Ground Plane Analysis for EDGES-3 Test Deployment in Oregon

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I. INTRODUCTION

A wire grid ground plane has been studied for a test deployment of EDGES-3 in Oregon. A wire grid is easy to construct and remove for a temporary deployment compared with welded mesh ground planes used for EDGES-2 at the MRO.

The Experiment to Detect the Global EoR Signature (EDGES) looks to detect this absorption feature in the redshifted 21 cm line of hydrogen. EDGES-3, the third iteration of this experiment, consists of a blade box dipole antenna design placed over a flat conductive ground plane. The ground plane shields the antenna from ground, which produces its own radio spectrum at approximately 300 K and also blocks the sky spectrum. This leaves the experiment in the position that the signal we want to study can only be seen above the ground, and everything coming from below the ground is noise. A perfect ground plane would block the ground signal completely, and allow the antenna to receive only signals from above the ground plane. However this is difficult to achieve, and there will always be some side lobes in the antenna gain allowing ground leakage into the antenna. Barring other sources or effects and assuming the sky spectrum follows the power law

$$T_{sky} = (300\ \mathrm{K}) * \left(\frac{f}{150\ \mathrm{MHz}}\right)^{-2.5} \tag{1}$$

the measured spectrum will be

$$T = 300\left(\frac{f}{150}\right)^{-2.5}(1 - Loss(f)) + 300\ Loss(f) \tag{2}$$

where f is the frequency, and $Loss(f)$ is the fraction of the total antenna gain below the ground plane. It is best to choose a ground plain design that minimizes the total loss, but also has a loss with a smooth distribution, making it easy to model accurately. In this analysis the loss characteristics of a meandering wire ground plain are explored in order to lower the impact of the loss on the antenna.

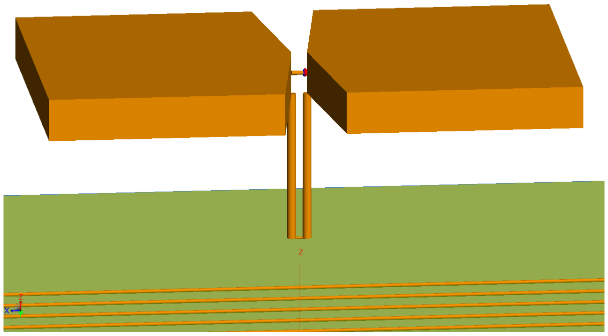

FIG. 1: The geometry of the EDGES-3 antenna used in FEKO modeling

II. METHODS

A. Antenna

The EDGES-3 antenna is modeled as two pentagonal boxes with a closest separation of 0.044 m(FIG. 1). The total width, length, and height of the two boxes together are 0.953 m, 1.512 m, and 0.12 m, respectively. The antenna port is between the two boxes and there are two pipes that run vertically down 0.42 meters with a cross pipe connecting them at the bottom. The ground plane consists of parallel wires running along the length of the plane with a spacing of 0.125 m(FIG. 2). These wires are either separate (FIG. 4), or connected by small wires on the end (FIG. 3), turning the ground plane into one very long wire that meanders across the plane.

The reason for testing the ground plane with and without the connections was because of a potential trade off between ease of deployment and performance. The ground plane with the connections is made of a single wire, so deployment is easy, but the connections also complicate the geometry a little bit, which needs to be taken into account. The ground plane without the connections is a little more challenging to deploy because instead of one wire, there are now many wires to deal with. However, the simpler geometry reduces the number of resonances.

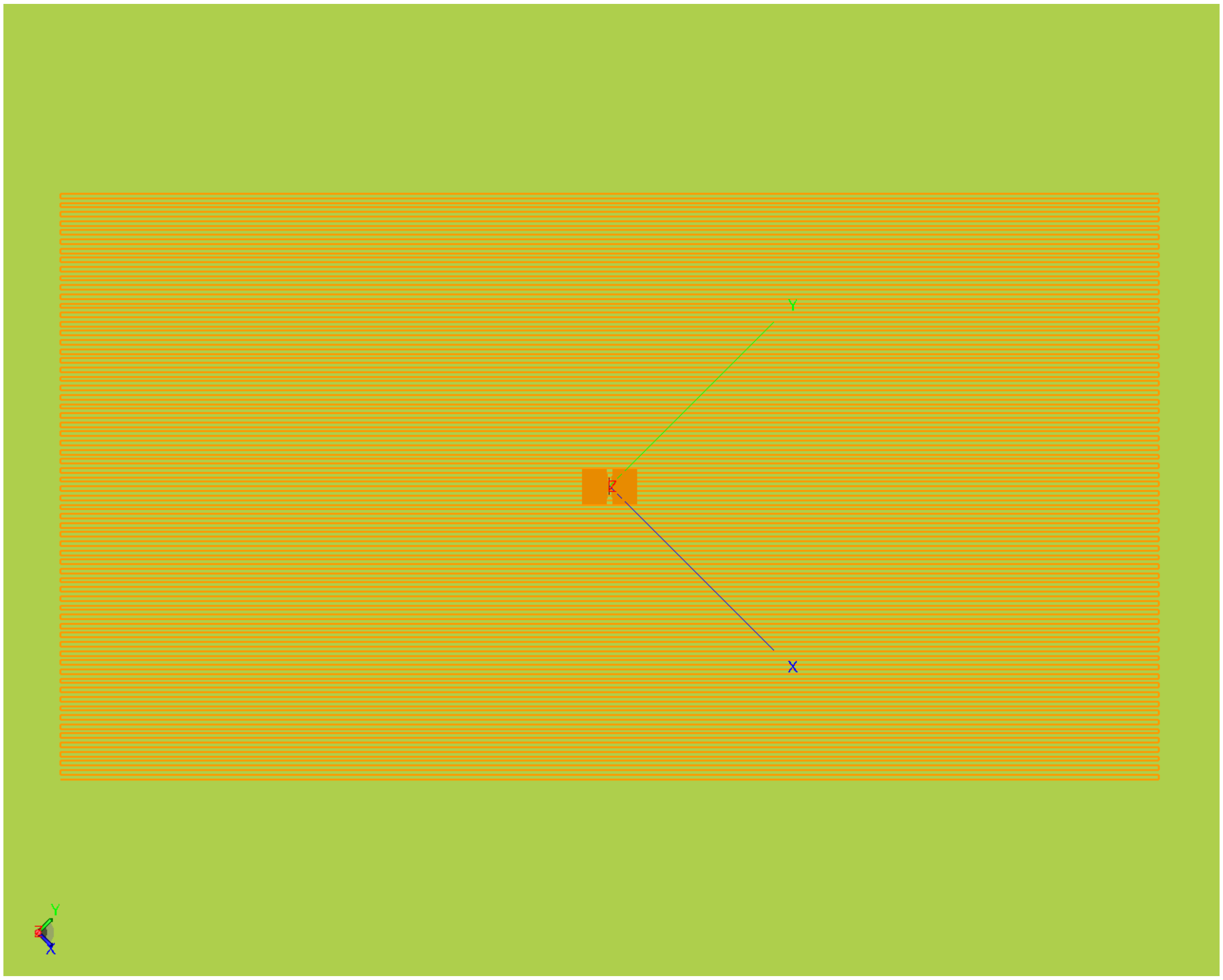

FIG. 2: Top down view of the 30m by 16m ground plane with the antenna in the center in POSTFEKO

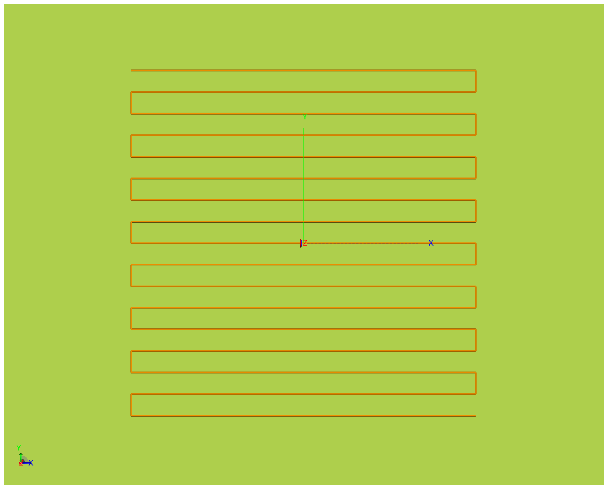

FIG. 3: Top down view of a 2m by 2m ground plane with end connections and no antenna in POSTFEKO

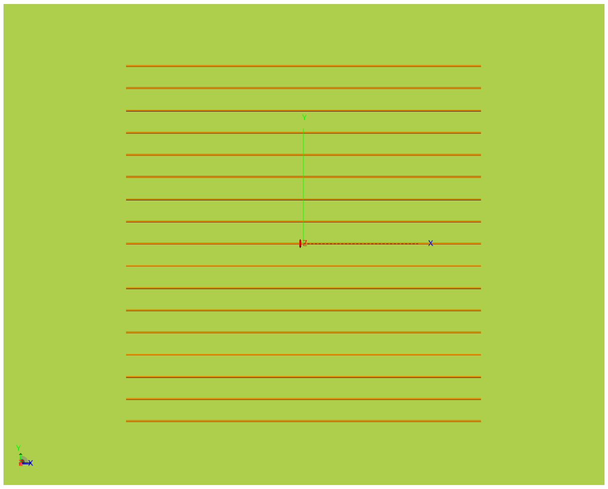

FIG. 4: Top down view of a 2m by 2m ground plane with no antenna and the end connections removed in POSTFEKO

Simulations were done for a variety of sizes of ground plane. Most of the effort was put towards a 30 m by 16 m ground plane, which is the likely candidate for deployment of the antenna. Additional simulations were done with smaller ground planes of 2 m by 2 m and 4m by 4m.

B. FEKO

The antenna and ground plane were modeled in the electromagnetic computation software FEKO. The simulation calculated the directional gain for the full sphere around the antenna at intervals of 1 degree using a special Green's function to incorpoarate the parameters of the environment into the simulation [1]. From that the total gain was calculated by integrating over the entire sphere and the gain below the ground plane was calculated by integrating over all points with the azimuthal angle, $\theta > 90°$. The loss from the ground plane was taken to be the ratio of the gain below the ground to the total gain, and is described by

$$Loss(f) = \frac{\iint_L Gain(f,\phi,\theta)\ sin(\theta)\ d\phi\, d\theta}{\oiint Gain(f,\phi,\theta)\ sin(\theta)\ d\phi\, d\theta} \qquad (3)$$

where L represents the lower hemisphere and the denominator is an integral of the gain over the entire sphere. In practice both of these integrals were sums over points calculated by FEKO with 1 degree spacing. This was then multiplied by a power law sky spectrum given by equation (1). This puts the loss in units of kelvin which allows it to be compared to other spectra effectively, but often it is easier to see structure in the loss when dealing with the ratio. For the full bandwidth simulations from 50 MHz to 140 MHz, the frequencies were sampled at 2 MHz intervals, and for smaller ranges, higher resolutions were used as specified. This method works for models in free space and with a dielectric ground, but not with models that include the conductivity of the ground. The conductivity introduces loss into the soil and FEKO does not provide the measurements required to use this method on a lossy ground, so we have called this the lossless Green's function method.

C. Loss with Conductivity

The methods described above were used for models that did not include any conductivity in the ground, and because of limitations with FEKO, models that did include conductivity had to be solved differently. FEKO will only return values for gain in directions that are not inside a conductive material. When there is no conductivity, that means it can calculate all values and the above method works, but when the ground is conductive, FEKO will only calculate gain for the upper half of the sphere, so a different method is required to find the loss. To estimate the loss we used the following equation

$$Loss(f) = 1 - \frac{\iint_U Gain(f,\phi,\theta)\ sin(\theta)\ d\phi\, d\theta}{\oiint sin(\theta)\ d\phi\, d\theta} \qquad (4)$$

where the U refers to the upper hemisphere. This normalizes the above ground gain to a fraction of the total gain and then subtracts that from unity to find the fraction of below ground gain. The denominator ends up describing the area of a sphere of radius unity, which for an antenna of 100% efficiency should be equal to the integral of the total gain used in the denominator of equation (3).

$$\oiint Gain(f,\phi,\theta)\ sin(\theta)\ d\phi\, d\theta = \oiint sin(\theta)\ d\phi\, d\theta \qquad (5)$$

This unfortunately depends on FEKO calculating the magnitude of the gain correctly, whereas in equation (3) the normalization by the total gain makes it more likely to give correct results. We have called this the lossy Green's function method.

D. Frequency Resolution

As mentioned above, for the full band models, a spacing of 2 MHz was used, which made the simulations run faster than if a smaller spacing had been used, but this creates the issue that because all of the features in the loss are much smaller than 2 MHz, the full band models miss almost all of these features. Only when the features line up exactly with one of the sample points is there any evidence of them, making it appear from the full band models that the loss is relatively smooth with only a few scattered "glitches", when in reality, there was the possibility for lots of fine structure throughout the entire frequency range. This made the higher resolution models over smaller frequency ranges vital to understanding the impact the ground plane geometry has on the loss. It would not have been practical to use high resolutions for the full band because it would have made computation times very large and unmanageable. The exceptions to these were the simulations of the antenna in free space and the small ground planes of 2m by 2m and 4m by 4m, which went considerably faster and thus it was possible to get models of the entire band at 0.0625 MHz resolution. For the rest of the report, low resolution will mean 2 MHz spacing while high resolution will mean 0.0625 MHz spacing.

E. FEKO Meshing differences

It was found that depending on how the geometry of the ground plane was designed, FEKO could create different meshes for the same ground plane. The initial models were created at a 45°angle from parallel to the axes. Since this rotation introduces irrational numbers into the coordinates of points, the positions are rounded and not exact. This lead to some of the wire lengths being slightly longer than 30 m and some being slightly shorter. The maximum mesh size was set to 0.5 m, which means that for a wire of exactly 30 m, there would be 60 wire segments. For a wire slightly shorter than 30 m, the segments are shortened slightly as well and the model still has 60 segments. However, if the wire is slightly longer than 30 m, you cannot make up the distance by making the segments longer than 0.5 m, so instead the segments are shortened and an additional segment is added to the end, making 61 segments of equal length. This did not appear to have a large impact on the ground loss, but it was not studied in detail.

F. FEKO Errors

In previous attempts to estimate the ground loss, FEKO has given unreasonable or inconsistent results, which has lead us to approximate the loss as independent of frequency previously. Because of this, all of FEKO's results must be considered carefully and the possibility of any results containing errors. Part of the work is determining which features are real and which are errors from FEKO.

G. Fitting Functions

Ultimately, the goal would be to use a function to approximate how much of the sky spectrum is lost in kelvin,

$$T_L = 300\left(\frac{f}{150}\right)^{-2.5} * Loss(f) \tag{6}$$

so that it can be incorporated into the analysis of the sky spectrum signal. Here, three different fitting functions were used to approximate the loss:

$$T_{loss} = \sum_{n=0}^{N-1} a_n \left(\frac{f}{150}\right)^n \qquad \text{Polynomial} \tag{7a}$$

$$T_{loss} = \left(\frac{f}{150}\right)^{-2.5} \sum_{n=0}^{N-1} a_n \left(\frac{f}{150}\right)^n \qquad \text{LinPoly} \tag{7b}$$

$$T_{loss} = \left(\frac{f}{150}\right)^{-2.5} \sum_{n=0}^{N-1} a_n \left(\ln\frac{f}{150}\right)^n \qquad \text{LinLog} \tag{7c}$$

III. RESULTS

A. Full Ground Plane Analysis

The majority of the effort was put towards the 30 m by 16 m ground plane with 12.5 cm spacing for the wires(FIG. 2), which is the current favored choice for the EDGES-3 deployment. Two different designs were tested, one with the wire connections on the ends, and one without the wire connections. These two designs were simulated under three different sets of conditions: in completely free space, above a dielectric material with no conductive loss, and above a dielectric material with some conductive loss. The third set of conditions, with the conductivity, is the most physically accurate, but the others were helpful in revealing features that might not be seen because of the conductivity.

In the free space models (FIG. 5), there are clear resonances spaced every 10 MHz, which matches with the 30 m length of the ground plane wires. In the free space models these resonances are quite large, increasing the loss by a few percentage points in each case. Since these resonances are not confined to single frequency peaks, but are a little broader and consistent across the entire spectrum, they are likely real phenomena and not FEKO errors. It is interesting that even though these have a spacing of 10 MHz, they are not themselves multiples of 10 MHz. Thus if this pattern continues down into very low frequency, the lowest resonance will not occur at exactly 10 MHz.

The addition of the side connections adds some additional structure to the loss. This contributes a second set of resonances that repeat approximately every 10.5 Mhz, making it a slightly larger period than the original resonances. There is also a very flat region between the two pairs of resonances for the ground plane with side connections.

Changing the length of the ground plane from 30 m to 22.5 m changes the spacing of the resonances

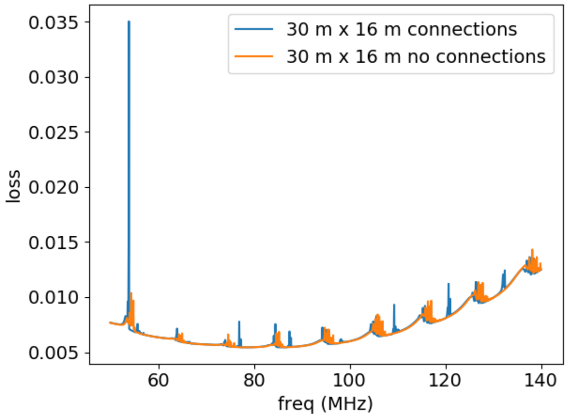

FIG. 5: Loss spectrum for the ground plane with wire connections and no wire connections and in free space at a resolution of 0.0625 MHz. They match fairly well, both having resonances at 10 MHz intervals, but the ground plane with the connections has additional resonances.

to approximately 13.3 MHz, which is the frequency associated with a wavelength of 22.5 m (FIG. 6). This makes it very likely that the resonances are indeed real, and associated with the ground plane.

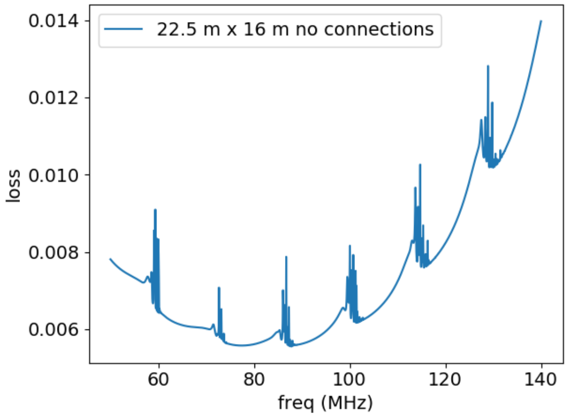

FIG. 6: Loss fraction for a free space model of a 22.5 m by 16 m ground plane with no wire connections. The resonances are now about 13.3 MHz apart, which matches the change in the length of the ground plane.

The antenna was placed on a ground with relative permittivity constant $\epsilon_r = 3.5$. In this configuration, all features in the loss are significantly smaller in magnitude, and much more spread out. While the free space models had features with a period of about 10 MHz, when the dielectric constant is included, the features repeat approximately every 7.5 MHz(FIG. 8, FIG. 9), which has a wavelength of about 40 m, which is longer than the length of the ground plane. The resonant frequencies are likely to be dependent on the capacitance of the system, and the inclusion of a dielectric ground would increase the overall capacitance. It is possible this would lead to a narrower spacing of the resonances. The dielectric also probably damps the resonances, which spreads out and decreases the magnitude of the peaks. These are all effects that are visible in the simulations of the model with the dielectric. With the inclusion of the dielectric, the total loss also increased.

The EDGES-2 antenna used a different ground plane. Instead of a meandering wire, it had a 30 m by 30 m mesh ground plane[2] which was much more expensive and took longer to deploy. It was however a ground plane with more coverage, so as a comparison, the EDGES-3 antenna was simulated with the EDGES-2 ground plane (FIG. 10). As expected, the loss was much lower, but a high resolution band revealed some interesting results in FIG. 11. First, there is a very clear discontinuity at around 63 MHz, and possibly another at 55.2 MHz. Since this is most likely not physical, these might be errors from the FEKO calculations. Ignoring the discontinuities for now, there might also be a small oscillatory signal in the residuals.

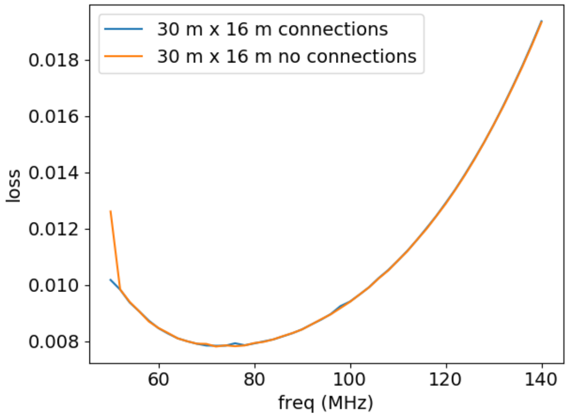

FIG. 7: Loss spectra for the ground plane 30 m x 16 m ground plane with and without connections over a dielectric material at a resolution of 2 MHz

When a ground conductivity of 0.01 S/m was included, all of the resonances are completely damped out, leaving a very smooth curve, shown in FIG. 12, except for three discontinuities at 81.3 MHz, 86.9 MHz, and 87.7 MHz, visible in FIG. 13. These discontinuities cannot be explained by physics and are most likely glitches in the FEKO calculations. They also exist across multiple simulations of different ge-

	1	2	3	4	5
Polynomial	8.9368701 K	6.8767774 K	4.2221450 K	2.4276375 K	1.2692023 K
LinPoly	3.9671877 K	3.6787774 K	1.1820804 K	0.6750101 K	0.2542842 K
LinLog	3.9671877 K	3.4314474 K	0.4540649 K	0.4000460 K	0.0286862 K

TABLE I: RMS values on the 30 m by 16 m ground plane with conductivity for the three fitting functions with different numbers of parameters. Note that the RMS values for LinPoly and LinLog are the same with 1 parameter because they reduce to the same function.

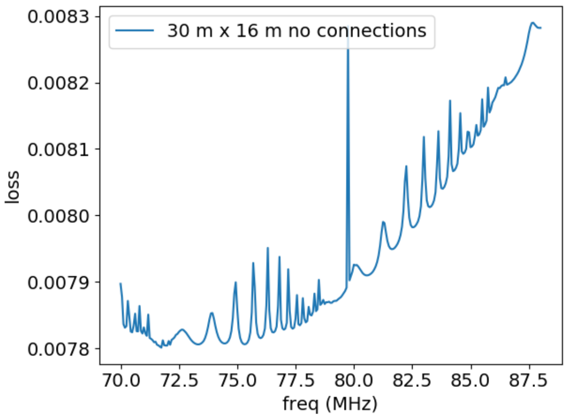

FIG. 8: Loss spectrum for the ground plane with no wire connections over a dielectric material over the range 70 Mhz to 88 Mhz with resolution 0.0625 MHz

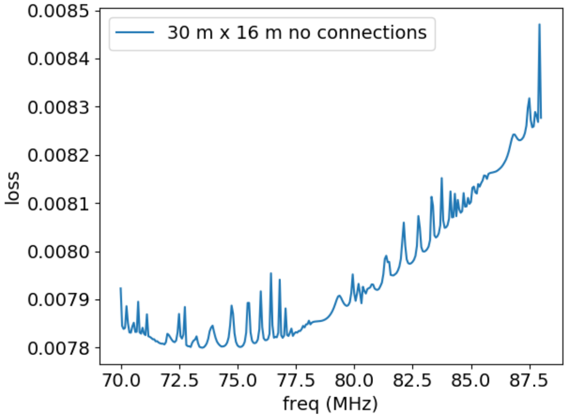

FIG. 9: Loss spectrum for the ground plane with wire connections over a dielectric material over the range 70 Mhz to 88 Mhz with resolution 0.0625 MHz

ometries as shown in FIG 14.

It is also interesting to note that while the wire connections did not make a huge difference to the loss in free space and with just the dielectric. With the conductivity, the loss for the ground plane with connections is significantly higher than for the ground plane without. The reason for this is not clear, but this might be something to investigate in the future.

Including the dielectric and conductivity constants gives a reasonable approximation of soil that one might find below the ground plane, so with the exception of the FEKO glitches, the calculated loss is a reasonable approximation of the actual loss for the antenna. When converted to kelvin, the fit for the loss is also reasonably good, with the LinLog function performing the best. The RMS values for each function are given in Table I. The signal we are looking for is on the order of a few hundred millikelvin, so ideally, the RMS for the fit would be well below that. In this case, fitting for the entire spectrum with LinLog can produce RMS values on the same order of magnitude as the signal with three or more parameters. However, this is inflated by the discontinuities, which can’t be modelled by a smooth curve. Looking at the residuals around the discontinuities, taken at high resolution, the variation in loss is on the order of a few millikelvin, excluding the discontinuities. If we assume that the actual loss will not have discontinuities, then the contribution to the

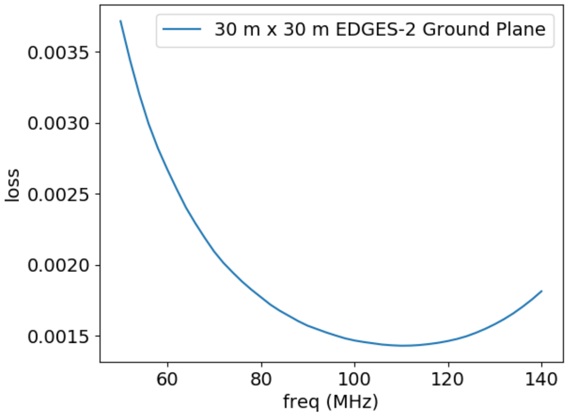

FIG. 10: Loss fraction for the EDGES-2 ground plane. Has much lower loss than the EDGES-3 ground plane, and less frequency structure.

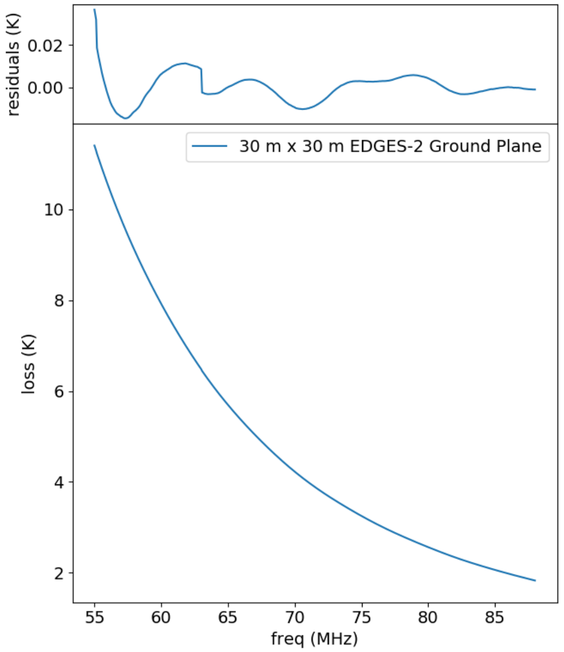

FIG. 11: Loss in Kelvin of the EDGES-2 ground plane from 55 MHz to 88 MHz at high resolution and the residuals to a 5 parameter LinLog model fit. There is a discontinuity at 63 MHz, and a possible one at 55.2 MHz. There may also be an oscillatory signal in the residuals.

RMS from the ground loss should be much lower in practice.

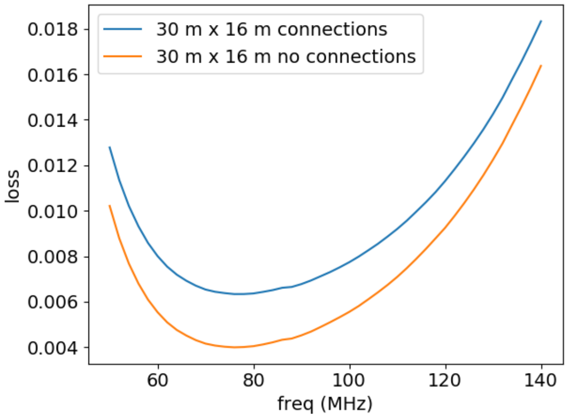

FIG. 12: Loss spectrum for the ground plane over a dielectric material with conductivity at a resolution of 2 MHz

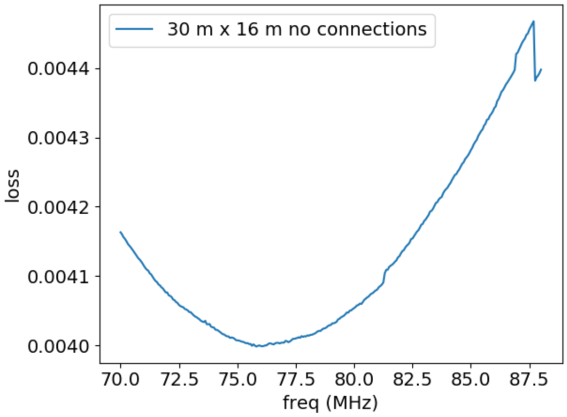

FIG. 13: Loss spectrum for the ground plane with no wire connections over a dielectric material with conductivity at a resolution of 0.0625 MHz on the range 70 MHz to 88 MHz. Three discontinuities at 81.3, 86.9, and 87.7 MHz are visible.

B. Mixed Wire Spacing

There was some testing with a ground plane with a change in wire spacing. The idea is that the most important part of the ground plane for reflection is the center, which is closest to the antenna. So, by having a high density center, but lower density outer edge, one could achieve similar levels of loss as when the entire ground plane was at the higher wire density, but with much less wire required. For example, the 30 m by 16 m ground plane with 12.5 cm spacing modeled takes 3.886 km of wire to produce. If we wanted to half the spacing and double the number of wires to bring down the loss, that would bring the ground plane to 7.726 km of wire. If we instead only increase the wire density for the center 3.75 m of the ground plane, the wire required is only 4.786 km. However, a concern of this design is that the change in density might introduce additional resonances. In the geometry explored here, the inner 3.75 m of width have a spacing of 6.25 cm while the rest have a spacing of 12.5 cm. FIG. 15 shows the loss for this ground plane on the dielectric soil. It is much lower than the loss for the standard 30 m by 16 m ground plane, and only requires slightly more wire. The mixed ground plane also provide additional evidence that the FEKO calculations for the ground plane with conductive soil is not entirely accurate. In FIG. 16 the loss clearly goes negative, which is not physical.

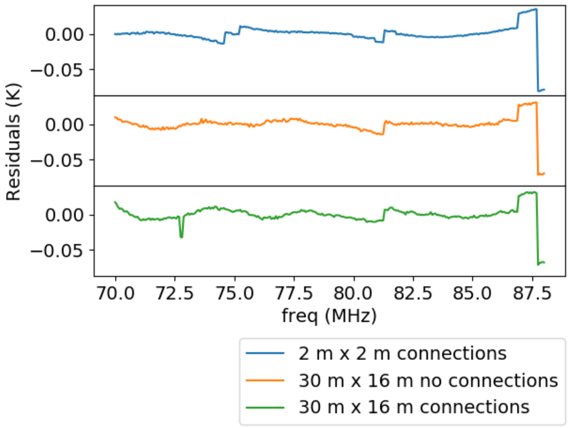

FIG. 14: Residuals for three conductive simulations fitted to a LinLog function with 5 parameters. The three glitches at 81.3, 86.9, and 87.7 MHz are present in all three, indicating that this is most likely not a result of the geometry of the ground plane.

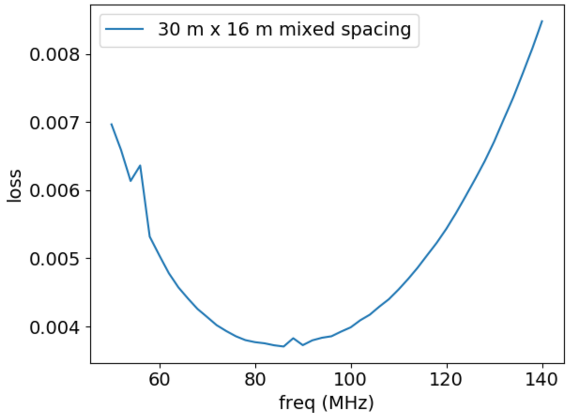

FIG. 15: Loss fraction for the mixed wire spacing ground plane on a dielectric soil. The small spikes seen are most likely just glimpses of much larger structures with features much narrower than 2 MHz.

C. Small Ground Planes

Some smaller ground planes were investigated, since they would be much easier and faster to deploy for quick tests. The ground plane sizes tested were 2 m by 2 m, and 4 m by 4 m(FIG. 17). Because there is less coverage than for the 30 m by 16 m ground plane, the loss is much larger. It is also easy to see the effect of the wire connections on the loss, which creates large resonances throughout(FIG. 18). Without the wire connections, the loss is relatively structure free, except for a peak at 50.2 MHz, just barely in the range of the spectrum. Curiously, 50 MHz corresponds to a wavelength of 6 m, which is a length that does not appear in the antenna or ground plane. If we continue using the logic that the spacing between peaks corresponds to a wavelength equal to the length of the wires, than we would expect the next resonance to be at about 200 MHz, which is outside of the range of these simulations.

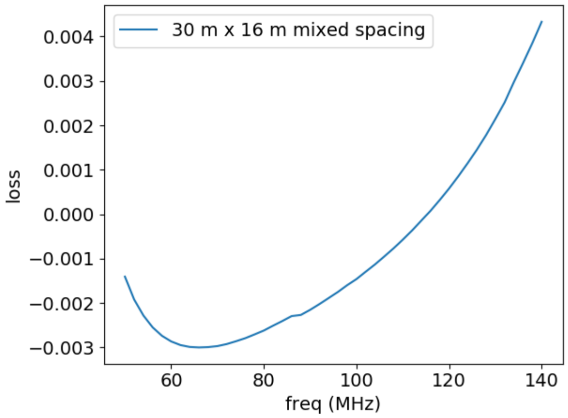

FIG. 16: Loss for the mixed ground plane on conductive soil. The loss goes negative which is not physical.

For the 4 m ground plane, without wire connections, there is a feature at approximately 75 Mhz, and another much smaller feature starting at 135 MHz and extending beyond 140 MHz. The first feature at 75 MHz could be a resonance at 4 m wavelength but we would expect the resonance to have shifted because of the dielectric. Once again, the connections add additional resonances to the loss spectrum.

D. Comparison of Loss Calculation Methods

The method used for the free space and dielectric models was determined to be more accurate than the full Green’s function method used for the conductive soil models by virtue of not depending on FEKO to get the absolute gain correct, only the relative gain for each sample point. To determine just how different the two methods are, I did a comparison on a 2 m by 2m ground plane over a dielectric soil. The full Green’s function solution has the advantage of working on all three models, making this comparison possible. The two simulations shown in FIG. 19 match noise structure almost exactly, but as expected the magnitude of loss calculated through each method is slightly different. Unfortunately, when

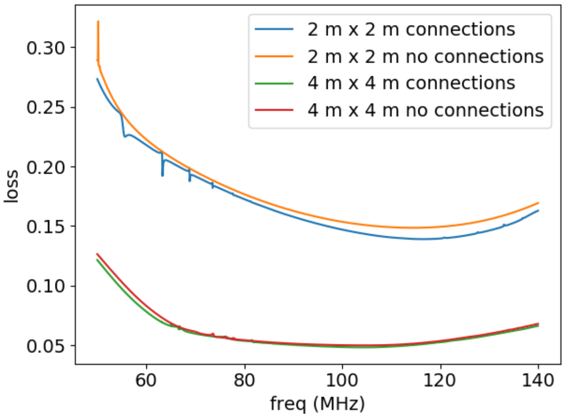

FIG. 17: Loss for the small ground planes on dielectric soil.

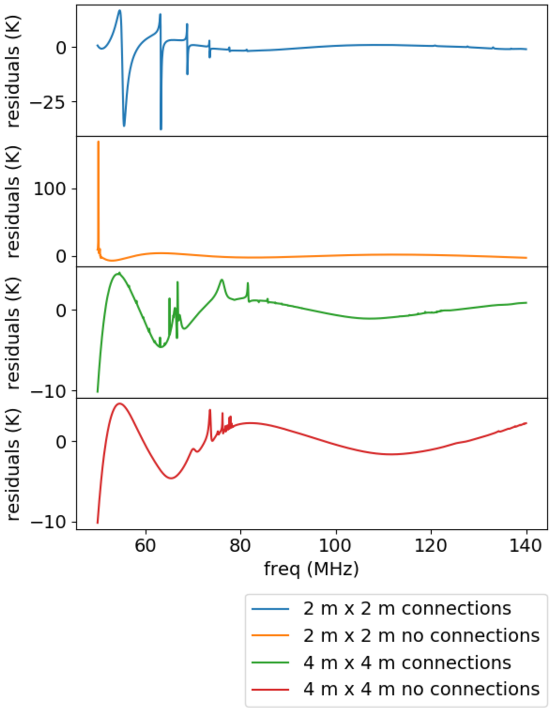

FIG. 18: Residuals to a 5 parameter LinLog fit for the small ground planes.

this is multiplied by the sky spectrum, the resulting loss in kelvin gets much larger. The difference between the two losses gets to greater than 20 K for low frequencies (FIG. 20). How this will ultimately be dealt with is not yet clear.

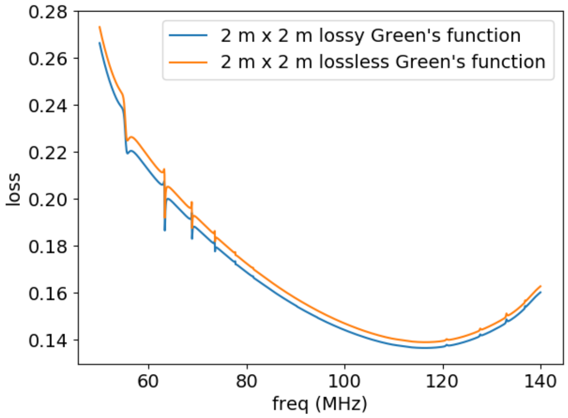

FIG. 19: Loss fraction for a 2 m by 2 m ground plane on a dielectric soil for both the lossless Green's function and lossy Green's function methods.

IV. CONCLUSION

The glitches that were found for both the lossless Green's function method and the lossy Green's function method are a little concerning. They indicate that there are errors in the calculations FEKO is performing, and while this was anticipated for the case of the lossy Green's function, it was unexpected for the method without loss. The lossy method depended on FEKO to get the absolute magnitude of the gain correct for all points on the sphere, and we accepted that that might not be possible. However, the lossless method did not depend on the absolute magnitude and only required that the calculated points be consistent with each other. The fact that it can still produce discontinuities like in FIG. 11 means that this is not always happening. At this point the reliability of both methods is not solid. That being said, we will continue for now under the assumption that the FEKO software is as accurate as it can be, and is accurate enough for our purposes.

The 30 m by 16 m ground plane with 12.5 cm spacing looks like it could perform well. In free space and with a dielectric, lossless soil, there is a lot of fine structure is the loss, but that all gets damped out when the conductivity is included. The resonances most likely do not disappear entirely, but are small enough that they can't be easily detected. We have shown that the loss can be adequately modelled with a LinLog function so a possible next step would be to try to integrate loss corrections into the EDGES antenna to try to remove the loss from the data. It would also be good to confirm that with conductivity included, the wire connections do increase the loss for all ground planes. An understanding of the related causes would be helpful as well.

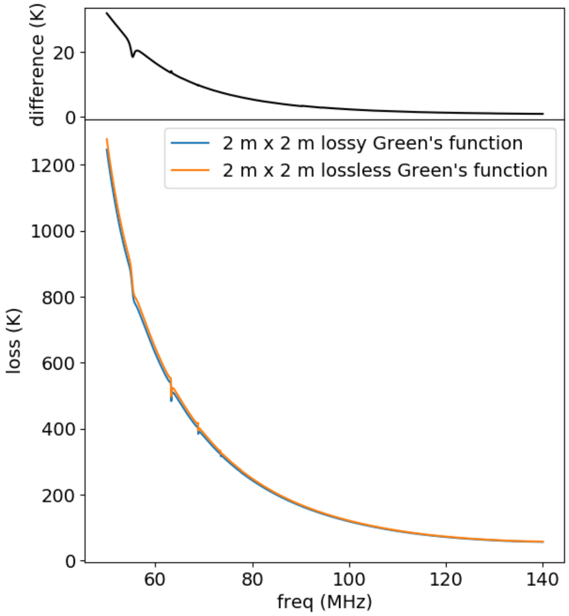

FIG. 20: Loss in Kelvin and the residuals for a 2 m by 2 m ground plane on a dielectric soil for both the lossless Green's function and lossy Green's function methods.

The mixed spacing ground plane is promising as an efficient way to improve ground loss. It was not quite as low as the loss for the mesh ground plane used by EDGES-2, but it was still considerably lower than the loss for the constant 12.5 cm spacing ground plane. Additional analysis needs to be done to ensure that the boundary between the 12.5 cm spacing and the 6.25 cm spacing does not introduce any large resonances, in the lossy model.

The small ground planes did not yield any additional findings, but they do reinforce the fact that the wire connections do complicate the geometry of the ground plane. For both the 2 m by 2 m and 4 m by 4 m ground planes, the wire connections added resonances that were detectable in the dielectric model. The loss for the small ground planes is far too large to be used for any real data, but is probably sufficient of simple tests of specific aspects of the antenna.

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[1] Proprietary Information of Altair Engineering, *User manual for FEKO 2018.1* (Altair Engineering, Inc., 2018), URL `altairhyperwork.com`.

[2] J. D. Bowman, A. E. Rogers, R. A. Monsalve, T. J. Mozdzen, and N. Mahesh, Nature **555**, 67 (2018), ISSN 14764687, URL `http://dx.doi.org/10.1038/nature25792`.