A Ground Plane Artifact that Induces an Absorption Profile in Averaged Spectra from Global 21 cm Measurements, with Possible Application to EDGES

Richard F. Bradley1, Keith Tauscher2,3, David Rapetti2,4, and Jack O. Burns2

1 National Radio Astronomy Observatory, NRAO Technology Center, 1180 Boxwood Estate Road, Charlottesville, VA 22903-4602, USA; rbradley@nrao.edu
2 Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309, USA
3 Department of Physics, University of Colorado, Boulder, CO 80309, USA
4 NASA Ames Research Center, Moffett Field, CA 94035, USA

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Abstract

Most of the current Global 21 cm experiments include ground screens that help moderate effects from the Earth. In this paper, we report on a possible systematic artifact within the ground plane that may produce broad absorption features in the spectra observed by these experiments. Using analytical approximations and numerical modeling, the origin of the artifact and its impact on the sky-averaged spectrum are described. The publicly released EDGES data set, from which a 78 MHz absorption feature was recently suggested, is used to probe for the potential presence of ground plane resonances. While the lack of a noise level for the EDGES spectrum makes traditional goodness-of-fit statistics unattainable, the rms residual can be used to assess the relative goodness of fits performed under similar circumstances. The fit to the EDGES spectrum using a model with a simple two-term foreground and three cavity-mode resonances is compared to a fit to the same spectrum with a model used by the EDGES team consisting of a five-term foreground and a flattened-Gaussian signal. The fits with the physically motivated resonance and empirical flattened-Gaussian models have rms residuals of 20.8 mK (11 parameters) and 24.5 mK (9 parameters), respectively, allowing us to conclude that ground plane resonances constitute another plausible explanation for the EDGES data.

Key words: cosmology: observations – instrumentation: detectors – methods: observational

1. Introduction

The weak nature of the highly redshifted 21 cm signature in the presence of strong foreground radiation, instrument systematics, and radio frequency interference makes the detection of a spectral feature in this band challenging in terms of measurement sensitivity and calibration. The Experiment to Detect the Global Epoch of Reionization Signature (EDGES) collaboration recently published in Bowman et al. (2018) a sky-averaged spectrum covering 50–100 MHz, revealing an absorption feature near 78 MHz (z ≈ 17) that may have important cosmological implications if its astrophysical origin can be verified (Ewall-Wice et al. 2018; Fraser et al. 2018; Kovetz et al. 2018). However, very subtle systematic errors within the instrument can have a profound effect on the interpretation of the data if they are not fully encapsulated by the calibration. For example, Hills et al. (2018) described a possible fit to the released EDGES data without any absorption trough when there is a periodic feature with an amplitude of ≲0.05 K in the sky spectrum. Here, we attempt to address the question whether there is a systematic artifact within the EDGES instrument that could produce such an absorption trough.

We explored the viability of a ground plane artifact producing an energy-absorbing feature at 78 MHz. We first analyzed the geometrical and material properties of the ground plane and soil from an electromagnetic perspective, leading to a lossy resonant cavity model, i.e., a patch antenna, with specific modes that exhibit spectral absorption features at frequencies defined by physical parameters. While parameters related to the ground plane’s horizontal dimensions are well defined, those involving the soil properties (dielectric permittivity and loss) and depth are less so, instead being bounded within a range of values estimated from measured soil samples in the vicinity of the instrument. Nonetheless, this analysis motivated an independent search for resonances within the EDGES data, where we found that three such features along with a two-term foreground model fit the data with rms residuals similar in magnitude to that of the five-term foreground and flattened-Gaussian signal model postulated by the EDGES team. Without the noise level of the data and thus the ability to compute a goodness-of-fit statistic (such as the traditional $\chi^2$, or $\psi^2$ as defined in Tauscher et al. 2018a), however, the significance of the differences in parameter count and rms residual level between the two fits cannot be determined. We extracted the cavity parameters from the resonant features fit to the EDGES data, yielding values that agree with the EDGES central solid ground plane horizontal dimensions and lie within the expected ranges for the soil characteristics.

In this paper, the physical characteristics of the artifact are described in Section 2, and the model-based analysis is presented in Section 3. Details of the procedure and results of the independent least-squares fit of three resonance features to the published EDGES data are provided in Section 4 along with a comparison to a similar fit for a flattened-Gaussian model. Estimates for the physical resonance model parameters are calculated in Section 5. Further considerations on initial experimental and simulation tests are discussed in Section 6, followed by concluding remarks in Section 7.

2. Physical Characteristics of the Ground Plane Artifact

A photograph of the EDGES instrument is shown in Figure 1. The antenna system consists of a pair of horizontally oriented, flat metal plates forming the dipole element suspended above the ground plane by a fiberglass supporting
structure. The ground plane consists of two components: a 2 m square inner portion of solid sheet metal, and a larger mesh that extends out to approximately 30 m. The entire antenna and ground system rest directly on the soil, whose characteristics are summarized in Table 1. These were based on measured soil samples from the Murchison Radioastronomy Observatory (MRO) that were characterized for several moisture levels at spot frequencies (Sutinjo et al. 2015). Moist soil must exist in the vicinity of the instrument to support the vegetation present in Figure 1.

The artifact secluded within the instrument is illustrated by the cross-sectional sketch of the ground plane and soil shown in Figure 2. The metal ground plane (solid sheet and welded steel mesh) and subsurface moist soil form the upper and lower conductors of a lossy transmission line, with the dry soil between these two conductors as the dielectric material. While waves may propagate under the entire ground plane via the transverse electromagnetic (TEM) mode that exists on this transmission line, the central sheet metal region is of particular interest.

Careful inspection of Figure 1 shows that the aluminum sheet metal portion of the ground plane lies slightly above the galvanized welded steel mesh. Because the soil near this interface is not compacted, persons walking near the instrument to service the electronics will force the mesh partway into the soil and can easily loosen or break the connections between the two ground structures. Galvanic interaction between the two dissimilar metals may also be a factor. For example, ZnO, formed at the interface by this process, is a wide-bandgap (3.35 eV), II–VI group semiconductor with native n-type doping that could form a Schottky barrier that effectively blocks weak signals (Sze 1981). Unfortunately, the integrity of this interface cannot be inspected from above because of its design.

It should be noted that soil moisture is not the only possibility for the lower conductor. For example, a thin seam of a metallic mineral can also serve this purpose. A careful analysis of the soil structure underground planes using trenching or ground-penetrating radar techniques is required for an accurate assessment. Alternatively, a synthetic ground plane foundation should be considered to carefully engineer subsurface electromagnetic properties.

If an electrical discontinuity does exist between the sheet metal and mesh components of the ground plane, a resonant cavity or short section of transmission line is formed that supports a TEM-like mode of propagation (Pozar 1990). Because this line is open at the discontinuities, the structure becomes a harmonic oscillator, resonant at select frequencies that are multiples of half the guide wavelength within the material. Fringing electric fields at the edges of the sheet provide access to the upper half-space above the ground plane, where the resonator can be excited by the impinging waves. Hence, this artifact, known as a resonant patch antenna, extracts and dissipates a small fraction of the sky radiation from the waves that reach the ground plane, i.e., energy is absorbed from the reflected waves in a frequency and spatially dependent manner, producing an absorption profile in the dipole-measured spectrum that is characterized by the geometry and material properties of this resonator.
3. Analytical Formulation of the Patch Antenna

The rectangular patch antenna may be analyzed as two orthogonal transmission lines that are open at both ends to form a two-dimensional resonant structure. The central region is square for EDGES and will respond equally to the two linear polarizations of the impinging sky radiation. For this analysis, a Cartesian coordinate system is imposed, whose origin is at the corner of the square and that is oriented such that the x- and y-axes are aligned to the ground plane sides with z as the vertical axis. Transverse magnetic (TM) waves, which have a z-directed E-field, can propagate separately along either the x or y transmission line (TM10, TM01, TM20, etc.) or simultaneously along both (TM11, TM22, etc.). Resonance occurs when the electrical length of the transmission pathways equals multiples of a half-wavelength.

The resonant frequencies, \( \nu_{mn} \), of the patch depend upon its geometry and material properties (Balanis 1997). For a lossless (non-dispersive) patch, \( \nu_{mn} = \frac{c}{2\pi\sqrt{\varepsilon_{re}}} \sqrt{\left(\frac{m\pi}{D}\right)^2 + \left(\frac{n\pi}{W}\right)^2} \), (1)

where \( \varepsilon_{re} \) is the effective relative permittivity of the substrate material including the effects of electric field fringing, \( c \) is the speed of light in vacuo, and \( m, n \) are positive integers indicating the number of half-cycle variations of the field in the x and y directions. \( D \) and \( W \) are the horizontal dimensions of the patch. According to Balanis (1997), the fringing field modifies the dielectric constant as

\[ \varepsilon_{re} = \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{2}\right) \left[1 + 12\left(\frac{h}{W}\right)^{-0.5}\right] \] (2)

where \( \varepsilon_r \) is the relative dielectric constant of the dry soil and \( h \) is the vertical distance between the ground plane and the lower underground conductor (moist soil).

The initial estimates of the potential resonant frequencies for the EDGES experiment were calculated assuming a \( D = W = 2.1 \) m square patch (2 m of physical length with 10 cm extra to account for fringing) on top of 40 cm of soil with a dielectric constant \( \varepsilon_r = 4.5 \) (yielding \( \varepsilon_{re} = 3.7 \)). Not included in this basic analysis is dispersion resulting from the lossy dielectric and lower conductor. However, it is included in the analysis of Section 5 to improve the accuracy of the parameter estimation. Table 2 lists the first nine resonant \( TM_{mn} \) frequencies.

### Table 2

| Mode | \( m \) | \( n \) | \( k \) (m\(^{-1}\)) | \( \nu_{mn} \) (MHz) | Note |
|------|------|------|-------------|-------------|-----|
| TM10 | 1    | 0    | 1.50        | 37.0        | Fundamental |
| TM11 | 1    | 1    | 2.12        | 52.4        | In-band |
| TM20 | 2    | 0    | 2.99        | 74.1        | In-band |
| TM21 | 2    | 1    | 3.35        | 82.8        | In-band |
| TM22 | 2    | 2    | 4.23        | 105         | Partially In-band |
| TM30 | 3    | 0    | 4.49        | 111         | Partially In-band |
| TM31 | 3    | 1    | 4.73        | 117         | ... |
| TM32 | 3    | 2    | 5.39        | 134         | ... |
| TM33 | 3    | 3    | 6.35        | 157         | ... |

The spectral shape of each resonance is that of a harmonic oscillator, as shown in Figure 3. An absorption resonance is characterized by three parameters: \( \nu_0 \), the frequency at which maximum absorption occurs, the depth of the profile \( A(\nu_0) \), and the quality factor, \( Q \), which is the ratio of the frequency of maximum absorption to the spectral width of the absorption, usually specified as the full width at half-maximum (FWHM). In low-loss situations \( (Q \gg 100) \), the Lorentzian curve is traditionally used to approximate the spectral profile \( A(\nu) \).

However, in the case of a very lossy resonator such as soil, this approximation is inaccurate and the actual curve

\[ A(\nu) = 1 - \frac{\nu^3}{\nu^4 + Q^2(\nu^2 - \nu_0^2)^2} \] (3)

must be used.

4. Fitting to EDGES Spectral Data

4.1. Likelihood and Minimization Procedure

To test the EDGES data for the presence of resonances like those described in the previous section, we use the gradient descent to fit the data by minimizing a negative log-likelihood, which up to an additive constant is given by

\[ -\ln L \equiv \frac{1}{2} [y - \mathcal{M}(\theta)]^T \mathbf{C}^{-1} [y - \mathcal{M}(\theta)] \] (4)

where \( y \) is the spectrum of data released by Bowman et al. (2018), shown in Figure 4, \( \mathbf{C} \) is the noise covariance, and \( \mathcal{M}(\theta) \) is the model of the spectrum at parameters \( \theta \). In accordance with the radiometer equation, we assume that the standard deviation of the noise is proportional to the data itself (see, e.g., Condon & Ransom 2016), i.e.,

\[ C_{ij} \propto y_i^2 \delta_{ij} \] (5)

The precise proportionality factor is unknown because no estimate of the noise level or total integration time was released with the averaged spectrum. Our choice of proportionality constant is arbitrary, however, because changing the proportionality constant would only change the magnitude of the log-likelihood, not its shape as a function of the parameters, thus
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leaving the maximum likelihood parameter estimation unaffected.

The model \( \mathcal{M}(\theta) \) is a combination of a concise foreground model and models for the resonances described in this paper. For the foreground, we use a similar model form as Bowman et al. (2018):

\[
T_{fg} = \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{-2.5} \sum_{k=1}^{N} a_k \left[ \ln \left( \frac{\nu}{\nu_{\text{ref}}} \right) \right]^{k-1}. \tag{6}
\]

The difference between our model and the model used throughout most of Bowman et al. (2018) is that we use only \( N = 2 \) terms and the polynomial part is in \( \ln \nu \) space. We stress that as more terms are added, polynomial models become increasingly flexible and possibly unphysical, especially in the presence of other models (e.g., \( 21 \) cm signal models).

The model chosen to represent the possible ground plane resonances in the time-averaged data is given by three copies of the negative term in Equation (3). The amplitudes, center frequencies, and \( Q \)-factors of all three resonances are allowed to vary independently to account for their different beam patterns and the difference in the skin depth of the soil at different frequencies.

We implement model gradients analytically, allowing us to also compute the log-likelihood gradient analytically. We take advantage of this gradient by employing the minimize function of the optimize module of the scipy code\(^5\) to perform a gradient descent minimization of the negative log-likelihood given in Equation (4). Because the results of gradient descent procedures depend on the initial guess given to the algorithm, we perform it many times from many different initial parameter vectors and choose from the set of results the final parameter vector that has the highest likelihood value. This is similar to the “basin hopping” minimization method of Wales & Doye (1997) in its two-tiered nature, but different in that the individual gradient descent iterations are completely independent of each other. All iterations of the minimization procedure converged on the same region of parameter space, indicating that there is a single dominant global minimum. The fitting method employed here is available for use as part of the pylinex code,\(^6\) which was originally developed for fits with linear models (Tauscher et al. 2018b), but has since been extended to allow for nonlinear models as well.

4.2. Fit Results

Figure 5 summarizes the results of the fit to the data with three resonances and a two-term foreground model. This fit, the parameters of which are shown in Table 3, should be compared to the fit in Figure 6, which was performed with a flattened-Gaussian signal model,

\[
T_{21} = \frac{A(1 - e^{-\gamma \Delta \nu})}{1 - e^{-\gamma}},
\]

and a foreground model given by

\[
T_{fg} = a_0 \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{-2.5} + a_1 \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{-2.5} \ln \left( \frac{\nu}{\nu_{\text{ref}}} \right)
+ a_2 \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{-2.5} \left[ \ln \left( \frac{\nu}{\nu_{\text{ref}}} \right) \right]^2
+ a_3 \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{-4.5} + a_4 \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{-2}, \tag{8}
\]

both used for Figure 1 of Bowman et al. (2018).

The rms residuals of the resonance and flattened-Gaussian fits are 20.8 mK and 24.5 mK, respectively, while the two fits have 11 and 9 parameters, respectively. Because the absolute magnitude of the noise level of the data is unknown, the numbers of parameters and rms residuals do not allow us to conclude whether either fit is good in an absolute sense or if one fit is better than the other; however, their relative values allow us to conclude that the physically motivated resonance model yields another viable explanation of the EDGES data.

5. Physical Model Parameter Estimation

The dimensions of the patch and properties of the soil may be estimated from the characteristics of the resonances found in Section 4. An analytical model that includes dispersion must be used for accuracy. While it is likely that a moisture gradient is present, the details are unknown, so a piecewise homogeneous, layered profile, as depicted in Figure 2, was adopted for this proof-of-principle analysis. In addition, a thin dry soil model is invoked \((h \ll \lambda)\), where the field variations along the height

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\(^5\) https://scipy.org

\(^6\) https://bitbucket.org/ktausch/pylinex

Table 3: Maximum Likelihood Parameters for the Fitted Resonances Whose Sum Is Plotted in the Left Panel of Figure 5

| Mode     | \(\nu_0\)  | \(A(\nu_0)\) | \(Q\) |
|----------|------------|--------------|------|
| TM20     | 73.8       | -2235        | 3.9  |
| TM21     | 84.2       | -2469        | 3.8  |
| TM30     | 111.8      | -9403        | 1.3  |
are considered constant and the electric field is nearly normal to the surface of the patch (except at the edges where fringing occurs). In this way, the three-dimensional cavity may be treated as a two-dimensional microstrip line resonator.

The line geometry and boundary conditions restrict the wavenumber, \( k \), to discrete values, \( k_{mn} \), where \( m \) and \( n \) are integers. The constraint can be derived from the homogeneous wave equation involving the vector potential, yielding \( k_{mn}D = m\pi \) and

\[
k_{mn}^2 = k_o^2 - \left[ \frac{n\pi}{W} \right]^2, \tag{9}
\]

where \( k_o \) is the complex wavenumber or phase constant associated with the dispersive transmission line. According to Collin (1966), this is related to the resonant frequencies of the cavity as

\[
k_o = 2\pi\nu_{mn}\sqrt{\mu\varepsilon}. \tag{10}
\]

The determination of \( k_o \) involves the soil properties. The electrical conductivities of the soil, given in Table 1, are quite low and will greatly limit the \( Q \) of the resonances. However, the permittivity of the dry soil is a complex quantity, \( \varepsilon = \varepsilon' - i(\varepsilon'' + \frac{\sigma_o}{2\pi\nu_o}) \), affecting the propagation constant. If magnetizable minerals are present in the soil, the permeability may also be complex, with \( \mu = \mu' - i\mu'' \) to include damping. The moist soil, a lossy ohmic conductor, adds a frequency dependent internal inductance, \( L_{\text{int}} \), to the distributed model due to the skin effect, which also affects the propagation constant. This is described as

\[
L_{\text{int}} = \frac{1}{2} \sqrt{\frac{\mu_o}{\pi\sigma_o\nu_{mn}}}, \tag{11}
\]

where \( \sigma_o \) is the conductivity of the moist soil.

As a result, the propagation constant is the imaginary part of \( ik_o \) given by

\[
\text{Im}[ik_o] = 2\pi\nu_{mn} \left[ \frac{\varepsilon'\mu' - \left(\varepsilon'' + \frac{\sigma_o}{2\pi\nu_o}\right)\mu''}{2} \right] \sqrt{1 + \left[ \frac{\left(\varepsilon'\mu' + \left(\varepsilon'' + \frac{\sigma_o}{2\pi\nu_o}\right)\mu''\right)^2}{\left(\varepsilon'\mu' - \left(\varepsilon'' + \frac{\sigma_o}{2\pi\nu_o}\right)\mu''\right)^2 + 1} \right]} = 2\pi\nu_{mn}\sqrt{L_{\text{int}}C_L}. \tag{12}
\]

A TEM transmission line formed by the metal patch, thin dry soil layer (\( h \ll \lambda \) assumed), and underlying conductor can be described in a unique manner by a distributed-parameter electric network consisting of series inductance (\( L_L \)) and shunt capacitance (\( C_L \)) per unit length for energy storage and series resistance (\( R_L \)) and shunt conductance (\( G_L \)) per unit length for energy dissipation.

Under the conditions of small dielectric loss (\( \varepsilon'' \approx 0 \)) and no magnetic loss (\( \mu'' \approx 0 \)), Equation (12) becomes separable, yielding

\[
C_L = \frac{\varepsilon'}{2} \left[ 1 + \left( \frac{\sigma_o}{2\pi\nu_{mn}\varepsilon'} \right)^2 \right] + 1 \tag{13}
\]

and

\[
L_L = L_{\text{int}} + L_{\text{ext}} = L_{\text{int}} + \left( \frac{Z_{\text{co}}}{S} \right)^2 C_L = \mu' \tag{14}
\]

where, as adopted from Pozar (1990), the characteristic impedance of the lossless microstrip quasi-TEM line is given by

\[
Z_{\text{co}} = \frac{L_{\text{ext}}}{C_L} = \sqrt{\frac{120\pi}{W/h + 1.393 + 0.677\ln(W/h + 1.444)}} = \frac{120\pi S}{\sqrt{\varepsilon_e}}, \tag{15}
\]

with \( S \) as the dimensionless geometrical factor relating the line impedance to the characteristic impedance of the medium. \( L_{\text{ext}} \) is the inductance per unit length of the line when the conductors are lossless.
556 mK amplitude, is centered at 78.2 MHz, has an FWHM of 18.8 MHz, and has a

which is derived from the skin-depth analysis. Because

Finally, the \( Q \) of a resonance is the ratio of time-averaged energy stored to energy dissipated per unit length at the given resonant frequency. Because the loss is dominated by the lower conductor (i.e., for the dry soil, \( \alpha = Re[ik_w] \approx 0 \), yielding \( G_L \approx 0 \)), then \( Q_{mn} \approx 2\nu_w l_{ext}/(RLS) \), with

\[
R_L = \frac{1}{2} \sqrt{\frac{\pi \mu_w \nu_w l_{ext}}{\sigma_w}},
\]

which is derived from the skin-depth analysis. Because \( Q \) is defined on a per unit length basis, it must be scaled by the number of half-wavelengths present at the given resonance.

These equations were used to estimate the frequencies and \( Q \) values of the three in-band resonances and the band-adjacent resonances, given physically realizable values for \( D, W, h, \nu', \sigma_d, \) and \( \nu_w \). The results are summarized in Table 4. It should be stressed that this solution is not unique, but represents one plausible configuration that fits the available information. As expected, in Table 2, TM22 is nearly degenerate with TM30 and cannot be resolved given the low \( Q \)-factors.

The characteristics of the two dominant resonances in Table 4, TM20 and TM21, were anchored to the fit results of Table 3. However, the analytical model suggests that the frequencies of the TM22/TM30 modes are approximately 0.7% lower. The more weakly coupled TM11 mode shown here is likely below the residual noise in the data.

6. Experimental and Simulation Tests

6.1. Moist Soil

A rudimentary experiment was conducted at the Green Bank Observatory to confirm that nominal moisture content of soil is sufficient to form the lower conductor of the patch antenna. From FCC (2018), the estimated soil conductivity for the Green Bank, WV, region is 0.002 S m\(^{-1}\). In contrast with the soil at the EDGES site, the moist soil here extends to the surface, with the air and pine wood frame under the mesh serving as the dielectric. The patch was made from 3 m \( \times \) 3 m, #23 gauge, galvanized welded steel mesh (4 squares per inch) attached to a pine frame with double-folded overlapping seams.

The patch is an unbalanced antenna that can be fed by way of a coaxial cable. For the ground connection, an aluminum rod was driven approximately 50 cm into the soil adjacent to the edge of the patch. The outer shield of the coaxial cable was clamped to the rod, and the inner conductor was attached to the mesh using a spring clip. The height of the mesh above ground was set using concrete blocks positioned at the corners, while the entire patch was moved laterally to change the feed point position.

The patch was excited by an Anritsu Model MS2024A/15 Vector Network Analyzer (VNA) attached to the other end of the coaxial cable (characteristic impedance Zo = 50 \( \Omega \)) located approximately 30 m from the patch. One-port network calibration was performed at the antenna end of the cable using the coaxial open, short, and 50 \( \Omega \) load termination standards provided by the manufacturer of the VNA. The plot shown in Figure 7 is referenced to this calibration plane and shows the TM-mode resonances that occurred in the patch for several heights of the mesh above ground and for two feed locations—one at the midpoint of the patch edge and the other at the corner. The results of this experiment confirm that soil with an electrical conductivity as low as 0.002 S m\(^{-1}\) will form a lossy, lower conductor for the patch antenna. From Table 1, lower soil moisture content at the MRO site can yield conductivities several orders of magnitude greater than this value.

6.2. Beam Patterns of the Patch Absorber

The commercial electromagnetic simulation package Microwave Studio by CST was used to estimate the beam patterns of the patch absorber. Fringing electromagnetic fields across a gap in the ground plane allow a fraction of the energy carried by the

\[ \text{https://www.gpo.gov/fdsys/pkg/CFR-2004-title47-vol4/pdf/CFR-2004-title47-vol4-sec73-190.pdf} \]

Figure 6. Similar to Figure 5, except that the foreground model is given by Equation (8) and a flattened-Gaussian model is used in place of the resonances. This is the same model as was used in the fit that produced Figure 1 of Bowman et al. (2018). The residuals of this fit have an rms of 24.5 mK. The flattened Gaussian has a 556 mK amplitude, is centered at 78.2 MHz, has an FWHM of 18.8 MHz, and has a flattening parameter \( \tau \) of 5.8.

Table 4

| \( W \) (m) | \( D \) (m) | \( h \) (m) | \( \nu' \) | \( \sigma_d \) (S m\(^{-1}\)) | \( \sigma_w \) (S m\(^{-1}\)) | \( Q_{11} \) | \( Q_{20} \) | \( Q_{21} \) | \( Q_{22} \) | \( \nu_{1} \) (MHz) | \( \nu_{20} \) (MHz) | \( \nu_{21} \) (MHz) | \( \nu_{22} \) (MHz) | \( \nu_{30} \) (MHz) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.9 | 2.1 | 0.2 | 4.0 | 0.0005 | 1.0 | 3.4 | 2.8 | 2.6 | 2.4 | 2.3 | 55.0 | 73.8 | 84.2 | 110.7 | 111.0 |
impinging plane waves, normally confined to the upper half-space, to excite the patch structure within the soil.

The model used in this simulation was a 20 m square ground plane with a 2 m square patch located at the center. A 5 cm gap was included around the patch for fringe-field coupling. The soil structure under the ground plane consisted of 20 cm thick dry component ($\epsilon_r = 4.0$, and $\sigma_d = 0.0005 \text{ S m}^{-1}$) with moist soil ($\sigma_w = 1.0 \text{ S m}^{-1}$) underneath. For beam pattern estimation, the patch was excited by a discrete port located midway along the edge of the patch and extending in the $z$-direction downward from the patch to the moist soil.

Plots of the simulated beam patterns are given in Figure 8. The most outstanding feature of the beams is the multi-lobed response far removed from the bore sight of the dipole antenna ($+z$ axis). The left panel shows the pattern at 75 MHz where the TM20 mode dominates, while the right panel shows the rotated pattern at 85 MHz where the TM21 mode becomes engaged.

Two points are important regarding these patterns. First, the resonances, TM20 and TM21, are each excited by different regions of the sky. Second, the amplitudes of the absorption features should each be time-varying as the sources traverse through the complicated beam patterns. Hence, the characteristics of the broad spectral feature formed by these two resonances will change shape as a function of time.

### 6.3. Plane Wave Excitation

To gauge the absorption characteristics of the patch, a simple dipole antenna was added to the simulation model described in Section 6.2. It was tuned for 91 MHz and placed 80 cm above the ground plane, as shown in the left panel of Figure 9. A plane wave, with $E$-field orientation in the $x$ direction,
propagates in the $−y$ direction toward the dipole from an elevation of 45° above the ground plane. The right panel of Figure 9 shows the power loss in the ground plane compared to that of a solid ground plane, assuming the plane wave emanates from a (nominal) 4000 K sky region. The primary in-band absorption resonances are clearly visible, with magnitudes comparable to the fit resonances. This simulation illustrates that a patch antenna embedded in the ground plane can imprint spectral structure on the power received by the dipole. The magnitudes of such features can be quite difficult to discern from dipole reflection coefficient and beam pattern measurements because a dynamic range greater than 30 dB is required.

7. Conclusions

We described a ground screen artifact that can produce absorption features in the spectrum of Global 21 cm experiments. We developed a plausible physical model, based on patch antenna theory and defined by physical parameters, and we compared the associated in-band and adjacent band resonances of the patch antenna cavity modes with those found from fitting to the published EDGES data. The ground screen absorbing characteristics were discussed along with examples of patch antenna beam patterns.

The conclusions may be summarized as follows:

1. The three cavity-mode resonant features of the ground plane patch absorber together with an $N = 2$ term polynomial foreground model fits the published EDGES data (11 parameters, 20.8 mK rms) as well as that of the flattened-Gaussian feature model with a five-term foreground model (9 parameters, 24.5 mK rms). The significance of the difference between the numbers of parameters and rms residual values of the two fits can only be determined from a goodness-of-fit statistics calibrated to the noise level.

2. The parameters defining the geometrical and soil characteristics estimated from the fitting results that used an analytical model of the patch absorber are consistent with the physical environment of the instrument and the spectral trough in the data.

3. Measurements conducted at the Green Bank Observatory illustrate that soil moisture can form the lower conductor for the resonant patch absorber. However, mineral deposits may also be a factor.

4. Electromagnetic simulations show that an absorption trough can be imprinted onto the sky spectrum acquired by a dipole when it is located above a ground plane containing an isolated patch.

5. High-order polynomial foreground models are unreliable for two main reasons: (a) they can fit out signal or hidden systematic features that are as spectrally smooth as the foreground, and (b) it is unclear whether they can model foreground emission to precision levels necessary for accurate extraction of the 21 cm global signal.

6. Beam chromaticity and instrument systematics are serious problems, especially when they interact with generic flexible models such as polynomials.

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Facilities: National Radio Astronomy Observatory, Green Bank Observatory.

Software: CST Microwave Studio, Numpy, Scipy, and Matplotlib Python packages.

ORCID iDs

Keith Tauscher @ https://orcid.org/0000-0003-1932-9829
David Rapetti @ https://orcid.org/0000-0003-2196-6675
Jack O. Burns @ https://orcid.org/0000-0002-4468-2117

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