EDGES Beam modelling and data comparison

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Introduction

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- If the antenna beam pattern is frequency dependent:
  - ***spatial structure*** in the foreground would couple ***into the spectral domain***
  - result in a ***non-smooth spectral*** response to structure in the continuum sky emission,
  - which can be ***difficult to model*** to the accuracy needed for 21 cm signal detection.

- With this effort we hope to answer the following questions:
  - How do solutions from different EM solvers compare?
  - How chromatic is the EDGES Beam?
  - Is it the chromaticity within acceptable levels?
  - Do our beam modelling solutions match expectations?

EDGES Low-band Antenna

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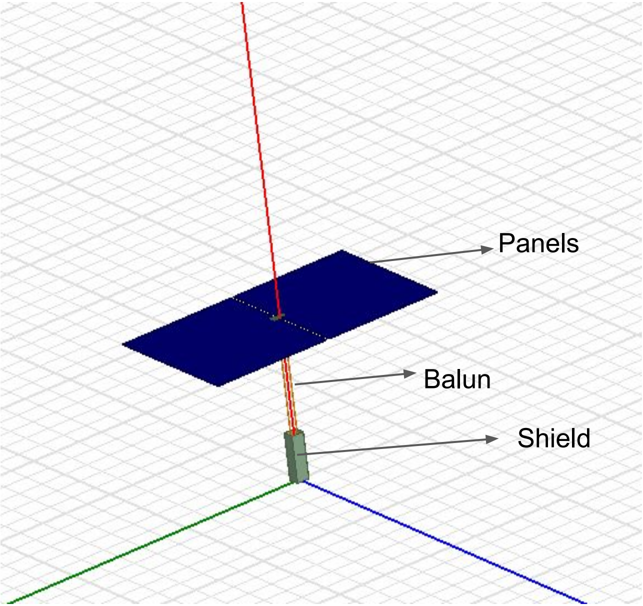
EM Model of the Antenna



Parameter	Value
Panel Width	125.2 cm
Panel Length	96.4 cm
Gap between panels	1.3 cm
Height from the ground	104 cm
Ground plane dimensions	10m X 10m
Extended Ground plane	30m X 30m
Frequency	40-100MHz

EDGES Low-band Antenna

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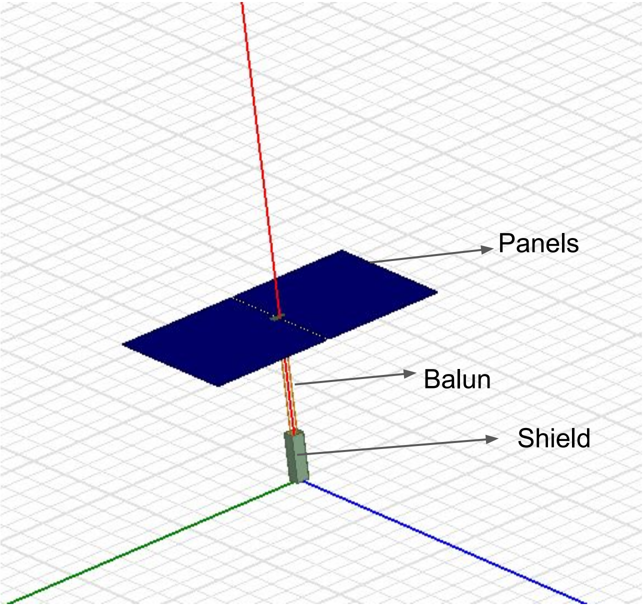
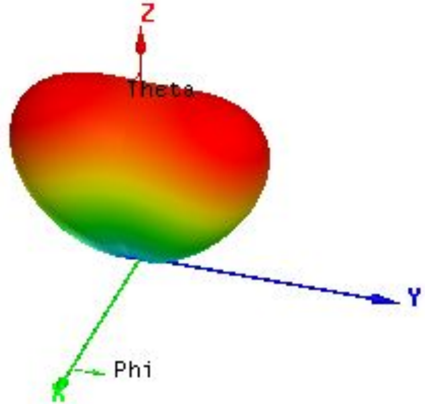
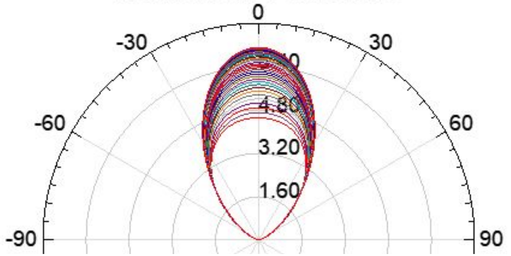
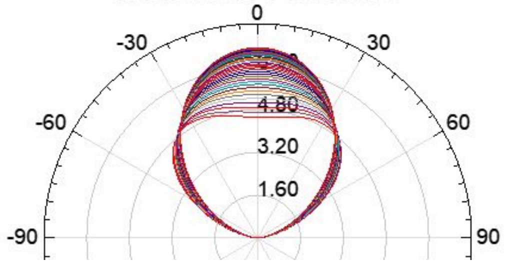
EM Model of the Antenna



Beam Patterns







Simulation Set-up

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Available techniques

Method of Moments(MoM) - FEKO, CST-I, HFSS-IE

Has the capability to model infinite real ground

Finite Element Method (FEM) - HFSS, CST - F

Finite Difference Time Domain (FDTD) - CST-T

How Chromatic is the Beam?

- Derivative along the frequency axis
- Residues of the beam to low order polynomial at certain viewing angles

Question #1:

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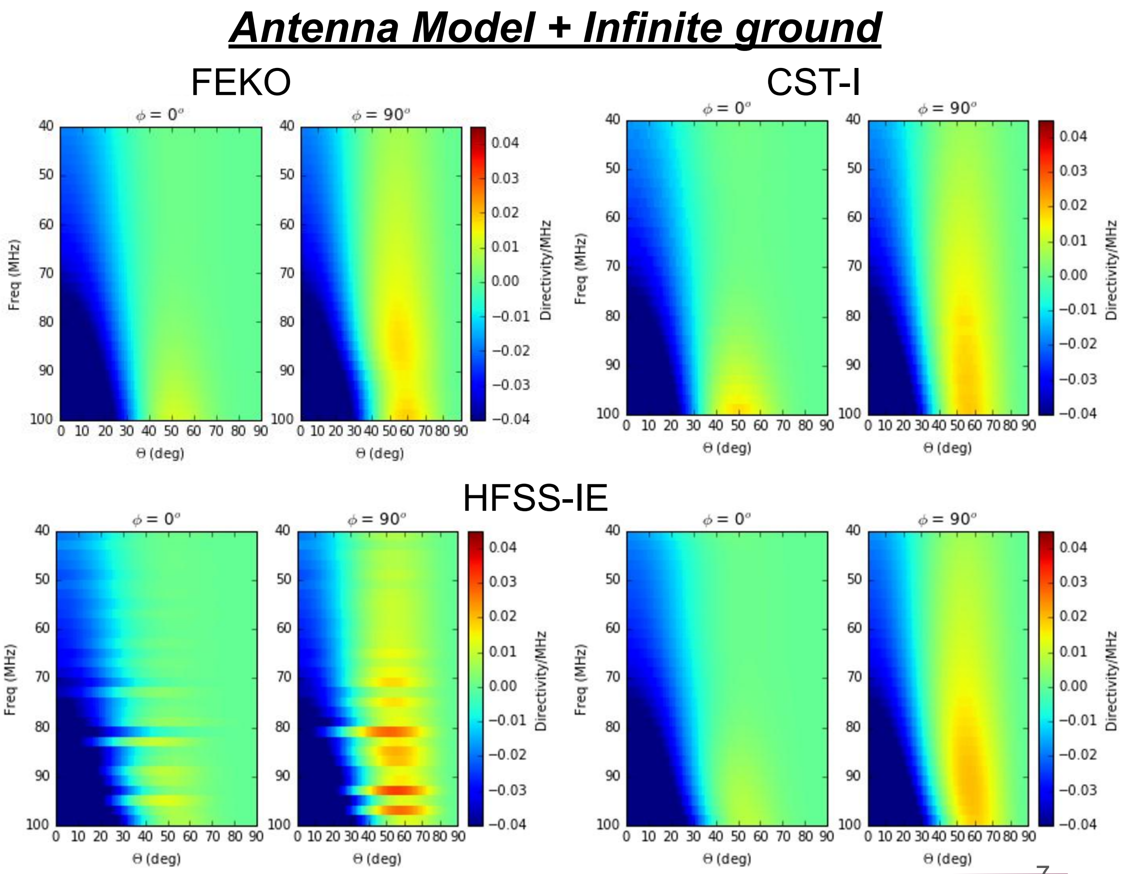
Simple Case:

Antenna + PEC ground

Do solutions from all the solvers match?

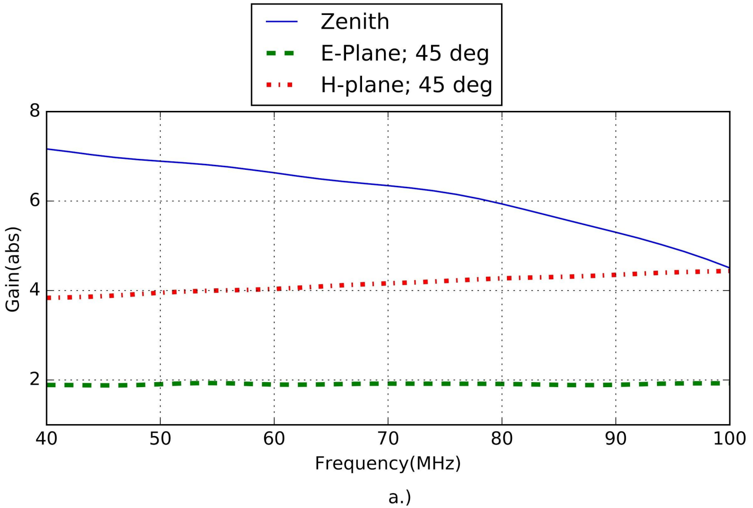
Verification with MoM

- **Solves Maxwell's Eqns in integral form.**
- **Uses currents to obtain the gain patterns.**
- CST-I & FEKO solutions produced qualitatively similar gain derivatives.
- HFSS-IE: Rapid fluctuations along frequency direction.
- Remedy: Smooth the gain solutions in Frequency.



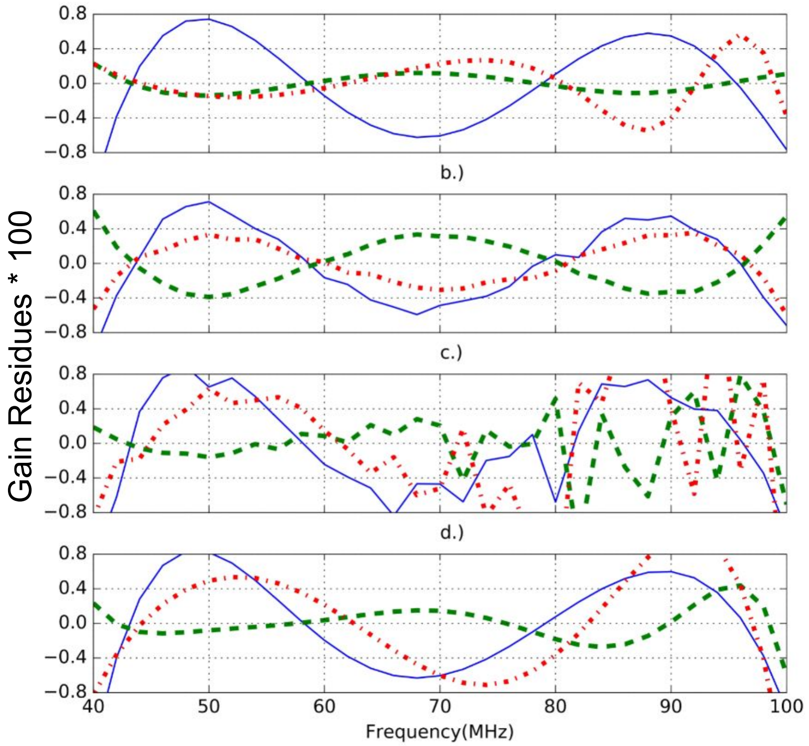
Verification with MoM

Actual Gain along the puncture points



a.)

Residues to the Gain along the puncture points After 3rd order fit



Maximum deviation of the gain from a 3rd order poly = 8 milli gain units

Question #2:

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Simple Case:

Antenna + PEC ground

Do solutions from all the solvers match? *Yes!*

Now,

Real case:

Antenna + 10m X 10m PEC + Soil Below

Real ground: Model Comparisons

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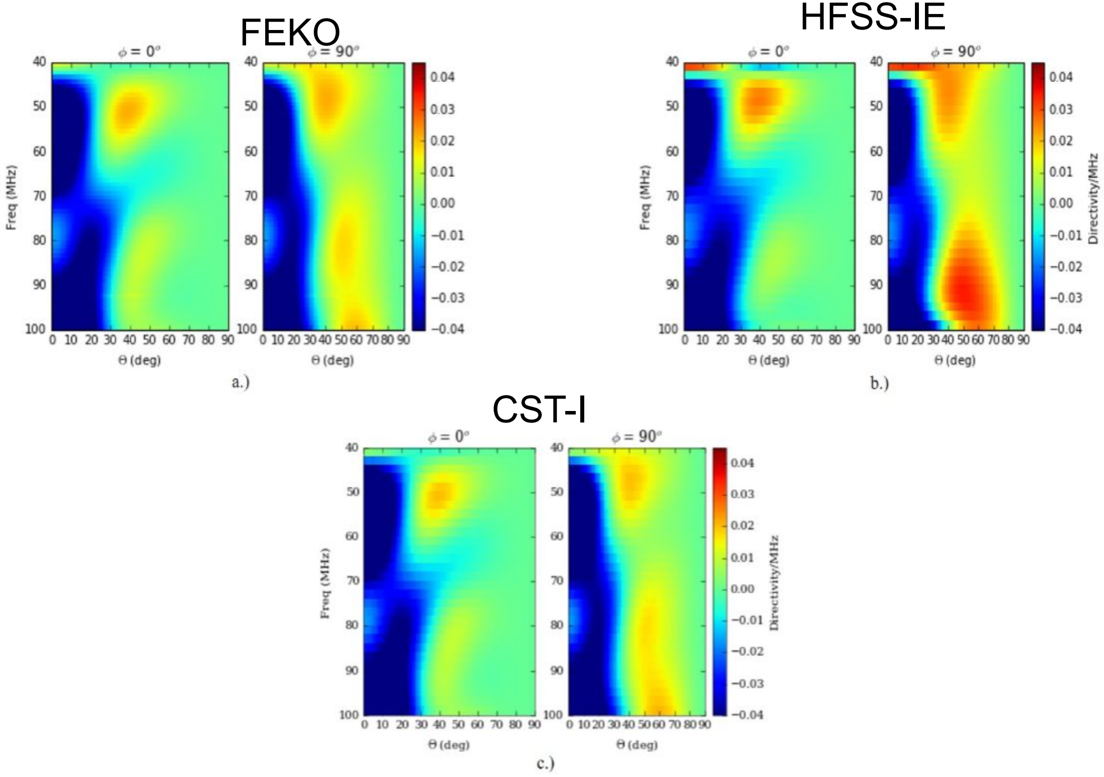
<u>Antenna Model + 10m X 10m metal plate + Soil</u>

- The only solution technique: MOM
- Soil Parameters: ϵ_r = 3.5 & **σ** = 0.02 S/m
- Qualitatively FEKO and CST-I are similar
- The HFSS-IE solutions were smoothened like in the PEC case
- HFSS-IE: Predicts higher chromaticity.
- Caveat: This could still be residual numerical errors



Real ground: Model Comparisons

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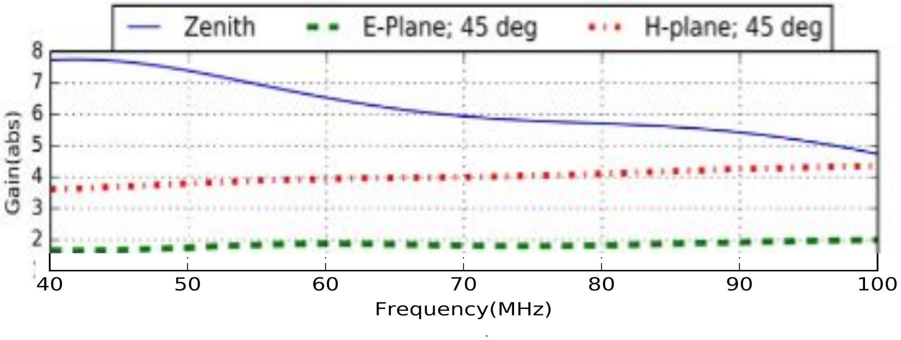
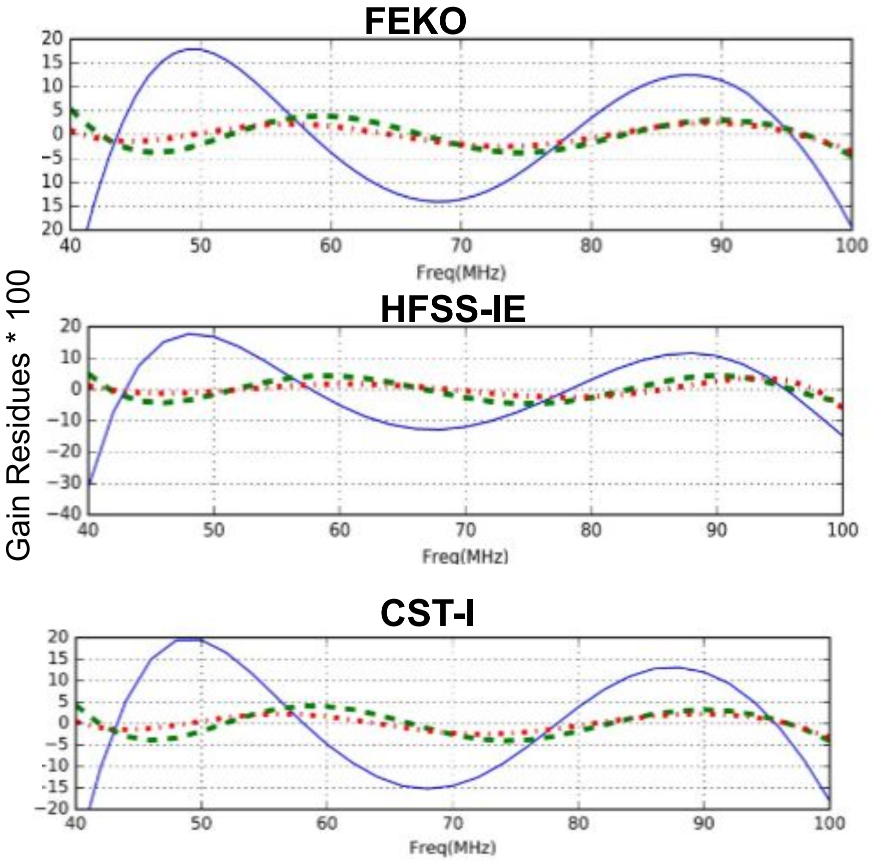
Actual Gain along the puncture points



Qualitatively the residue variation is very similar across the beam

Maximum gain variation to the 3rd order polynomial = 200 milli gain units



Question #3:

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Is the chromaticity of the model beam solutions acceptable?

Can the cosmological signal still be detected?

Simulating Observations

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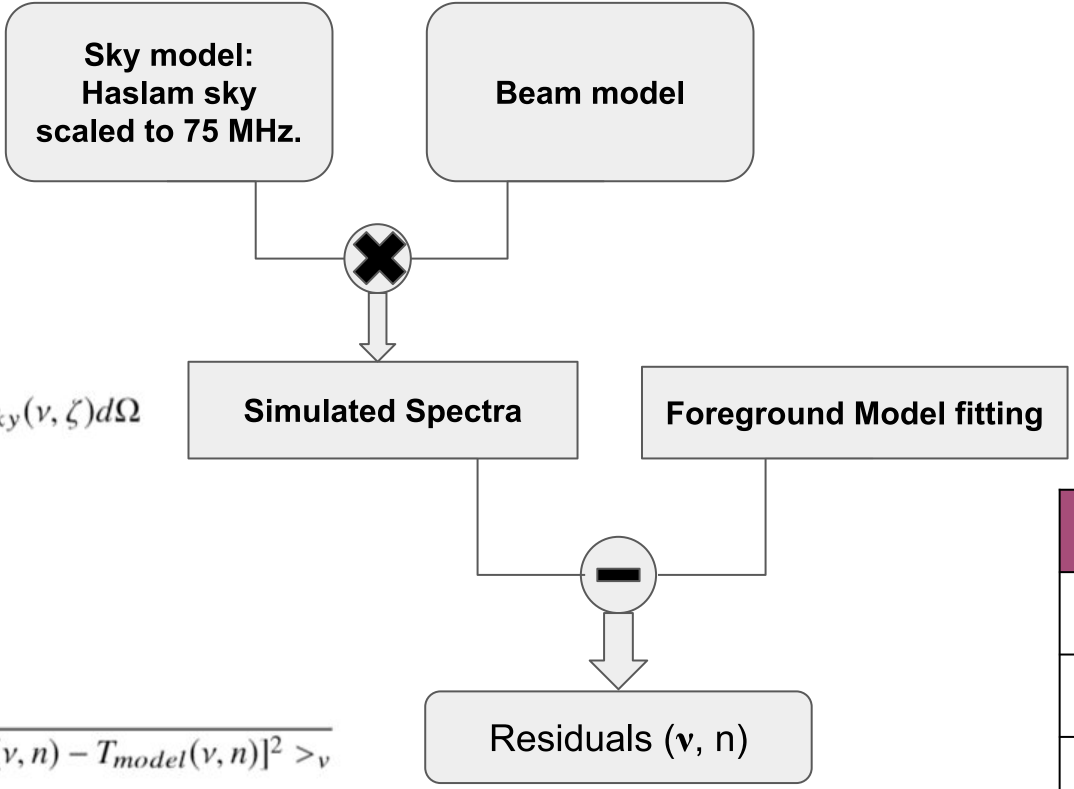


$$T_{an}(\nu) = \int B(\nu, \zeta, n) T_{sky}(\nu, \zeta) d\Omega$$

$$FOM = \sqrt{< [T_{an}(\nu, n) - T_{model}(\nu, n)]^2 >_\nu}$$

PEC

Solver	FoM(mK)
FEKO	21.1
HFSS -IE	21.4
CST-I	24.2

Soil Ground

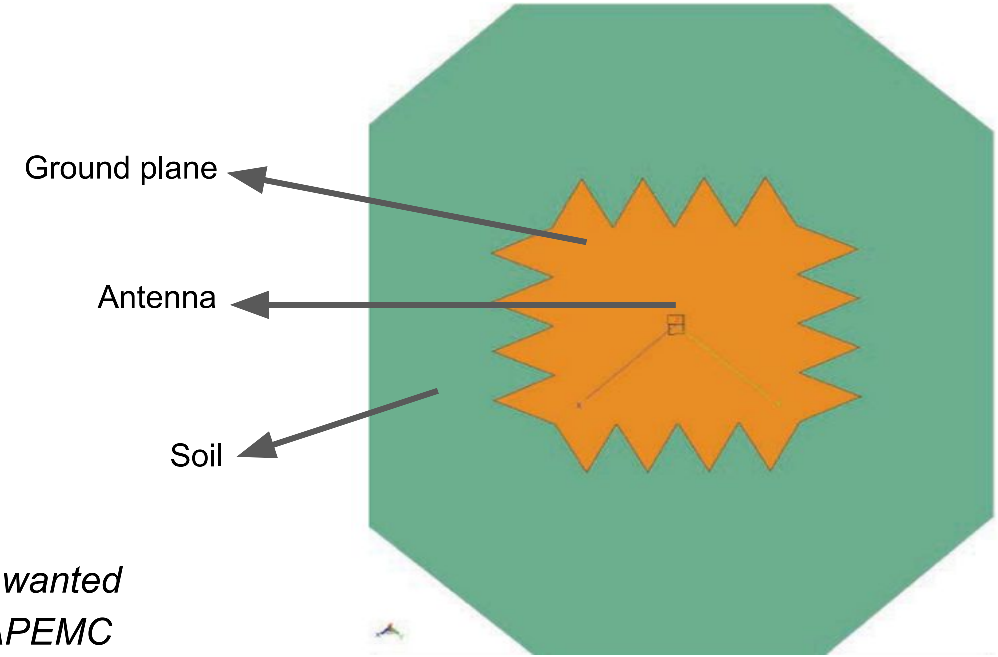
Solver	FoM(mK)
FEKO	260
HFSS-IE	190
CST-I	211

Improving ground plane design

- different ground plane sizes:

Size	FoM(mK)
10	255
15	170
30	64

- Target: LST-averaged RMS < 50mK.
- Perforated edges - *D. Meng, "Reducing Unwanted Reflections in NIM's OATS Optimization," APEMC 2015.*
- Minimize reflections from ground⇒ minimize chromaticity.



- Extended ground plane design:
  - 20m X 20m central square
  - 4 triangles of 5m X 5m at each edge.
- FOM ~ 30mK.

Extended Ground Plane Design

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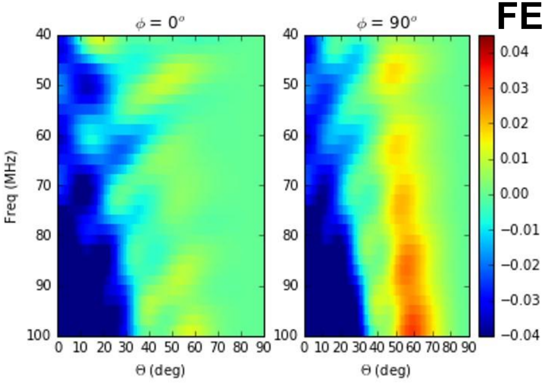
- Soil: ϵ_r = 3.5 & **σ** = 0.02 S/m
- HFSS-IE not used: The chromaticity may be confused with numerical errors
- Derivative Metric: similar; CST-I more fluctuations along Φ =90
- Residual metric: maximum fluctuation of order 40 gain milli units

FEKO



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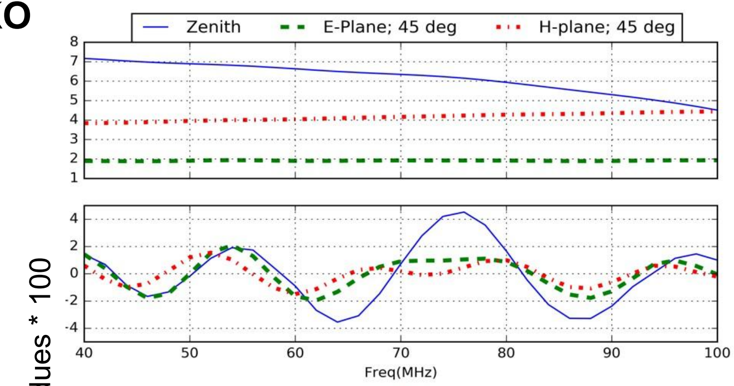
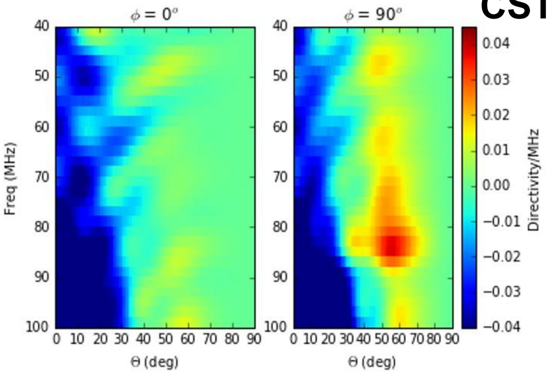
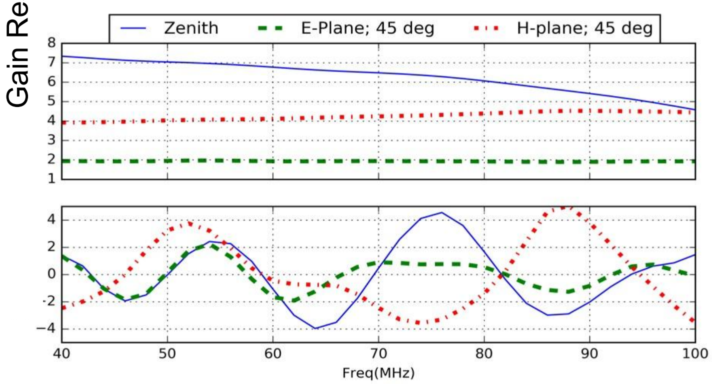


b.)

CST-I



c.)



d.)

Question #4:

Do our beam modelling solutions match expectations?

How close to reality?

Comparison with data: Drift Scan

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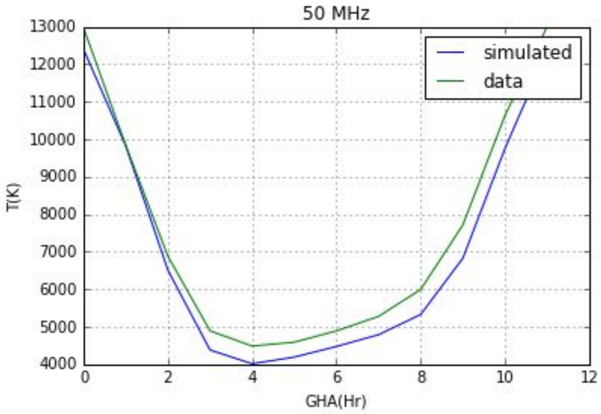
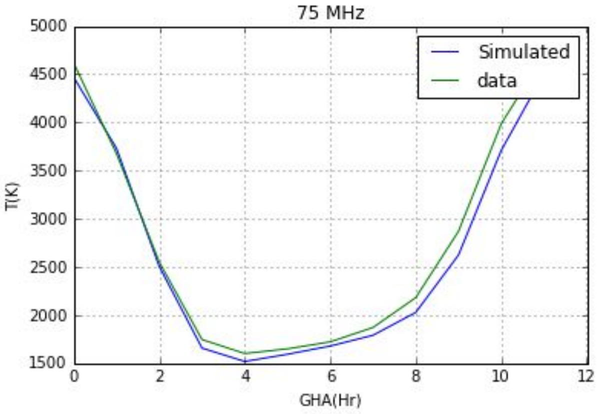
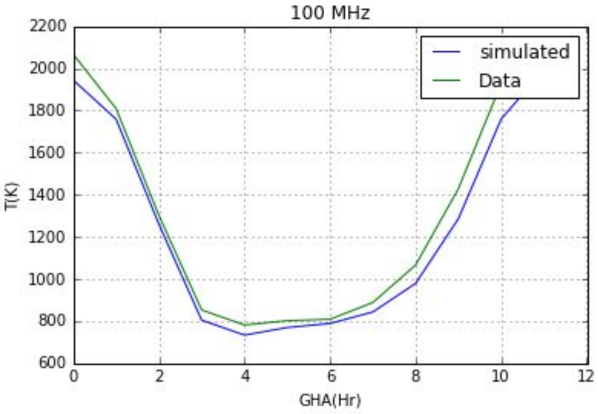
10x10 meter Ground Plane

- Data (268 days) and simulated spectra averaged over 2 hr LST bins and plotted for certain frequency points.







The agreement between the data and simulated spectra is within 15%
Possible disagreement ⇒ Sky model uncertainty

Comparison with data: Drift Scan

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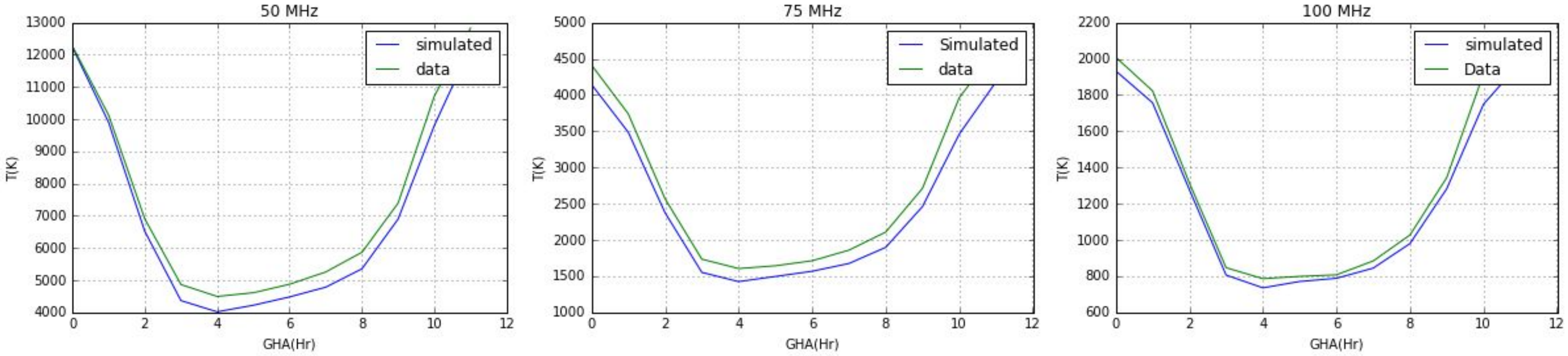
Extended Ground Plane

- Data and simulated spectra averaged over 2 hr LST bins and plotted for certain frequency points.



The agreement between the data and simulated spectra is within 15%
Possible disagreement ⇒ Sky model uncertainty

Comparison to Data: residues after foreground fits

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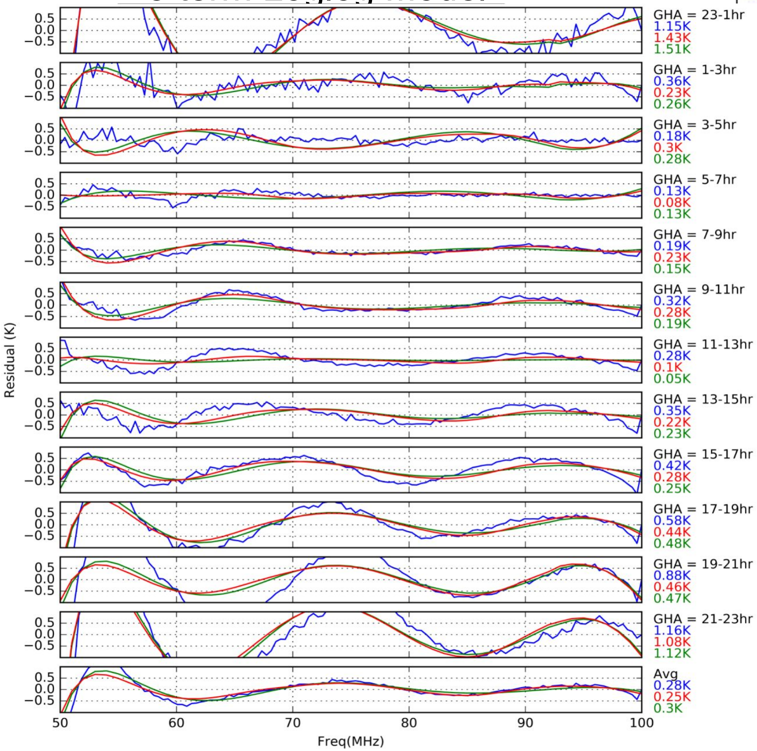
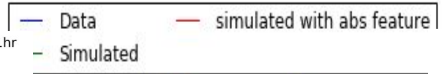
5 term Loglog Model

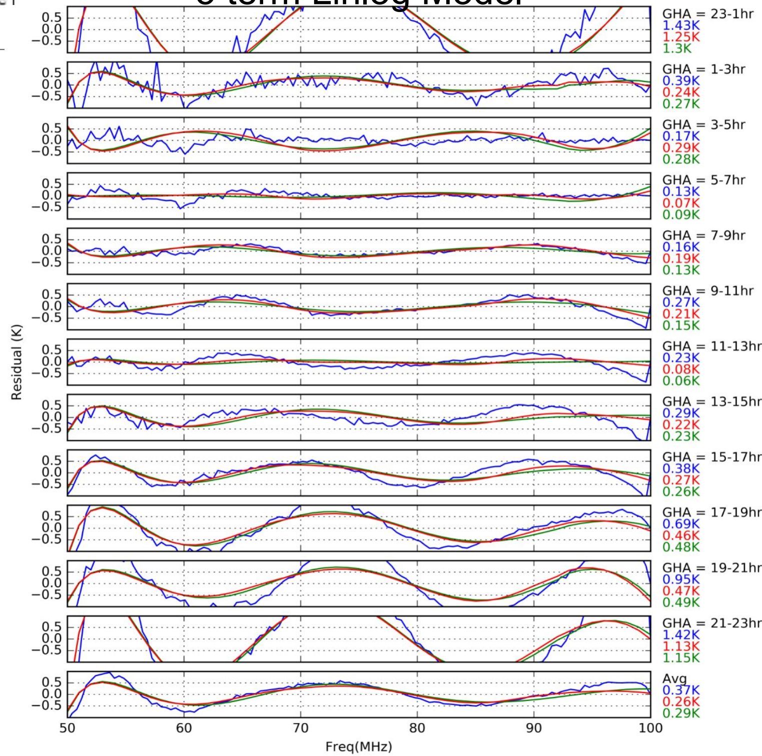




<u>10x10 meter Ground Plane</u>

Rows are 2hr GHA binned data

5 term Linlog Model



- Simulated Residues to both the model fits capture the data residues similarly
- Adding the absorption feature to the simulation does very little improvement because the residues are of the order of the feature

Comparison to Data: residues after foreground fits

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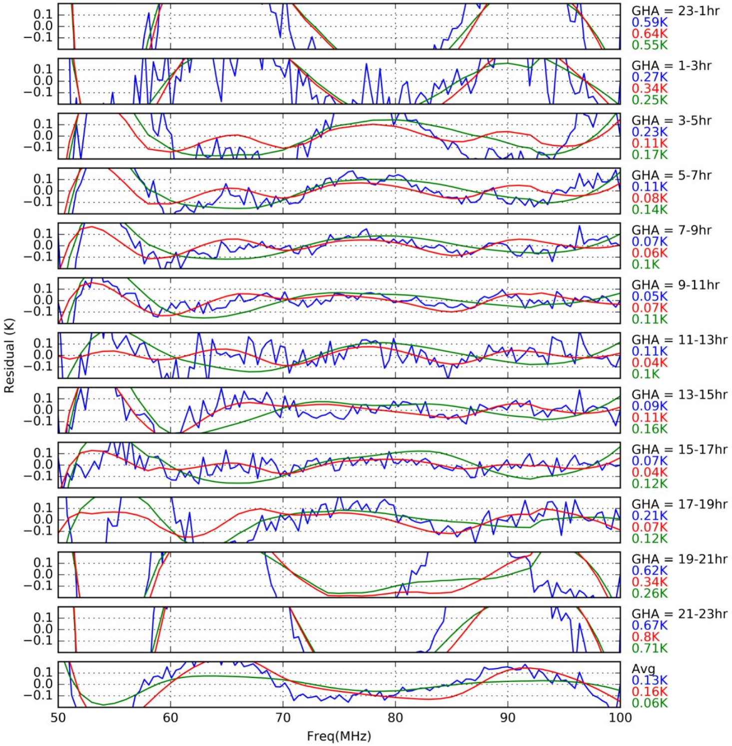
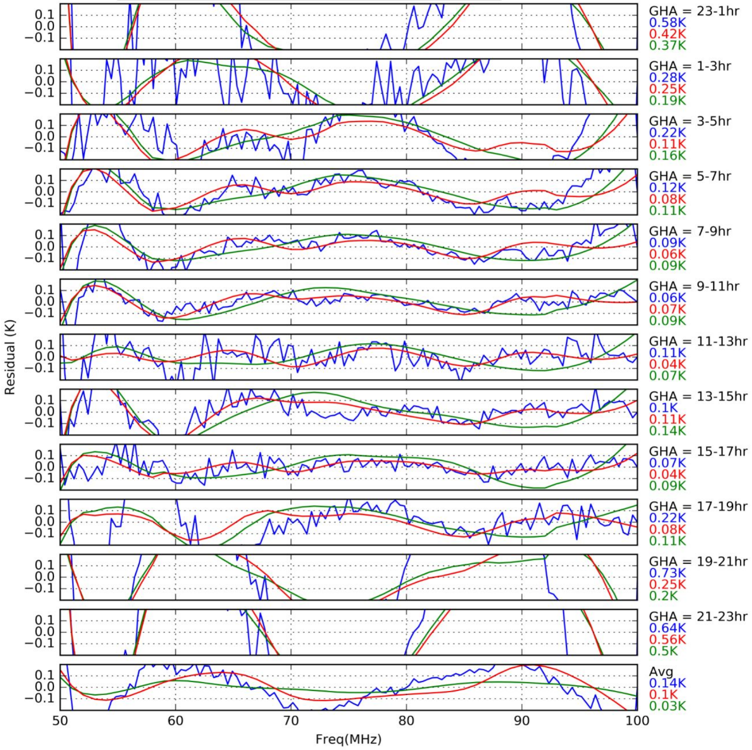
5 term Loglog Model



Extended Ground Plane

Rows are 2hr GHA binned data

5 term Linlog Model



- Adding the absorption feature to the simulation improves the agreement with data; at these level of residues the feature is significant

Soil Properties Confirmation

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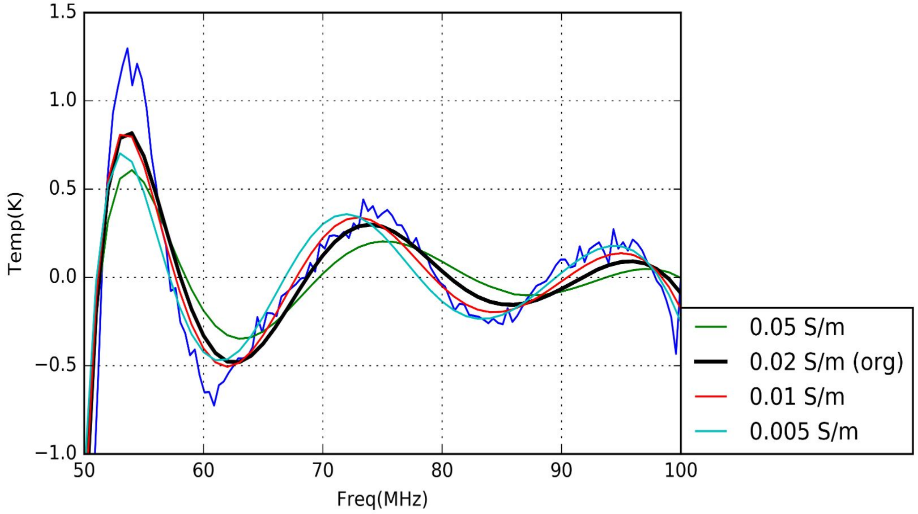
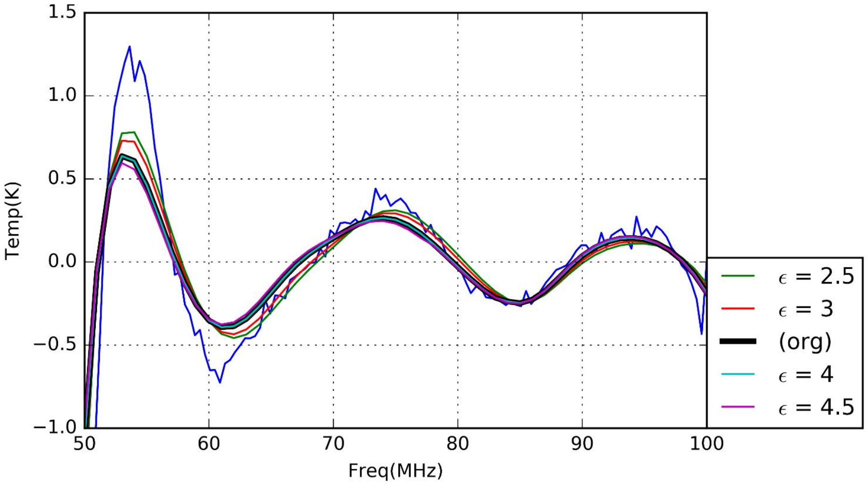
The typical values for the soil properties are taken from:
Sutinjo, A. T. et al. Characterization of a low-frequency radio astronomy prototype array in Western Australia. IEEE Trans. Antenn. Propag. 63, 5433–5442 (2015).





The averaged residues of the simulated spectra generated with different soil conditions are compared with the data.
The conductivity is confirmed to be within: 0.01 - 0.02 S/m
The dielectric constant: less sensitive

Summary

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- How do solutions from different EM solvers compare?
  - FEKO and CST-I gains are within 5%
- How chromatic is the EDGES Beam?
  - Compared to the ideal case:
    - the 10m X 10m is 10 times greater
    - Extended is 2 times greater
- Is it the chromaticity within acceptable levels?
  - The extended ground plane resulted in residues with an RMS ~50mK
- Do our beam modelling solutions match expectations?
  - Drift scan comparisons indicated within 15%
- The MRO soil properties quoted in Sutinjo paper is confirmed.

EXTRA SLIDES

Forward modelling: All solvers

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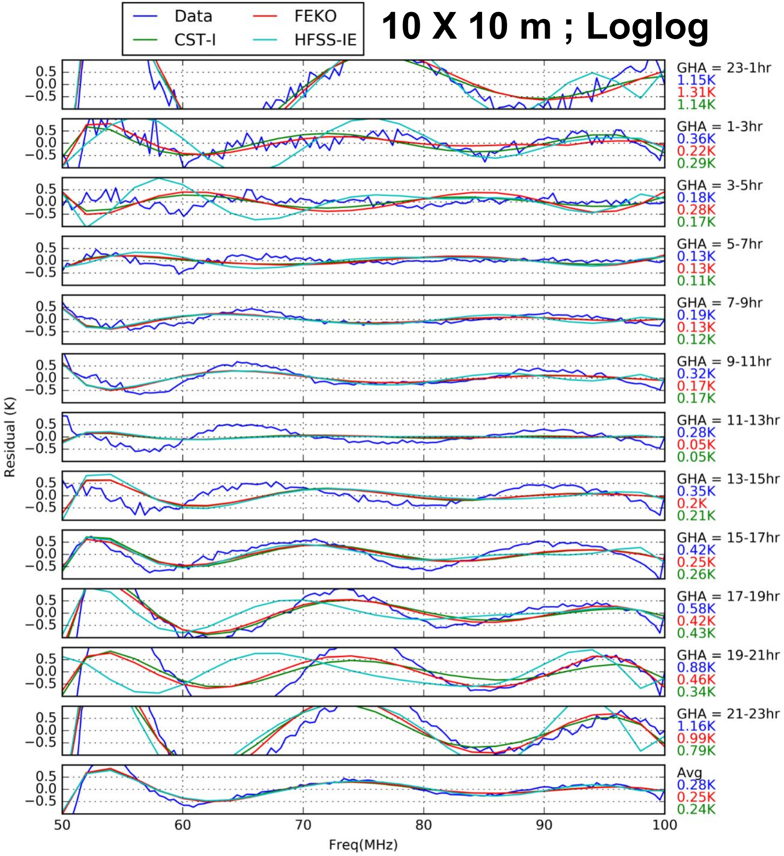
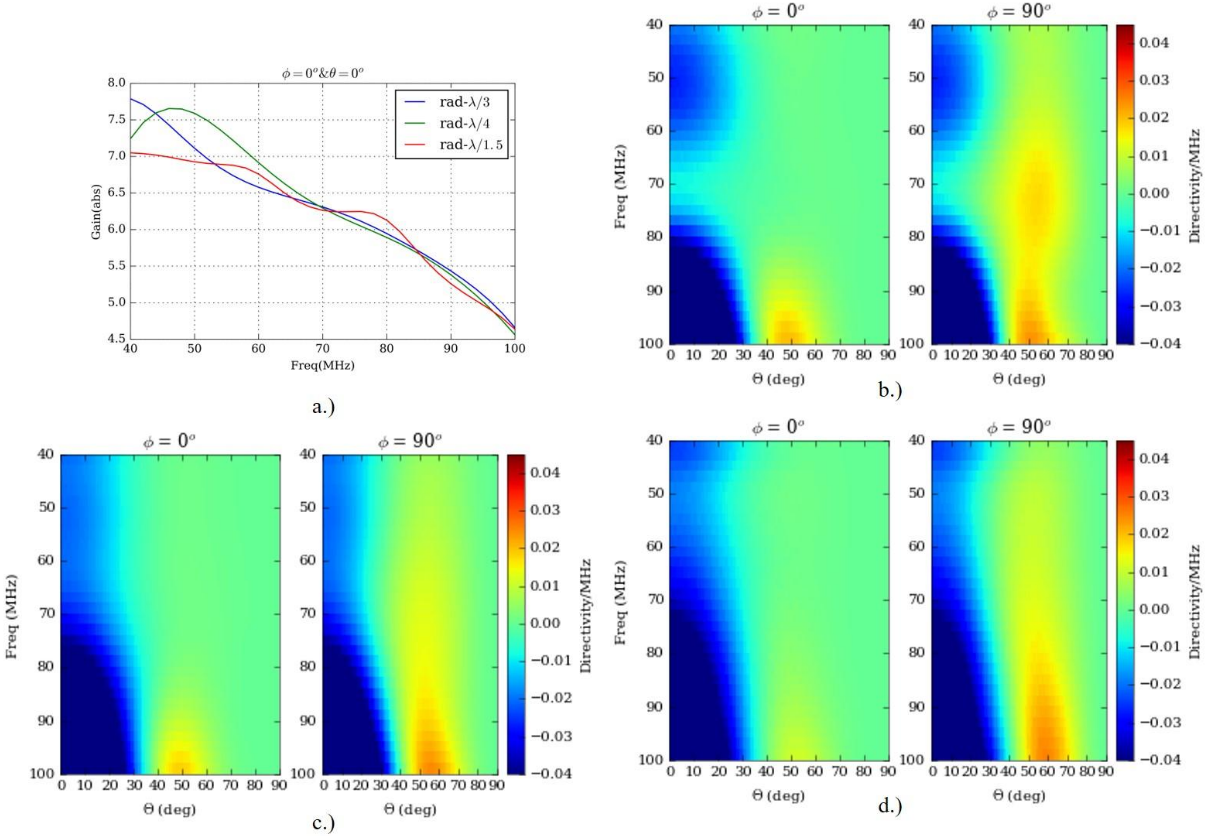
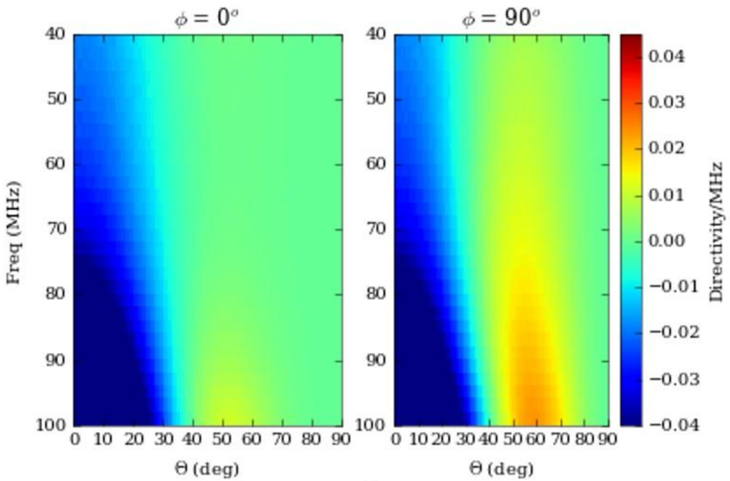
10 X 10 m ; Loglog



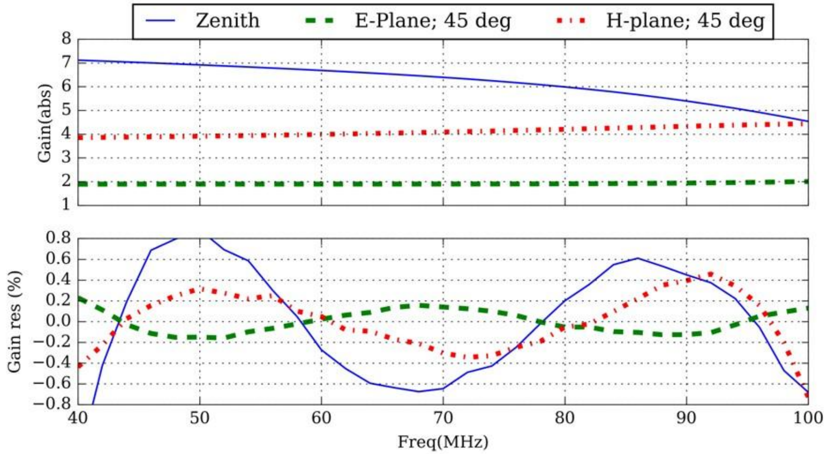
Verification with FEM



Verification with FDTD



a.)

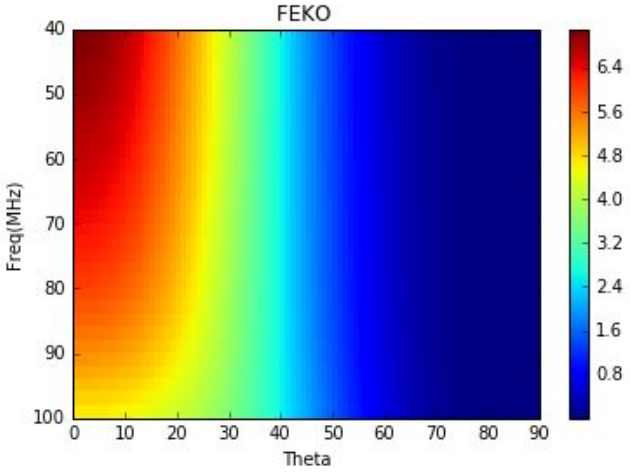


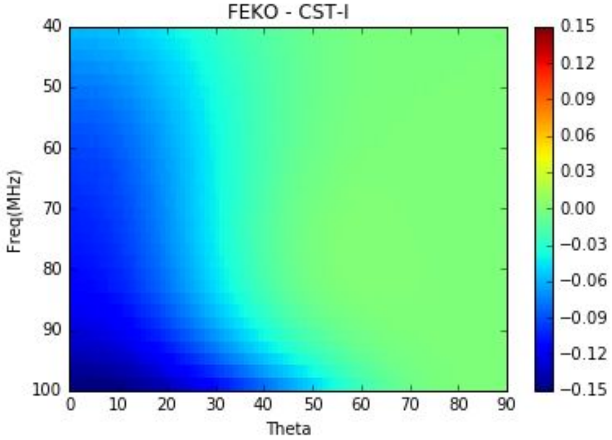
b.)

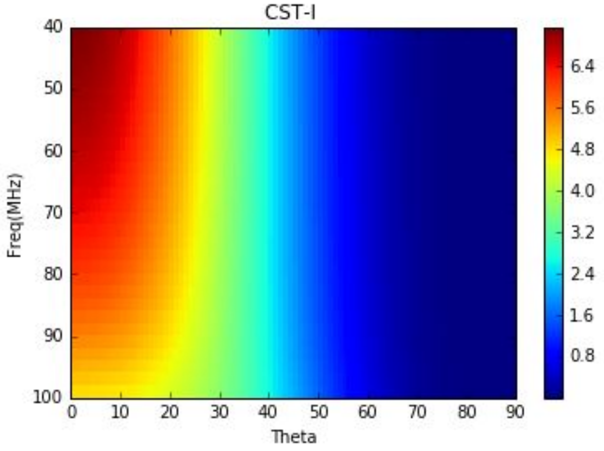
Different ground Shapes

Size	Shape	FoM (mK)
5	Square	280
10	Square	250
20	Square	180
15	Plus	170
30	Plus	64

PEC Ground: Gain along Excitation axis







PEC Ground: Gain Perpendicular to Excitation axis

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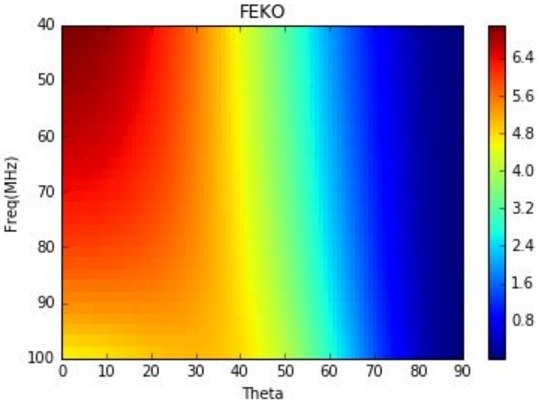

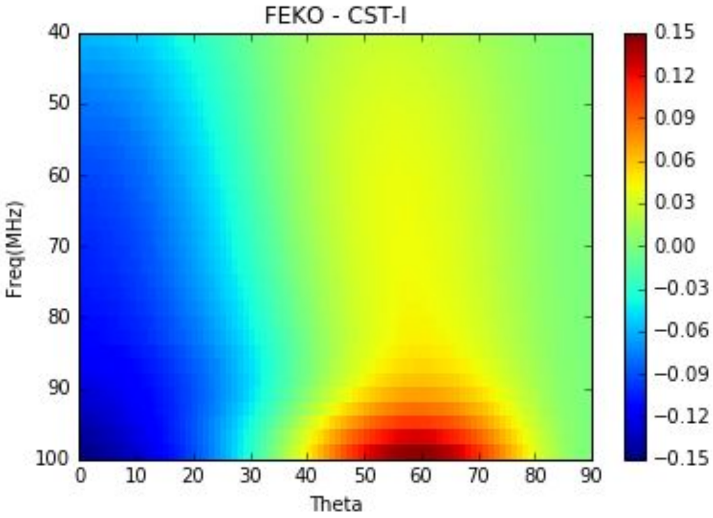

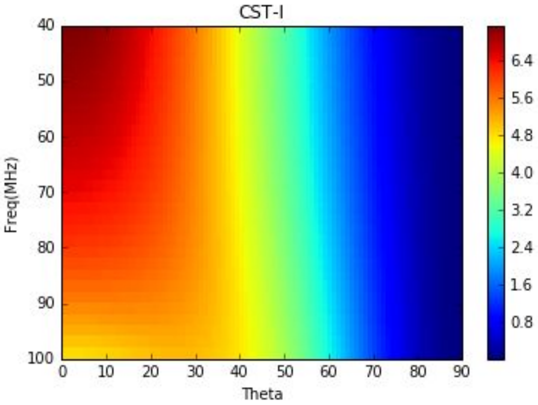

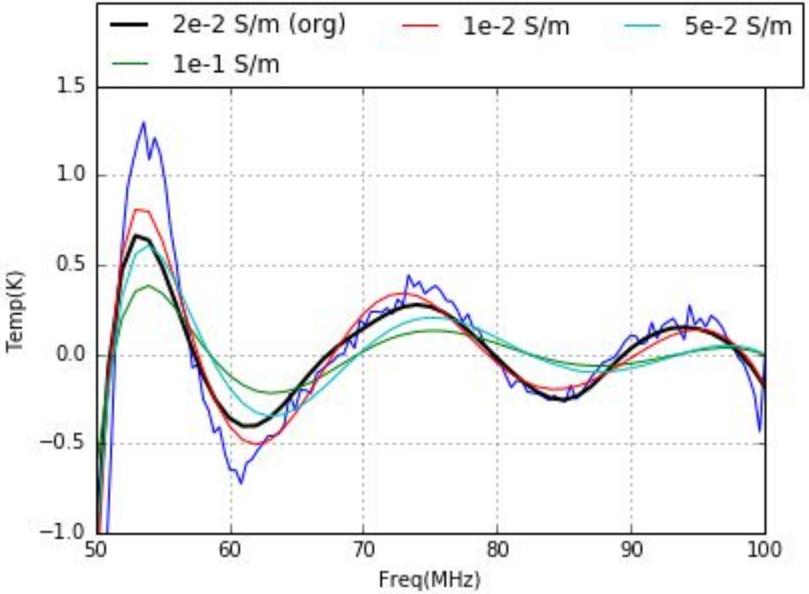
2e-2 S/m (org)
1e-2 S/m
5e-2 S/m
1e-1 S/m
Temp(K)
Freq(MHz)
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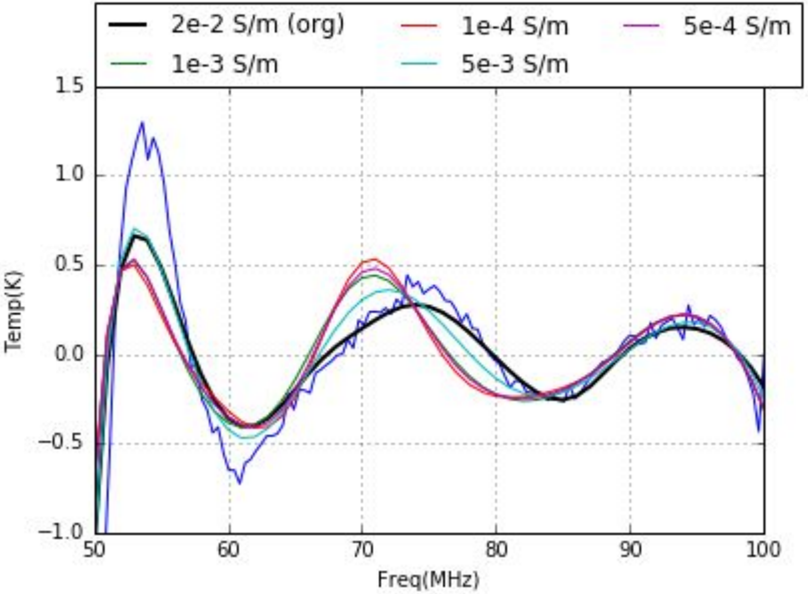
1.0
0.5
0.0
−0.5
−1.0
50
60
70
80
90
100


2e-2 S/m (org)
1e-4 S/m
5e-4 S/m
1e-3 S/m
5e-3 S/m
Temp(K)
Freq(MHz)
1.5
1.0
0.5
0.0
−0.5
−1.0
50
60
70
80
90
100

Summary

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- The realistic scenario was modelled using FEKO and HFSS-IE (MoM)
- Simulated residues from the new ground plane is lesser than the expected amplitude of the signature in that frequency regime.
- The simulation captured the residues from the actual data quite accurately.
- Different soil properties were simulated and beam solutions compared to data.