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

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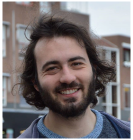

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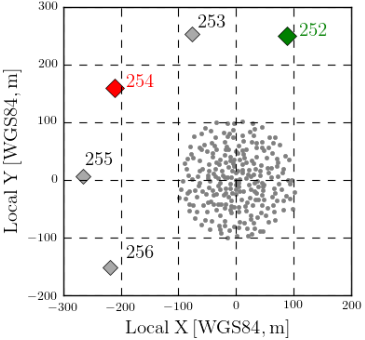
LEDA

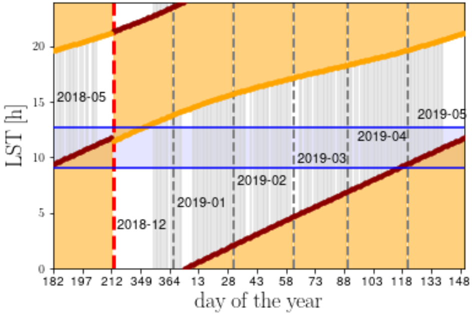
Large-aperture Experiment to detect the Dark Ages

- 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

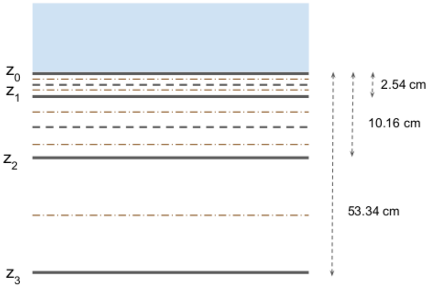


Improving the beam: soil modelling

analytic beam (Dowell 2011) ⇒ FEKO

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

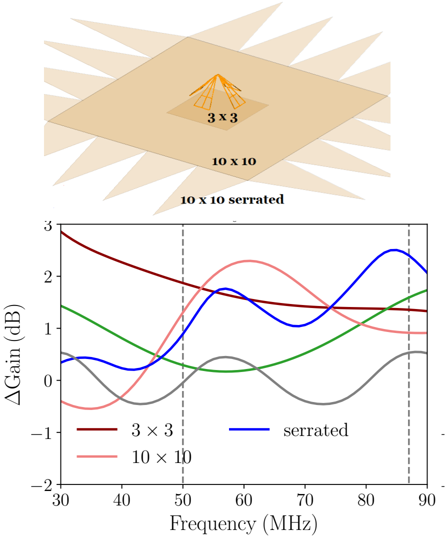
- estimated value of complex permittivity from LWA team (one-layer)
- three accurate measurement at different depths (three-layers)
- iterative procedure to reach convergence linearly interpolating soil parameters between previous step layers (converged)



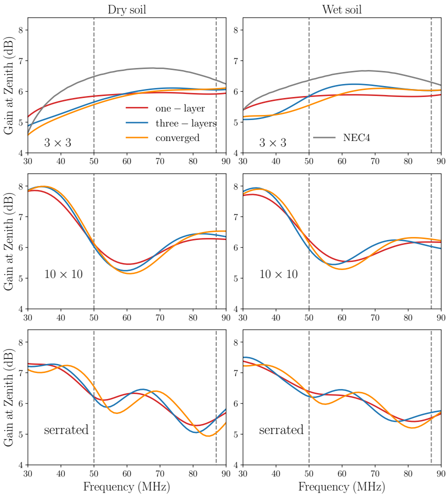
Soil layer parameters (σ in S/m, ϵ_r dimensionless)				
	σ_{dry}	σ_{wet}	$\epsilon_{r,\text{dry}}$	$\epsilon_{r,\text{wet}}$
one layer	0.004	0.01	4.4	6.5
three-layer 1	0.0013	0.005	3.73	8.09
three-layer 2	0.004	0.0068	4.25	6.45
three-layer 3	0.0187	0.0388	7.58	20.56

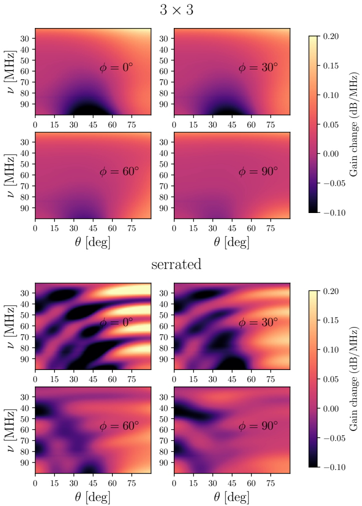
Improving the beam: ground planes

- 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





Mock sky spectra

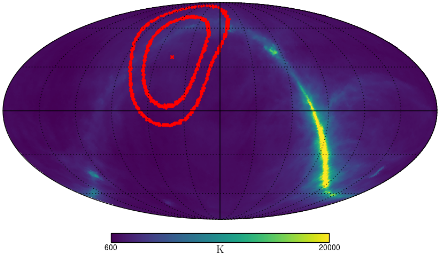
- sky model (Haslam scaled):

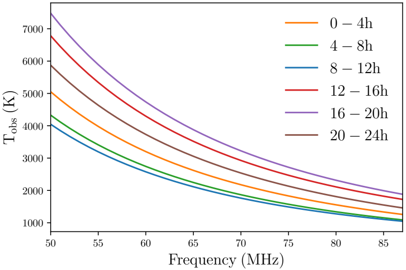
$$[T_{\rm H}(\Omega) - T_{\rm cmb}]\left(\frac{\nu}{408}\right)^{\beta} + T_{\rm cmb}$$

- observed temperature

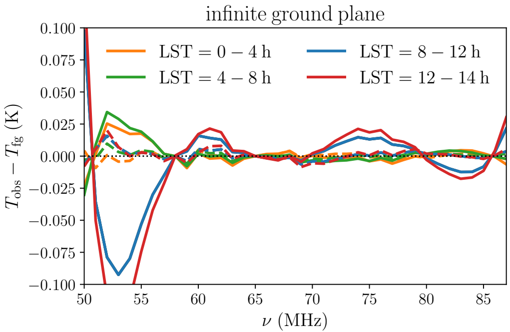
$$T_{\rm obs}(\nu) = \frac{\int_{\Omega} T_{\rm sky}(\nu,\Omega)B(\nu,\Omega)d\Omega}{\int_{\Omega} B(\nu,\Omega)d\Omega}$$

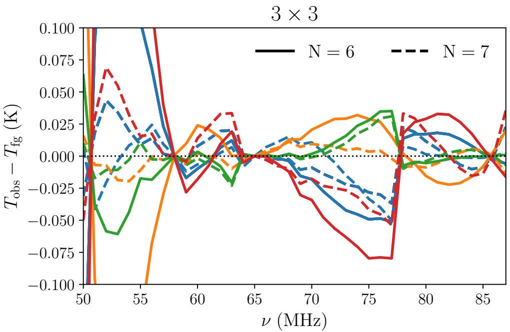
- beam model:
  baseline (one-layer, dry condition 3×3)
- assume available LEDA data (thermal) noise level and LST range





Foreground smoothness





- LST range matters
- N= 6 ok for infinite ground plane

- 3×3 shows structured residuals
- increasing N does not help much

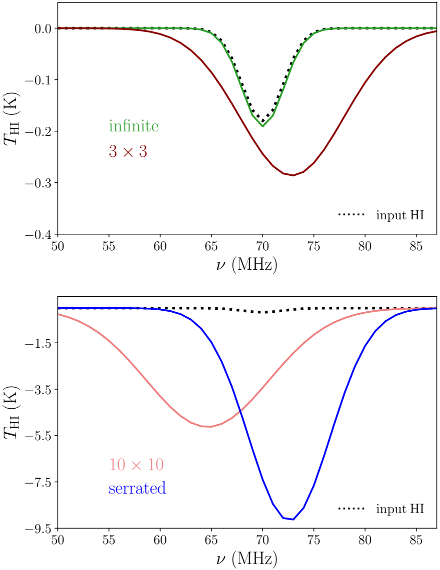
Bayesian analysis

- 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



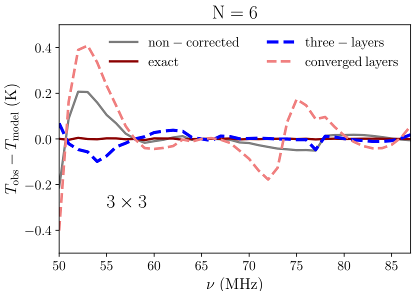
Chromaticity correction

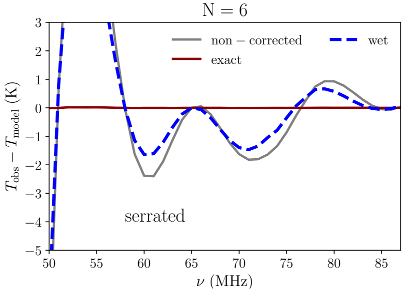
$$B_c(\nu) = \frac{\int_\Omega T_{\rm sky}(\nu_0,\Omega)B(\nu,\Omega)d\Omega}{\int_\Omega T_{\rm sky}(\nu_0,\Omega)B(\nu_0,\Omega)d\Omega}$$

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?

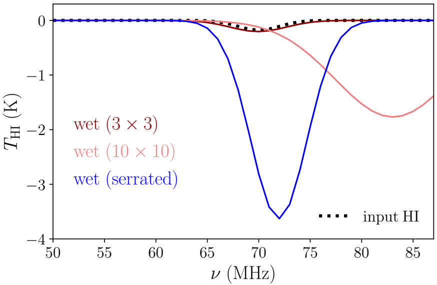


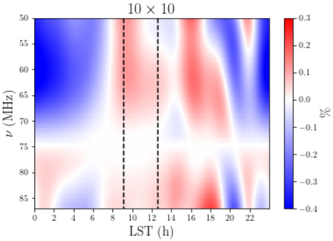


Dry vs wet conditions

- 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

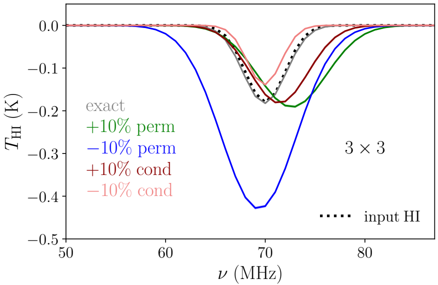


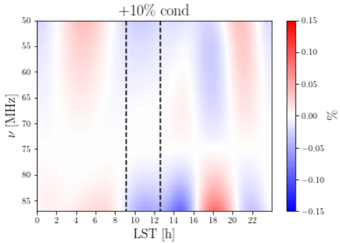


Small soil moisture variations

- 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 ×2 even for this small variations

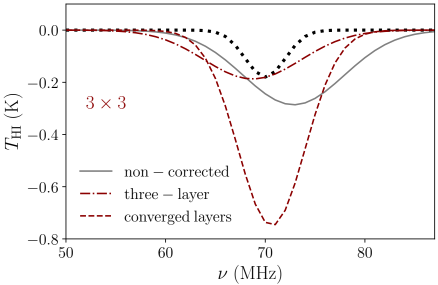


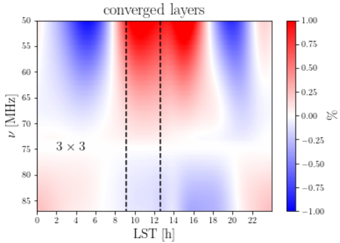


Multi-layer modelling

- 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

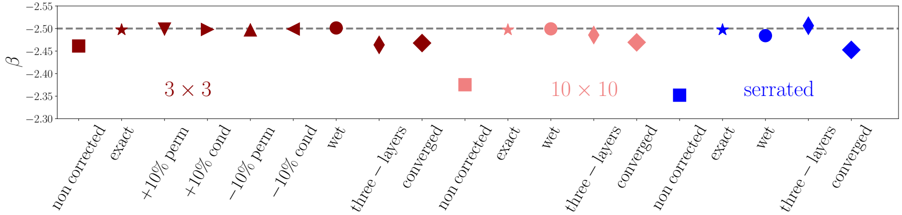




Conclusions

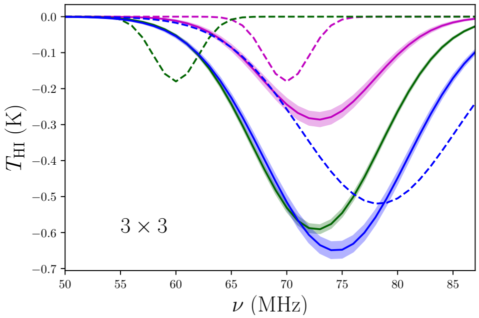
- LEDA data are an important test ground for future 21cm global signal analysis and need to be understood properly
- trends in the data seems to correlate with rains: is the soil moisture important?
- improved beam characterization using FEKO: change electromagnetic properties of the soil and its modelling, 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 ν_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)

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

- α, β, γ, δ described with a 13th order polynomial Dowell (2011).