A Simplified Algorithm for the Selection of Materials used to Construct OATS

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Abstract: One of the most critical decisions to be made in the construction of Open Area Test Sites (OATS) is the selection of materials to be used for weather protection, that is, the selection of materials to be used in the construction of the ceiling and walls. For common construction materials, it is the dielectric constant and the thickness which most affects the tendency of walls and ceilings to reflect RF signals. This paper presents a simple algorithm for selecting materials based on their dielectric constant and thickness

INTRODUCTION

The task of selecting materials for the construction of an Open Area Test Site (OATS) can be fraught with uncertainty. A radiated emissions test site, for example, can be built relatively inexpensively out of conventional construction materials, but the performance can be uncertain. A facility costing many hundreds of thousand dollars can be rendered worthless by unexpected reflections from ceilings and walls. Exotic structures can be purchased, built from materials guaranteed to meet applicable ANSI/IEEE and CISPR publications, but at prices that can approach a million dollars or more for larger sites.

In this paper, we will explore the physics of reflection and and propose a simplified algorithm for choosing construction materials for a radiated emissions test site.

We start with the general proposition that an "open field" facility built with weather protection should be as transparent to radio frequency energy as possible. Our starting point, therefore, is the physics of an electromagnetic wave as it impinges on a wall. If we assume that we are dealing with far field conditions, then our model becomes that of a plane wave striking a wall at an oblique angle. Part of the wave will be reflected at an angle equal to the angle of incidence and part will be refracted as it passes through the wall. What we wish to know is how much energy is reflected.

REVIEW OF THE PHYSICS OF REFLECTION

Any good physics book will contain part of the answer. The magnitude of the reflected field will depend in part on the field's polarization. Figure 1 shows an aerial view of a test site undergoing an analysis of its reflections. The antennas are mounted in horizontal polarization and we are primarily concerned about the reflection from the four vertical walls. (We discuss reflections from the ceiling below.) Figure 1 shows us that the electric field vector lies in the same plane as the drawing itself. The plane of the drawing is known as the "plane of incidence," that is, the plane that slices perpendicularly through the reflective surface we wish to analyze. The electromagnetic wave created by the transmitting antenna bounces off the partially reflective wall and is picked up as an undesirable signal by the receiving antenna.

Figure 2 shows the same analysis applied for vertically polarized

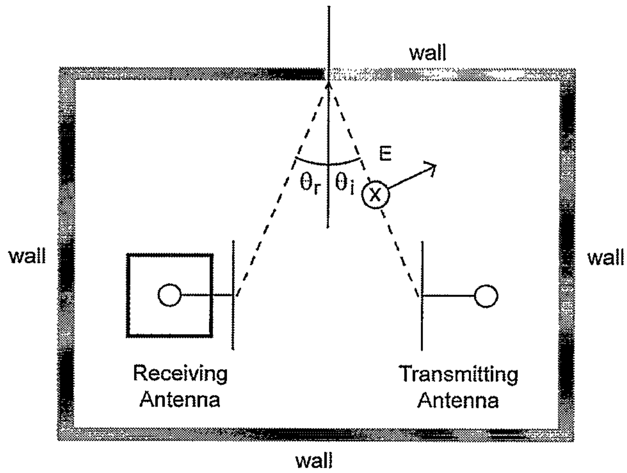

Figure 1

transmitting and receiving antennas. Here the magnetic field is parallel to the plane of incidence and the electric field is perpendicular to it. Our physics text tells us that the amount of signal reflected under such circumstances is likely to be different from the case illustrated in Figure 1. The handbook formulas analyze the case of a wave impinging on an infinitely thick wall. An incident wave of angle θ_i strikes a wall of infinite depth and is reflected at an equal angle θ_r. Part of the energy is transmitted into medium two (the wall) at a slightly refracted angle θ_t. The air (medium one) has a characteristic conductivity, dielectric constant and permeability (σ_1, ϵ_1, and μ_1 respectively). Similarly, the wall (medium two) has its own characteristic parameters, σ_2, ϵ_2, μ_2.

We can simplify the physics by assuming no conductivity for either medium, and that μ_1 and μ_2 are equal. This would be the case for most insulators. Here, the amount of reflection is the function of the polarization of the wave, the dielectric constant of the mediums and the angle of incidence. If the electric field is perpendicular to the plane of incidence, which is the case for a vertically polarized wave

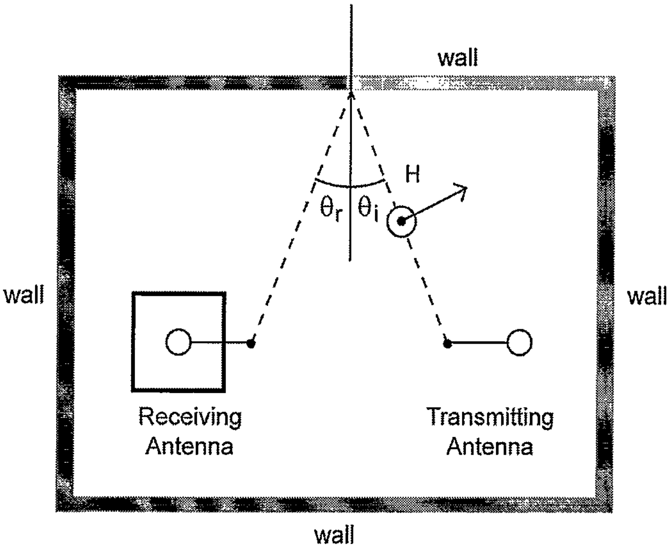

Figure 2

bouncing off a vertical wall, we can define a "reflection coefficient," as the percentage of the electric field reflected:

$$r(\perp)=\frac{Z_2\cos\theta_i-Z_1\cos\theta_t}{Z_2\cos\theta_i+Z_1\cos\theta_t} \qquad (1)$$

Where:
Z_1 = Free Space impedance = 377 ohms.
Z_2 = Impedance of the medium.
θ_i = Angle of incidence.
θ_t = Angle of transmission.

For horizontal polarization, the electrical field is parallel to the plane incidence as it bounces off the walls. Here the reflection coefficient is:

$$r(\parallel)=\frac{Z_2\cos\theta_t-Z_1\cos\theta_i}{Z_2\cos\theta_t+Z_1\cos\theta_i} \qquad (2)$$

We can calculate Z from the formula for the impedance of a plane wave:

$$Z_1=\sqrt{\frac{\mu_1}{\epsilon_1}}=377\ \textit{ohms (free space)} \qquad Z_2=\sqrt{\frac{\mu_2}{\epsilon_2}}=\sqrt{\frac{\mu_1}{\epsilon_2}}=\frac{377}{\sqrt{\epsilon_r}} \qquad (3)$$

We can calculate the angle of transmission from Snell's Law [1].

Given the assumptions we have made, the reflection coefficients are, therefore, a function of dielectric constant and angle (Figure 3). In the case of an electric field perpendicular to the plane of incidence, the reflection coefficient steadily rises as the angle of incidence increases. When the electric field is parallel to the plane of incidence, the reflection coefficient falls initially, eventually reaching zero at the

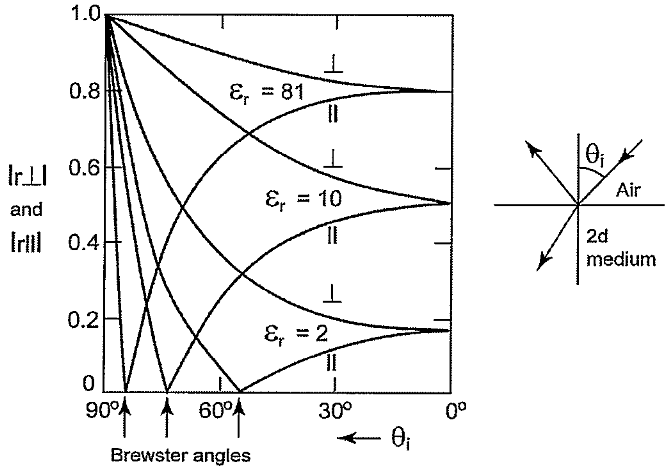

Figure 3

"Brewster angle" then rising rapidly as the angle approaches 90°. At the Brewster angle, the wall appears transparent.

SELECTION OF MATERIALS

We can use Figures 1, 2 and 3 to guide our design choices. We will be primarily concerned about our performance in vertical polarization. In vertical polarization, the electric field is perpendicular to the plane of incidence and a higher reflection coefficient will result at all oblique angles than in the case of horizontal polarization. In the case of reflections from the ceiling, the opposite analysis applies. The ceiling will be more reflective for horizontally polarized signals. However, as a practical matter, reflections from a ceiling are less problematic. First, there is only one ceiling and there are four side walls. Secondly, in the case of our open field test site, reflections from the ceiling are at least partially masked by reflections from the floor caused by the mandatory ground plane. Finally, ceilings are often built at oblique angles, introducing both parallel and perpendicular components of reflection.

Normal incidence is a special case. Here Equations (1) and (2) reduce to the following:

$$r(\parallel)=r(\perp)=\frac{Z_2-Z_1}{Z_2+Z_1} \qquad (7)$$

Circuit designers will recognize this as the formula for reflection on a transmission line. That is very convenient. It means that we can analyze reflections at normal incidence using transmission line models, including the myriad of software tools now available. Such analysis will allow us to predict the worst case reflection for most test sites in horizontal polarization. It would also provide useful data for estimating the magnitude of the reflection coefficient in the vertical case, keeping in mind that the reflection coefficient will rise somewhat as the angle of incidence increases. This increase is relatively small, however, for most practical test sites (those with an angle of incidence less than 30°).

Equations (1) and (2) describe the reflections expected in the case of an electromagnetic wave passing from one infinite medium to another. However, our test sites are different. Here the walls are thin compared to the wavelength. A different formula can be used for more precise analysis. As mentioned, plane wave passing from one medium to another at normal incidence can be modeled quite accurately as a transmission line. In the case of a thin wall, we pass through three media: medium one (air), medium two (the wall), and medium three (air again). At normal incidence this can be modeled as a transmission line with characteristic impedance of 377 Ω which has had spliced into it a small section of line of differing characteristic impedance. The reflections at normal incidence can be still be readily calculated using transmission line formulas.

Ramo, Whinnery and Van Duzer have done that for us [2]. Their formula for reflection is as follows:

$$r = j\left(\frac{k_2\, l}{2}\right)\left(\frac{\eta_2}{\eta_1} - \frac{\eta_1}{\eta_2}\right) \qquad (8)$$

Where:
r = Reflection coefficient for both the perpendicular and the parallel case.
k_2 = Wavenumber in the wall = $2\pi/\lambda$
l = Thickness of the wall in meters.
η_1 ,η_2 = Index of refraction for the respective media.

We can calculate the wavelength in the wall (λ_2) readily:

$$\lambda_f = \frac{c}{f} \qquad \lambda_f = \frac{1}{\sqrt{\mu_0 \epsilon_0}}\frac{1}{f}$$

$$\lambda_2 = \frac{1}{\sqrt{\mu_0 \epsilon_0 \epsilon_r}}\frac{1}{f} \qquad \lambda_2 = \frac{1}{\sqrt{\epsilon_r}}\frac{1}{\sqrt{\mu_0 \epsilon_0}}\frac{1}{f} = \frac{1}{\sqrt{\epsilon_r}}\lambda_f \qquad (9, 10)$$

Where:
λ_f = Wavelength in free space.
c = Speed of light = $1/\sqrt{(\mu_0 \epsilon_0)}$.
f = Frequency in Hertz.

Therefore, our reflection coefficient is:

$$r = j\left(\frac{\pi\, l}{\lambda_2}\right)\left(\sqrt{\epsilon_r} - \frac{1}{\sqrt{\epsilon_r}}\right) = j\left(\frac{\pi\, l}{\lambda_f}\right)(\epsilon_r - 1) \qquad (11)$$

What we are really interested in is the magnitude of the reflection coefficient, which can be expressed simply as:

$$|r| = \frac{\pi\, l\, (\epsilon_r - 1)}{\lambda_f} \qquad (12)$$

If we want the magnitude of the reflection coefficient to be less than .1 and our upper frequency of interest is 1 GHz (λ_f= .3m), then we can calculate a "permissible thickness" for a given non ferrous, non conductive wall. It is:

$$l_p = \frac{(.1)\ (.3)}{\pi(\epsilon_r - 1)} \cong \frac{.01}{\epsilon_r - 1} \qquad (13)$$

For a thickness in centimeters, our maximum permissible thickness at 1 GHz becomes:

$$l_p(cm) \cong \frac{1}{\epsilon_r - 1} \qquad (14)$$

In other words, if the upper frequency we are interested in is 1 GHz, then the maximum thickness we should tolerate for our walls is simply one over the relative permittivity (ϵ_r) minus one.

The formula offers a convenient rule of thumb for evaluating nonferrous, nonconductive media used as walls in test sites.

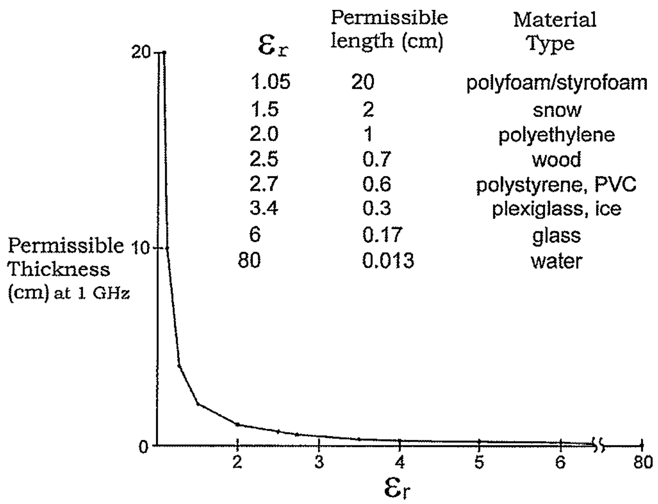

Figure 4

A contour mapping maximum permissible thicknesses in centimeters versus relative permittivity is shown in Figure 4.

REFERENCES

[1] J. D. Kraus, Electromagnetics, Fourth Edition, McGraw Hill Inc., 1992, page 617.

[2] Ramo, Whinnery and Van Duzer, Fields and Waves in Communications Electronics, John Wiley and Sons, 1965, page 350.