Antenna beam characterisation for the global 21cm experiment LEDA and its impact on signal model parameter reconstruction

REACH workshop - Cambridge -13 April 2022

Marta Spinelli with
Kyriakou, Bernardi, Bolli, Greenhill, Fialkov, Garsden
LEDA
Large-aperture Experiment to detect the Dark Ages

- outriggers of LWA stations at Owens Valley Radio Observatory
- main analysis: 254 and 252 E-W orientation (polarization A)
- frequency range: 30-87 MHz
- instrument overview, RFI flagging and calibration: Price et al. (2018)
LEDA observations

- 137 days: Dec 2018 to May 2019 (+ May 2018)
- best window: night-time (less RFI and ionospheric disturbance) and avoid galactic plane (less chromaticity)
- Dec/Jan (dry soil)
- analysis in Spinelli et al. (2021)
- analytic beam simulations
Improving the beam: soil modelling

analytic beam (Dowell 2011) ⇒ FEKO

used 2018/2019 available measurements for both dry and wet conditions and multi-layer approach

- estimated value of complex permittivity from LWA team (one-layer)
- three accurate measurement at different depths (three-layers)
- iterative procedure to reach convergence linearly interpolating soil parameters between previous step layers (converged)

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{dry}}$</th>
<th>$\sigma_{\text{wet}}$</th>
<th>$\varepsilon_{r,\text{dry}}$</th>
<th>$\varepsilon_{r,\text{wet}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>one layer</td>
<td>0.004</td>
<td>0.01</td>
<td>4.4</td>
<td>6.5</td>
</tr>
<tr>
<td>three-layer 1</td>
<td>0.0013</td>
<td>0.005</td>
<td>3.73</td>
<td>8.09</td>
</tr>
<tr>
<td>three-layer 2</td>
<td>0.004</td>
<td>0.0068</td>
<td>4.25</td>
<td>6.45</td>
</tr>
<tr>
<td>three-layer 3</td>
<td>0.0187</td>
<td>0.0388</td>
<td>7.58</td>
<td>20.56</td>
</tr>
</tbody>
</table>
Improving the beam: ground planes

- Data collected with three different ground planes: 3 × 3, 10 × 10, and 10 × 10 serrated
- ΔGain wrt infinite ground plane
- Higher frequency oscillations for larger ground planes (as expected)
- Serrated worse than standard 20 × 20
- Peculiarity of LWA antennas?
Beam pattern

Dry soil

- One-layer
- Three-layers
- Converged

Wet soil

- NEC4

Gain at Zenith (dB)

Gain change (dB/MHz)

- Serrated
Mock sky spectra

- sky model (Haslam scaled):
  \[ [T_H(\Omega) - T_{cmb}] \left( \frac{\nu}{408} \right)^{\beta} + T_{cmb} \]

- observed temperature
  \[ T_{obs}(\nu) = \frac{\int_{\Omega} T_{sky}(\nu, \Omega) B(\nu, \Omega) d\Omega}{\int_{\Omega} B(\nu, \Omega) d\Omega} \]

- beam model:
  baseline (one-layer, dry condition $3 \times 3$)

- assume available LEDA data (thermal) noise level and LST range
Foreground smoothness

- LST range matters
- N= 6 ok for infinite ground plane
- 3 × 3 shows structured residuals
- increasing N does not help much
Bayesian analysis

- N. term log-polynomial modeling of the foregrounds
- Simple Gaussian signal added
- Bayesian exploration of the posterior (MultiNest)

Infinite ground plane is not a problem

Reconstruction compromised for the 3×3 ground plane

Reconstruction failed for the larger ground planes
Chromaticity correction

\[ B_c(\nu) = \frac{\int_{\Omega} T_{\text{sky}}(\nu_0, \Omega) B(\nu, \Omega) d\Omega}{\int_{\Omega} T_{\text{sky}}(\nu_0, \Omega) B(\nu_0, \Omega) d\Omega} \]

Mozdzen et. al 2017, 2019

- chromaticity correction with the exact B gives smooth spectra
- absorption feature reconstructed with a few mK residuals (with MCMC)

what about the uncertainties on the beam?
Dry vs wet conditions

- generate mock data with baseline beam (one-layer, dry condition)
- correct for chromaticity with another beam model
- what happens if one assumes wet soil condition instead of dry?

Larger ground planes do not attenuate the effect of soil electromagnetic properties
Small soil moisture variations

- generate mock data with baseline beam (one-layer, dry condition)
- correct for chromaticity with another beam model
- and if conductivity and permittivity are changed only slightly?

bias can be as large as a factor $\times 2$ even for this small variations
Multi-layer modelling

- generate mock data with baseline beam (one-layer, dry condition)
- correct for chromaticity with another beam model
- what is the effect of the multi-layer approach?

bias increases for larger ground planes
Conclusions

- LEDA data are an important test ground for future 21cm global signal analysis and need to be understood properly.
- Trends in the data seem to correlate with rains: is the soil moisture important?
- **Improved beam characterization using FEKO**: change electromagnetic properties of the soil and its modelling, study the different ground planes.
- How much beam uncertainties can impact the result? Non negligible effect.
- What about a more sophisticated pipeline (REACH)?
Effect on the spectral index
Input dependence

- baseline for this analysis
- same as before but different $\nu_0$
- EDGES-like absorption feature
Old beam model

\[ A(\nu, \theta, \phi) = \sqrt{[p_E(\nu, \theta)\cos\phi]^2 + [p_H(\nu, \theta)\sin\phi]^2} \]

*Taylor et al. (2012), Ellingson et al. (2013), Dowell (2011)*

\[ p_i(\nu, \theta) = [1 - \left(\frac{\theta}{\pi/2}\right)^{\alpha_i(\nu)}]\cos\theta\beta_i(\nu) + \gamma_i(\nu)\left(\frac{\theta}{\pi/2}\right)\cos\theta\gamma_i(\nu) \]

- \(\alpha, \beta, \gamma, \delta\) described with a 13th order polynomial Dowell (2011).