers. The solutions show a decrease near the zenith with increasing frequency consistent with the beginning of structure due to the ground plane.

- The FDTD and FEM solutions required the bounding box to have PML (Perfectly Matched Layer) condition, that minimizes reflections, to obtain the beam directivity derivatives as shown in figure 2(a&b).
- The MOM technique was not limited by the boundary box conditions because it solves the fields to infinity.
- HFSS IE solver accuracy is lower than that of HFSS and it requires a 6th order polynomial fit across frequency to obtain beam directivity derivatives as shown in figure 2 (a&b).

B.) Figure of Merit

The beam directivity derivatives are seen to match within an order of 10^{-2} in the linear scale. On taking the difference of the beam solutions obtained from different solvers, the derivatives are seen to vary by +/- 0.006 in the linear scale. Thus we compare the Figure of Merit (FOM) of each solution.

We obtain the antenna temperature by convolving the beam with a sky model to access the effect of the antenna in the detection of the 21cm signal. We use the residues obtained by taking the difference between an N-order polynomial and the convoluted signal to calculate the FOM. The RMS of the residues over frequency is plotted against each LST in fig3.

- Chromatic antenna beams that couple little structure into the measured spectrum will produce small residues.
- A good antenna for the global redshifted 21 cm measurement would yield residuals well below the expected 21 cm signal strength of 10 - 40 mK while minimizing the number of free parameters in the model.

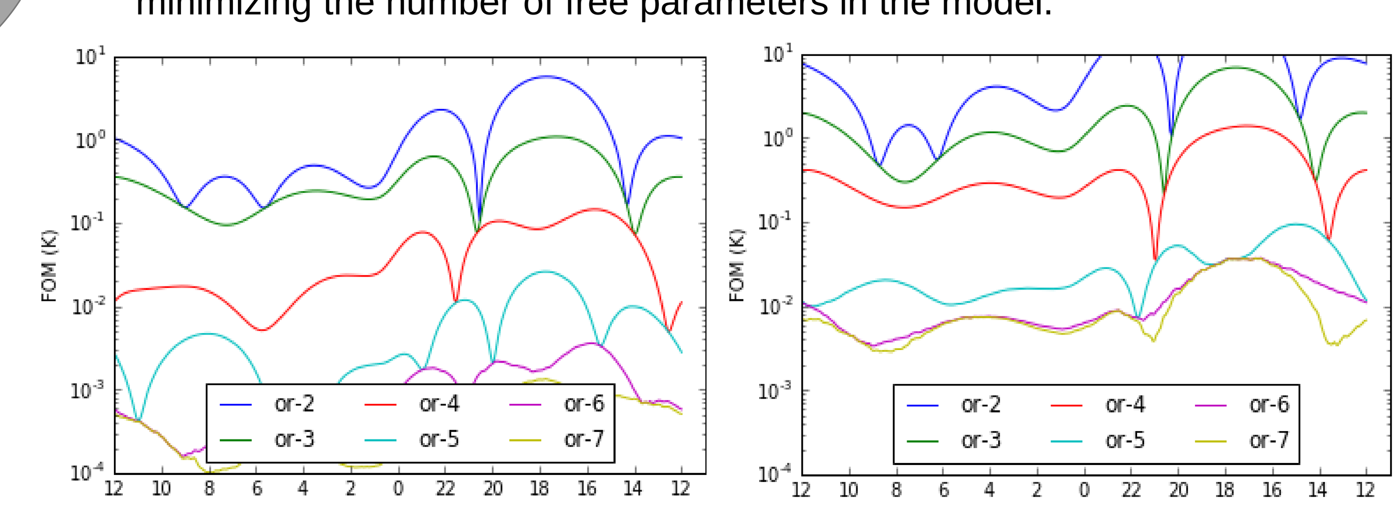

Figure 3: Blade FoM vs LST at latitude -26^o for the High band antenna(left) and Lowband antenna (Right). The curves illustrate the effects of varying the number of polynomial terms in the T_{model} fit, from N=2 (top) to N=7 (bottom). The lowband residues are proportionately higher by $2^{2.5}$

The table compares the average RMS (residues averaged over LST and then RMS-ed over frequency) of all the different solutions obtained for both the antennas. The average RMS values are calculated with 5 polynomial terms removed.

Solvers / Antenna	FEKO	HFSS	CST-T	CST-F	HFSS-IE	CST-I
Highband (mK)	1.70	2.00	1.99	2.10	1.86	1.75
Lowband (mK)	7.51	13.9	8.88	18.1	38.2	10.3

C.) Real Ground

After gaining confidence in the solutions from different solvers for the PEC ground case, we proceeded to simulate the real ground below the antenna structure.

The softwares with capability to simulate an infinite dielectric ground are those employing the MOM technique.

Soil parameters used: $\epsilon_r = 3.5$ & $\sigma = 0.02\ S/m$

Solvers / Antenna	FEKO	HFSS-IE	CST-I
Highband (mK)	18.5	17.8	56.3
Lowband (mK)	260	190	536

FEKO and HFSS-IE produced similar average RMS values for both High band and Low band cases. These values are also confirmed with the residues obtained from actual data.

CONCLUSIONS

- **All the different EM modelling techniques give similar beam chromaticity, within an order of magnitude, for the PEC ground case.**
- **The real ground simulation captures the data residuals better than the PEC ground model.**
- **Simulated residues from the new ground plane for the low band is lesser than the expected amplitude of the signature in that frequency regime.**

GROUND PLANE CONSIDERATIONS

A.) Need to Model

The beam chromaticity due to the size and parameters of the ground plane are studied in both the Low band and High band regions.

For High Band (100-190MHz):

- The average RMS of the data after 5 term polynomial fit ~ 15mK.
- The actual ground captures the beam chromaticity more accurately (Figure 5).
- The average RMS with the soil is ~ 18mK compared to 2mK obtained with the PEC case.

For Low Band (50 – 95MHz):

- The average RMS of the data after 5 term polynomial fit ~ 100mK.
- Like with the Highband, the actual ground captures the beam chromaticity more accurately (Figure 5).
- The average RMS with the soil is ~ 200mK compared to 10mK obtained with the PEC case.

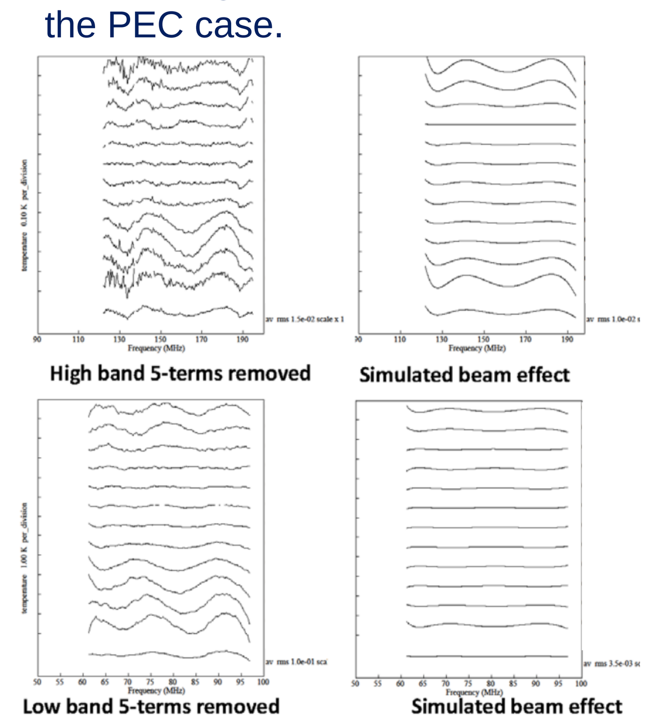

Figure 4 : Comparison of RMS from 5 term fit to data (left) with beam simulated over infinite PEC (right) for High band(top) and low band(bottom). Each row corresponds to a GHA and the last row is the average RMS over all GHA.

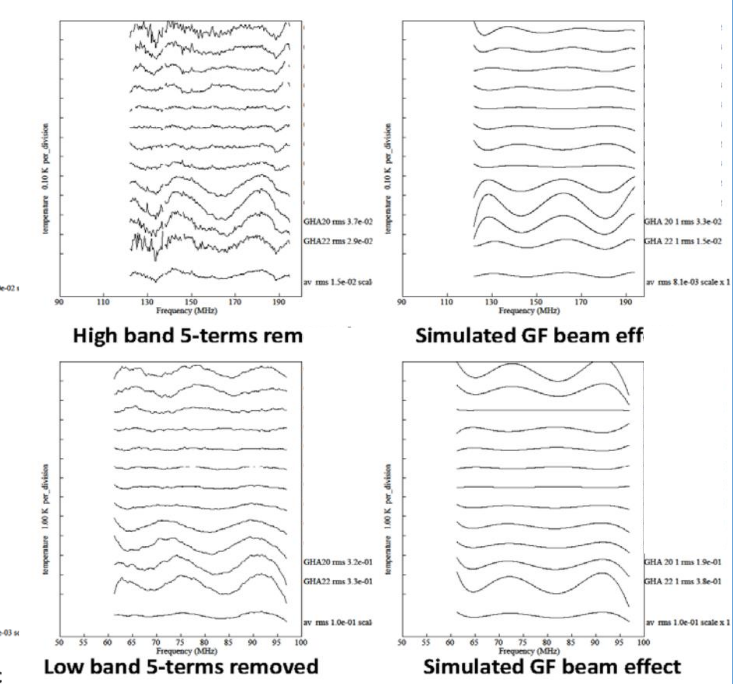

Figure 5 : Comparison of RMS from 5 term fit to data (left) with beam simulated actual ground over infinite dielectric of ϵ_r =3.5.(right) for High band(top) and low band(bottom). Each row corresponds to a GHA and the last row is the average RMS over all GHA

In the low band the beam effects due to the ground plane are significant and comparable to the amplitude of the predicted 21 cm signal.

B.) Size and Shape of the Ground Plane

Larger ground planes would reduce the beam effects. This is because the current at the edge of the ground plane is inversely proportional to the size. This is confirmed by EM modelling analysis and summarized by the values in the table.

		rms to 5-term fit mK	
Size (m)	Shape	Peak	Average
5	Square	3000	280
10	Square	1000	250
20	Square	450	180
15	Plus	650	170
30	Plus	230	64
Infinite	Plus	200	21

- Plus shaped ground plane size of 30m has residues close to the values simulated by infinite ground.
- Ideally, a large square of area 900m² would be perfect.
- But with considerations on material requirement a design for the low band ground plane was proposed with an area of 600m² (Figure 6).

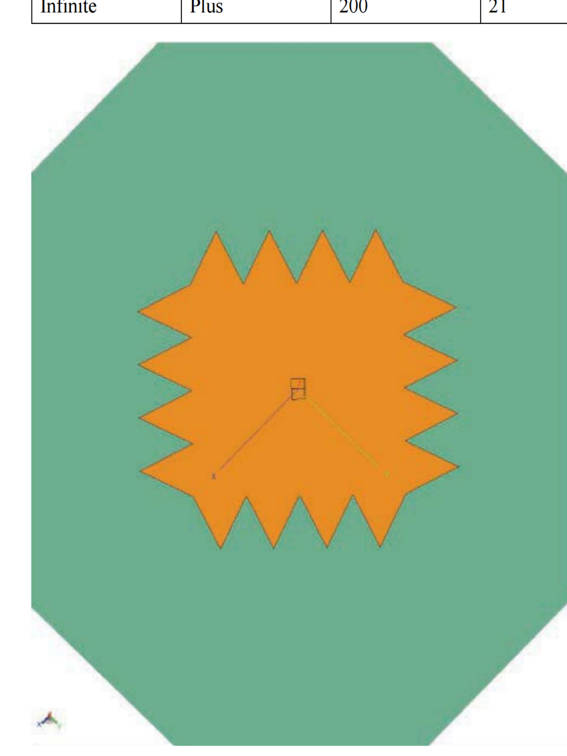

Figure 6: Simulation model of the new ground plane for the low band receiver. It is a square metal plane of 20mX20m with 4 isosceles triangles of 5m base and 5m height on each side.

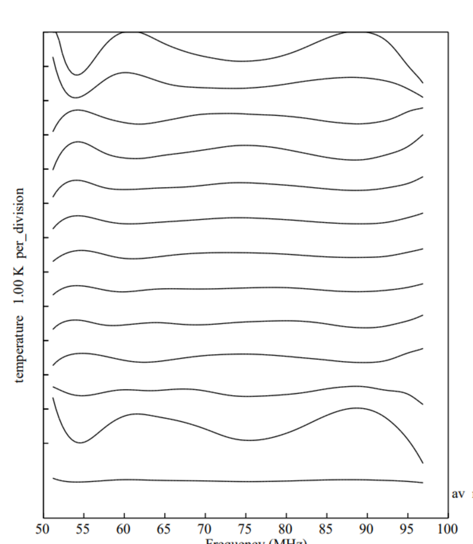

Figure 7: Simulated antenna beam with the new ground plane. Each row represents each GHA. The last row is the averaged residue over all GHAs.

From the simulations using the new ground plane, the beam chromaticity is seen to have reduced: Average RMS decreased from 100mK ➔ 23mK (or 1.9mK – 72-97MHz).

C.) Confirmation

The new extended ground plane has been installed below the low band antenna. Data from it has been analyzed to obtain its residues. *Looking at the residues, the new ground plane shows a considerable amount of improvement.*

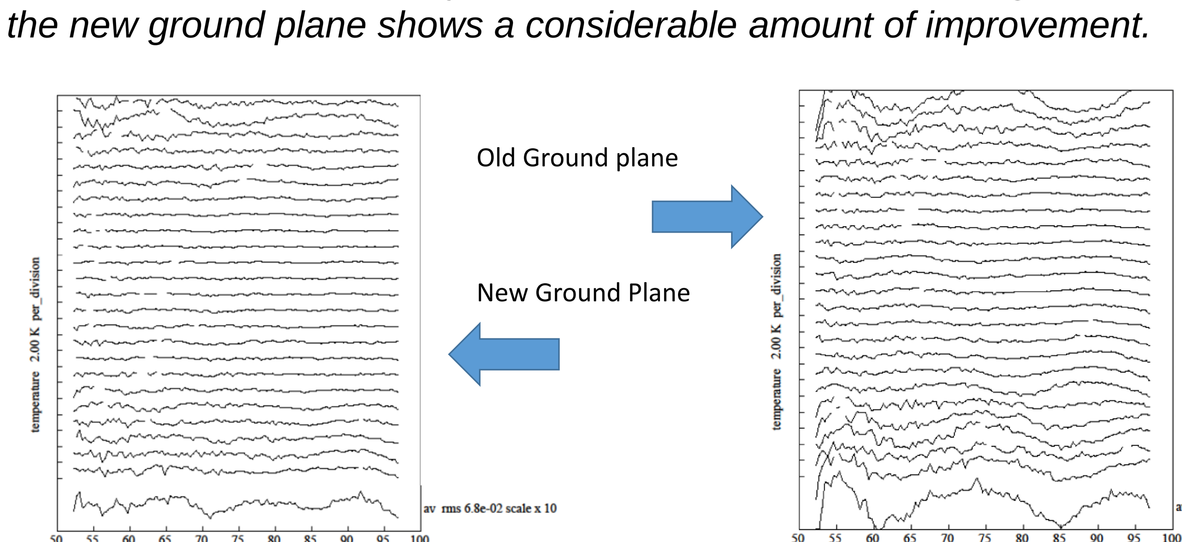

Figure 8: Residues of the data from the extended low band ground plane fit with an 5th order polynomial . Each row represents each GHA. The last row is the averaged residue over all GHAs.

Figure 9: Residues of the data from the 10m X 10 m low band ground plane fit with an 5th order polynomial . Each row represents each GHA. The last row is the averaged residue over all GHAs.