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EMP SHIELDING EFFECTIVENESS AND MIL-STD 285

by

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ABSTRACT

The relationship between electromagnetic-pulse (EMP) shielding effectiveness and MIL-STD-285 is investigated analytically. It is found that measurements carried out in the manner prescribed by MIL-STD-285 using small cw dipole and loop sources located at fixed relative positions 12 in. from the walls will give upper and lower bounds for the EMP (plane wave) shielding effectiveness of any metallic structure at all frequencies of interest (10^2 to 10^8Hz). Upper bounds are provided by dipole measurements and lower bounds by loop measurements for each EMP frequency corresponding to a frequency employed in MIL-STD-285. A closed form expression $\delta(r,f)$ is obtained for the difference between EMP shielding effectiveness and loop shielding effectiveness. This expression is independent of any metallic structure and depends only on the ratio between wave impedances of the EMP and loop fields. That is, it depends only on the impedance mismatch between EMP and loop fields at the surface of the structure. In general, it is a function of frequency f and distance r between the source and structure. Since both EMP and loop wave impedances are known, $\delta(r,f)$ can be explicitly evaluated for a source distance of 12 in. and added to measured values of loop shielding effectiveness to give estimates of EMP shielding effectiveness at any frequency. A similar result is obtained for a dipole source. In this way, MIL-STD-285 measurements can be used to estimate EMP shielding effectiveness.

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1. INTRODUCTION

Natural and man-made electromagnetic-pulse (EMP) sources, such as lightning and nuclear explosions, are capable of producing transient, high-intensity electromagnetic fields over a wide area. These intense fields are a potential cause of damage to sensitive electronic equipment unless steps are taken to shield the equipment from direct exposure to the EMP. To provide this shielding, sensitive circuits are frequently placed within metallic enclosures intended to reduce the intensity of ambient fields to a tolerable level by reflecting and attenuating the external EMP fields. The effectiveness of these EMP shields is naturally of great concern to systems designers, and many test methods have been used to measure shielding effectiveness directly in the field. Since a full-scale simulation of the actual EMP source is usually not possible, recourse is often made to test methods employing much smaller scale electromagnetic sources. One of the most attractive of these from the standpoint of simplicity and ease of operation is the method described in Military Standard 285.[1] This method uses small cw loop and dipole antennas located close to the shielded enclosure and measures the shielding effectiveness, SE, in terms of the attenuation in dB of the received power on opposite sides of the shield when the shield is illuminated by electromagnetic radiation. Thus, if E_1 is the electric field measured at the surface of the shield on the side towards the antenna and E_2 is the electric field measured on the side of the shield away from the antenna, the shielding effectiveness at the source frequency is computed as follows:

$$\text{SE} = \text{Attenuation (dB)} = 20 \log \frac{E_1}{E_2} \tag{1.1}$$

Unfortunately, the shielding effectiveness of a metallic enclosure as measured in this manner using a loop or dipole source will not, in general, be the same as the shielding effectiveness which would have been measured for the same enclosure if an actual threat EMP (i.e., lightning or nuclear burst) had been used. This is to be expected because the magnitude of SE for any enclosure depends critically on the wave impedance of the incident field,[2] and the latter can vary widely depending on the type of source (EMP, loop, dipole, etc.) and the distance between the source and the shield. Thus, tests carried out in accordance with MIL-STD-285 do not measure directly the shielding effectiveness of a metallic enclosure with respect to EMP sources.

In view of the preceding, the question arises as to what, if anything, can be learned from MIL-STD-285 tests concerning EMP shielding. In this study, we will argue that these tests give upper and lower bounds on the shielding effectiveness of the enclosure against EMP fields. That is, MIL-STD-285 will give best and worst case estimates of EMP-shielding effectiveness for each frequency component used in the test. The argument, which will be documented in succeeding

1. Anonymous, MIL-STD 285 "Method of Attenuation Measurements for Enclosures, Electromagnetic Shielding, for [sic] Electronic Test Purposes." Department of Defense, 25 June (1956).
2. Schelkunoff, S.A., Electromagnetic Waves, Van Nostrand, Princeton, N. J. (1943).

sections, runs as follows: At frequencies of most concern in EMP fields (10^2 to 10^8 Hz), the shielding effectiveness of an enclosure is primarily determined by the ratio of reflected to incident energy. The value of this ratio depends, in turn, on the ratio of the wave impedance of the incident field to the impedance of the enclosure, that is, it depends on the impedance mismatch at the surface of the enclosure. The greater the impedance mismatch, the greater the ratio of reflected to incident energy; hence, the greater the shielding effectiveness of the enclosure. Conversely, shielding effectiveness decreases as the ratio between wave impedance and enclosure impedance approaches 1. It will be shown in section 2 that, under conditions specified by MIL-STD-285, the wave impedance Z_L, Z_D, and Z_{EMP} of loop, dipole, and EMP sources, respectively, are ordered as follows:

$$|Z_L| < |Z_{EMP}| \approx 377\Omega < |Z_D| \tag{1.2}$$

It will be shown in sections 3 and 4 that the impedance, Z_S of a typical enclosure (which may have one or more narrow apertures) is bounded as follows:

$$|Z_S| < |Z_L| \tag{1.3}$$

Combining equations (1.2) and (1.3), we obtain

$$1 < \left|\frac{Z_L}{Z_S}\right| < \left|\frac{Z_{EMP}}{Z_S}\right| < \left|\frac{Z_D}{Z_S}\right| \tag{1.4}$$

This relationship shows that the impedance mismatch for EMP fields is bounded above by the mismatch for dipole fields and below by the mismatch for loop fields which is, in turn, greater than 1. It follows that the shielding effectiveness of the enclosure against fields produced by these three sources will be ordered in exactly the same way, and we conclude that tests carried out in the manner prescribed by MIL-STD-285 using dipole and loop antennas will give best- and worst-case estimates of the EMP shielding effectiveness.

Calculations described in sections 3 and 4 show that the difference between SE for a dipole source and SE for a loop source is usually quite large when sources are placed very close to the shield in the manner prescribed by MIL-STD-285. Differences of more than 200 dB are typical at the lower frequencies, and it is to be expected that shielding of the dipole field will often exceed the sensitivity of the receiver. In view of this, it would appear that the spread between upper and lower bounds provided by MIL-STD-285 measurements will be too great to yield accurate estimates of EMP-shielding effectiveness. Of course, worst-case estimates obtained from loop measurements will always err on the safe side. However, these estimates will be unnecessarily conservative in most cases. Calculations in sections 3 and 4 for typical enclosures show that SE can be up to 100 dB greater against EMP fields (considered as plane waves originating at infinity) than against loop fields. A more accurate estimate of EMP-shielding effectiveness is clearly needed. This could be obtained physically by moving the antennas far enough from the enclosure so that $Z_L \approx Z_D \approx Z_{EMP} \approx 377\Omega$. However, this procedure is not practical at

the lower frequencies, and, in any case, most of the operational advantages of MIL-STD-285 would be lost if it were attempted. Fortunately, such a procedure is not necessary, and much more accurate estimates of EMP shielding effectiveness can be obtained by analytically adjusting loop and dipole measurements. These adjustments are based on the following functional relationships between loop-shielding effectiveness, SE_L, dipole-shielding effectiveness, SE_D, and EMP-shielding effectiveness, SE_{EMP}:

$$\delta = SE_{EMP} - SE_L = 20 \log \left| \frac{Z_{EMP}}{Z_L} \right|$$
$$\delta = SE_D - SE_{EMP} = -20 \log \left| \frac{Z_{EMP}}{Z_D} \right| \qquad (1.5)$$

which are obtained in section 5. According to equation (1.5), the difference between EMP-shielding effectiveness and loop-(dipole) shielding effectiveness depends only on the mismatch between EMP- and loop- (dipole) wave impedances and not on the enclosure. Since Z_{EMP}, Z_L, and Z_D are known, these differences are easily calculated as functions of frequency. The resulting curve (fig 9) provides a means of adjusting MIL-STD-285 measurements to give estimates of EMP-shielding effectiveness. One need only add δ to the loop measurements and subtract δ from the dipole measurements. In this way two independent estimates of SE_{EMP} can be obtained at every frequency where both loop and dipole measurements are made.

2. WAVE IMPEDANCES OF SMALL LOOP AND DIPOLE ANTENNAS

MIL-STD-285 specifies a 12-in.-diameter loop antenna and a 41-in. monopole antenna with a conducting counterpoise. At the frequencies of interest, sources with these dimensions will be small compared to the radiated wavelength, λ, and, consequently, they may be regarded as elementary loop and dipole sources. The fields of such sources are well known. For an elementary dipole located at the origin of a spherical coordinate system with its current vector aligned parallel to the $\theta = 0$ axis (figure 1), the field components are[3]

$$H_\phi = \frac{I\ell \sin\theta\, e^{-j\beta r}}{4\pi r} \left(j\beta + \frac{1}{r} \right) \qquad (2.1)$$

$$E_\theta = \frac{\eta I\ell \sin\theta\, e^{-j\beta r}}{4\pi r} \left(j\beta + \frac{1}{r} + \frac{1}{j\beta r^2} \right) \qquad (2.2)$$

$$E_r = \frac{\eta I\ell \cos\theta\, e^{-j\beta r}}{2\pi r} \left(\frac{1}{r} + \frac{1}{j\beta r^2} \right) \qquad (2.3)$$

3. Jordan, E. C., Electromagnetic Waves and Radiating Systems, Prentice-Hall, Englewood Cliffs, N. J. (1950).

where η is the free space impedance ($\approx 377\Omega$), I is the current, ℓ is the length of the dipole, and $\beta = 2\pi/\lambda$. Similarly, the fields of an elementary loop antenna located at the origin in the $\theta = \pi/2$ plane of a spherical coordinate system[4]

$$E_\phi = \frac{\eta\beta^2 IA \sin\theta\, e^{-j\beta r}}{4\pi r}\left(1 + \frac{1}{j\beta r}\right) \tag{2.4}$$

$$H_\theta = -\frac{\beta^2 IA \sin\theta\, e^{-j\beta r}}{4\pi r}\left(1 + \frac{1}{j\beta r} - \frac{1}{\beta^2 r^2}\right) \tag{2.5}$$

$$H_r = \frac{j\beta IA \cos\theta\, e^{-j\beta r}}{2\pi r^2}\left(1 + \frac{1}{j\beta r}\right) \tag{2.6}$$

where A is the area of the loop, and all other quantities are as previously defined. These fields appear to bear little similarity to the fields of EMP sources which will be regarded in this study as plane waves originating at infinity and ranging in frequency from 10^2 to 10^8 Hz. There are, however, important similarities that greatly simplify the problem of relating the electromagnetic properties of small loops and dipoles to those of EMP sources. These similarities can be seen by calculating the wave impedances for elementary loops and dipoles using the preceding expressions for the fields. The wave impedance of a source at a field point is defined as the ratio of the electric fields to the magnetic fields in a plane transverse to the radius vector from the source to the field point. The wave impedance of the dipole, Z_D, is then

$$Z_D = \frac{E_\theta}{H_\phi} = \frac{\left(1 + \frac{1}{j\beta r} + \frac{1}{(j\beta r)^2}\right)}{1 + \frac{1}{j\beta r}} = \eta\left(\frac{1 + j\beta r - \beta^2 r^2}{j\beta r - \beta^2 r^2}\right) \tag{2.7}$$

where E_θ and H_ϕ are given by equations (2.1) and (2.2). This expression can be written in complex form as follows:

$$Z_D = R_D + jX_D$$

where:

$$R_D = \frac{\eta\,(\beta r)^2}{1 + (\beta r)^2} \tag{2.8}$$

4. Schelkunoff, S.A. and H.T. Friis, Antennas-Theory and Practice, John Wiley and Sons, N.Y. (1952).

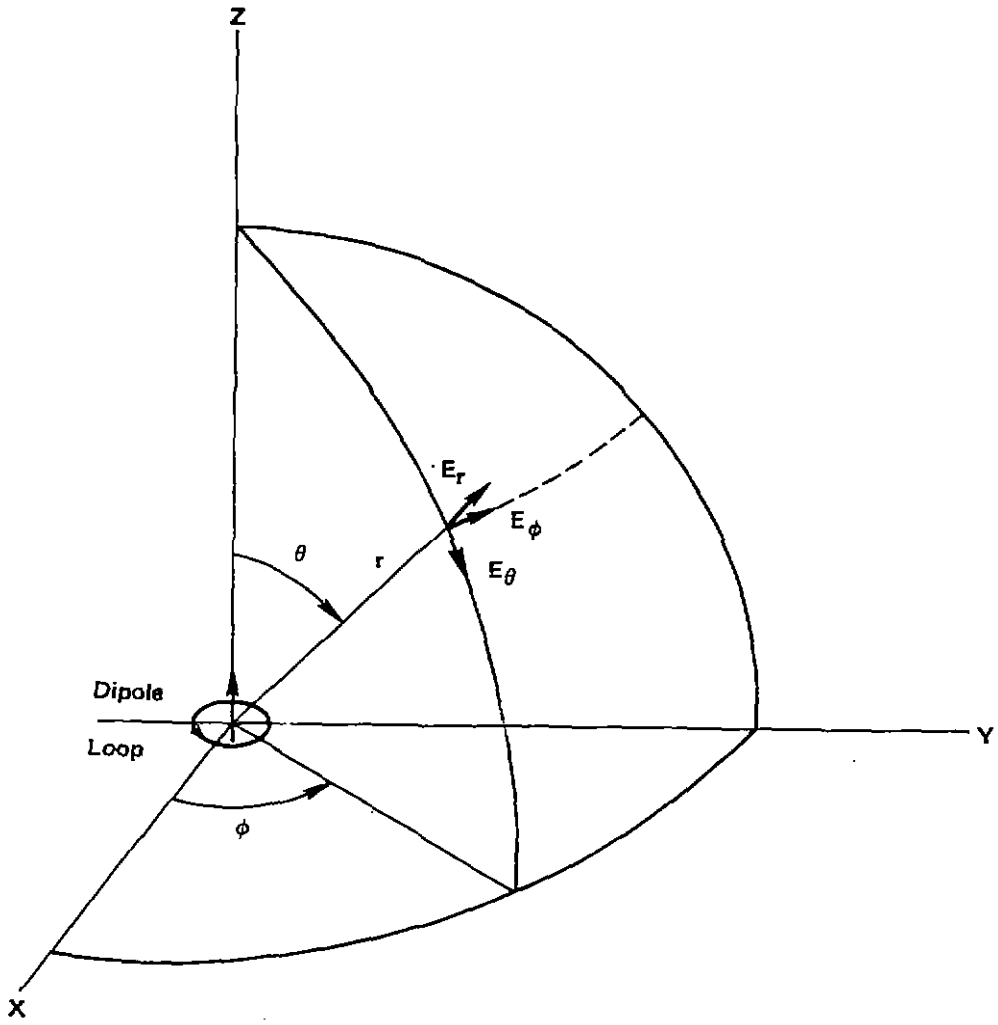

Figure 1. Elementary dipole and loop sources at the origin of a spherical coordinate system.

and

$$X_D = \frac{-\eta}{\beta r[1+(\beta r)^2]} \tag{2.9}$$

are the resistance and reactance, respectively. For a loop, the wave impedance, Z_L, is

$$Z_L = \frac{E_\phi}{H_\theta} = \eta \left(\frac{j\beta r - \beta^2 r^2}{1 + j\beta r - \beta^2 r^2} \right) \tag{2.10}$$

with E_ϕ and H_θ given by equations (2.4) and (2.5). In terms of resistance and reactance, equation (2.10) becomes

$$Z_L = R_L + jX_L$$

where:

$$R_L = \frac{\eta (\beta r)^4}{1 - (\beta r)^2 + (\beta r)^4} \tag{2.11}$$

$$X_L = \frac{\eta \beta r}{1 - (\beta r)^2 + (\beta r)^4} \tag{2.12}$$

Figure 2 is a plot of $|Z_L|$ and $|Z_D|$ as functions of frequency for r = 12 in. which is the distance between source and shield specified by MIL-STD-285. The line through 377Ω represents the expected wave impedance of EMP fields. We note that

$$|Z_L| < Z_{EMP} \approx 377\Omega < |Z_D| \tag{2.13}$$

for all frequencies of interest. Thus, the sources used in MIL-STD-285 provide upper and lower bounds for the wave impedance of EMP sources. We also note that the difference between the upper and lower bounds decreases as the frequency increases. This is to be expected since equations (2.7) and (2.10) imply the following:

$$\lim_{r\to\infty} Z_D = \lim_{\beta\to\infty} Z_D = Z_{EMP} = 377\Omega \tag{2.14}$$

$$\lim_{r\to\infty} Z_L = \lim_{\beta\to\infty} Z_L = Z_{EMP} = 377\Omega \tag{2.15}$$

Thus, Z_{EMP} is a special case of Z_D and Z_L.

The most important similarity between small loop and dipole sources and EMP sources lies in the fact that the wave impedances of all three sources are independent of spatial variations in directions transverse to the radius vector from the source to any field point. That is, Z_{EMP}, Z_D, and Z_L are all independent of the transverse coordinates θ and φ. Z_{EMP} is a constant while Z_D and Z_L are functions of r alone. It was pointed out by Schelkunoff[2] that if a field incident on an electrical discontinuity (such as an EMP shield) has an associated wave impedance which is independent of the transverse coordinates, and if the transmitted field also has an associated wave impedance which is independent of the transverse coordinates, then standard transmission line theory can be applied to compute the reflected and transmitted fields. This fact greatly simplifies the problem of estimating the shielding effectiveness seen by these three sources, and it insures the existence of an analytical relation between SE_D, SE_L, and SE_{EMP}.

2. Schelkunoff, S.A., Electromagnetic Waves, Van Nostrand, Princeton, N.J., p. 251 (1943).

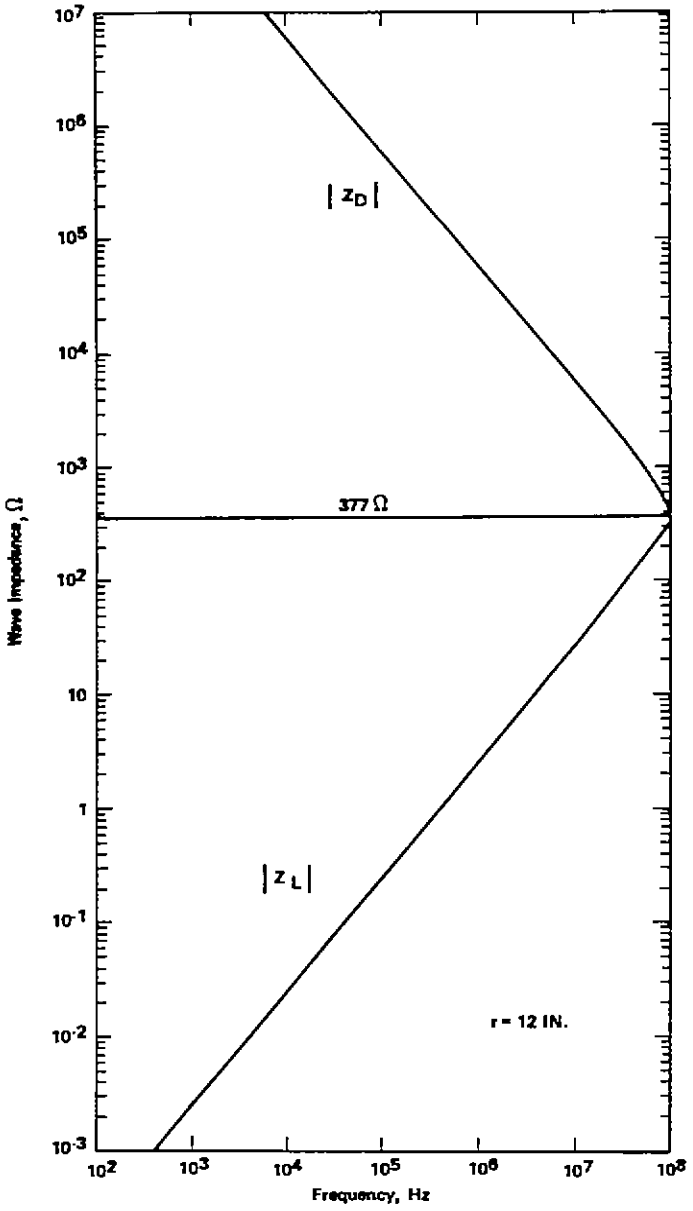

Figure 2. Wave impedances of elementary dipole and loop sources at a distance r = 12 in. plotted as a function of frequency.

3. EFFECTIVENESS OF AN IMPERFECTLY CONDUCTING, CONTINUOUS, METALLIC SHIELD AGAINST EMP AND SMALL LOOP AND DIPOLE FIELDS

An expression for the shielding effectiveness (SE) of a continuous (no holes), imperfectly conducting shield can be written as follows:

$$SE = R + A + B \tag{3.1}$$

where:

$$R = 20 \log \frac{|k+1|^2}{4|k|} \tag{3.2}$$

$$A = 8.686\, \alpha t \tag{3.3}$$

$$B = 20 \log \left| 1 - \frac{(k-1)^2}{(k+1)^2} e^{-2(1+j)\alpha t} \right| \tag{3.4}$$

$$k = \frac{Z_{wave}}{Z_{shield}} \quad \text{(impedance ratio of shield and source)} \tag{3.5}$$

$$\alpha = (\pi \mu \sigma f)^{\frac{1}{2}} \quad \text{(reciprocal of skin depth)} \tag{3.6}$$

$$Z_{shield} = \left(\frac{j 2\pi \mu f}{\sigma} \right)^{\frac{1}{2}} \tag{3.7}$$

f is the frequency, and t, μ, and σ are the thickness, permeability, and conductivity of the shield, respectively. In this expression, R represents losses due to initial reflections, A is the loss due to attenuation of the field in penetrating the shield once, and B accounts for losses due to reflections which are not contained in R. Equation (3.1) was obtained by Schelkunoff[2] from his transmission line theory of shielding and applied by him to the problem of shielding parallel current filaments with surrounding cylindrical conductors. However, equation (3.1) is not limited to this application; it is actually applicable to many other combinations of sources and shields. For example, experimental and theoretical studies[5,6,7] have shown that equation (3.1) correctly describes the shielding of a small loop antenna by a conducting plane. One need only insert the loop wave impedance [equation (2.10)] into the numerator of the impedance ratio, equation (3.5). In the preceding section it was noted that transmission line theory should be applicable whenever wave impedances of the fields incident and transmitted through a shield are independent of spatial variations transverse to the direction of propagation. It is not surprising then that equation (3.1) can be applied for incident fields produced by loop sources since, as was seen, the wave

2. Schelkunoff, S.A., Electromagnetic Waves, Van Nostrand, Princeton, N.J. (1943).
5. Moser, J.R., IEEE Trans. EMC, Vol. EMC-9, p. 6 (1967).
6. Ryan, C.M., IEEE Trans. EMC, Vol. EMC-9, p. 83 (1967).
7. Bannister, P.R., USL Report No. 851, U.S. Navy Underwater Sound Laboratory, Fort Trumbull, New London, Conn. (1967).

impedance of a small loop will satisfy this condition to a good approximation. By extension, equation (3.1) should also be applicable to incident fields produced by EMP and small dipole sources. The only adjustment necessary in these cases is to use the appropriate wave impedances for the fields 377Ω for Z_{EMP} and equation (2.7) for Z_D in the numerator of equation (3.5). It is perhaps more surprising that equation (3.1) is applicable, without modification, to shielding calculations for structures as geometrically diverse as cylindrical shells and plane sheets since it is not obvious that the fields transmitted through these shields also satisfy the requirements of transmission line theory. The fact that the structure of fields transmitted by cylindrical and plane shields, as well as most other shields regardless of geometry, does indeed satisfy the requirements of transmission-line theory can be shown with the aid of figure 3. In this figure, S_o is a source (dipole, loop, or EMP) illuminating a metallic shield S_h of unspecified geometry. For convenience we show only the cross section of S_h in the X,Z plane, but it will be understood that S_h is a general three-dimensional metallic shell with a uniform wall thickness t and uniform electrical characteristics μ and σ. It will be further understood that our remarks apply to all points on the shield, not only those which happen to lie on the X,Y plane. The lines r_1, r_2, and r_3 are representative ray paths from the source to points on the shield where the dotted lines N_1, N_2, and N_3 are normals to the surface at those points. Consider the ray r_1 where θ_i is the angle of incidence and θ_r is the angle of refraction. It can be easily shown that for any metallic shield θ_r will always be an extremely small angle at all frequencies of interest and all possible angles of incidence. That is, it can be shown that all rays from S_o entering the shield will do so to a very good approximation along the normal to the surface at the point of entry as indicated for rays r_2 and r_3 in the figure. This can be seen with the aid of the following expression giving θ_r in terms of μ, σ, θ_i, and source frequency F[8]

$$\theta_r = \sin^{-1}\left[\frac{2 \sin \theta_i}{c}\left(\frac{\pi f}{\mu\sigma}\right)^{\frac{1}{2}}\right], \quad c = \text{speed of light} \tag{3.8}$$

From equation (3.8 we note that, for a given shield, the maximum value of θ_r occurs for grazing incidence, where θ_i = 90 deg and sin θ_i = 1, and for the highest frequency of interest, f_{max}. Hence,

$$\max \theta_r = \sin^{-1}\left[\frac{2}{c}\left(\frac{\pi f_{max}}{\mu\sigma}\right)^{\frac{1}{2}}\right] \tag{3.9}$$

Taking the case of a steel shield ($\mu = 400\pi \times 10^{-7}$, H/m, $\sigma = 4 \times 10^6$ mho/m) with $f_{max} = 10^8$ Hz, equation (3.9) gives max $\theta_r = 3 \times 10^{-4}$ deg. This is a very small angle indeed, and it shows that we are completely justified in regarding wave propagation within the metallic shell as being directed along the normal to the surface at any point. Comparable results are obtained with other metals.

8. Kraichman, M.B., Handbook of Electromagnetic Propagation in Conducting Media, U.S. Government Printing Office, Washington, D.C. (1970).

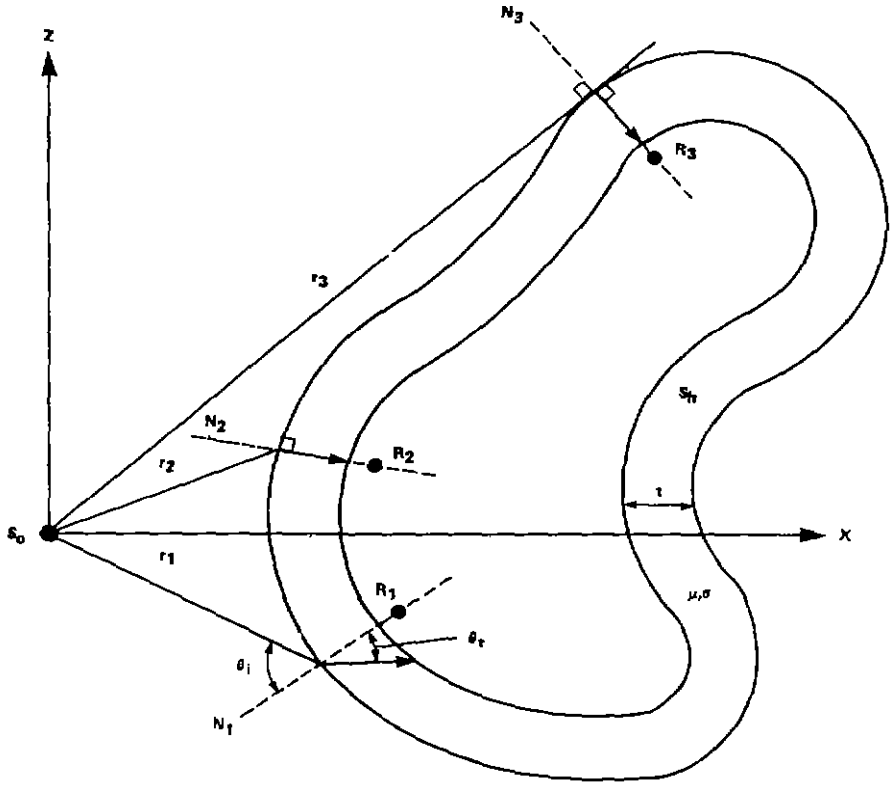

Figure 3. A source S_o illuminating a uniform, continuous, metallic shield S_h.

The preceding has shown that fields propagate into a conductor along the inward normal to the surface. If, in addition, the surface of the shield is such that the following inequality is satisfied,

$$\frac{\lambda_m}{\rho} << 1 \tag{3.10}$$

where λ_m is the wavelength of the field in the conductor, and ρ is the smallest radius of curvature of the shield, then it can also be shown that the Leontovich[9] or impedance boundary condition[8]

$$Z_{shield} = \frac{E_1}{H_1} = \left(\frac{j2\pi\mu f}{\sigma}\right)^{\frac{1}{2}} \tag{3.11}$$

8. Kraichman, M.B., Handbook of Electromagnetic Propagation in Conducting Media, U.S. Government Printing Office, Washington, D.C. (1970).
9. Leontovich, M.A., in Investigation of Propagation of Radio Waves, edited by B.A. Vvedensky, Academy of Sciences, Moscow, U.S.S.R. (1948).

will be satisfied at all points on the surface of the shield. Equation (3.11) is the field impedance normal to the shield at any point, i.e., it is the ratio of the E field to the H field in a plane perpendicular to the normal at any point in the surface. Since we have shown that the direction of propagation is always along the normal, it follows that equation (3.11) is the wave impedance in the direction of propagation in the shell. Equation (3.11) is independent of all spatial variables; hence Z_{shield} in particular is independent of spatial variations transverse to the direction of propagation. We may therefore conclude that the transmission line theory of shielding as represented by equation (3.1) is indeed applicable to continuous metallic shells of any geometrical form provided only that condition (3.10) is satisfied. Condition (3.10) should not impose a serious limitation on equation (3.1) in most cases. The wavelength in any metal will be quite small even at extremely low frequencies. For example, in steel, $\lambda_m = 1.58$ cm at a frequency of 100 Hz. Most shields have radii of curvature much larger than this.

In the preceding argument we have used the Leontovich boundary condition [equation (3.11)] to show that Schelkunoff's transmission-line theory of shielding, and equation (3.1) in particular, is applicable to uniform, continuous, metallic shields of quite general shape. This argument is further supported by the fact that equation (3.11) is identical to the expression used by Schelkunoff for Z_{shield} [equation (3.7)]. Thus, Schelkunoff's 1943 theory incorporates what later became known as the Leontovich boundary condition. Z_{shield} (referred to hereafter as Z_s) is critical in the application of equation (3.1) because k, the ratio of the incident wave impedance to Z_s, determines the loss due to reflections. Figure 4 is a plot of $|Z_s|$ as a function of frequency for a representative group of metals. Loop impedance $|Z_L|$ is also shown. Comparing figure 4 with figure 2, we see that

$$|Z_s| << |Z_L| < Z_{EMP} < |Z_D| \tag{3.13}$$

for all frequencies of interest. From equation (3.13) it is clear that the impedance mismatch is ordered as follows:

$$1 << \frac{|Z_L|}{|Z_s|} < \frac{Z_{EMP}}{|Z_s|} < \frac{|Z_D|}{|Z_s|} \tag{3.14}$$

and we would expect the effectiveness of any metallic shield to be ordered in the same way,

$$SE_L < SE_{EMP} < SE_D \tag{3.15}$$

for loop, dipole, and EMP sources. This expectation is realized in figure 5, which is a plot of equation (3.1) for a copper shield 0.001-m thick.

4. EFFECTIVENESS OF A PERFECTLY CONDUCTING SLOTTED SHIELD

In the preceding section we applied the transmission line theory of shielding to the problem of calculating the shielding effectiveness of a continuous, imperfectly conducting shield. The word

continuous in this context means that no holes or other imperfections are permitted in the shield. It is a difficult task to build a shield in which continuity is achieved to a degree actually approximating that assumed in the theory, and most existing shields fail to satisfy

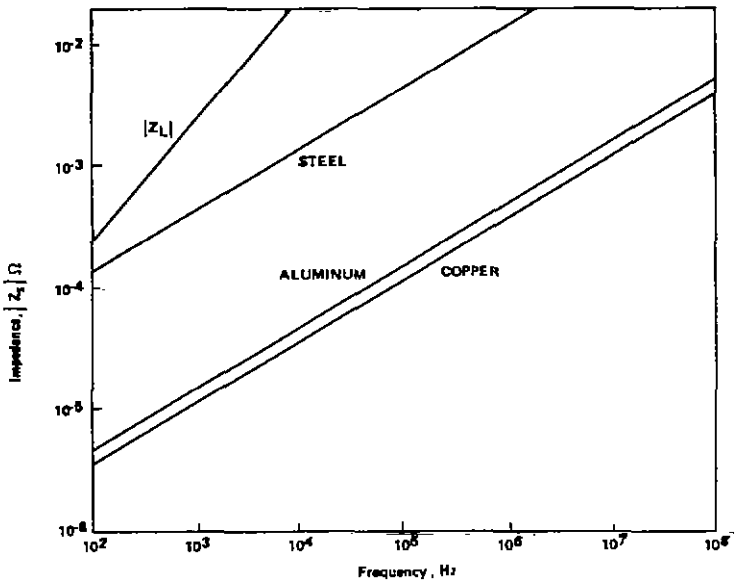

Figure 4. Shield impedance $|Z_s|$ (equation (3.7)) for copper, aluminum, and steel and the loop wave impedance $|Z_L|$ (r = 12 in. plotted as functions of frequency.

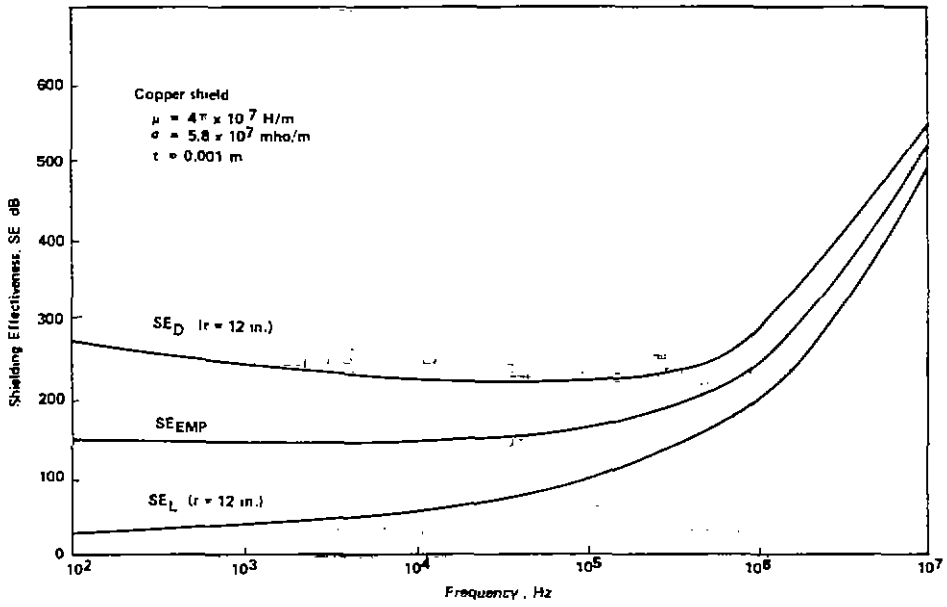

Figure 5. Shielding effectiveness of a copper shield 0.001 m thick computed with Equation (3.1) for loop, dipole, and EMP sources.

this condition in some respects. We must therefore consider the effect of discontinuities on the shielding effectiveness of such structures when illuminated by loop, dipole, and EMP sources. In this section we will not attempt to discuss all the various discontinuities which might be present in a shield; rather, we will consider only a representative type, namely, the narrow slot - where by narrow we mean that the width of the slot is much shorter than its length and also very much shorter than the free space wavelength of the source field. According to Jarva[10], "the slot is representative of the greatest number of flaws that are found in shielded enclosures." It is a working approximation to the type of seams and joints often used in constructing these structures.

Consider an electromagnetic source S_o illuminating a slotted, perfectly conducting surface as indicated in figure 6, where L is one-half the length of the slot and a is one-half the width. For a narrow slot, where:

$$L >> a$$
$$\lambda = \frac{c}{f} >> a, \tag{4.1}$$

the illumination will be approximately uniform, and, as in the preceding section, transmission line theory can be used to compute the reflected and transmitted fields.[2] Our expression for the shielding effectiveness due to reflection from the slot is then

$$SE = 20 \log \left|\frac{k+1}{4k}\right|^2 \tag{4.2}$$

Equation (4.2) is identical to equation (3.2) for the shielding effectiveness of a continuous shell due to reflections except that k in equation (4.2) is the ratio of the incident wave impedance to the slot impedance Z_{sl}

$$k = \frac{Z_{wave}}{Z_{sl}} \tag{4.3}$$

rather than the ratio of the incident wave impedance to the shield impedance as defined by equations (3.5) and (3.7).

The slot impedance, like the shield impedance, is independent of all spatial variables; but, unlike the latter, it is strongly dependent on the polarization of the incident field. Maximum response is achieved when the incident field is aligned with its E field transverse to the slot as indicated in figure 6. In this case, the slot impedance is related to the driving point impedance, Z_{cd}, of the complementary dipole as follows:

2. Schelkunoff, S.A., Electromagnetic Waves, Van Nostrand, Princeton, N.J., p. 247 (1943).
10. Jarva, W., IEEE Trans. EMC, Vol. EMC-12, p. 12 (1970).

$$Z_{sl} = \frac{\eta^2}{4Z_{cd}} = \frac{\eta^2}{4}\left(\frac{R_{cd} - jx_{cd}}{R_{cd}^2 + x_{cd}^2}\right) \tag{4.4}$$

where R_{cd} and X_{cd} are the real and imaginary parts of Z_{cd}.[11] The complementary dipole may be taken as a cylindrical dipole of radius a and length 2L. Approximate expressions for the real and imaginary parts of the driving point impedance for a cylindrical dipole are given by Jordan.[3] From these, we have the following expressions for R_{cd} and X_{cd}:

$$R_{cd} = \frac{Z_o}{2}\left(\frac{\sin h\ (2\gamma)}{\cos h^2\ (\gamma) - \cos^2\ (\beta L)}\right) \tag{4.5}$$

$$X_{cd} = \frac{Z_o}{2}\left(\frac{-\sin\ (2\beta L)}{\cos h^2\ (\gamma) - \cos^2\ (\beta L)}\right) \tag{4.6}$$

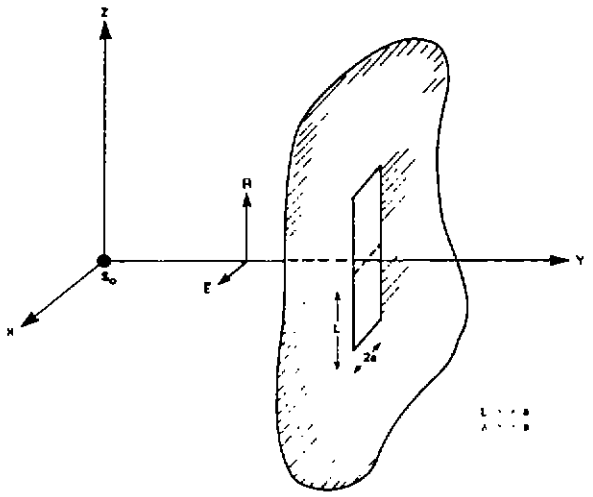

Figure 6. A source S_o illuminating a narrow rectangular slot with $\vec{E}$ parallel to the width of the slot.

3. Jordan, E.C., Electromagnetic Waves and Radiating Systems, Prentice-Hall, Englewood Cliffs, N.J., p. 468 (1950).
11. Krauss, J.D., Antennas, McGraw-Hill, N.Y., p. 369 (1950).

where:

$$Z_o = 120 \left[\ln\left(\frac{L}{a}\right) - 1 - \tfrac{1}{2}\ln\left(\frac{2L}{\lambda}\right)\right] \tag{4.7}$$

$$\gamma = \frac{2\,R_{ad}}{Z_o} \tag{4.8}$$

$$R_{ad} = 15 \Big\{ \left[2+2\cos(2\beta L)\right] S_1(2\beta L) - \cos(2\beta L)\, S_1(4\beta L) - 2\sin(2\beta L) S_i(2\beta L) + \sin(2\beta L) S_i(4\beta L) \Big\} \tag{4.9}$$

and all other quantities are as previously defined except S_1 and S_i which are defined as follows:

$$S_1(x) = \int_0^x \frac{1-\cos(s)}{s}\, ds \; ; \; S_i(x) = \int_0^x \frac{\sin(s)}{s}\, ds \tag{4.10}$$

Figure 7 is a plot of $|Z_{sl}|$ versus frequency for a typical group of slots. From the figure we note that $|Z_{sl}|$, like the magnitude of the shield impedance, is bounded by $|Z_L|$. That is,

$$|Z_{sl}| << |Z_L| \tag{4.11}$$

As in the preceding section, the impedance mismatch will be ordered in the following way,

$$1 << \left|\frac{Z_L}{Z_{sl}}\right| < \frac{Z_{EMP}}{|Z_{sl}|} < \left|\frac{Z_D}{Z_{sl}}\right| \tag{4.12}$$

and similarly, the shielding effectiveness

$$SE_L < SE_{EMP} < SE_D \tag{4.13}$$

Figure 8 is a plot of SE_D, SE_{EMP}, and SE_L computed with equation (4.2) for a slot 0.01-m long and 0.00001-m wide. This shows that SE_D and SE_{EMP} are decreasing functions of frequency while SE_L is nearly independent of frequency. The latter is a reflection of the fact that $|Z_L|/|Z_{sl}|$ is nearly constant over the whole range of frequencies as can be seen in figure 7. The severe effect of even a small opening on the high frequency performance of an EMP shield is obvious in a comparison of figures 5 and 8. According to figure 5, SE_{EMP} for a continuous copper shield 0.001-m thick is 525 dB at a frequency of 10^7Hz. Figure 8 indicates that the same shield with a

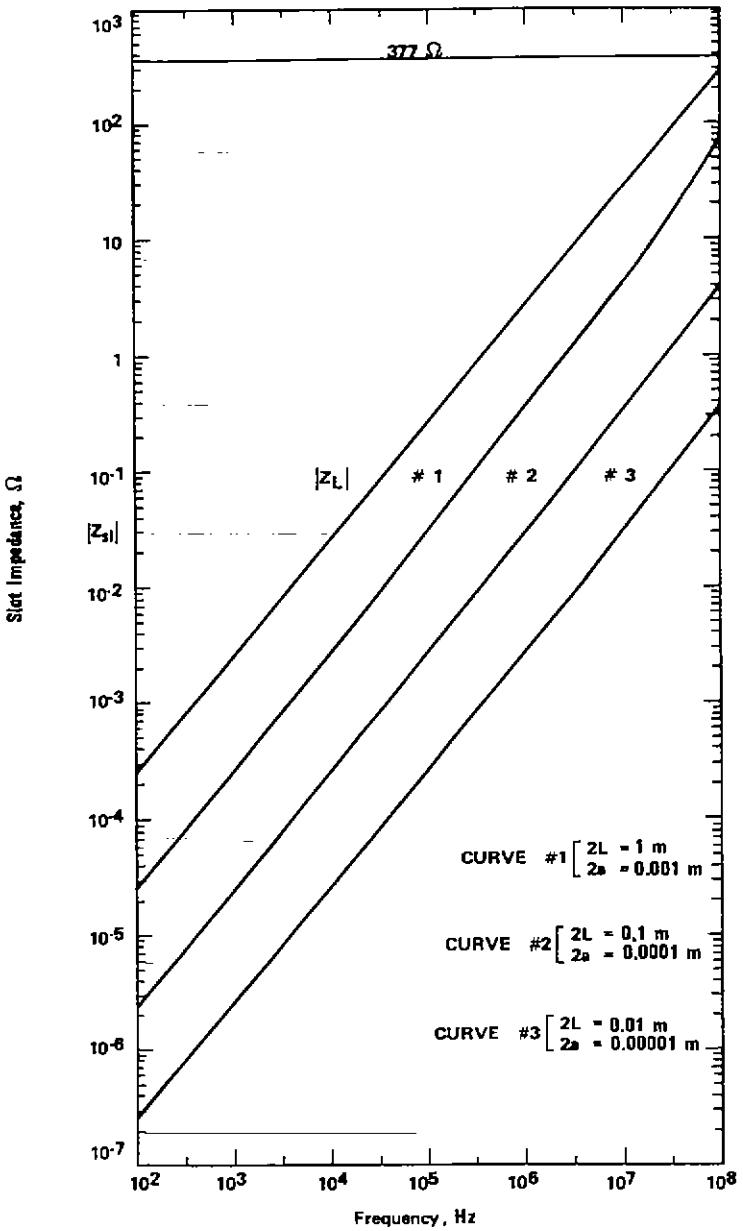

Figure 7. Slot impedance $|Z_{sl}|$ for long (#1), medium (#2), and short (#3) slots together with $|Z_L|$ versus frequency.

1-cm slot will provide 70 db of shielding against an EMP field at 10^7Hz - a loss in shielding effectiveness of 455 dB!

5. A METHOD FOR ESTIMATING EMP SHIELDING EFFECTIVENESS USING MIL-STD 285 MEASUREMENTS

The preceding sections have shown that the computed shielding effectiveness of typical metallic enclosures for small, close-in dipole and loop sources gives upper and lower bounds for EMP (plane wave) shielding effectiveness at all frequencies of interest. This result depends basically on the general relationships between shield impedance and loop, dipole, and EMP wave impedances contained in equations (2.13), (3.13), and (4.11). These relationships are insensitive to variations in design and composition (provided metal is the primary material), and they are, therefore, likely to be satisfied by actual shields when illuminated with actual sources. From this, we can reasonably conclude that shielding measurements carried out in accordance with MIL-STD-285 using dipole and loop sources at a distance of 12 in. from the shield will give best and worst case estimates of the EMP shielding effectiveness of the structure. However, figures 5 and 8 show that the difference between the upper and lower bounds obtained in this manner is likely to be so great, particularly at low frequencies, that these measurements alone will not give one an accurate estimate of SE_{EMP}. To obtain accurate EMP shielding estimates from MIL-STD-285 measurements, a general expression relating SE_L, SE_D, and SE_{EMP} is needed. Such a relationship, for instance, $SE_{EMP} = F(SE_L, SE_D)$, can be used to obtain estimated values of SE_{EMP}

$$SE_{EMP}^{(estimated)} = F\left(SE_L^{(measured)}, SE_D^{(measured)}\right) \tag{5.1}$$

using measured values of SE_L and SE_D. That such a relationship does indeed exist can be seen with the aid of figures 5 and 8. Direct measurement from the curves in these figures reveals that

$$SE_D - SE_{EMP} = SE_{EMP} - SE_L = \delta(f) \tag{5.2}$$

where $\delta(f)$ is the same function of frequency for both continuous (figure 5) and slotted (figure 8) shields, that is, $\delta(f)$ is independent of the shield. From equation (5.2) we immediately obtain one form of equation (5.1), namely

$$SE_{EMP}^{(estimated)} = \tfrac{1}{2}\left(SE_L^{(measured)} + SE_D^{(measured)}\right) \tag{5.3}$$

Hence, SE_{EMP} can be estimated for any shield by taking the arithmetic average of the loop and dipole measurements. The usefulness of equation (5.3) is limited by the fact that, in general, both SE_L and SE_D will not be measured at all frequencies of interest. As mentioned previously, the shielding of the dipole field will often exceed the sensitivity of the receiver. What is needed then is a relationship involving only SE_{EMP} and SE_L.

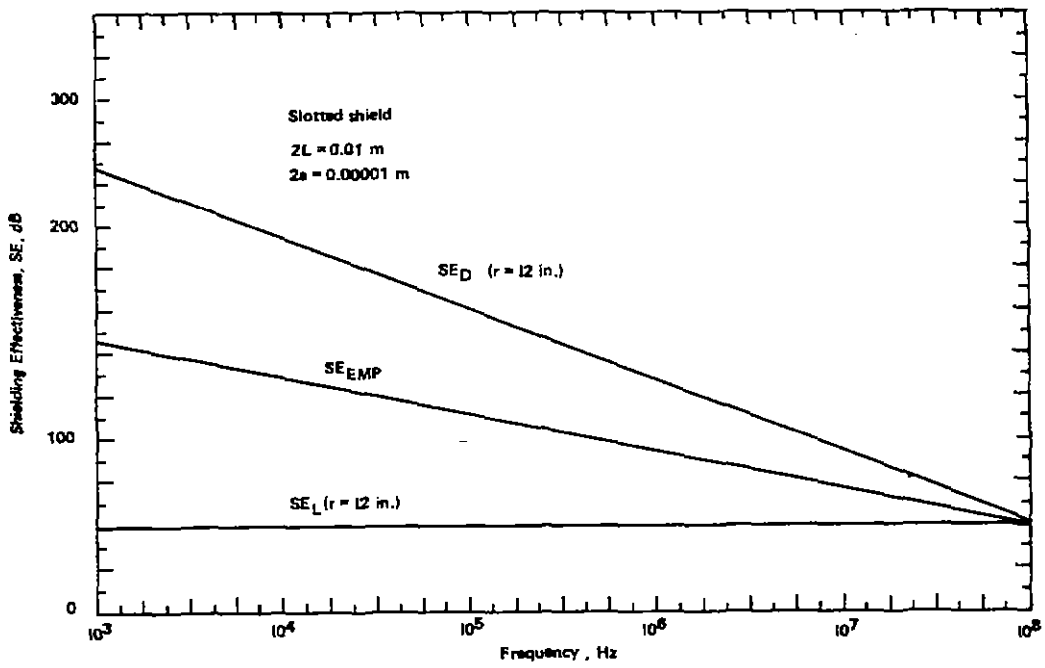

Figure 8. Shielding effectiveness of a perfectly conducting shield with a rectangular slot 0.01 m long and 0.00001 m wide computed with equation (4.2) for loop dipole, and EMP sources.

Following the lead provided by equation (5.2), we form the difference $SE_{EMP} - SE_L$ and attempt to evaluate $\delta(f)$ using equation (3.1). We obtain

$$\delta = SE_{EMP} - SE_L = 20 \log\left(\frac{|k_{EMP}+1|^2 4|k_L|}{4|k_{EMP}|\,|k_L+1|^2}\right)$$

$$+ 20 \log \left[\frac{\left|1 - \left(\frac{k_{EMP}-1}{k_{EMP}+1}\right)^2 e^{-2(1+j)\alpha t}\right|}{\left|1 - \left(\frac{k_L-1}{k_L+1}\right)^2 e^{-2(1+j)\alpha t}\right|}\right] \qquad (5.4)$$

where:

$$k_{EMP} = \frac{Z_{EMP}}{Z_s} \qquad (5.5)$$

$$k_L = \frac{Z_L}{Z_s} \qquad (5.6)$$

From equation (3.13) we have

$$|k_{EMP}| >> 1 \tag{5.7}$$

$$|k_L| >> 1 \tag{5.8}$$

Hence, $|k_{EMP} \pm 1| \cong |k_{EMP}|$ and $|k_L \pm 1| \cong |k_L|$, and equation (5.4) reduces to

$$\delta = 20 \log \left(\frac{|k_{EMP}|}{|k_L|} \right) + 20 \log \left(\frac{|1-e^{-2(1+j)\alpha t}|}{|1-e^{-2(1+j)\alpha t}|} \right)$$

or

$$\delta = 20 \log \left(\frac{|Z_{EMP}|}{|Z_L|} \right) \tag{5.9}$$

As expected, δ is independent of the shield; it depends only on the impedance mismatch between loop and EMP, and, in general, it will be a function of distance and frequency. The reader can easily verify that the same expression is obtained for a slotted shield by starting with equation (4.2) and using equation (4.11). Following similar arguments, it can be shown that

$$SE_D - SE_{EMP} = -20 \log \left(\frac{|Z_{EMP}|}{|Z_D|} \right) \tag{5.10}$$

for both continuous and slotted shields. Furthermore, since $Z_{EMP} = \eta \simeq 377\Omega$, it can be shown using equation (2.7) and equation (2.10) that

$$-20 \log \left(\frac{Z_{EMP}}{|Z_D|} \right) = 20 \log \left(\frac{Z_{EMP}}{|Z_L|} \right) \tag{5.11}$$

Hence, equation (5.10) can be combined with equation (5.9) in a single statement

$$\begin{aligned} \delta = S_{EMP} - SE_L &= 20 \log \left(\frac{Z_{EMP}}{|Z_L|} \right) \\ &= SE_D - SE_{EMP} = -20 \log \left(\frac{Z_{EMP}}{|Z_D|} \right) \end{aligned} \tag{5.12}$$

thus verifying the correctness of equation (5.2).

Since Z_{EMP}, Z_L, and Z_D are known, δ can be computed explicitly from equation (5.12) using either the combination of Z_{EMP} and Z_L or Z_{EMP} and Z_D. Figure 9 is a plot of δ as a function of frequency at the MIL-STD-285 source distance of 12 in. Thus, in addition to equation (5.3), we may use

$$SE_{EMP}^{(estimated)} = SE_L^{(measured)} + \delta \qquad (5.13)$$

or

$$SE_{EMP}^{(estimated)} = SE_D^{(measured)} - \delta \qquad (5.14)$$

to provide independent estimates of EMP shielding on the basis of MIL-STD-285 measurements.

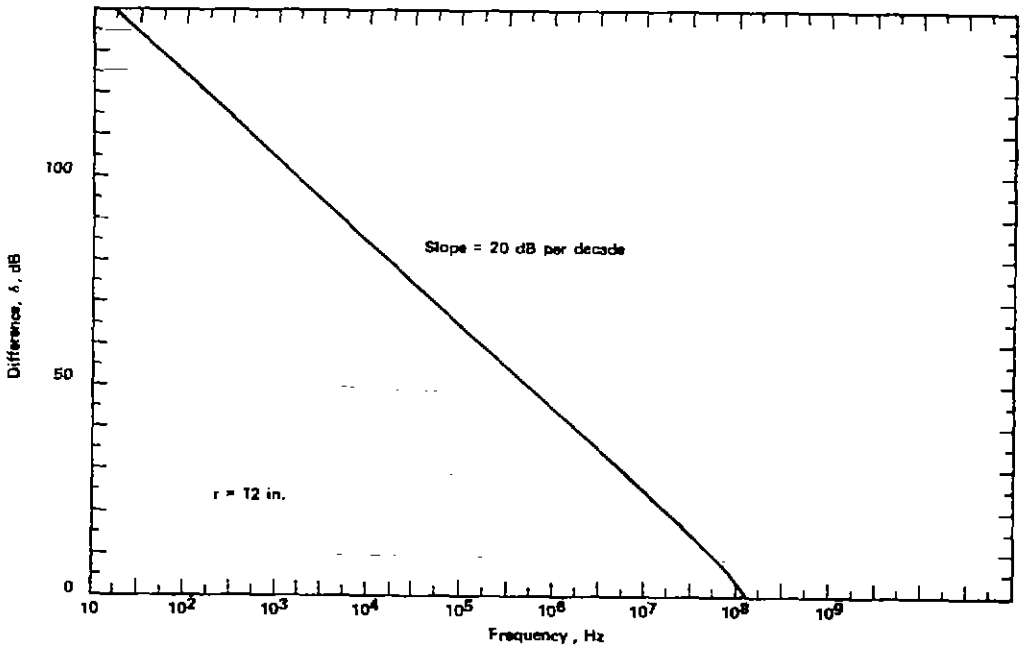

Figure 9. The difference δ between shielding effectiveness measured with a plane wave source and shielding effectiveness measured with a small loop (or dipole) source located at a distance r = 12 in. from the shield.

6. DISCUSSION

MIL-STD-285 specifies that shielding measurements shall be made on all sides of the enclosure with special attention to utility entrances, doors, and access panels and that the minimum attenuation, i.e., shielding effectiveness, shall be recorded. It further specifies that the source and receiver antennas shall be located 12 in. from the outer and inner surfaces of the shield, respectively, and that the relative position of source and receiver shall remain fixed

during the measurements. If these procedures are followed rigorously, there should be no difficulty in using the results of the preceding section to obtain conservative, but accurate, estimates of the EMP shielding effectiveness of the enclosure.

By making measurements at various locations and noting the minimum shielding effectiveness, the principal point-of-entry, if any, will be located and a conservative figure will be assigned to the shielding effectiveness of the enclosure as a whole. Fixing the relative positions of source and receiver makes certain that the wave impedance at the surface of shield will not change from one measurement to the next and thereby helps to insure that, when antennas are moved to a new location, any major change in shielding effectiveness is due to a change in the shield and not in the wave impedance of the source. Figure 10 is a schematic representation of a series of shielding measurements carried out in accordance with MIL-STD-285 for an enclosure with a single principal point-of-entry (PPE) consisting of some type of narrow aperture. As measurements are made with loop antennas at locations S_1R_1, S_2R_2, ..., S_n R_n (where S_1 is the source location for the first measurement, R_1 is the corresponding receiver location, and S_2 R_2, S_3 R_3, ..., S_n R_n are similarly defined for the second, third, and nth measurement) it will be noted that the measured shielding effectiveness decreases as PPE is approached and reaches a minimum in the immediate vicinity of the aperture (S_4 R_4). This minimum value is a worst-case estimate of the shielding effectiveness against close-in loop sources; and when adjusted by addition of δ from figure 9, it is a conservative estimate of the EMP shielding effectiveness of the enclosure as a whole. If there is no one principal point-of-entry or, as is more likely, if there are many points of entry, then the shielding effectiveness will change relatively little (~10-12 dB at most) as the antennas are moved along the shield. The average measured value then can be used along with δ to provide an accurate estimate of the EMP shielding effectiveness of the enclosure.

For a variety of reasons, it may not always be possible or practical to adhere strictly to the procedures of MIL-STD-285. In particular, it may not be possible to maintain the antennas in fixed relative positions at all times. A situation that may arise is illustrated in figure 11. Here the source S_o remains in a fixed position relative to the shield, but the receiver is moved successively to positions R_1, R_2, R_3, ..., R_n within the enclosure. In this case, the minimum or average measured shielding effectiveness can still be used to estimate the EMP shielding effectiveness of the enclosure; however, it must be recognized that the wave impedance from source to receiver will not be constant as before, but will change as a function of the distance r_1, r_2, ..., r_n. The resulting variation in impedance mismatch will cause changes in measured shielding effectiveness as the receiver is moved from R_1 to R_2, etc. These changes can be very important. Figure 12 is an extension of figure 2, showing the magnitudes of loop and dipole wave impedances at various distances as functions of frequency. According to this figure, $|Z_L|$ at a frequency of 10^6 Hz increases from 2.6 to 26Ω as the distance, r, changes from 1 to 10 ft. Since a tenfold change in wave impedance can result in a 20 dB-or-more change in shielding effectiveness, it is clear that changes in distance between source and receiver must be accounted for when estimating EMP shielding effectiveness from measured values of EMP shielding effectiveness. That is, the

correction factor δ must now be regarded as a function of both frequency and distance. One way to do this is to extend figure 9 in the same way that figure 2 was extended in figure 12 by including a family of curves corresponding to various values of r. This has been done in figure 13 for r ranging from 0.1 to 10^5 ft. An appropriate value of δ for every combination of range and frequency likely to be encountered in practice can be obtained by interpolating between the curves on this figure.

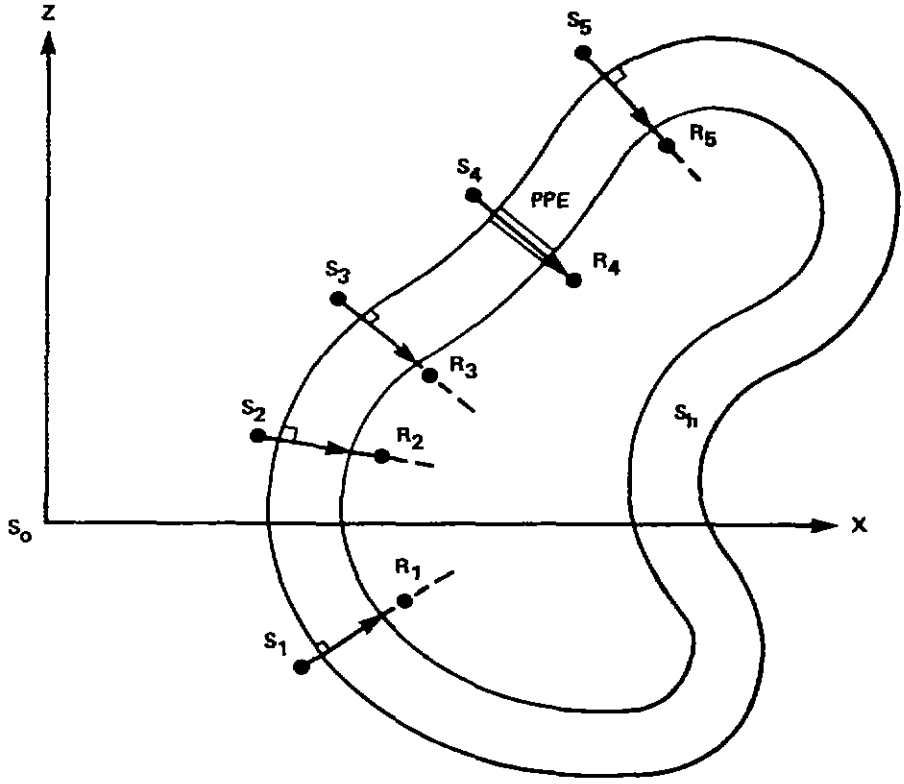

Figure 10. Schematic representation of a series of MIL-STD 285 measurements for an enclosure with a single principal point-of-entry (PPE).

It will be noted that the curves in figure 13 exhibit a curious undershoot as δ approaches zero when the frequency becomes sufficiently high. That is, δ crosses the 0 dB axis and approaches zero asymptotically from the negative side of the axis. This reflects the fact, shown in figure 12, that $|Z_L|$ overshoots 377Ω before approaching the free space wave impedance from above. Similarly, $|Z_D|$ undershoots 377Ω and approaches it from below. The maximum overshoot (and undershoot) is about 150Ω. This effect is real in so far as equations (2.7) and (2.10) are concerned, but one might well doubt that it will be seen with real antennas. In any case, the effect on δ will be small; a maximum 150Ω overshoot in $|Z_L|$ translates into a maximum 3 dB undershoot for δ. For most purposes, one may regard δ as zero beyond the cross-over point without serious loss in accuracy.

Greater accuracy, if desired, can be obtained by increasing the number of curves in the figure. Alternatively, one may prepare a table of correction factors computed for closely-spaced values of r at certain selected frequencies. To apply these curves, r must be known. That is, it must be measured in the field at each location where shielding measurements are made. This is the operational price that must be paid when the relative positions of source and receiver are not fixed during a series of measurements.

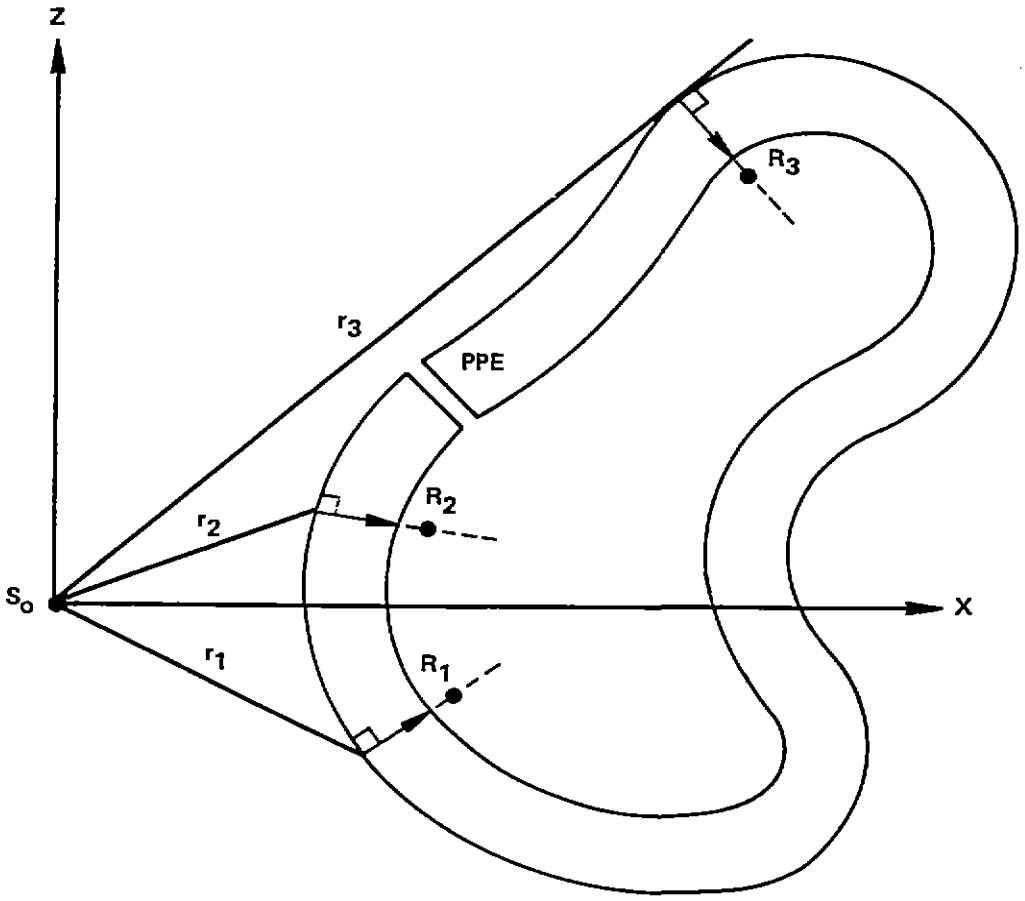

Figure 11. A fixed source S_o illuminating an enclosure with receivers located at various points R_1, R_2, R_3.

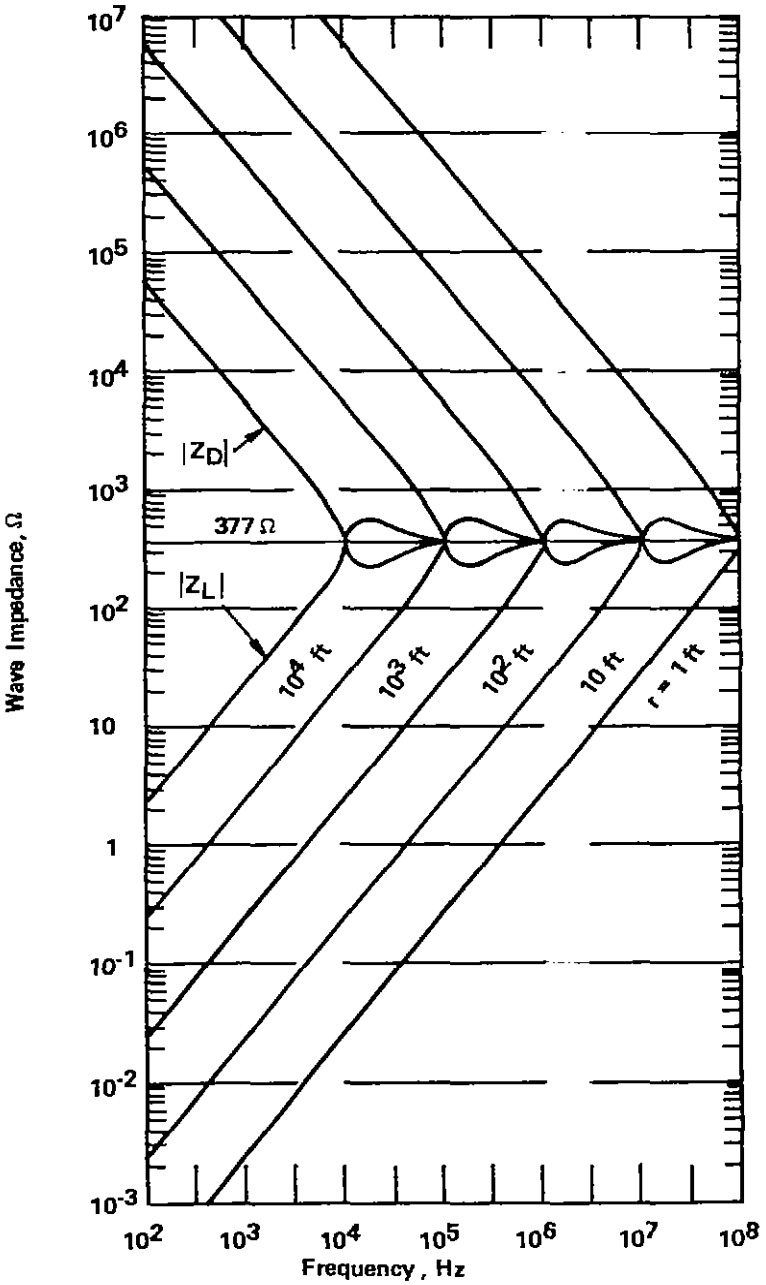

Figure 12. Wave impedances of elementary dipole and loop sources.

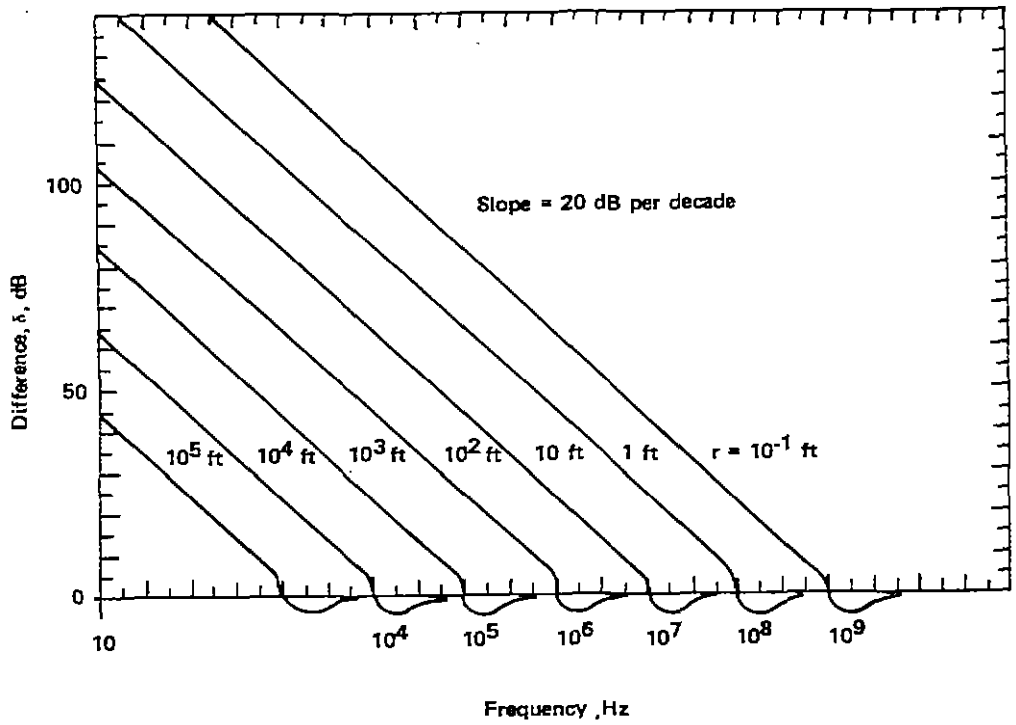

Figure 13. The difference δ between EMP (plane wave) shielding effectiveness and shielding effectiveness measured with a small loop (or dipole) located at various distances from the shield.

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