Preparing for 21-cm Cosmology with the OVRO-LWA

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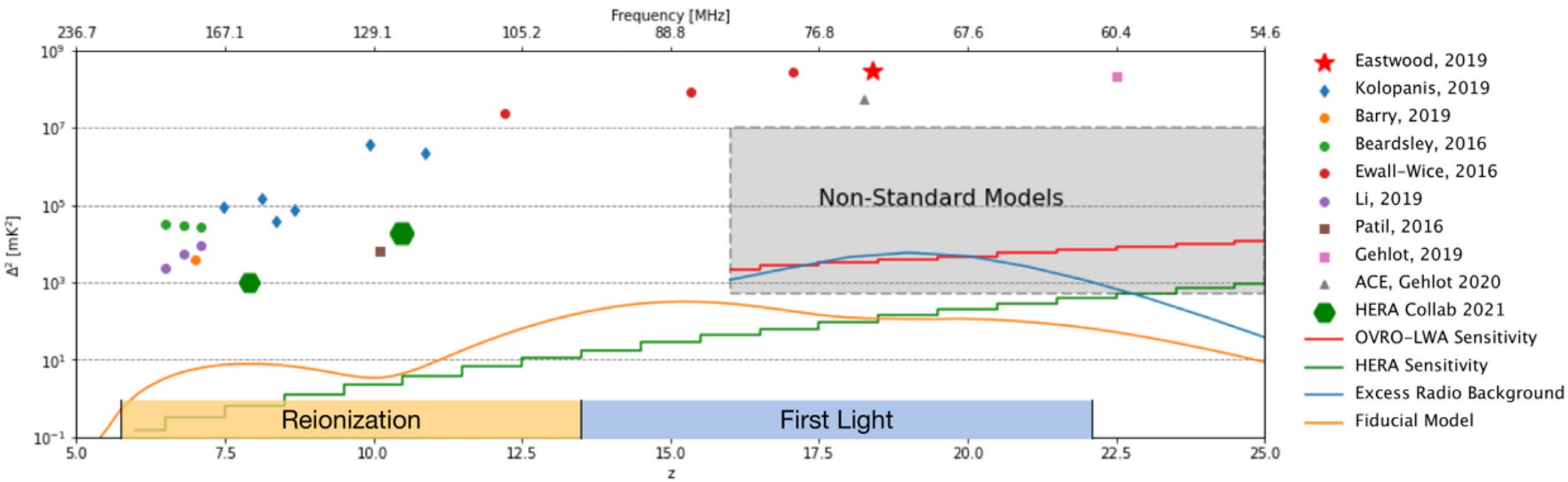
Behalf of the OVRO-LWA collaboration

Redshifted 21 cm measurements offer the most comprehensive view of the collective radiative processes of the earliest objects, including faint low-mass galaxies



Ref: Bowman, Jacobs++

- ***Objective*** : achieve noise-limited performance for the first time with the recently upgraded and expanded OVRO-LWA.
- For most existing arrays, observing the 21 cm signal in the Cosmic Dawn band is a post-hoc science goal.
- Upgraded OVRO-LWA is designed from the ground up and optimized for the CD band
- Upgrades have been targeted at reducing crucial spectral systematics that fundamentally limit all 21 cm instruments.

Will discuss

- Characterizing the OVRO-LWA beams
  - Chromaticity (variation with frequency)
  - Mutual coupling
  - Polarization leakage
- Forward modeling
  - Access effects of the beam, instrument on the science cases
  - Validation by simulation
- Delay Spectra analysis
  - Quantify the systematic effects

Beam Dream Team workshop, Jan 2023

Why do we care about the Beam?

The statistical detection of the Cosmological signal of interest can be via:

- Foreground removal
- Foreground avoidance

Effectiveness of either approach is limited by the beam convolved sky

Source peeling leads to residuals ~ level of signal of interest if we the knowledge of the beam limited

Beam convolves the foreground to higher k-modes reducing the window of cosmological detection

TLDR; I am my own problem

If we have to rely on beam modeling, pick the right EM solver!

(Mahesh++2021)

<u>Main Capability:</u>Simulate real soil ⇒ infinite extents X and Y directions

Most EM solver techniques have a defined “simulation box” extents. From where low level artificial reflections occur.

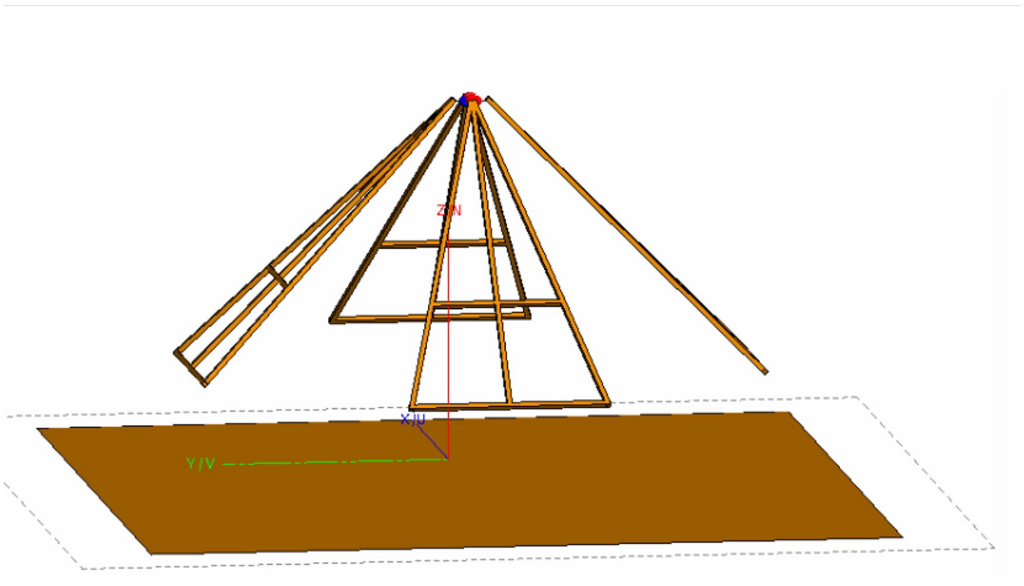
MOM technique: This employs Green Function to solve for Farfields. And allows for realistic soil simulation (infinite extents in XY plane)

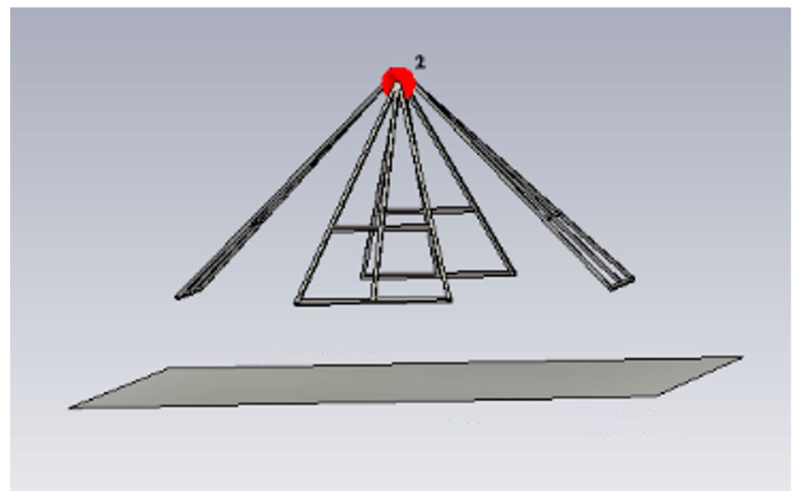
Possible packages:

- CST (I-solver)
- FEKO (MOM, Default)
- HFSS (IE)

Modeling a single LWA dipole in free space

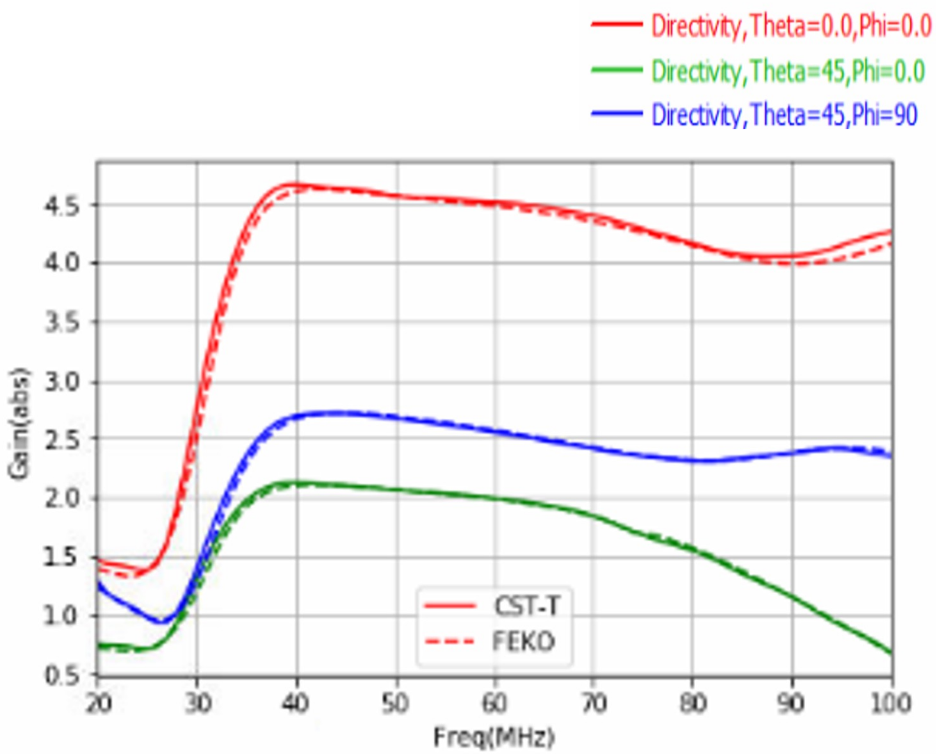
FEKO	CST



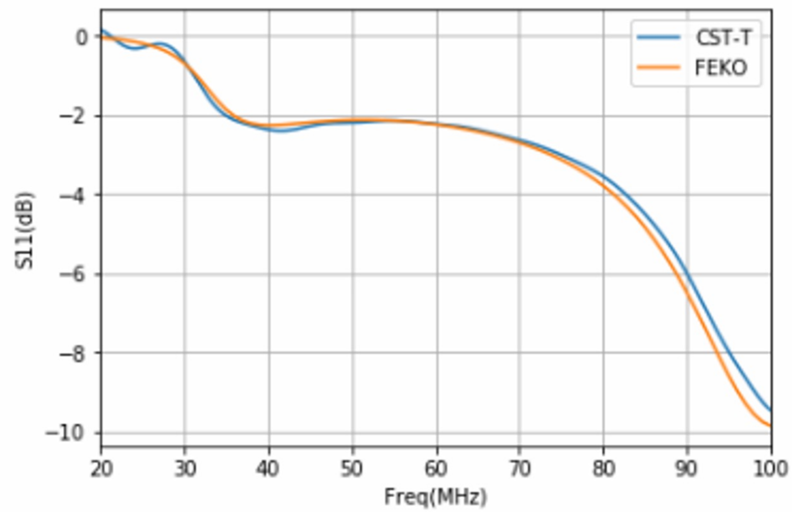


Trusting simulations: Comparing the two softwares

Gain Vs Frequency at a few viewing points

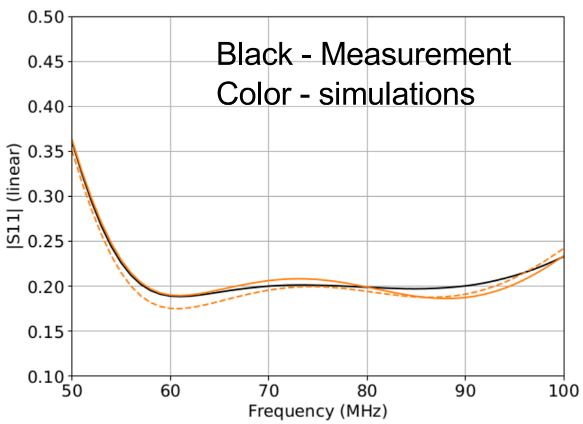


S11/Reflection coeff Vs Frequency



How does one trust simulations? *Need for Validation*

- S11 measurement (in-situ)



EDGES example (Mahesh++ 2021)

Vinand has procured the LNA boards to make the in-situ S11 measurements

- Gain measurements from the field
  - Beam Holography (Vydula, ASU)
    - Memo describing the need, the sources that can be used.
    - Limitation: Mapping the ***entire beam with the needed accuracy***
    - Possibilities: Measurements at a few viewing angles and complementing with simulations
  - Drone Measurements
    - Danny's talk
    - Established Linearity

Getting fancy: ***same*** LWA dipole ***now over soil***

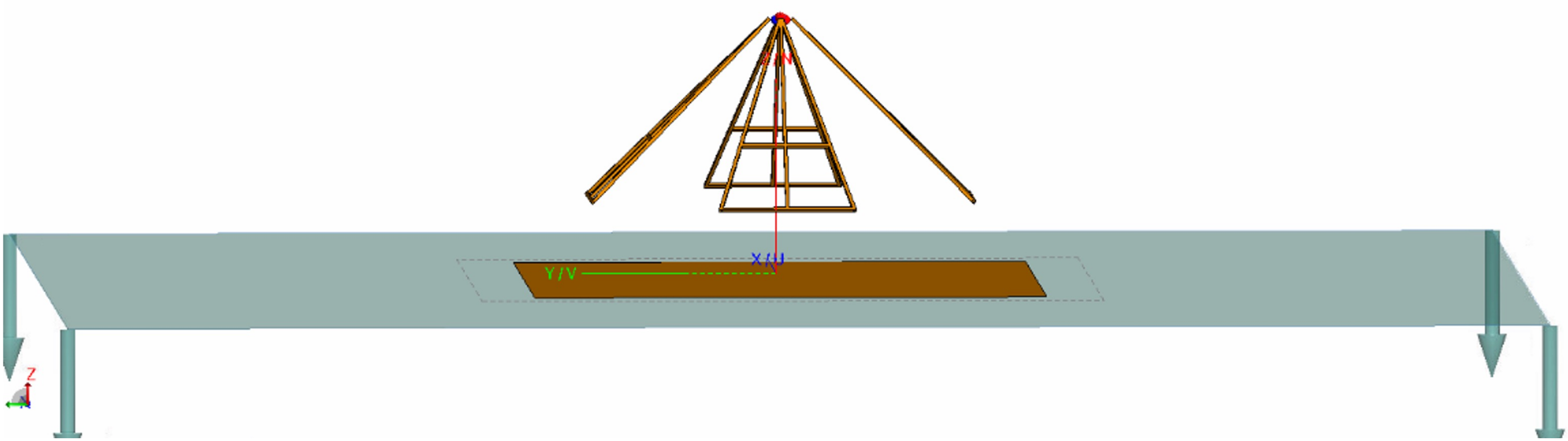
Took some measurements from Spinelli+ 2022 →

Table 1. Soil parameters for the one-layer and the multi-layer model, extracted from measurements of soil at the LWA site during both dry and wet conditions at depths z_i, $i = 1, 2, 3$.

Soil layer parameters (σ in S/m, ϵ_r dimensionless)

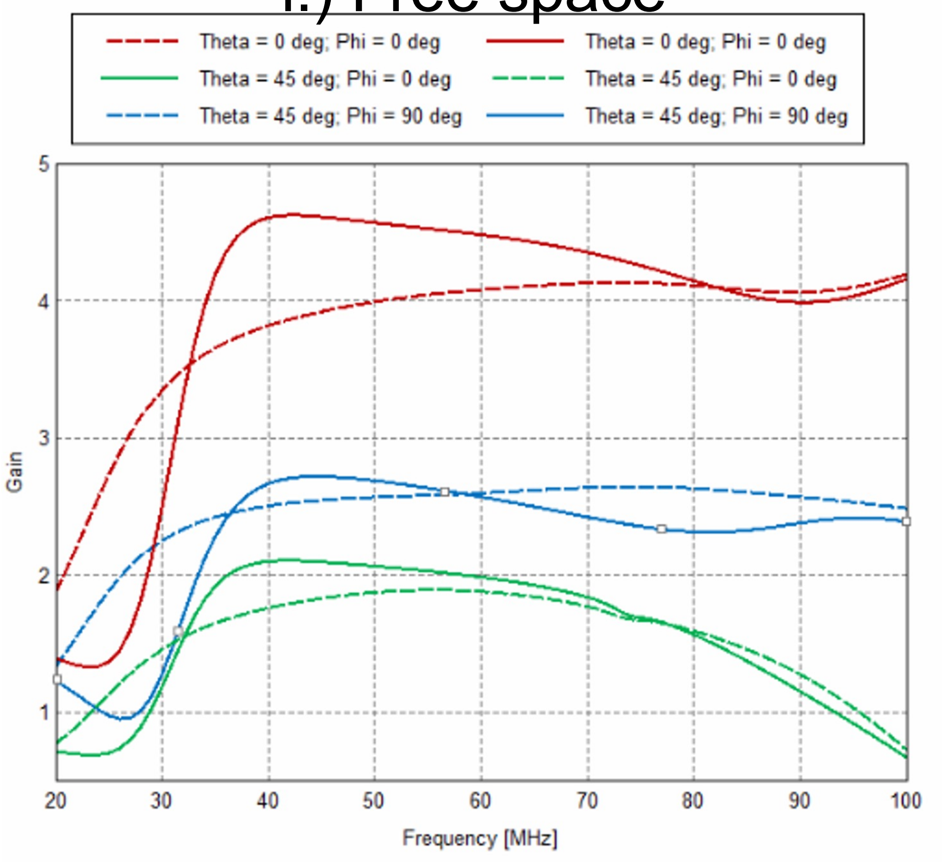
	σ_{dry}	σ_{wet}	$\epsilon_{r,\text{dry}}$	$\epsilon_{r,\text{wet}}$
one layer	0.004	0.01	4.4	6.5
$z_1 = 10.16\ cm$	0.0013	0.005	3.73	8.09
$z_2 = 35.56\ cm$	0.004	0.0068	4.25	6.45
$z_3 = 53.34\ cm$	0.0187	0.0388	7.58	20.56

Long term plan: install hygrometer and collect soil data to be input for simulations

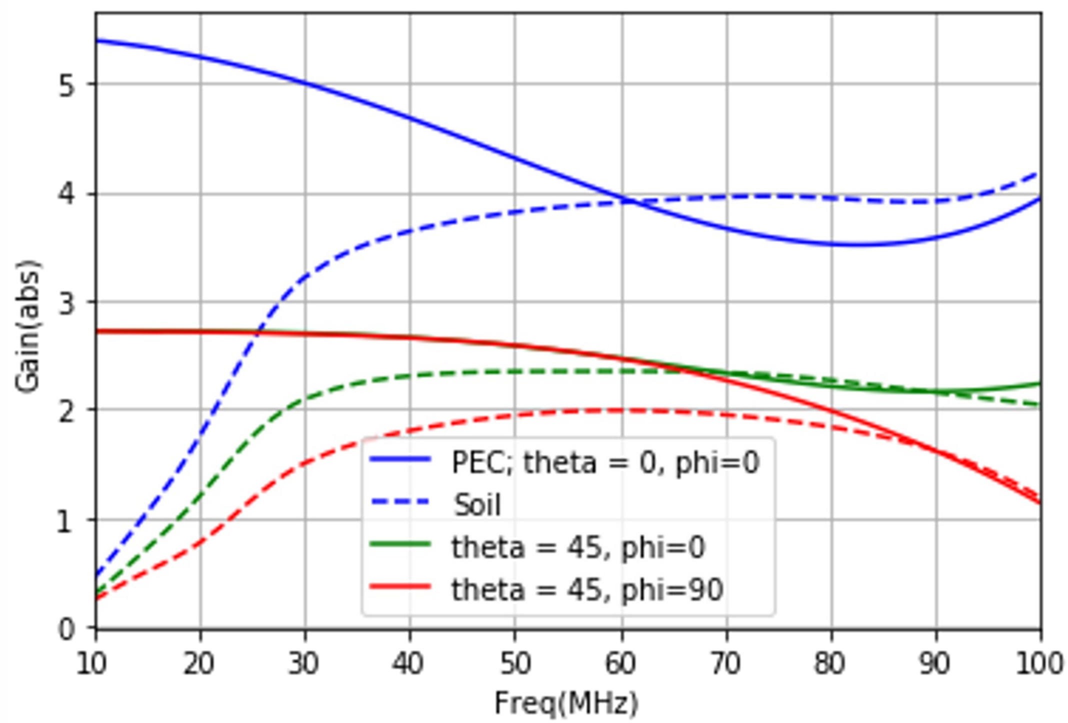


Comparison of Gain vs Freq of OVRO-LWA over soil (--) with cases:

i.) Free space



ii) PEC

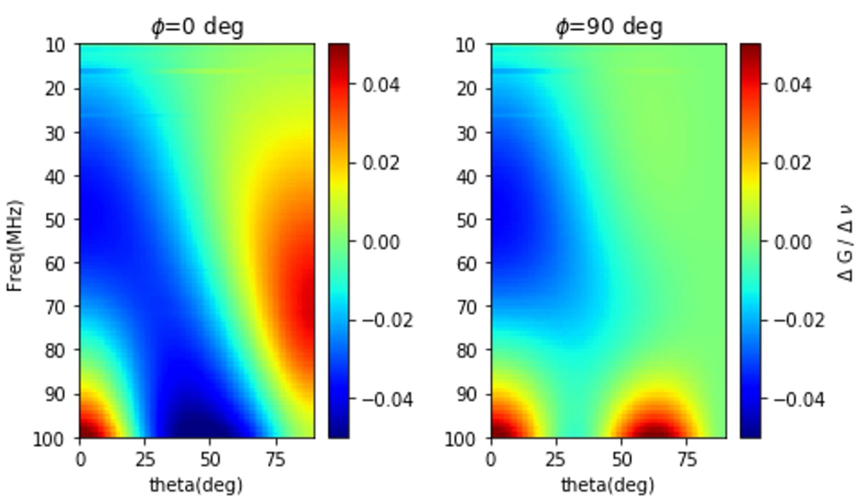


We have all these simulations
Lets, Access the Chromaticity !

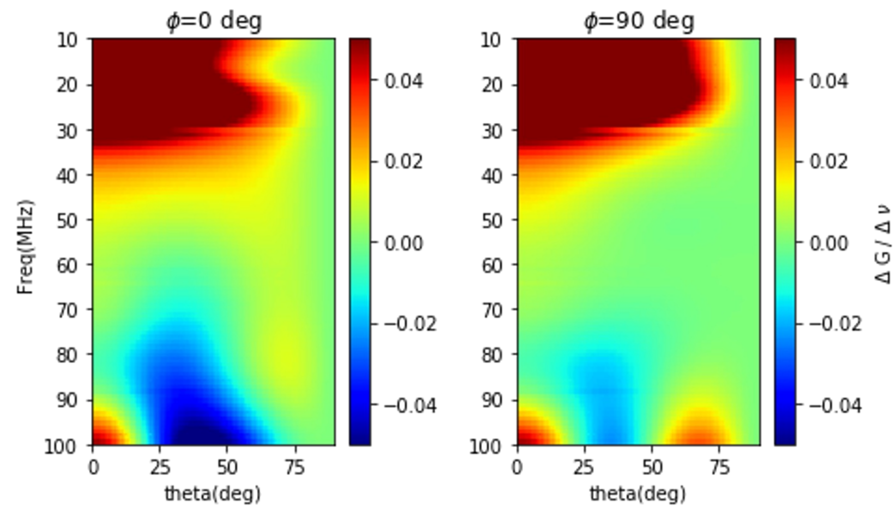
1. Derivative plots (Mahesh++ 2021)
   a. More qualitative
2. Delay Spectra analysis (Gehlot, Murray, ASU)
   a. Quantitative and easier to quantify its effect on 21cm interferometric measurements

Beam derivatives on FEKO Simulations

Over PEC



Over soil

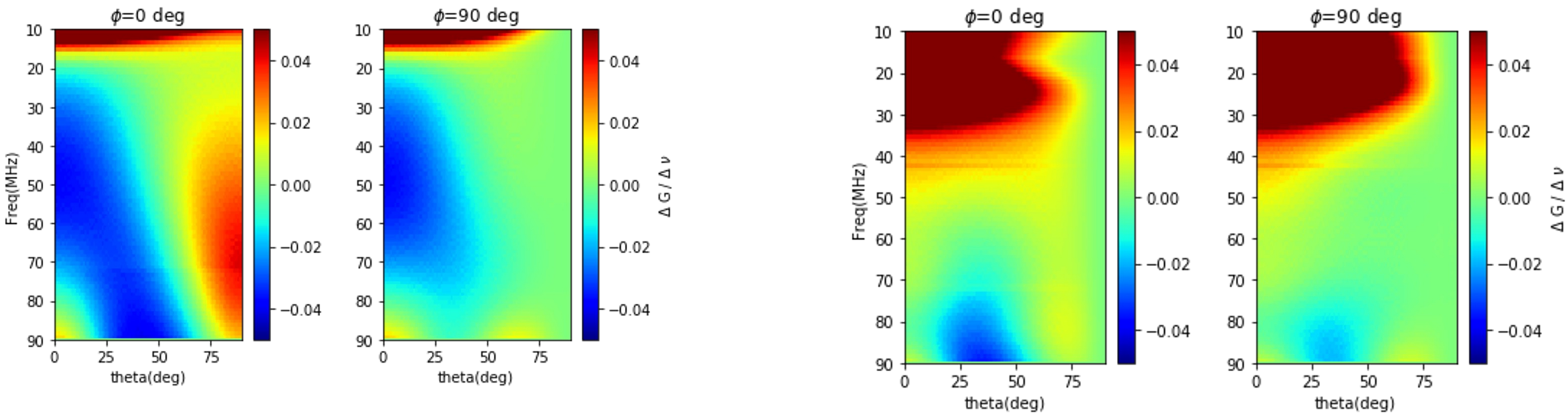


Plot quantity: Gain derivatives (/1MHz)
Qualitatively: PEC has the least chromaticity, chromaticity of *Over the soil* is not as worse as the free space

Beam derivatives on CST Simulations

Over PEC

Over soil

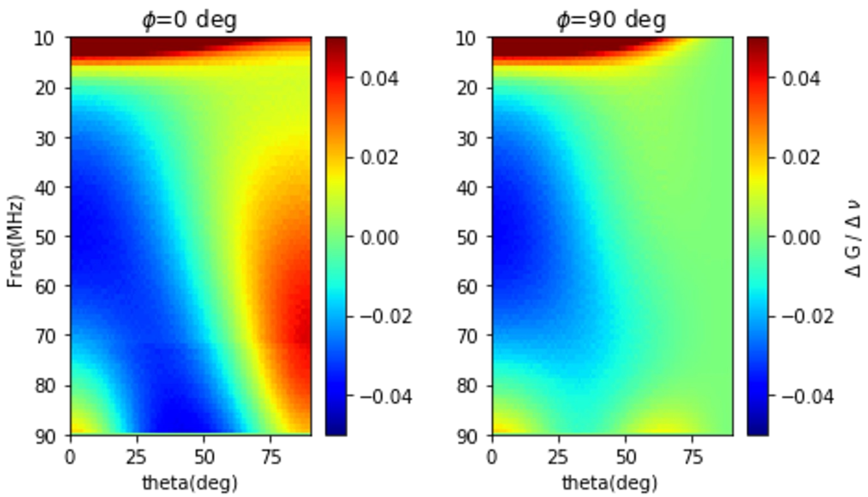


Plot quantity: Gain derivatives (/1MHz)

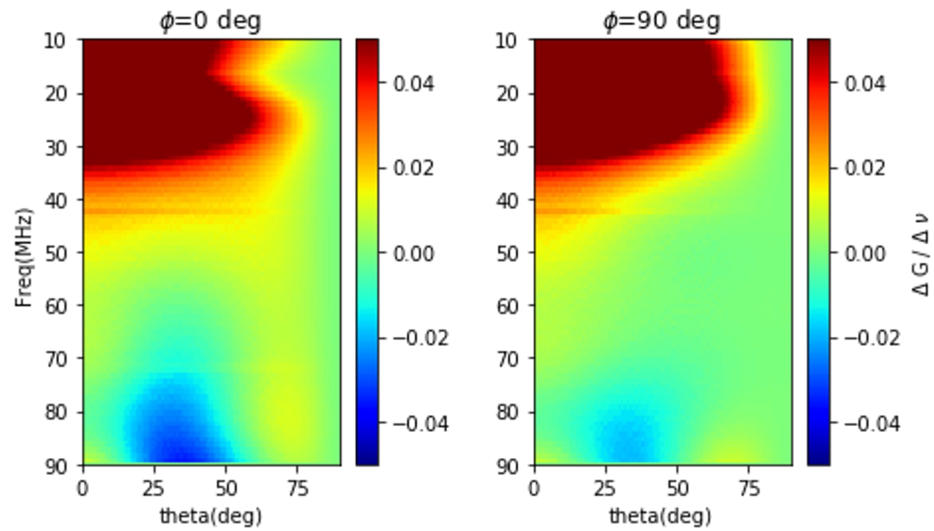
Qualitatively: Similar to FEKO simulations. PEC case below <15 MHz; CST predicts worse chromaticity

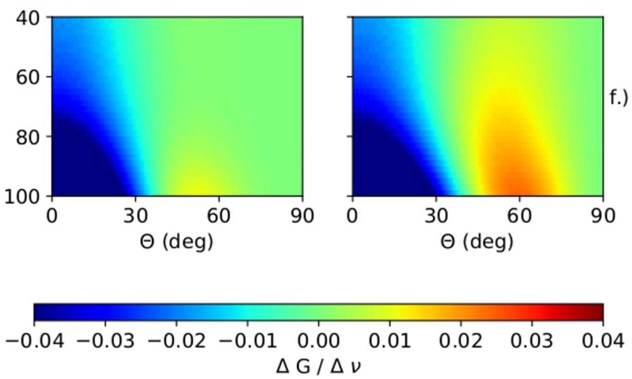
Comparing with EDGES beams?

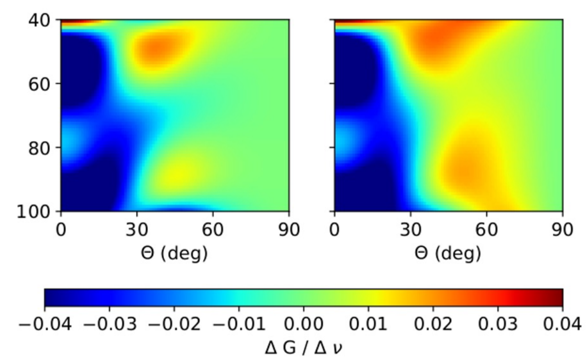
Over PEC



Over soil



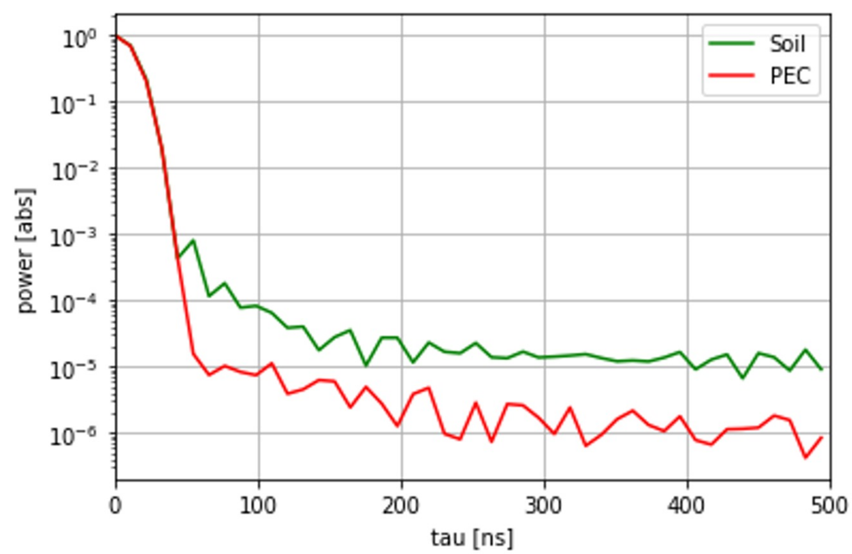




Delay spectra analysis on the beam

At Zenith

The maximum delay is set by the simulation resolution ~1MHz

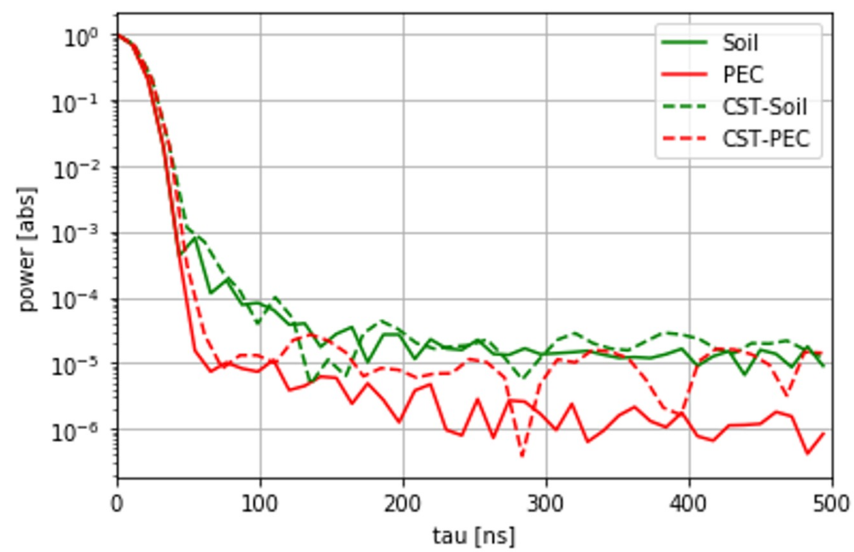


PEC - Ideal case: The power is suppressed at
delays > 100ns
Or baselines> 60 m

Soil - realistic case: The desired suppression is at
delays >200 ns
or baselines > 120 m

Delay spectra analysis on the beam

At Zenith



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That discrepancy we saw between CST & FEKO < 15 MHz translates as higher power all delay modes > 100ns

Delay spectra analysis on the beam

The maximum delay is set by the simulation resolution ~1MHz

PEC - Ideal case: The power is suppressed at
delays > 100ns
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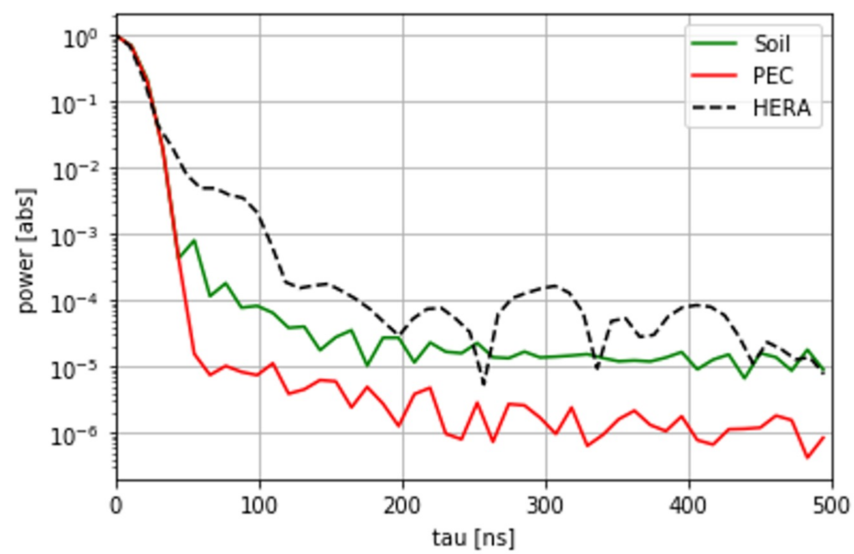
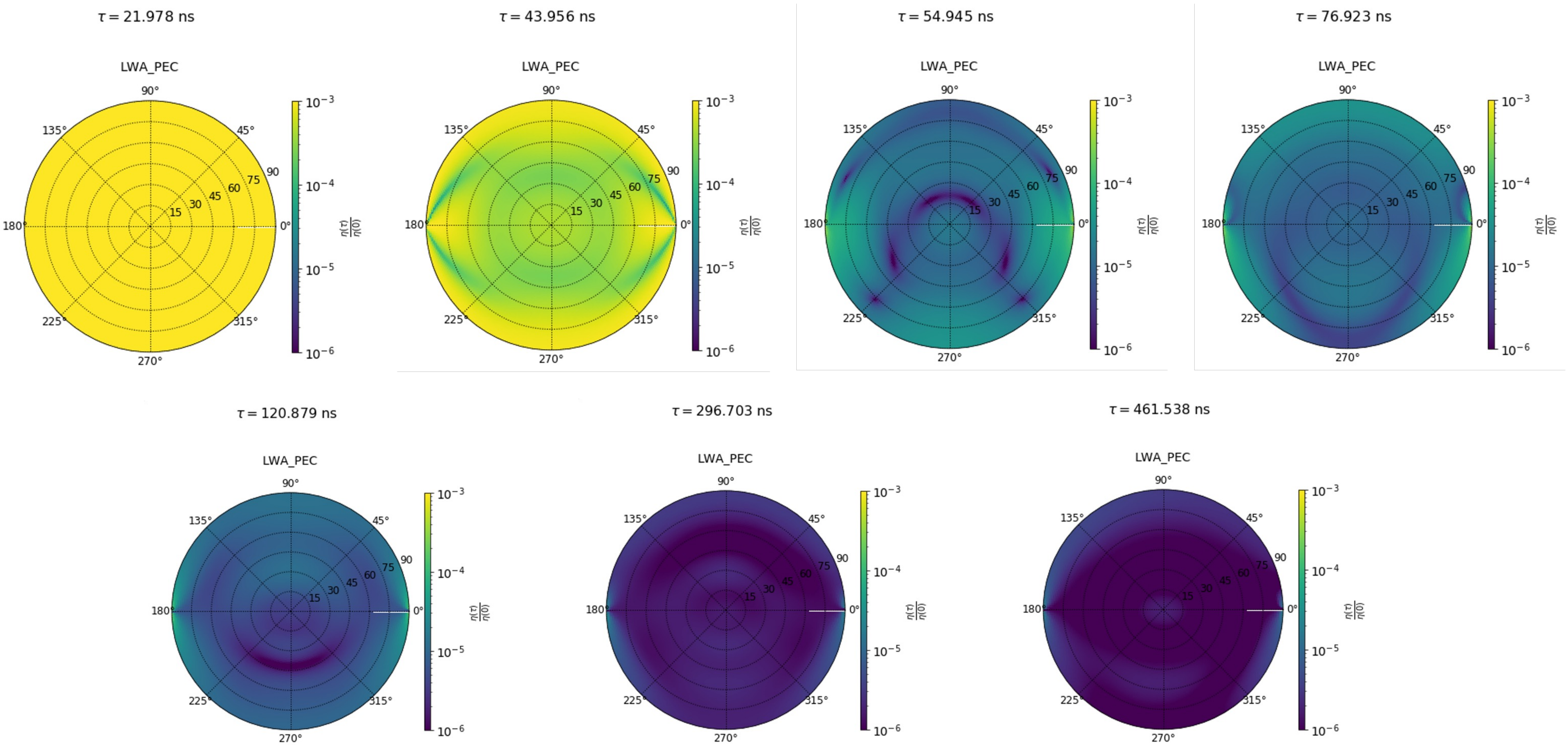
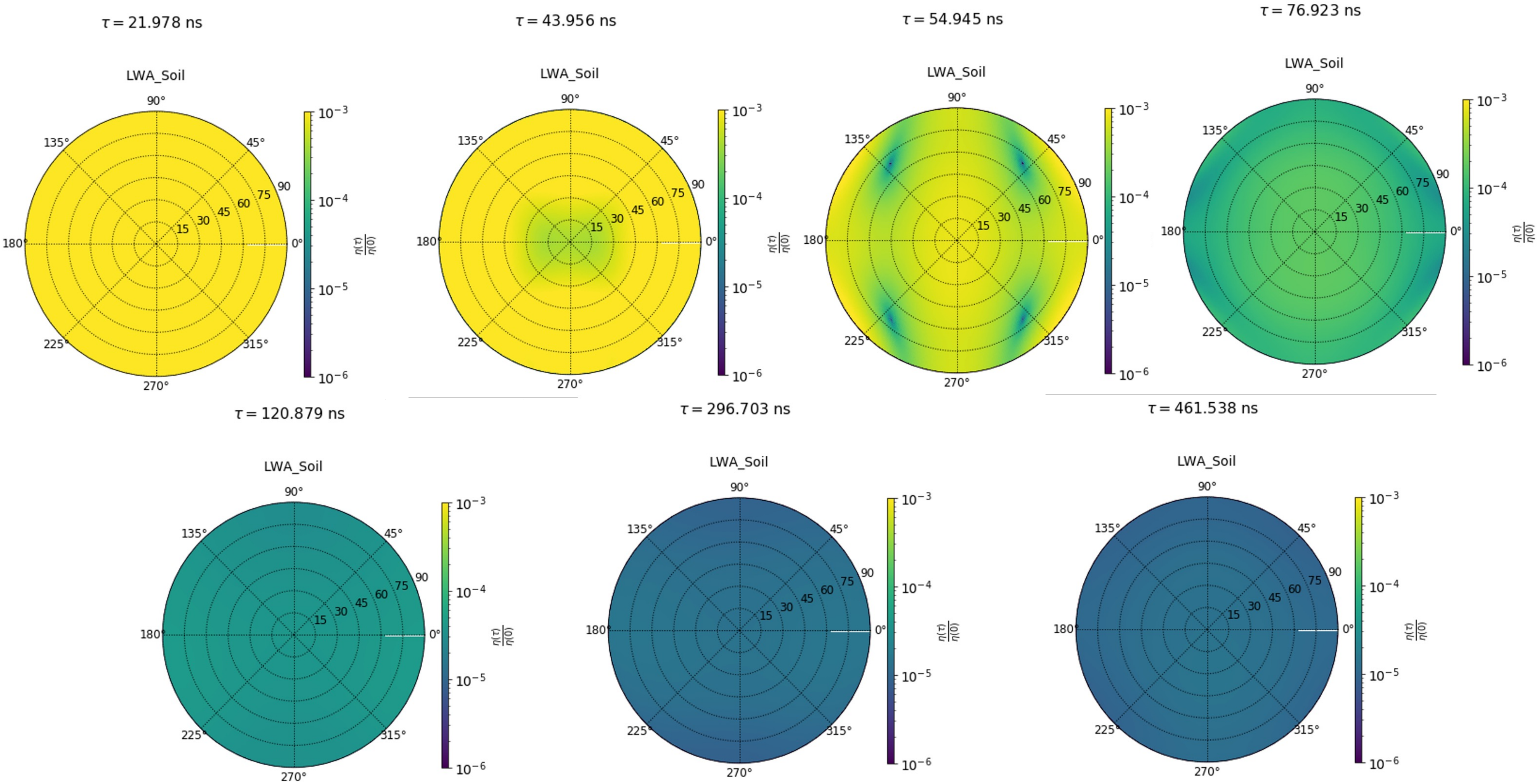
At Zenith



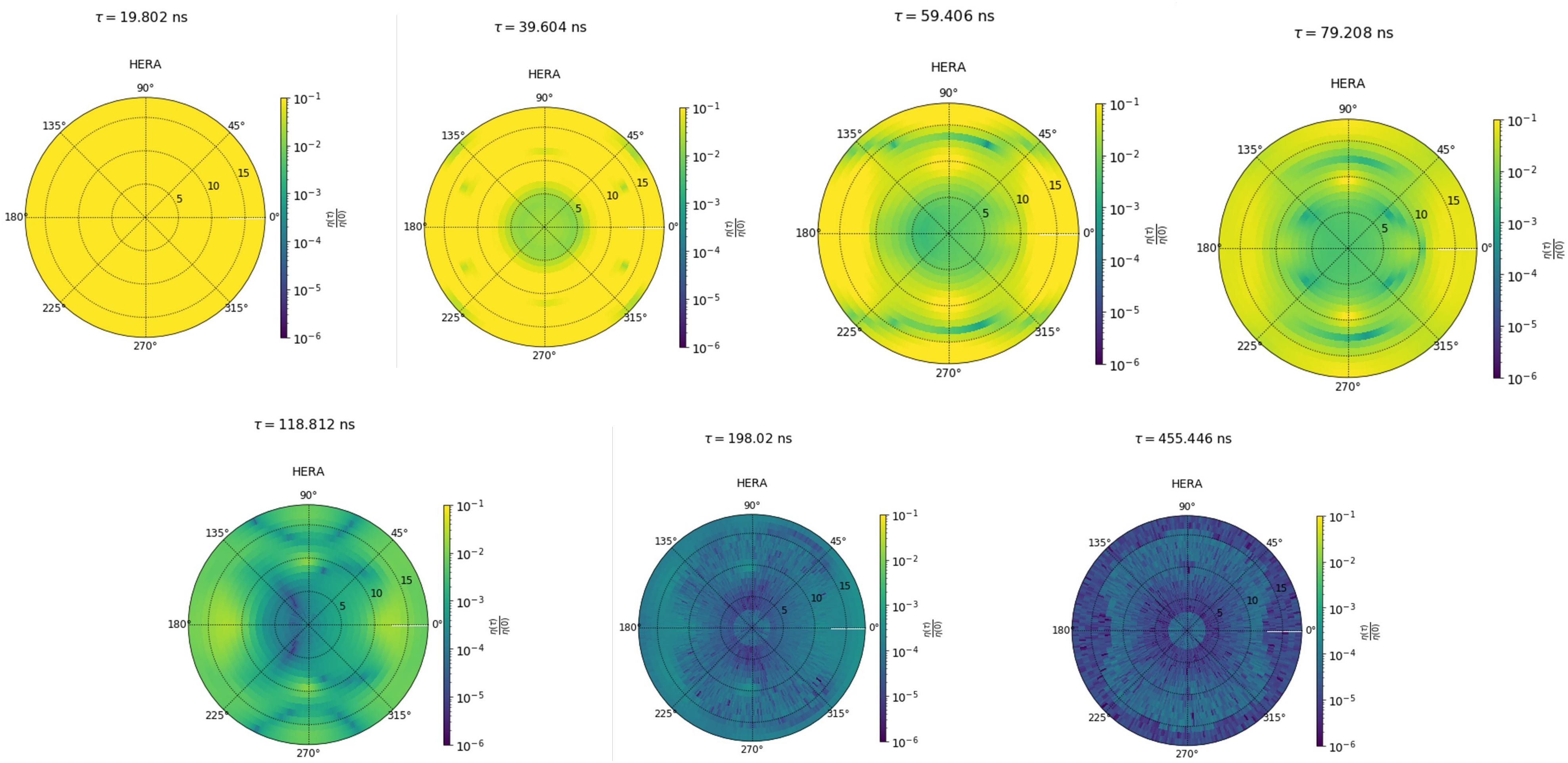
Direction dependent delay spectra for ***LWA over PEC***



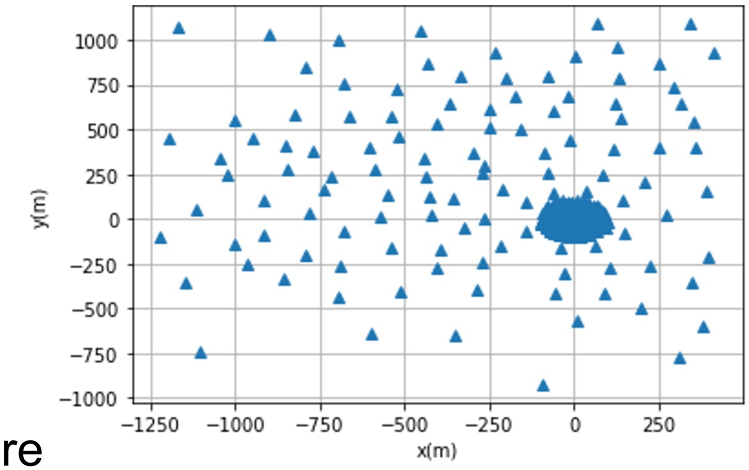
Direction dependent delay spectra for ***LWA over Soil***



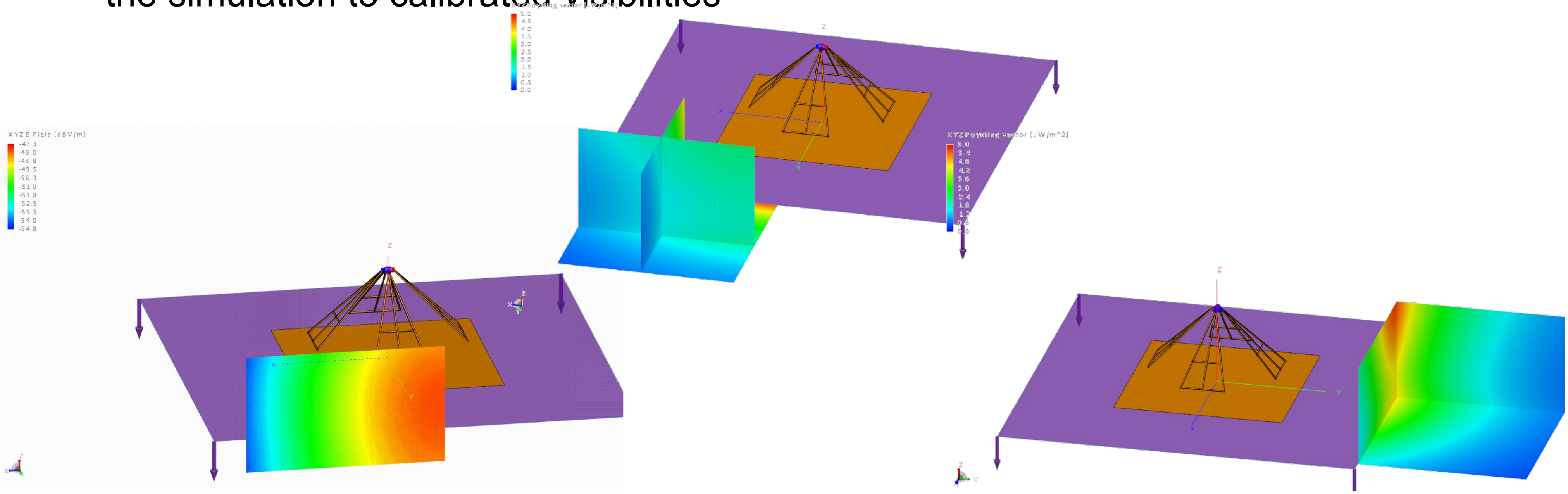
Direction dependent delay spectra for ***HERA Vivaldi***



Plan for Mutual coupling effects



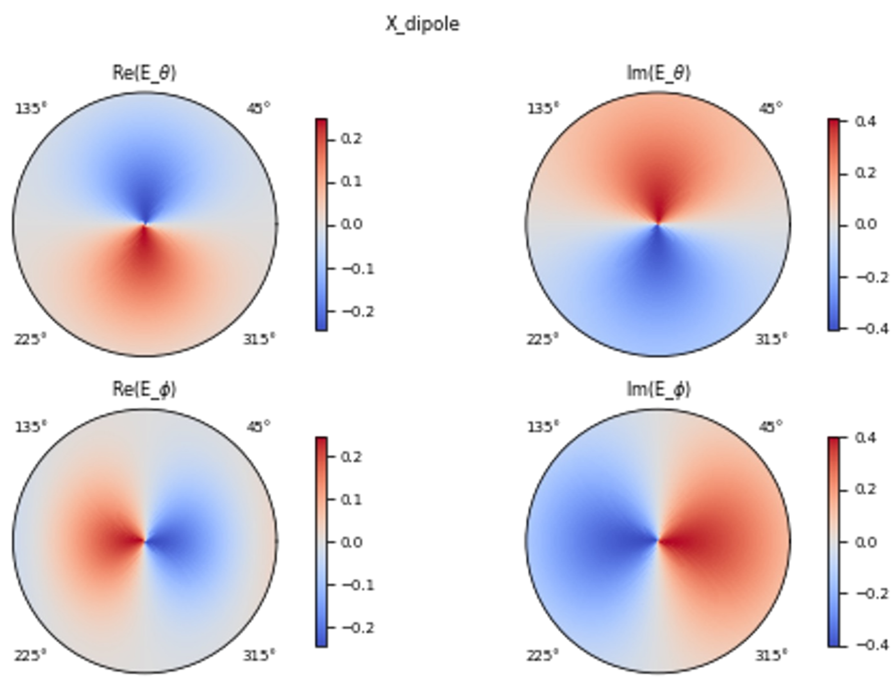
- Access the near field currents at locations of nearest neighbours
- Simulate a few near neighbours
  - Quantify chromaticity: Derivative plots, dspec plots
- As we keep adding antennas to the simulation Compare the simulation to calibrated visibilities

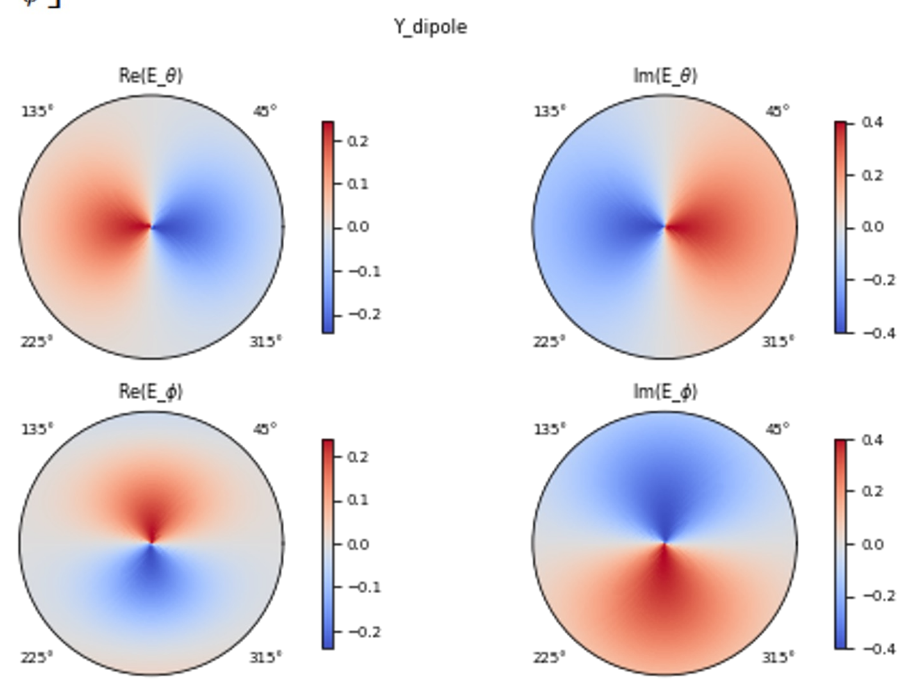


Polarization Analysis of the beams

Electric field patterns of the LWA dipoles at 50 MHz

$$J = \begin{bmatrix} E_\theta^x & E_\phi^x \\ E_\theta^y & E_\phi^y \end{bmatrix}$$





Polarization Analysis of the beams

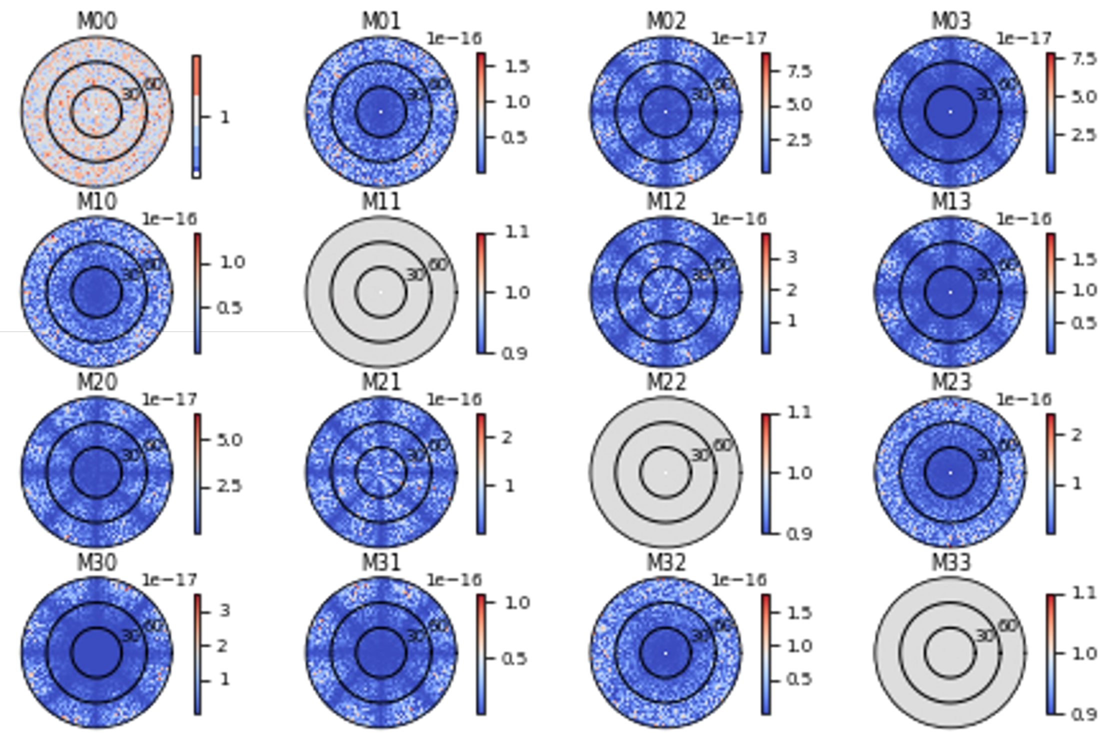
Ideal correction ⇒ M^{-1} & M from the same beam

50 MHz

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = M \begin{bmatrix} e_{xx} \\ e_{xy} \\ e_{yx} \\ e_{yy} \end{bmatrix}$$

to get back the original:

$$M^{-1}\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = M^{-1} M \begin{bmatrix} e_{xx} \\ e_{xy} \\ e_{yx} \\ e_{yy} \end{bmatrix}$$



All the off diagonal terms are zero

No leakage

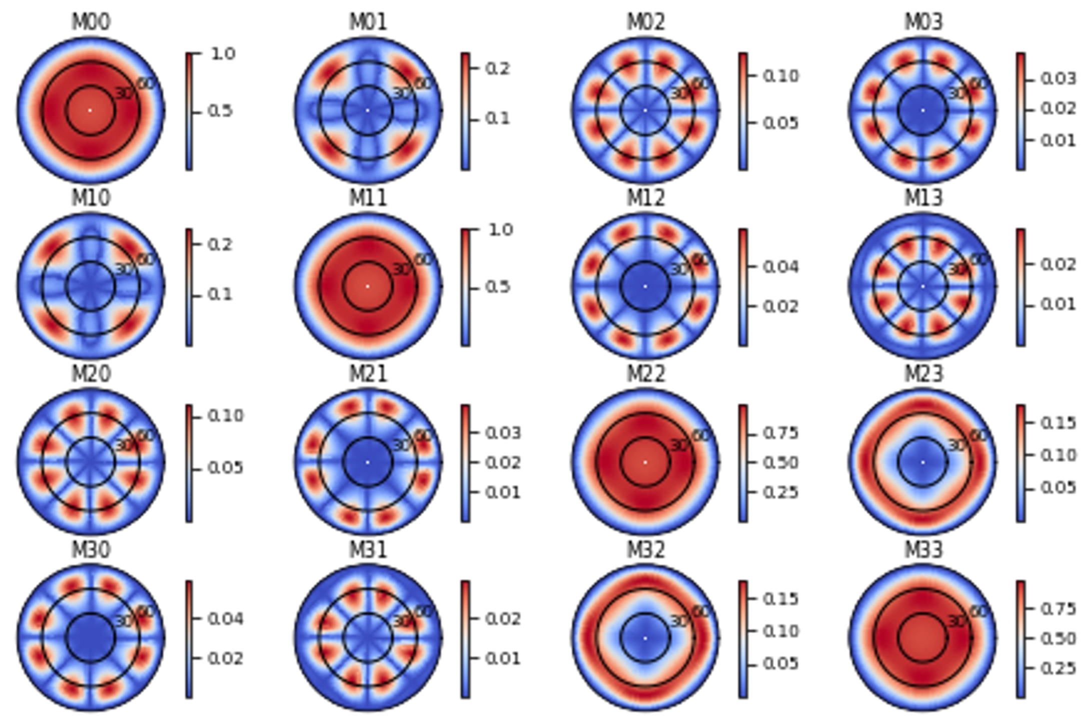
Polarization Analysis of the beams

Error in Correction ⇒ M^{-1} & M not from the same beam

Using J_soil to correct for J_space

The off diagonal terms are non-zero ⇒ leakage

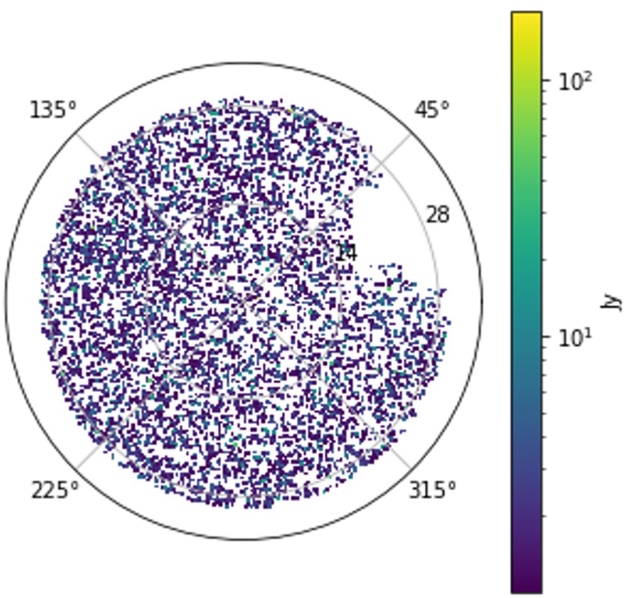
50 MHz



Forward modeled a model sky through the OVRO-LWA

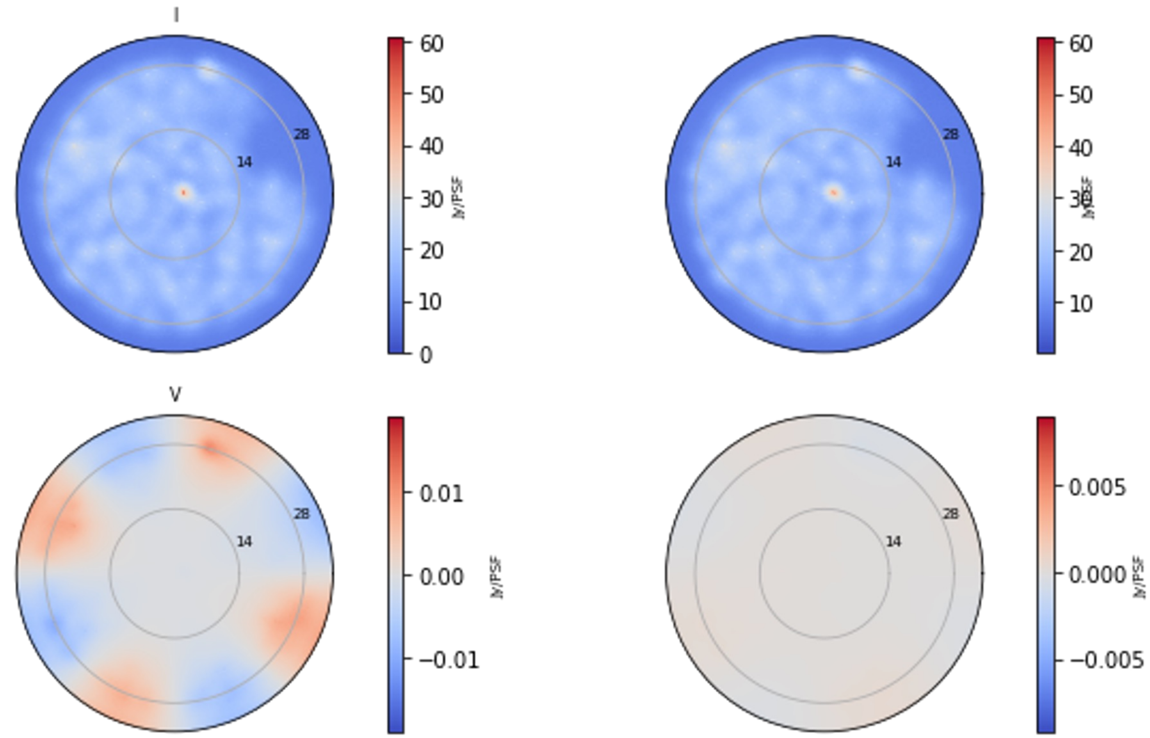
Primitive pipeline developed for FARSIDE (Mahesh++, in prep)

1. GLEAM point source sky (only Stokes I)
2. 2 different cases of OVRO-LWA beams
3. Array layout (flat sky approx.)



LWA over Soil

LWA over PEC



Forward modeling

Useful for:

- Testing instrumental effects (Beam), Ionosphere, range of systematics
- Power spectra of the known i/p can be used to verify that no signal was lost and the statistics match expectation.

Plan:

Forward model everything in the instrument pipeline

- Electromagnetic simulations of the beams
- Ionosphere
- A full sky model of diffuse emission
- Point sources
- Accurate wide-field visibility simulation
- Thermal noise
- Range of systematics

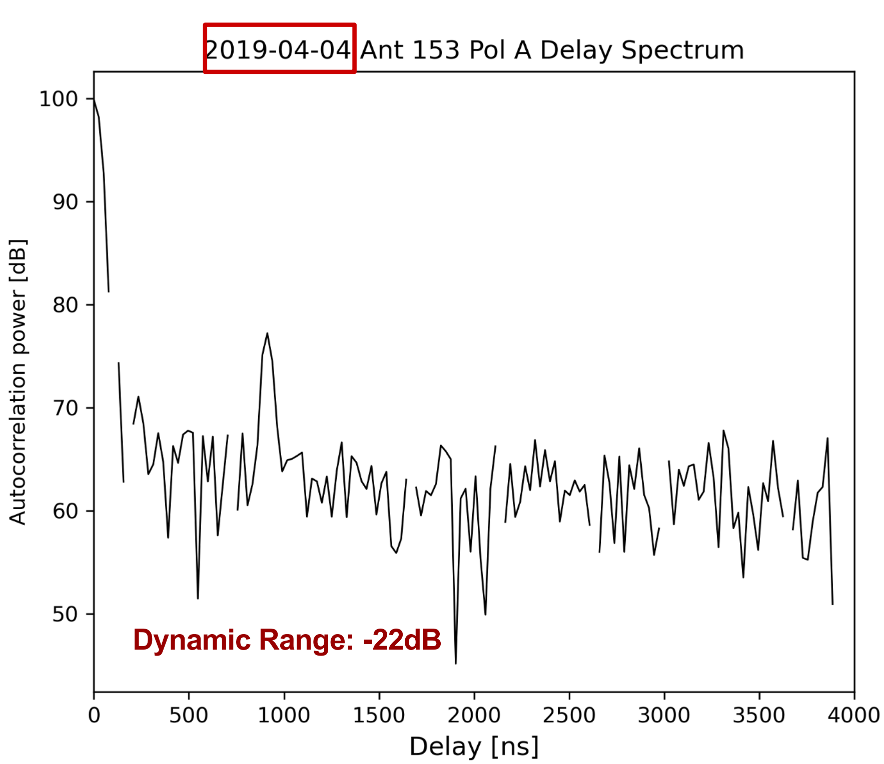
Quality Assurance & Check-out

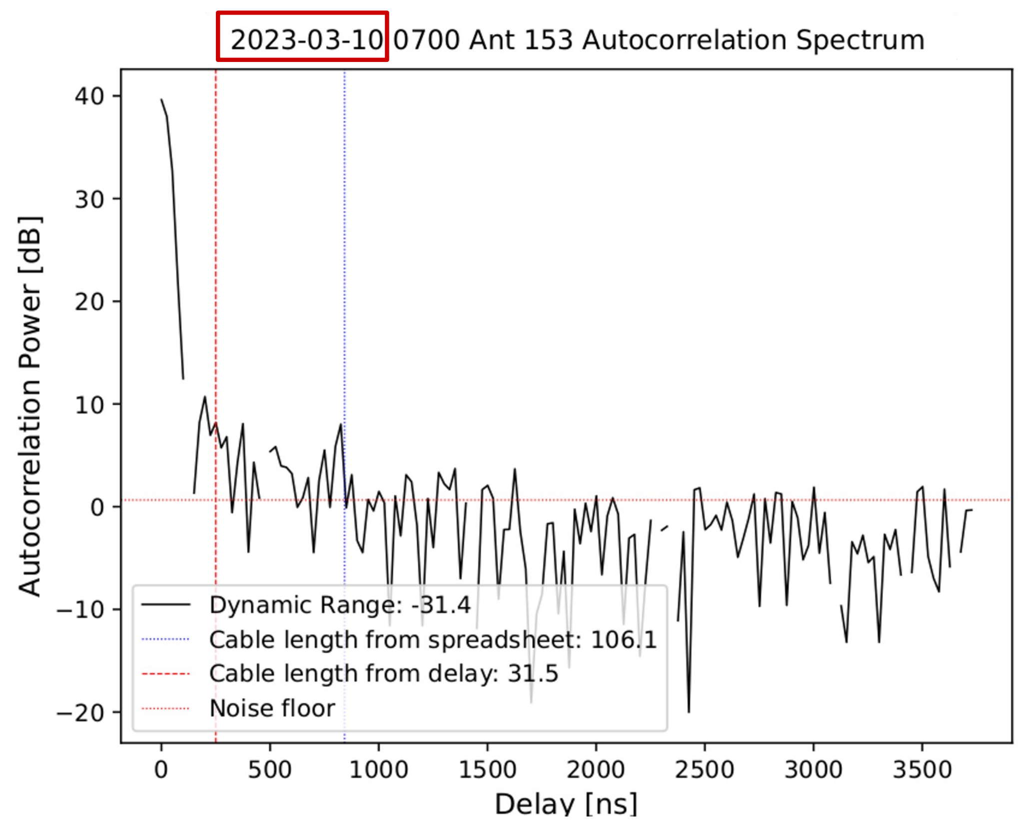
- Delay spectra analysis: An iterative development approach to Cosmic Dawn analysis on the OVRO-LWA
    - Fourier transforms of the visibilities along frequency
- Preliminary assessment and validation of early data
- Helps assess bandpass smoothness
- Used for sensitive diagnostics for common instrumental concerns
    - cable reflections (Katherine Elder's work)
    - cross-coupling,
    - stability,
    - and interference
- DS to yield the first 21 cm power spectrum limits from the project.

Simple DS {Kolopanis et al., 2019; Aguirre et al., 2021, and HERA Memos #87, #90}

Delay Spectra to analyse cable reflections (K.Elder, ASU)

Indicates cable reflection has indeed reduced in the upgraded system!





My favourite update: ***Absolute flux measurement***

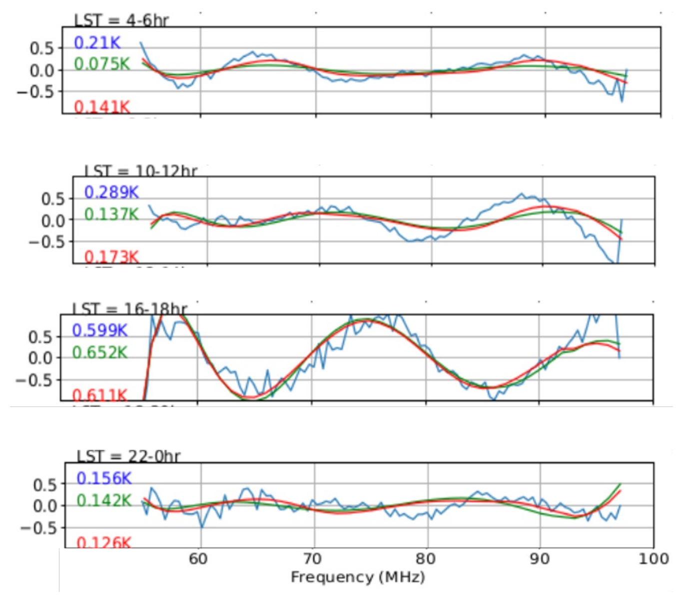
In collaboration with: Gregg Hallinan, Vinand Prayag (Caltech);

Andrew Romero-Wolf, Julie Rolla, Andrew Ludwig (JPL)

Science cases: Global 21cm measurement, Cosmic ray studies, complements *m*-mode maps.

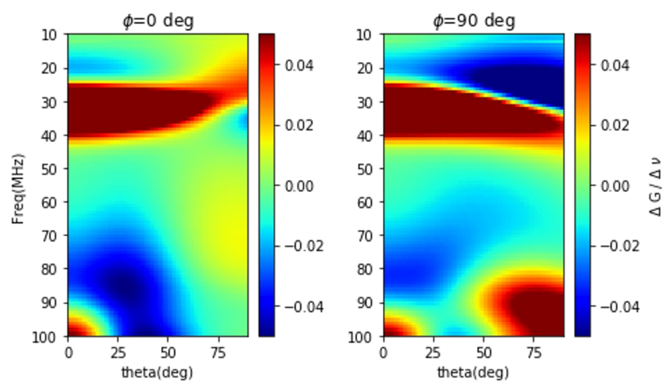
Currently:

- Beam chromaticity analysis of the individual dipoles
- Simulating spectra (Residuals of beam convolved sky)
- Deciding Receiver scheme: absolute calibration (EDGES 3) Vs correlator receiver (SARAS 2)

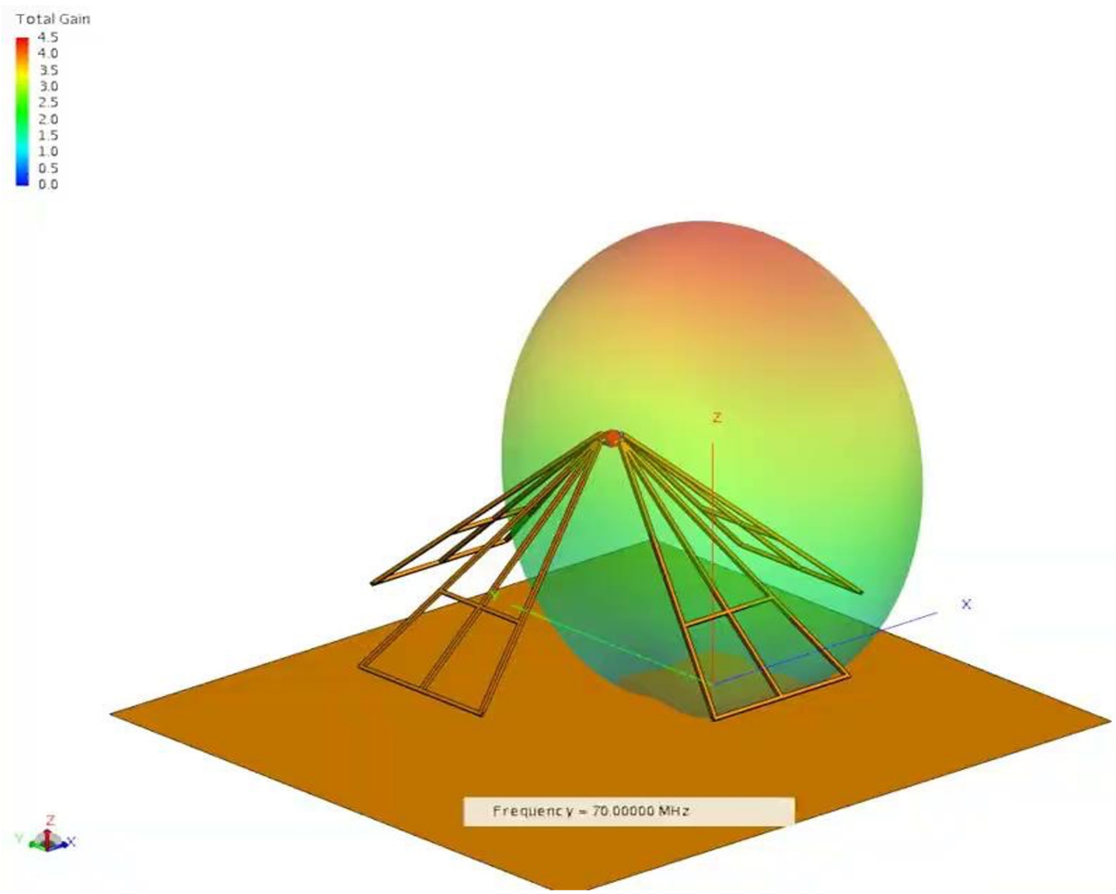


Extras

3m x 3m + free space

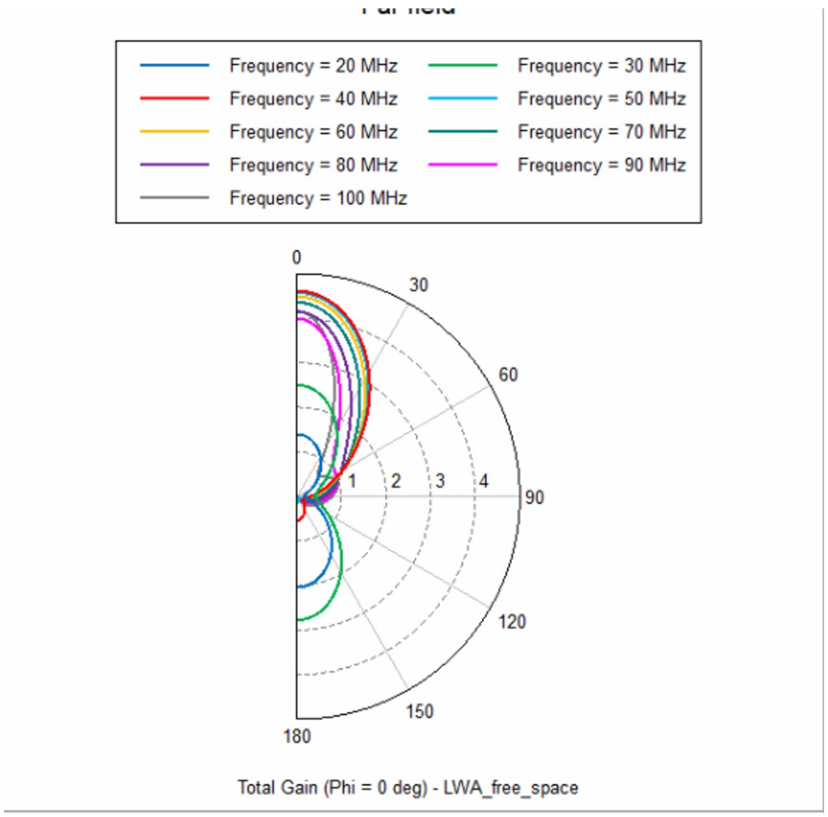


Beam pattern as a function of frequency

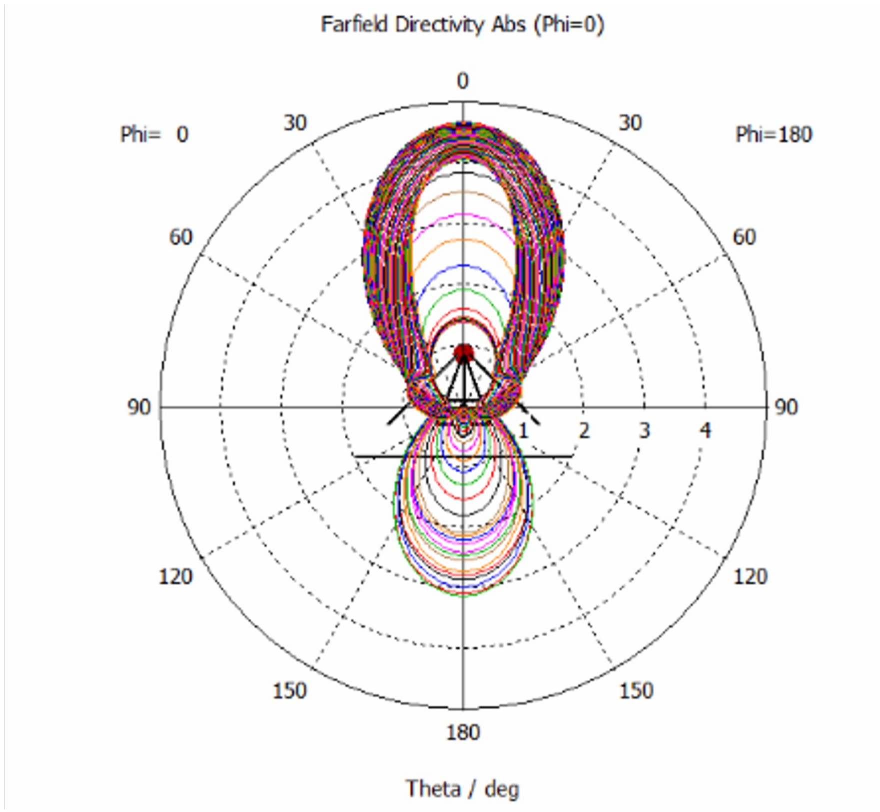


Beam cuts as a function of frequency

FEKO



CST-T



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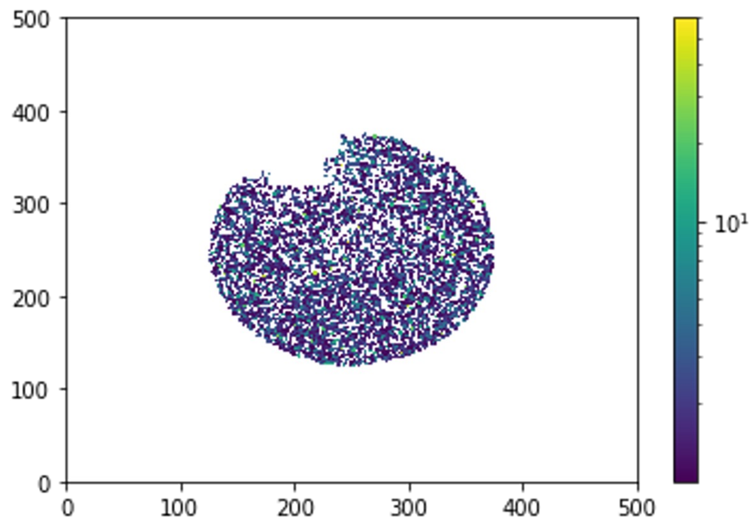
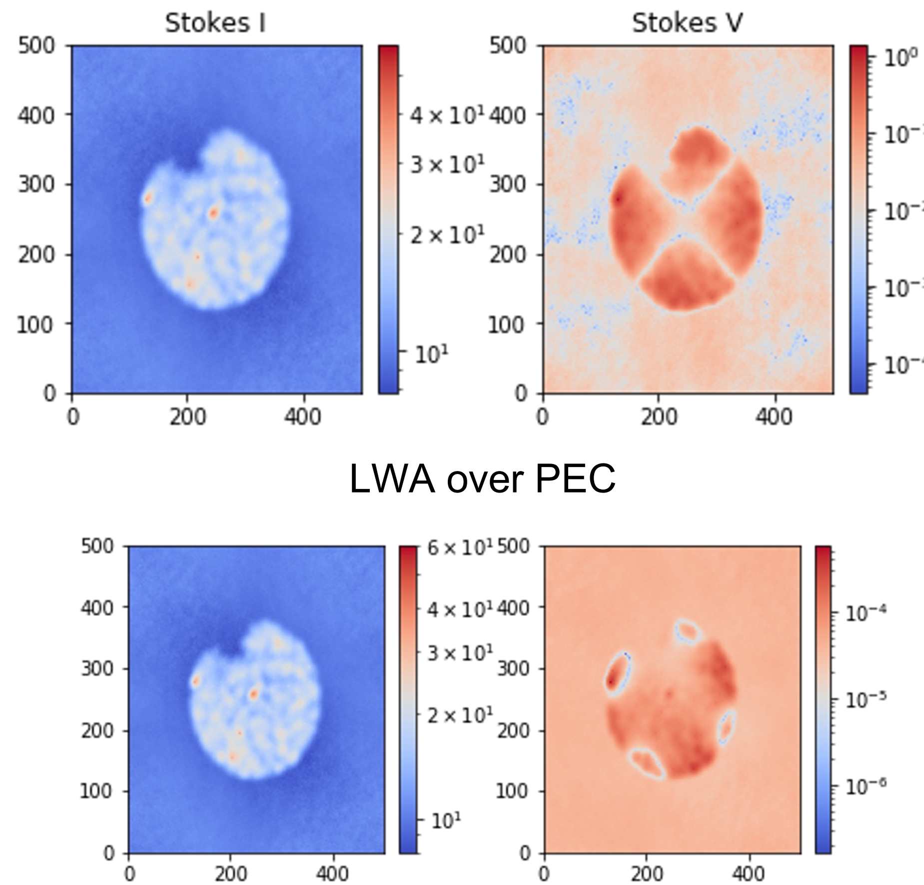
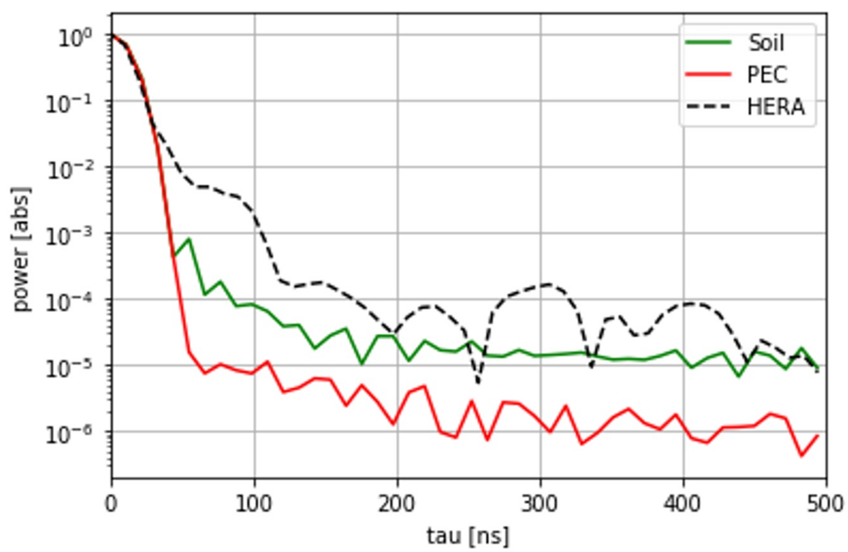
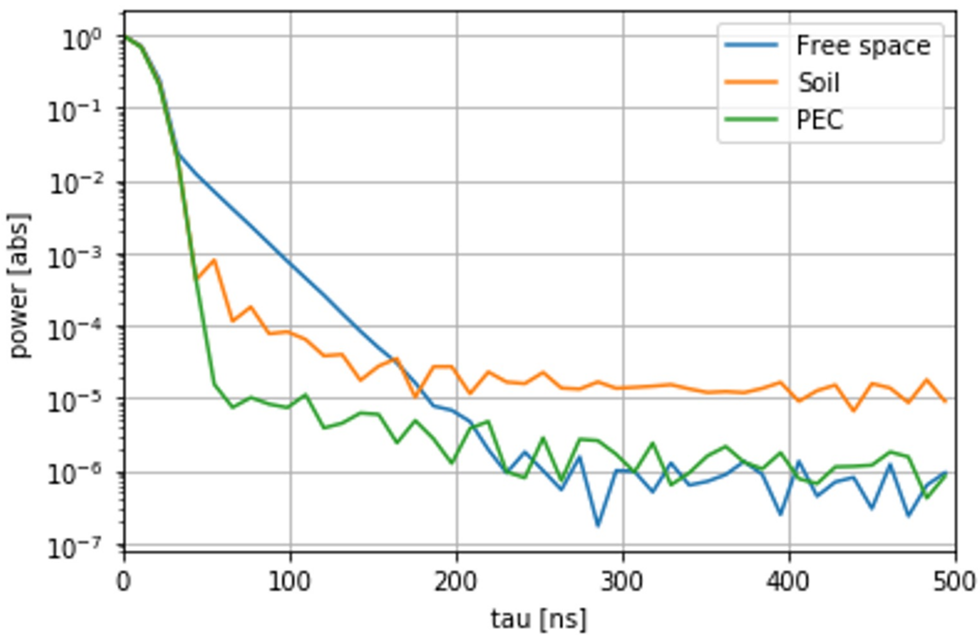
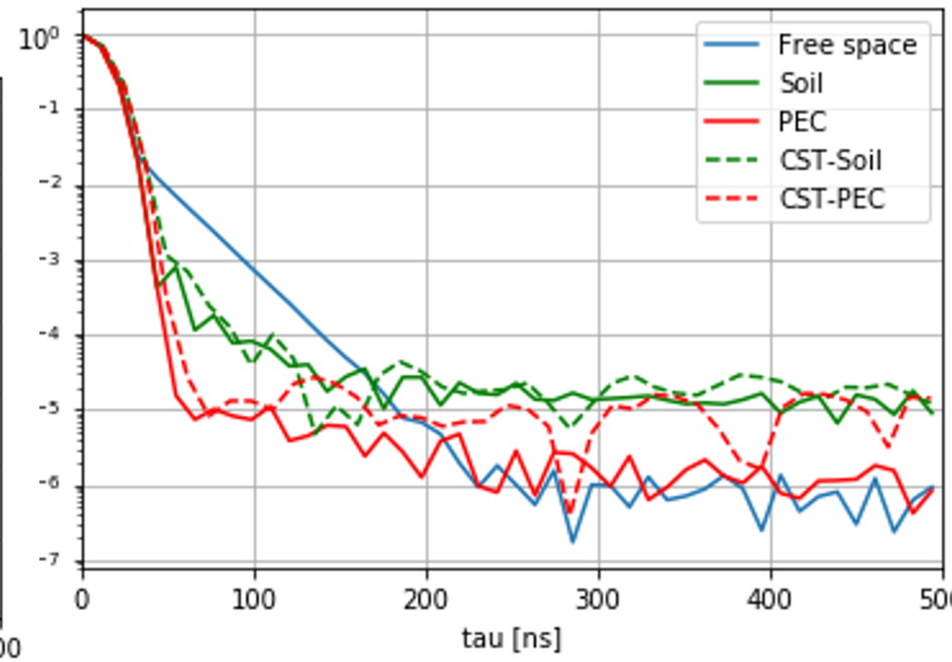




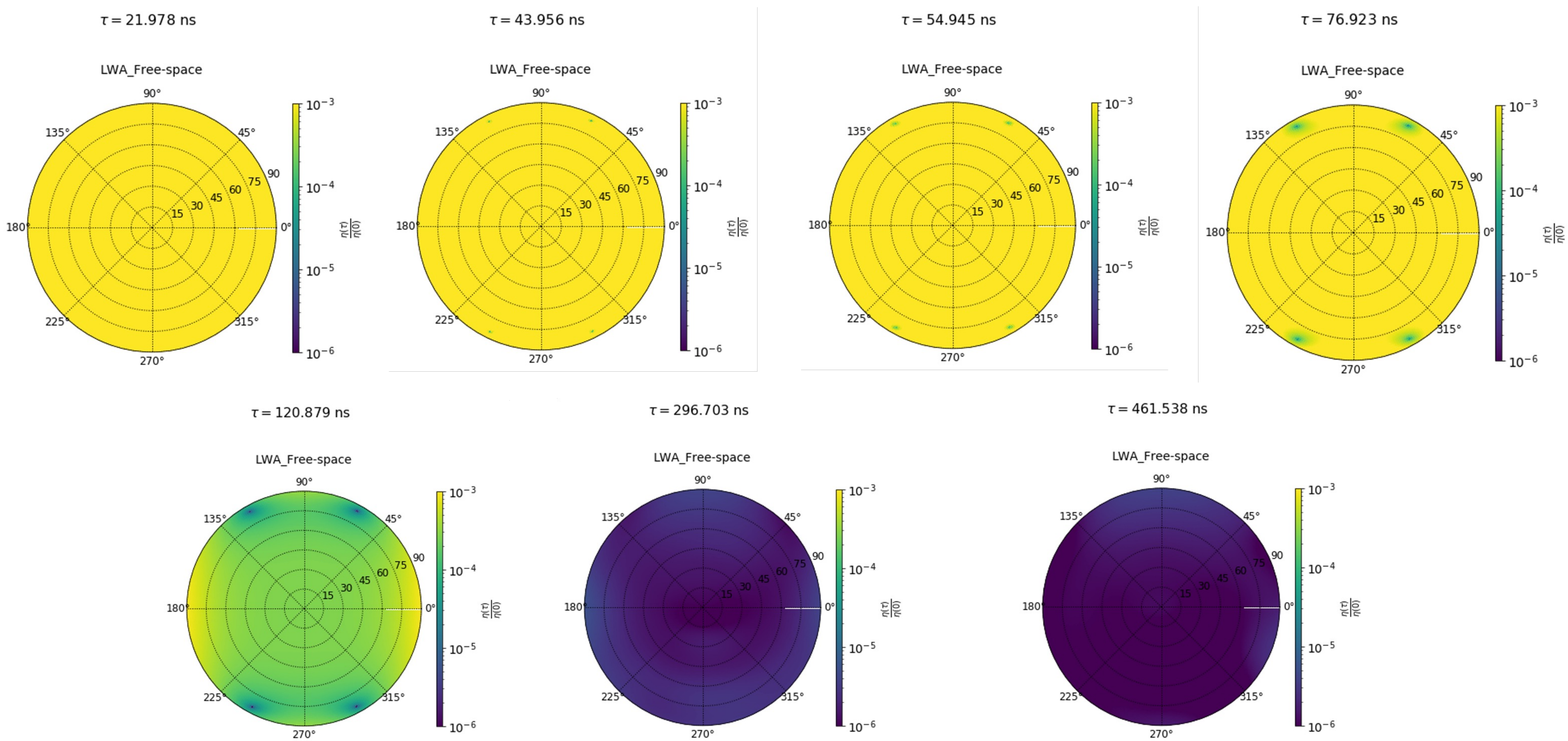


Soil
PEC
HERA
power [abs]
tau [ns]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
100
200
300
400
500

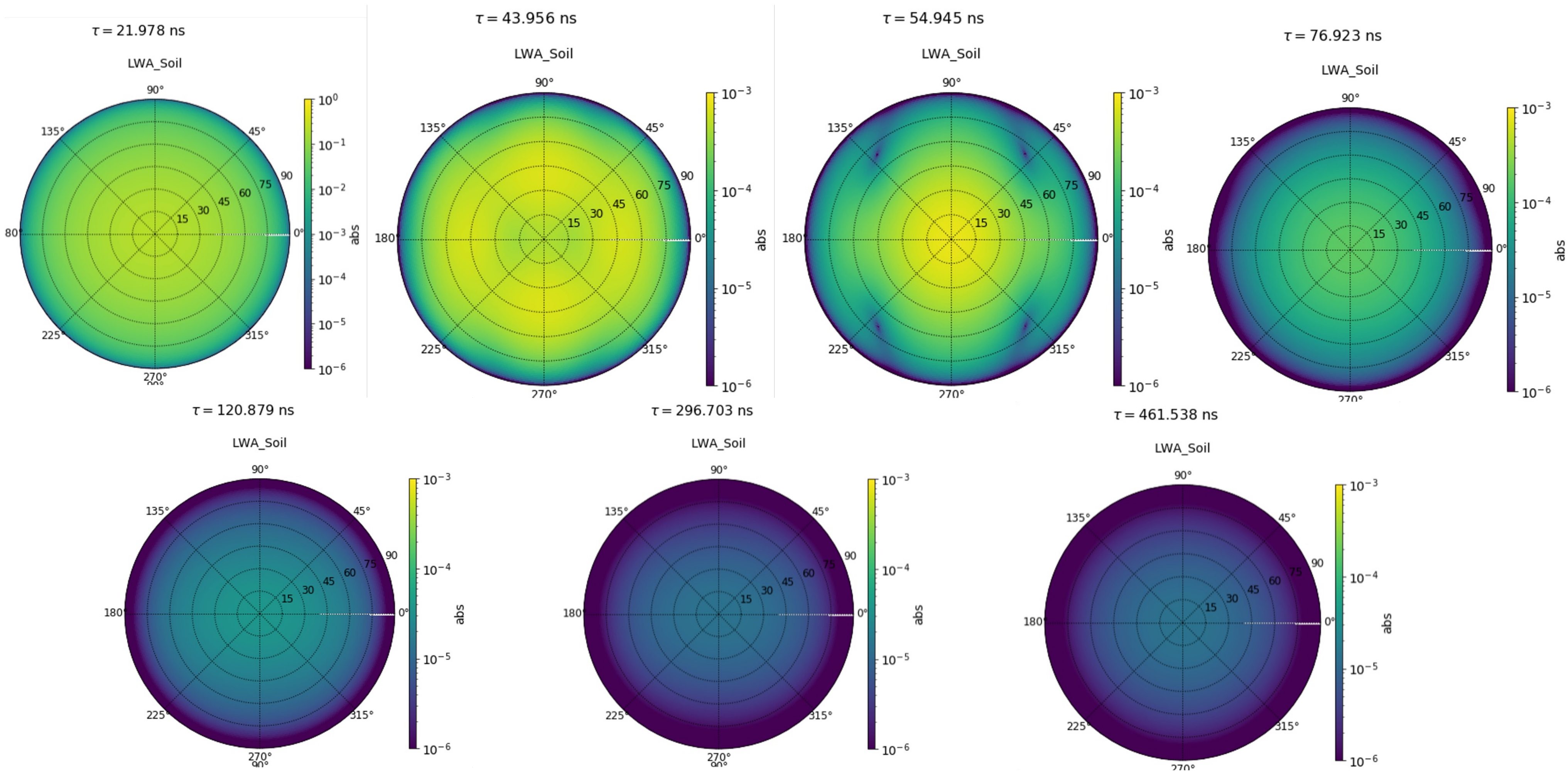

Free space
Soil
PEC
power [abs]
tau [ns]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
100
200
300
400
500


Free space
Soil
PEC
CST-Soil
CST-PEC
tau [ns]
10^{0}
-1
-2
-3
-4
-5
-6
-7
0
100
200
300
400
500

Direction dependent delay spectra for ***LWA+GP in free space***



Direction dependent delay spectra for ***LWA over Soil***



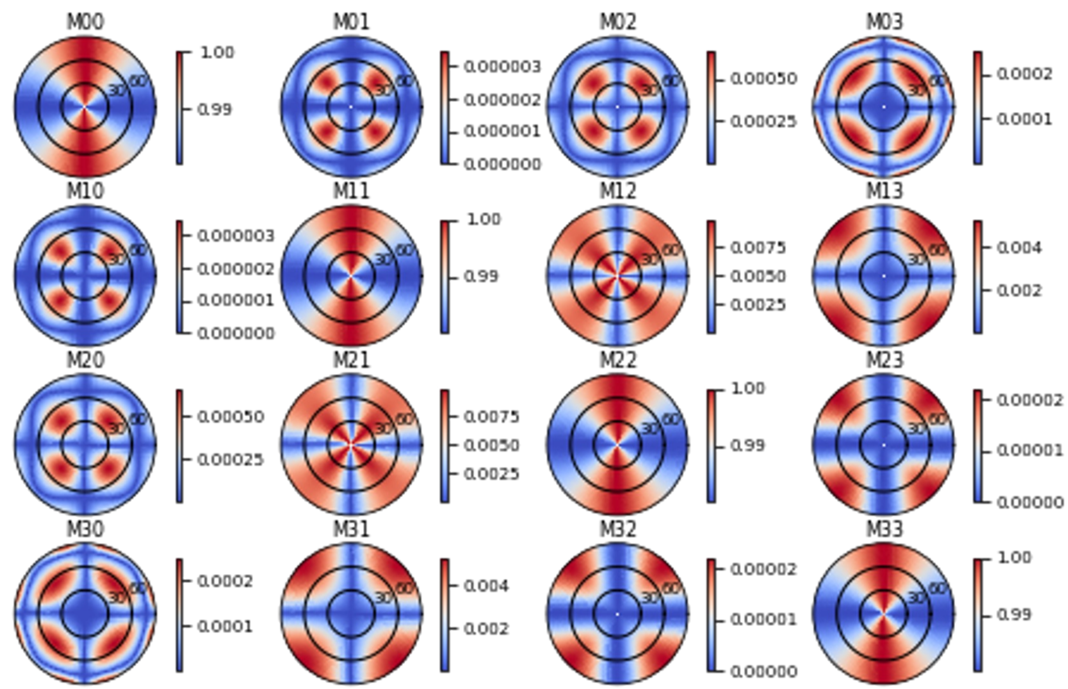
Error in Correction

Using J_perturb to correct for J_space

$$J_{pert} = \begin{bmatrix} E_\theta^x & E_\phi^x \\ E_\theta^y & E_\phi^y \end{bmatrix} + \begin{bmatrix} E_\theta^x & 0.1 * E_\phi^x \\ 0.1 * E_\theta^y & E_\phi^y \end{bmatrix}$$

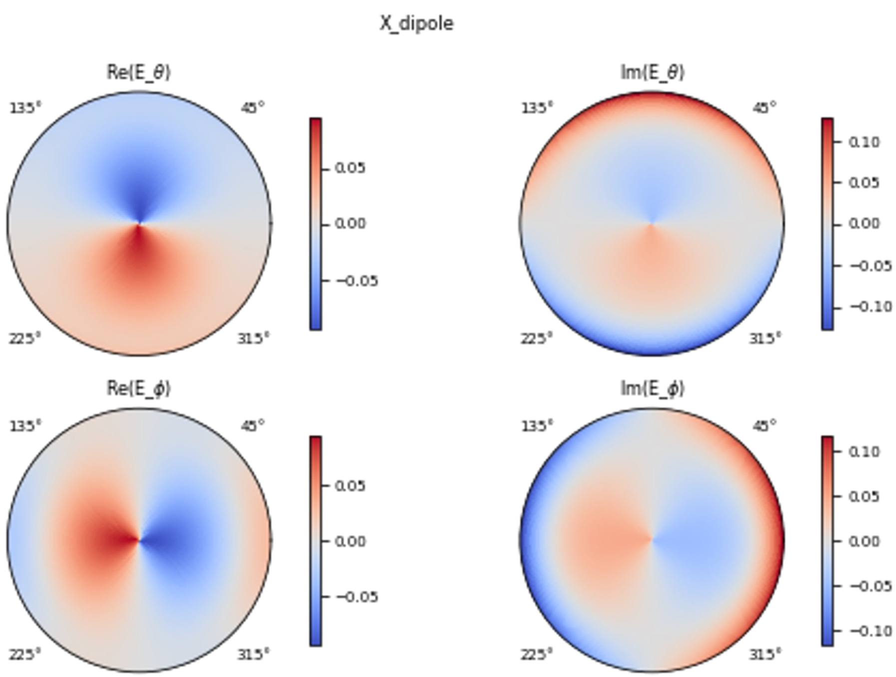
The off diagonal terms are non-zero ⇒ leakage

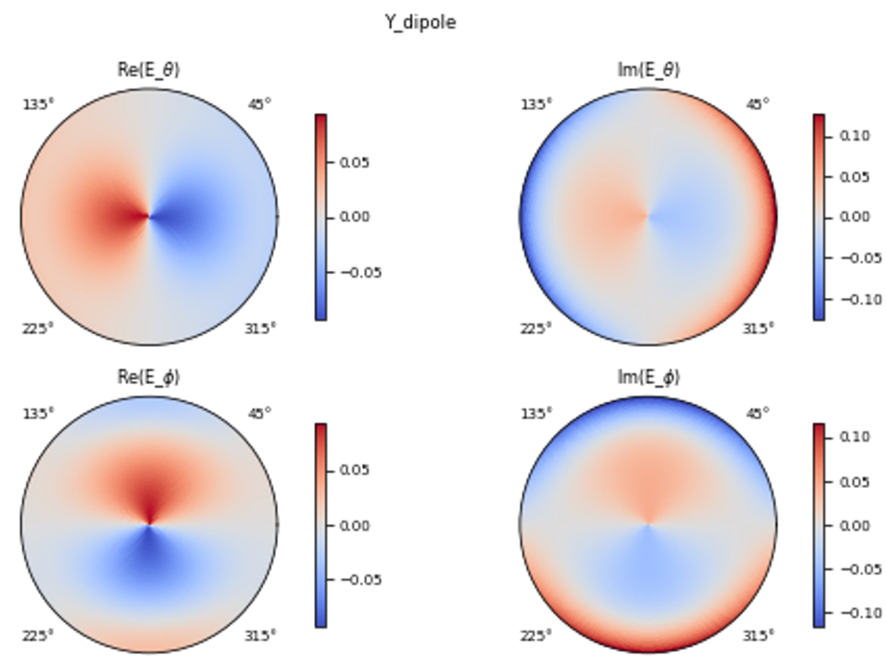
50 MHz



Electric field patterns of the LWA dipoles ***over soil*** at 50 MHz

J = J_Soil - J_space





Polarization Analysis of the beams

$$\begin{bmatrix} I_{xx} \\ I_{xy} \\ I_{yx} \\ I_{yy} \end{bmatrix} = \begin{bmatrix} E_\theta^x & E_\phi^x \\ E_\theta^y & E_\phi^y \end{bmatrix} \otimes \begin{bmatrix} E_\theta^x & E_\phi^x \\ E_\theta^y & E_\phi^y \end{bmatrix}^* \begin{bmatrix} e_{xx} \\ e_{xy} \\ e_{yx} \\ e_{yy} \end{bmatrix}$$

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -j & j & 0 \end{bmatrix} \begin{bmatrix} E_\theta^x & E_\phi^x \\ E_\theta^y & E_\phi^y \end{bmatrix} \otimes \begin{bmatrix} E_\theta^x & E_\phi^x \\ E_\theta^y & E_\phi^y \end{bmatrix}^* \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & -j & j & 0 \end{bmatrix}^T \begin{bmatrix} e_{xx} \\ e_{xy} \\ e_{yx} \\ e_{yy} \end{bmatrix}$$

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = M \begin{bmatrix} e_{xx} \\ e_{xy} \\ e_{yx} \\ e_{yy} \end{bmatrix}$$

to get back the original:

$$M^{-1} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = M^{-1} M \begin{bmatrix} e_{xx} \\ e_{xy} \\ e_{yx} \\ e_{yy} \end{bmatrix}$$