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Input Impedance of a Probe Antenna Exciting a TEM Cell

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Input Impedance of a Probe Antenna Exciting a TEM Cell

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FOREWORD

This report describes theoretical and experimental analyses developed by staff of the University of Colorado at Boulder in collaboration with the Electromagnetic Fields Division of the National Bureau of Standards (NBS), under a contract sponsored by NBS. Professor David C. Chang heads the University team. Dr. Mark T. Ma of NBS serves as the technical contract monitor. The period covered by this report extends from July 1980 to July 1981.

The work presented in this report represents a further aspect of establishing a theoretical basis for the technical analyses of transverse electromagnetic (TEM) transmission line cells. The general purpose of pursuing theoretical studies is to evaluate the use of TEM cells for (1) measuring the total rf radiated power by a device inserted into the cell for test, or (2) performing necessary susceptibility tests on a small electronic device.

The particular topic addressed herein is to determine the input impedance of a probe antenna which may be inserted into a TEM cell to measure or excite fields. The formulation of the problem is based on a variational principle, which insures that the input impedance so obtained is stationary for small arbitrary variations in the probe current distribution about its true value. The evaluation of the variational integral requires a knowledge of the field distribution inside the cell excited by a vertical short electric dipole. This latter problem was the subject of a previous report by the same authors [4], the results of which are readily adapted to the present problem. Thus, the input impedance treated in this report represents an extension to the previous studies.

The analysis of the present problem is significantly simplified by assuming that the gap between the inner septum and the outer walls of the cell is electrically small, and that the operating frequency is such that no higher order modes are excited inside the cell. These assumptions are consistent with the practical cell utilization and design principle.

The final impedance expression is shown to consist of two distinct terms, which can be clearly identified as the respective contributions by the ordinary rectangular waveguide and the gap perturbation.

Previous publications under the same effort include:

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Tippet, J. C., Chang, D. C., and Crawford, M. L., An analytical and experimental determination of the cut-off frequencies of higher-order TE modes in a TEM cell, NBSIR 76-841 (June 1976).

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Sreenivasiah, I. and Chang, D. C., A variational expression for the scattering matrix of a coaxial line step discontinuity and its application to an over moded coaxial TEM cell, NBSIR 79-1606 (May 1979).

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INPUT IMPEDANCE OF A PROBE ANTENNA EXCITING A TEM CELL

P. F. Wilson, D. C. Chang and M. T. Ma

The input impedance of a probe antenna exciting a transverse electromagnetic (TEM) transmission line cell is formulated by a variational approach. The formulation also utilizes the results from a previous work on the field distribution inside a TEM cell excited by a vertical electrical Hertzian dipole. The final result of impedance is shown to consist of two distinct terms, which are respectively contributed by the ordinary rectangular waveguide and the gap perturbation. Numerical results for both the real and imaginary parts of the impedance are given. The resistive part is found to be proportional to the square of the probe length, and the reactive part largely capacitive.

Key words: Green's function; input impedance; probe antenna; radiation resistance; rectangular coaxial transmission line; TEM cell; variational method.

1. INTRODUCTION

The National Bureau of Standards (NBS) has been interested in developing a method for testing the emission and susceptibility properties of electronic equipment. One approach to this problem is the transverse electromagnetic (TEM) transmission line cell. The TEM cell, shown in figure 1, consists of a section of rectangular coaxial tramission line (RCTL) coupled at each end to standard 50Ω cylindrical coaxial line via a tapered section. The RCTL section supports a dominant TEM mode and provides an isolated, standard test field environment. The TEM cell results may be related to the free space environment via results given by Tippet [1] and Sreenivasiah [2].

This report concerns the manner in which an idealized coaxial probe excites an infinite section of RCTL. The results may be used to study the effect of coaxial probes inserted into the TEM cell either to excite, or to measure fields. In addition, the configuration studied may be useful in modeling feed lines to electronic equipment. The method of solution is to formulate a variational expression for the input impedance of the probe at the aperture plane, as was done by Collin [3] in analyzing the coaxial probe excitation of a rectangular waveguide. The evaluation of the variational integral requires that the Green's function corresponding to the fields excited in an RCTL by a vertical electric dipole (VED) be known. The VED excitation of an RCTL was the subject of a previous report by the authors [4],

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the results of which will be adapted to the present problem. The analysis of the Green's function is significantly simplified by assuming that the gap between the inner septum and the outer walls, is electrically small, and that the operating frequency is not too large. Both these premises are consistent with the TEM cell usage.

Evaluating the variational impedance integral results in two physically distinct terms, which may be referred to as the ordinary rectangular waveguide contribution, and the gap perturbation contribution. The ordinary term gives the input reactance due to a coaxial probe in a rectangular waveguide with the same dimensions as that of the RCTL's upper chamber. Since the dimensions of the cell are such that the rectangular waveguide modes in the upper chamber would be cutoff, the result is a highly capacitive term for which the analysis yields an approximate analytic expression. The gap perturbation term represents the change from the ordinary result due to the presence of the gap fields, and contains the radiation resistance resulting from the dominant TEM mode. The perturbation term, as derived, remains in an integral form which must be treated numerically. However, if the TEM mode radiation resistance is extracted, the remaining reactive integral is negligible when compared to the highly capacitive ordinary contribution. Thus neglecting the perturbation reactance results in a computationally simple algebraic form for the probe input impedance.

Section 2 of this report will define the variational impedance integral to be evaluated and discuss the necessary probe idealizations. The Green's function associated with the VED excitation of an RCTL is examined in Section 3. Section 4 gives the result of the evaluation of the impedance integral and examines the distinct physical nature of the resulting terms. Certain special cases are used to verify the solution. These checks are examined in Section 5 along with numerical results. Many details of the analysis and a listing of the FORTRAN program written to evaluate the impedance terms are left to the Appendices.

2. VARIATIONAL FORMULA FOR THE PROBE INPUT IMPEDANCE

The RCTL cross section and the coaxial-line probe antenna are depicted in figure 2. The septum, of width $2w$, is allowed to be vertically offset with the heights of the upper and lower chambers given by b_1, and b_2, respectively. The width of the upper chamber is $2a_1$, and the width of the lower chamber is $2a_2$. The gap between the septum and the outer wall is g. The probe, of length d and radius t, is located in the upper chamber. A TEM cell would have an RCTL cross section with equal chamber widths and previous discussions have assumed this geometry. However, in order to avoid any degeneracies caused by letting $a_1 = a_2 = a$, the analysis will initially assume general chamber widths. The time convention will be $\exp(-i\omega t)$.

If the coaxial-line aperture is small, it is reasonable to neglect the higher order modes excited at the aperture discontinuity and assume only incident and reflected TEM modes exist in the coaxial-line. As shown by Collin [3] in his analysis of the coaxial-line probe antenna excitation of an ordinary rectangular waveguide, the above approximation allows the antenna input impedance Z to be expressed as follows

$$Z = \frac{-1}{I_t^2} \int_S \int_{S'} \bar{J}(\bar{x}) \cdot \bar{\bar{K}}(\bar{x},\bar{x}') \cdot \bar{J}(\bar{x}') ds' ds \qquad (1)$$

where $\bar{x}$ and $\bar{x}'$ denote source and observation points, $\bar{J}(\bar{x})$ is the unknown current density on the probe, $\bar{\bar{K}}(\bar{x},\bar{x}')$ is a dyadic Green's function corresponding to the electric field excited by a unit strength dipole source, and I_t is the total current at the aperture plane. S denotes the probe surface plus the aperture plane which carries an equivalent electric current $\bar{J}(\bar{x}) = \bar{n} \times \bar{H}(\bar{x})$ where $\bar{n}$ is a unit vector in the outward normal direction.

Experimental studies have shown that Z is effectively independent of the aperture size for electrically small apertures [3]. Therefore it is reasonable to idealize the probe as driven by a y-directed E-field concentrated at the base. Thus we need consider a y-directed current only, which reduces $\bar{J}(\bar{x})$ to $\bar{a}_y J(\bar{x})$, and $\bar{\bar{K}}(\bar{x},\bar{x}')$ to $\bar{a}_y K(\bar{x},\bar{x}')\bar{a}_y$ with $\bar{a}_y$ being the y-directed unit vector.

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The above impedance expression may be shown to be variational in $J(\bar{x})$. That is, a first order approximation for $J(\bar{x})$ leads to a second order approximation for Z. At normal TEM cell operating frequencies, the length of the probe will be small compared to a wavelength. Therefore, it is reasonable to assume that the current distribution is approximately sinusoidal,

$$J(\bar{x}) = \frac{I_0}{2\pi t} \sin k(b_1-d-y)\delta(\rho-t) \qquad (2)$$

where the delta function is interpreted in the sense of a generalized function. The form of the Green's function $K(\bar{x},\bar{x}')$ will be considered next.

3. THE GREEN'S FUNCTION $K(\bar{x},\bar{x}')$

The appropriate Green's function for the special case of equal chamber widths has been derived previously [4]. However, the modifications due to generalizing the chamber widths are not difficult. Since a VED in an RCTL will excite both transverse electric (TE or h-type), and transverse magnetic (TM or e-type) modes, both cases need to be treated. For each modal type we begin by formulating an integral equation for the unknown field in the gap. These integral equations could be solved by Chebyshev polynomial expansion methods [5]. However, a less cumbersome solution may be achieved by making the following pair of assumptions. First, the gap is assumed to be small, and second, the frequency is not allowed to be too high. These assumptions lead to an approximate integral equation which may be solved directly. The small gap assumption amounts to discarding terms which are of the order $G^2 \ell n G$, where G is a normalized gap parameter defined by $G=\pi g/2a$, $a=\min(a_1,a_2)$. Up to the order of this approximation only the TE type modes contribute significantly to the gap field.

The derivation of the Green's function begins with the removal of the z-dependence via a Fourier-transform defined by

$$K^{(j)}(\bar{x},\bar{x}') = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{K}^{(j)}(\bar{x}_t,\bar{x}'_t)e^{i\alpha z}d\alpha \qquad (3)$$

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where j=1,2 refer to the upper, and lower chambers respectively, the subscript t denotes the transverse plane, α is the transform variable representing a continuum of propagation factors, and the superscript tilde signifies a function in the transform domain. The analysis outlined above yields the following result

$$\tilde{K}^{(j)}(\bar{x}_t,\bar{x}_t') = \tilde{K}_1^{(j)}(\bar{x}_t,\bar{x}_t') + \tilde{K}_2^{(j)}(\bar{x}_t,\bar{x}_t') \tag{4}$$

where $\tilde{K}_1^{(j)}$ represents the Green's function expected if there were no gap, i.e., the ordinary rectangular waveguide result, and $\tilde{K}_2^{(j)}$ gives the gap field perturbation contribution. $\tilde{K}_1^{(j)}$ and $\tilde{K}_2^{(j)}$ derived in Appendix A are found to be

$$\tilde{K}_1^{(j)}(\bar{x}_t,\bar{x}_t') = -\delta_{1j}\frac{i\omega\mu}{k^2}\left\{\frac{\alpha^2}{\zeta^2}\delta(\bar{x}_t-\bar{x}_t') + \sum_{m,n=0}^{\infty}\frac{\Delta_n[M_j^2+\alpha^2]}{M_j^2+N_j^2-\zeta^2}g_{mn}^{(j)}(\bar{x}_t,\bar{x}_t')\right\} \tag{5}$$

$$\tilde{K}_2^{(j)}(\bar{x}_t,\bar{x}_t') = \frac{i\omega\mu\pi}{2a_1a_j\zeta^2}L(\alpha)f_j(\bar{x}_t)f_1(\bar{x}_t') \tag{6}$$

where $\omega = 2\pi f$ is the angular frequency, μ is the permeability, $k = \omega(\mu\varepsilon)^{1/2}$ is the TEM mode propagation constant, δ_{ij} is the Kronecker delta function, $\zeta^2 = k^2-\alpha^2$, $M_j = \bar{m}\pi/2a_j$, and $N_j = n\pi/b_j$. The remaining functions are defined by

$$g_{mn}^{(j)}(\bar{x}_t,\bar{x}_t') = (\frac{2}{a_jb_j})\sin M_j(x+a_j)\sin M_j(x'+a_j)\cos N_j y\cos N_j y' \tag{7}$$

$$L(\alpha) = \left\{\ln\frac{8\sqrt{a_1a_2}}{\pi g} + \frac{\pi}{2}\sum_{j=1}^{2}\frac{1}{a_j}\sum_{m_o}\frac{\cot K_m^{(j)}b_j}{K_m^{(j)}} + \frac{1}{M_j}\right\}^{-1} \tag{8}$$

$$f_j(\bar{x}_t) = \sum_{m_0} \frac{M_j \cos K_m^{(j)}(b_j - y)}{K_m^{(j)} \sin K_m^{(j)} b_j} \sin \frac{m\pi}{2} \cos M_j x \, J_0(M_j g) \tag{9}$$

$$K_m^{(j)2} = \zeta^2 - M_j^2 \tag{10}$$

$$\Delta_n = \left\{ \begin{array}{ll} \frac{1}{2} & n=0 \\ 1 & n=1 \end{array} \right. \tag{11}$$

with m_0 denoting the summation over odd m only (m=1,3,5...), and J_0 is the zeroth order Bessel function. Again the delta function should be understood in the sense of a generalized function.

4. THE INPUT IMPEDANCE Z

4.1. The Green's function terms $\tilde{K}_1^{(j)}$ and $\tilde{K}_2^{(j)}$ will lead to two distinct impedance contributions Z_1 and Z_2 which represent the ordinary and perturbation contributions to the probe input impedance. The total impedance is the sum of these two terms. Combining the form of the Green's function given by (4), with the impedance integral (1), yields $Z = Z_1 + Z_2$, where

$$Z_1 = \frac{-1}{2\pi I_t^2} \int_S \int_{S'} J(\bar{x}) \int_{-\infty}^{\infty} \tilde{K}_1^{(1)}(\bar{x}_t, \bar{x}_t') e^{i\alpha z} J(\bar{x}') \, d\alpha \, ds' \, ds \tag{12}$$

$$Z_2 = \frac{-1}{2\pi I_t^2} \int_S \int_{S'} J(\bar{x}) \int_{-\infty}^{\infty} \tilde{K}_2^{(1)}(\bar{x}_t, \bar{x}_t') e^{i\alpha z} J(\bar{x}') \, d\alpha \, ds' \, ds \tag{13}$$

The integrals defined for Z_1 and Z_2 are evaluated in Appendices B and C for a centrally located probe. The approximate form found for Z_1 depends upon two assumptions: (1) the probe is taken to be thin, i.e., $\pi t/2a_1 \ll 1$, and (2) the frequency is restricted so that $(ka_1)^2$ is small. More precisely, terms in t of the order $(\pi t/2a_1)^2$ are discarded and terms in ka_1 of the order $(k/2M_1)^4$

are discarded. The evaluation of Z_2 involves no approximations. However, Z_2 remains in an integral form. The results of Appendices B and C are as follows

$$Z_1 \approx \frac{i\omega\mu}{2\pi b_1 k^2} \tan^2 \frac{kd}{2} \left\{ \ell n \left(\frac{4a_1}{\pi t}\right) + \frac{a_1^2 k^2}{\pi^2} \ (4.207175) \right.$$

$$\left. -2k^2 \sum_{n=1}^{\infty} \left(1 - \frac{\sin^2 N_1 d/2}{\sin^2 kd/2}\right)^2 \frac{K_0[t(N_1^2 - K^2)^{1/2}]}{N_1^2 - K^2} \right\} \tag{14}$$

$$Z_2 = \frac{-i\omega\mu k^2}{4a_1^2} \csc^2 kd \int_{-\infty}^{\infty} \frac{L(\alpha)}{\zeta^2} \sum_{m_0} h_{m'}(\alpha,d) \sum_{m_0} h_m(\alpha,d) J_0[t(\alpha^2 + M_1^2)^{1/2}] \, d\alpha \tag{15}$$

$$h_m(\alpha,d) = \frac{M_1 \sin \frac{m\pi}{2} J_0(M_1 g)}{K_m^{(1)} \sin K_m^{(1)} b_1} \frac{(\cos kd - \cos K_m^{(1)} d)}{M_1^2 + \alpha^2} \tag{16}$$

where $K_0(x)$ is a modified Bessel function.

The perturbation term Z_2 contains the radiation resistance due to the propagating TEM mode, which may be extracted by evaluating the half residues at $\alpha = \pm k$ due to the forward and backward propagating TEM modes. The TEM mode radiation resistance is found to be:

$$R = \frac{\pi \eta_0 k^2}{4a_1^2} \csc^2 kd \ L(k) \sum_{m_0} h_{m'}(k,d) \sum_{m_0} h_m(k,d) J_0[t(k^2 + M^2)^{1/2}] \tag{17}$$

where $\eta_0 = 120\pi$.

If we now let $a_1 = a_2 = a$ so that we are considering a normal TEM cell geometry, and recall that the characteristic impedance Z_c of an RCTL is given by [4]

$$Z_c = \frac{\eta_0 \pi}{8} L(k) \tag{18}$$

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The radiation resistance may be written

$$R = \frac{2k^2}{a^2} Z_c \csc^2 kd \sum_{m_o} h_{m'}(k,d) \sum_{m_o} h_m(k,d) J_o[t(k^2+M^2)^{1/2}] \qquad (19)$$

Because only the TEM mode is allowed to propagate, R represents the total resistance. We may also express Z as the sum of the radiation resistance R and a reactance $i(X+\delta X)$, with X and δX defined by

$$X = \frac{\eta_o}{2\pi b_1 k} \tan^2 \frac{kd}{2} \left\{ \ell n(\frac{4a}{\pi t}) + \frac{a^2 k^2}{\pi^2} (4.207175) \right.$$

$$\left. -2k^2 \sum_{n=1}^{\infty} \left(1 - \frac{\sin^2 N_1 d/2}{\sin^2 kd/2}\right)^2 \frac{K_o[t(N_1^2-k^2)^{1/2}]}{N_1^2 - k^2} \right\} \qquad (20)$$

$$\delta X = \frac{-\omega\mu k^2}{4a^2} \csc^2 kd \; P \int_{-\infty}^{\infty} \frac{L(\alpha)}{\zeta^2} \sum_{m_o} h_{m'}(\alpha,d) \sum_{m_o} h_m(\alpha,d) J_o[t(\alpha^2+M^2)^{1/2}] \; d\alpha \qquad (21)$$

where the integral is now understood in the principal value sense. The dominant reactive contribution comes from the sum over n and therefore the ractance is highly capacitive. The capacitive behavior is expected from comparisons to either a monopole in free space, or a similar probe in a rectangular guide. For typical TEM cell geometries, the principal value integral does not significantly add to the reactance. Therefore, a very good algebraic approximation for the reactance is simply X which allows us to write Z as follows:

$$Z \simeq R + iX, \qquad (22)$$

where R and X are given respectively in (19) and (20).

5. NUMERICAL RESULTS AND DISCUSSIONS

In order to check our result we would like to compare our expression to certain special cases for which solutions are known. The impedance Z consists of three terms: (i) the radiation resistance R due to the propagating TEM mode, (ii) the reactive ordinary rectangular waveguide contribution Z_1, and (iii) the gap field perturbation reactance principal value integral. Ideally, since each of these terms has a distinct physical interpretation, each term should be checked individually. Because the probe is electrically short, the probe radiation resistance may be compared to that of a Hertzian dipole via a result given earlier by Tippet [1]. His expression for the radiation resistance of a Hertzian dipole involves the square of $IE_0 d\ell$ where I is the current magnitude, E_0 is the TEM mode electric field distribution, and $d\ell$ is the effective dipole length. In the monopole case, the dipole quantity $(IE_0 d\ell)$, may be replaced by an effective value which results from integrating the product $I(y) E_0(y)$ over the monople length. The two results agree up to the order of our approximations. Next, by letting the gap width go to zero $(g \rightarrow 0)$ thereby reducing the upper chamber to an ordinary rectangular waveguide, Z_1 may be compared to a result given by Collin [3]. If we allow the frequency to be large enough that the ordinary rectangular waveguide TE_{10} mode will propagate, then our result reduces exactly to that found by Collin. Both these checks are detailed in Appendix D for the special case when $a_1=a_2=a$.

The perturbation reactance term is more difficult to verify and is not comparable to any simple special case result. However, a good check of the self consistency of our expression exists. If we had allowed k to be sufficiently large, such that $k^2 > M_1^2$, the expression (12) for Z_1 would contain poles at $\alpha = \pm \beta_{10}^{(1)}$, where $\beta_{10}^{(1)} = (k^2 - M_1^2)^{1/2}$. This would imply an apparent mode propagating the same as an upper chamber TE_{10} mode. Equation (15) for Z_2 would also imply the existence of this mode. However, the guide as a whole supports no such mode, therefore, we expect that the contributions from Z_1 and Z_2, to this evident $TE_{10}^{(1)}$ mode, should cancel out to the order of our previous

approximations. It is found in Appendix D that the radiation resistance due to a propagating $TE_{10}^{(1)}$ mode in a rectangular waveguide of the dimensions of the upper chamber, is given by

$$R = \frac{\eta_0}{2a_1 b_1 k\beta_{10}^{(1)}} \tan^2 \frac{kd}{2} \tag{23}$$

Now consider the perturbation contribution given by Z_2 in (15). In order to avoid the degeneracy due to an additional $TE_{10}^{(1)}$ mode also propagating in the lower chamber, we refrain from letting the chamber widths be equal until after we have evaluated the pole contribution at $\alpha = \pm\beta_{10}^{(1)}$. As α approaches $\pm\beta_{10}^{(1)}$, we see that $k_1^{(1)} = (\beta_{10}^{(1)2} - \alpha^2)^{1/2} \to 0$. Evaluating the half residues at $\alpha = \pm\beta_{10}^{(1)}$, we find

$$L(\alpha) \to \frac{2a_1 b_1 (\beta_{10}^{(1)2} - \alpha^2)}{\pi} \tag{24}$$

$$\zeta^2 \to (\pi/2a_1)^2 \tag{25}$$

$$h_m(\alpha,d) \to \frac{\pi(1 - \cos kd)}{2a_1 b_1 k^2 (\beta_{10}^{(1)2} - \alpha^2)} J_0 (\frac{\pi g}{2a_1}) \tag{26}$$

$$J_0[t(M_1^2 + \alpha^2)^{1/2}] \to J_0(kt) \tag{27}$$

Because both $\pi g/2a_1$ and kt are small, the Bessel functions may be replaced by unity. Collecting results gives

$$Z_2\bigg|_{\alpha=\pm\beta_{10}^{(1)}} = \frac{-i\omega\mu k^2}{4a_1^2} \csc^2 kd(-2\pi i) \lim_{\alpha\to\pm\beta_{10}^{(1)}} \frac{L(\alpha)}{(\pi/2a_1)^2} h_1^2(\beta_{10}^{(1)},d)$$

$$\tag{28}$$

$$= \frac{-\eta_0}{2a_1 b_1 k \beta_{10}^{(1)}} \tan^2 \frac{kd}{2}$$

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which indeed will cancel the unperturbed result given by expression (23). Thus the poles at $\alpha = \pm \beta_{10}^{(1)}$, that apparently imply a physically meaningless mode, do not contribute up to the order of our approximations. The impedance expressions will next be used to generate numerical data for typical TEM cell geometries.

The radiation resistance R given by (19) is plotted in figure 3 for $g/a=0.1$ and 0.2. The dimensions of the RCTL cross section are $a_1=a_2=1.0$ m, and $b_1=b_2=1.0$ m. The probe varies in length from $d/a=0.0$ to $d/a=0.95$, and is of radius $t=1$ mm. The frequency is set at 1 MHz. The curves show a basically parabolic dependence on d with the main difference between the two curves resulting from the logarithmic dependence of Z_c on the gap size. This d^2 variation is significantly larger than the free-space probe radiation resistance which is proportional to $(kd)^2$, a frequency dependent quantity. This difference between the radiated power by a short monopole in free space and that delivered to a TEM mode has also been encountered in other types of problems such as the coupling between a dipole antenna and an infinite cable [8]. Figure 4 gives the dependence on d of the ordinary rectangular waveguide reactance X. The same set of parameters is used to plot X, given by (20), as that used to plot R. The curve shows a highly capacitive contribution which is independent of the gap size. Again, this result may be compared to the free-space result for an electrically short monopole which is known as proportional to $-i(kd)^{-1}$ [9]. From (20), the dominant reactance behavior for small kd is more like $-i(kd)^{-2}$. Thus, we find that the reactance of a monopole in a TEM cell is more highly capacitive than that in free space. Finally, the perturbation reactance δX is plotted in figure 5 using (21), again for the same parameter set. We find that $|\delta X|<1\Omega$ for the entire range of probe lengths. Thus δX is at least three orders of magnitude less than X. Therefore, neglecting δX will yield excellent results. The FORTRAN program used to compute Z is listed in Appendix E.

6. CONCLUDING REMARKS

This report has detailed the manner in which a coaxial probe excites a TEM cell. The analysis utilizes three simplifying assumptions, which are (i) the gap is small, that is $G^2 \ell nG \ll 1$ where $G = \pi g/2a$, (ii) the probe is thin, or $\pi t/2a \ll 1$ where t is the probe radius, and (iii) the frequency is not too high so that only the TEM mode propagates and $(ka)^2$ is small when compared to unity. None of the requirements is restrictive in terms of common TEM cell usage. The resulting expression for the probe input impedance consists of three distinct terms R, X, and δX, these being the radiation resistance due to the propagating TEM mode, the ordinary rectangular waveguide reactance, and the reactance perturbation due to the gap fields. The first two terms, R and X, are computationally simple, with R showing a basically d^2 dependence on probe length and X giving a highly capacitive reactance. Although δX consists of a nontrivial principal value integral, numerical results show that $|\delta X| \ll X$, and therefore δX may be neglected. Thus a reasonably straightforward form for Z is achieved which may be used to analyze probes inserted into a TEM cell either to measure, or excite fields as well as other types of feed lines.

7. ACKNOWLEDGMENTS

8. REFERENCES

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APPENDIX A

DERIVATION OF $\tilde{K}_1^{(j)}$ and $\tilde{K}_2^{(j)}$

Generalizing the chamber widths involves some modifications in the expressions derived in NBS Technical Note 103 [4]. For the most part, this involves nothing more than replacing a by a_j. The details will be briefly outlined beginning with the TE type mode kernel which becomes

$$Q^{(h)}(t,t') = Q_s^{(h)}(t,t') - Q_f^{(h)}(t,t') \tag{a-1}$$

$$Q_s^{(h)}(t,t') \approx - \frac{1}{\pi} \ell n \left[\left(\frac{\pi}{4a_1}\right)\left(\frac{\pi}{4a_2}\right) |t^2 - t'^2| \right] \tag{a-2}$$

$$Q_f^{(h)}(t,t') \approx \sum_{j=1}^{2} \frac{1}{a_j} \sum_{mo} \left[\frac{\cot K_m^{(j)} b_j}{K_m^{(j)}} + \frac{1}{M_j} \right] \equiv Q_f \tag{a-3}$$

where $t = a - x$, $t' = a - x'$, $a = \min(a_1, a_2)$, $K_m^{(j)2} = \zeta^2 - M_j^2$, $M_j = m\pi/2a_j$, and mo refers to the summation over odd m. This kernel will result in the following solution for the unknown gap field

$$f^{(h)}(t') = \frac{-I d\ell}{2a_1 \sqrt{g^2 - t'^2}} \, L(\alpha) f_1(\bar{x}_t') \tag{a-4}$$

$$L(\alpha) = \left[\ell n \left(\frac{8\sqrt{a_1 a_2}}{\pi g}\right) + \frac{\pi}{2} Q_f \right]^{-1} \tag{a-5}$$

$$f_j(\bar{x}_t) = \sum_{mo} \frac{M_j \cos K_m^{(j)}(b_j - y)}{K_m^{(j)} \sin K_m^{(j)} b_j} \, \sin \frac{m\pi}{2} \cos M_j x \, J_0(M_j g) \tag{a-6}$$

where we recall that $\bar{x}_t'$ is the dipole location. The above solution assumes that the dipole is centrally located.

The y-component of the electric field in the upper, and lower chambers may now be found. Both TE and TM type unperturbed (ordinary) modes, as well as TE type perturbed modes will contribute significantly to $\tilde{E}_y^{(j)}$. The unperturbed modes exist only in the upper chamber. Denoting the unperturbed

contribution by $\tilde{K}_1^{(j)}$, and the gap perturbation contribution by $\tilde{K}_2^{(j)}$, and referring to Appendix C of NBS Technical Note 1037 [4], we find

$$\tilde{K}_1^{(j)}(\overline{x}_t,\overline{x}_t') = \delta_{ij} \left\{ \frac{-i\omega\mu}{\zeta^2} \partial_x \tilde{H}_z^{(j)}(\overline{x}_t, \overline{x}_t') + \frac{i\alpha}{\zeta^2} \partial_y \tilde{E}_z^{(j)}(\overline{x}_t,\overline{x}_t') \right\} \qquad \text{(a-7)}$$

Suitably modifying equation (49) of NBS Technical Note 1037 [4] yields

$$\tilde{K}_2^{(j)}(\overline{x}_t, \overline{x}_t') = \frac{i\omega\mu\pi}{2a_1 a_j \zeta^2} \text{Id}\ell \, L(\alpha) \, f_j \,(\overline{x}_t) \, f_1 \,(\overline{x}_t') \qquad \text{(a-8)}$$

Taking the proper derivatives required in (a-7) and substituting the proper forms for $\tilde{E}_z^{(j)}$, and $\tilde{H}_z^{(j)}$ allows $\tilde{K}_1^{(j)}$ to be written as follows.

$$\tilde{K}_1^{(j)}(\overline{x}_t,\overline{x}_t') = \delta_{1j} \frac{i\omega\mu}{\zeta^2} \text{Id}\ell \sum_{m,n=0}^{\infty} \frac{\Delta_n M_j^2 + \frac{\alpha^2}{k^2} N_j^2}{M_j^2 + N_j^2 - \zeta^2} \, g_{mn}^{(j)}(\overline{x}_t,\overline{x}_t') \qquad \text{(a-9)}$$

$$g_{mn}^{(j)}(\overline{x}_t,\overline{x}_t') = (\frac{2}{a_j b_j}) \sin M_j(x + a_j) \sin(x'+a_j) \cos N_j y \cos N_j y' \qquad \text{(a-10)}$$

where
$$\Delta_n = \begin{cases} \tfrac{1}{2} & n = 0 \\ 1 & n \geq 1 \end{cases} \qquad \text{(a-11)}$$

and $N_j = n\pi/b_j$. It will prove convenient to extract the delta function nature in $\tilde{K}_1^{(j)}$ which occurs when $\overline{x}_t \to \overline{x}_t'$. Notice that

$$\Delta_n M_j^2 + \frac{\alpha^2}{k^2} N_j^2 = \Delta_n \frac{\alpha^2}{k^2} [M_j^2 + N_j^2 - \zeta^2 + \frac{\zeta^2}{\alpha^2} M_j^2 + \zeta^2] \qquad \text{(a-12)}$$

Therefore $\tilde{K}_1^{(j)}$ becomes

$$\tilde{K}_1^{(j)}(\overline{x}_t,\overline{x}_t') = \delta_{1j} \frac{i\omega\mu}{k^2} \text{Id}\ell \left\{ \frac{\alpha^2}{\zeta^2} \sum_{m,n=0}^{\infty} \Delta_n g_{mn}^{(j)}(\overline{x}_t,\overline{x}_t') \right.$$

$$\left. + \sum_{m,n=0}^{\infty} \frac{\Delta_n[M_j^2 + \alpha^2]}{M_j^2 + N_j^2 - \zeta^2} \, g_{mn}^{(j)}(\overline{x}_t,\overline{x}_t') \right\} \qquad \text{(a-13)}$$

If we expand a delta function in a double Fourier series over a chamber cross section we will find

$$\delta(\overline{x}_t - \overline{x}_t') = \sum_{m,n=0}^{\infty} \Delta_n \, g_{mn}^{(j)}(\overline{x}_t,\overline{x}_t') \qquad \text{(a-14)}$$

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Therefore $\tilde{K}_1^{(j)}$ becomes

$$\tilde{K}_1^{(j)}(\overline{x}_t, \overline{x}_t') = \delta_{1j} \frac{i\omega\mu}{k^2} \, \mathrm{Id}\ell \left\{ \frac{\alpha^2}{\zeta^2} \delta(\overline{x}_t - \overline{x}_t') \right.$$

$$\left. + \sum_{m,n=0}^{\infty} \frac{\Delta_n [M_j^2 + \alpha^2]}{M_j^2 + N_j^2 - \zeta^2} \, g_{mn}^{(j)}(\overline{x}_t, \overline{x}_t') \right\} \qquad (a\text{-}15)$$

$\tilde{K}_1^{(j)}$ and $\tilde{K}_2^{(j)}$ represent the y-component of the electric field excited by a symmetrically located VED at $\overline{x}_t'$. There remain only two small changes to adapt this result to the probe excitation problem. First, the probe carries a negative y-directed current. Thus $\mathrm{Id}\ell \rightarrow - \mathrm{Id}\ell$. Second, the Green's function represents results from a unit strength dipole. Therefore $-\mathrm{Id}\ell \rightarrow -1$. Therefore $\tilde{K}_1^{(j)}$ and $\tilde{K}_2^{(j)}$ finally become

$$\tilde{K}_1^{(j)}(\overline{x}_t, \overline{x}_t') = -\delta_{1j} \frac{i\omega\mu}{k^2} \left\{ \frac{\alpha^2}{\zeta^2} \delta(\overline{x}_t - \overline{x}_t') \right.$$

$$\left. + \sum_{m,n=0}^{\infty} \frac{\Delta_n [M_j^2 + \alpha^2]}{M_j^2 + N_j^2 - \zeta^2} \, g_{mn}^{(j)}(\overline{x}_t, \overline{x}_t') \right\} \qquad (a\text{-}16)$$

$$\tilde{K}_2^{(j)}(\overline{x}_t, \overline{x}_t') = \frac{i\omega\mu\pi}{2a_1 a_j \zeta^2} \, L(\alpha) f_j(\overline{x}_t) f_1(\overline{x}_t') \qquad (a\text{-}17)$$

EVALUATION OF Z_1

The integral defined for Z_1 is to be evaluated.

$$Z_1 = \frac{-1}{2\pi I_t^2} \int_S \int_{S'} J(\overline{x}) \int_{-\infty}^{\infty} \tilde{K}_1^{(1)}(\overline{x}_t, \overline{x}_t') e^{i\alpha z} J(\overline{x}') d\alpha \, ds' \, ds \tag{b-1}$$

$$\tilde{K}_1^{(1)}(\overline{x}_t, \overline{x}_t') = -\frac{i\omega\mu}{k^2} \left\{ \frac{\alpha^2}{\zeta^2} \delta(\overline{x}_t - \overline{x}_t') \right.$$

$$\left. + \sum_{m,n=0}^{\infty} \Delta_n \frac{M_1^2 + \alpha^2}{M_1^2 + N_1^2 - \zeta^2} g_{mn}^{(1)}(\overline{x}_t, \overline{x}_t') \right\} \tag{b-2}$$

The α-integration may be performed first, which requires evaluating the following pair of integrals.

$$I_1 = \int_{-\infty}^{\infty} \frac{\alpha^2}{\zeta^2} \delta(\overline{x}_t - \overline{x}_t') e^{i\alpha z} d\alpha \tag{b-3}$$

$$I_2 = \int_{-\infty}^{\infty} \sum_{m,n=0}^{\infty} \Delta_n \frac{M_1^2 + \alpha^2}{M_1^2 + N_1^2 - \zeta^2} g_{mn}^{(1)}(\overline{x}_t, \overline{x}_t') e^{i\alpha z} d\alpha \tag{b-4}$$

In each integral we will deform into the upper α half plane for $z > 0$ (forward waves), and into the lower α half plane for $z < 0$ (backward waves). For I_1, we find

$$I_1 = -i\pi k \delta(\overline{x}_t - \overline{x}_t') e^{ik|z|} \tag{b-5}$$

The denominator of I_2 may be factored as follows.

$$M_1^2 + N_1^2 - \zeta^2 = \alpha^2 + \Gamma_{mn}^{(1)2} \tag{b-6}$$

$$\Gamma_{mn}^{(1)} = [M_1^2 + N_1^2 - k^2]^{\frac{1}{2}} \tag{b-7}$$

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Thus we see that a simple pole arises in the I_2 integrand when $\alpha = \pm i\Gamma_{mn}^{(1)}$. Again deforming as for I_1 gives the following result.

$$I_2 = \pi \sum_{m,n=0}^{\infty} \Delta_n \frac{k^2 - N_1^2}{\Gamma_{mn}^{(1)}} g_{mn}^{(1)}(\overline{x}_t, \overline{x}_t') e^{-\Gamma_{mn}^{(1)}|z|} \qquad \text{(b-8)}$$

We next proceed to the integration over the current distributions $J(\overline{x})$ and $J(\overline{x}')$. The source current $J(\overline{x}')$ will be concentrated on an idealized linear antenna located at the origin, i.e. $\overline{x}_t' = (0,y')$. Therefore $\overline{x}_t \neq \overline{x}_{t'}$ on S and the delta function term will not contribute to Z_1. Thus Z_1 reduces to

$$Z_1 = \frac{i\omega\mu}{2k^2 I_t^2} \sum_{m,n=0}^{\infty} \Delta_n \frac{k^2 - N_1^2}{\Gamma_{mn}^{(1)}} \int_S \int_{S'} J(\overline{x}) g_{mn}^{(1)}(\overline{x}_t, \overline{x}_t') J(\overline{x}') e^{-\Gamma_{mn}^{(1)}|z|} ds' ds \qquad \text{(b-9)}$$

The simpler integration over the source current will be considered first. We recall that the assumed current density on the probe will be

$$J(\overline{x}) = \frac{I_0}{2\pi t} \sin k (b_1 - d - y)\delta(\rho - t) \qquad \text{(b-10)}$$

For the δ' integration we let $t' \to 0$, and therefore

$$\int_{S'} J(\overline{x}') g_{mn}^{(1)}(\overline{x}_t, \overline{x}_t') ds'$$

$$= I_3\left(\frac{2}{a_1 b_1}\right) I_0 \sin M_1(x + a_1) \sin \frac{m\pi}{2} \cos N_1 y \, e^{-\Gamma_{mn}^{(1)}|z|} \qquad \text{(b-11)}$$

where the integral I_3 is given by

$$I_3 = \int_{b_1-d}^{b_1} \sin k (b_1-d-y')\cos N_1 d' dy' = \frac{k \cos n\pi(\cos kd - \cos N_1 d)}{k^2 - N_1^2} \qquad \text{(b-12)}$$

Because of the factor $\sin m\pi/2$, only the summation over odd m will contribute. Therefore Z_1 takes the form

$$Z_1 = \frac{i\omega\mu I_0}{a_1 b_1 k I_t^2} \sum_{mo,n=0}^{\infty} \frac{\Delta_n \cos n\pi}{\Gamma_{mn}^{(1)}} (\cos kd - \cos N_1 d) \int_S J(\overline{x})\cos M_1 x \cos N_1 y$$

$$\times e^{-\Gamma_{mn}^{(1)}|z|} ds \qquad \text{(b-13)}$$

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The integration over S may be split into separate integrations over y and θ. The y-integration has already been encountered and we find

$$\int_S J(\bar{x})\cos M_1 x \cos N_1 y \, e^{-\Gamma_{mn}^{(1)}|z|} \, ds = \frac{I_0 I_3}{2\pi t} \int_0^{2\pi} \cos(M_1 t \cos \theta) e^{-\Gamma_{mn}^{(1)} t |\sin \theta|} t \, d\theta \qquad \text{(b-14)}$$

If we now interchange the remaining theta integration with the double summation, Z_1 may be written

$$Z_1 = \frac{i\omega\mu \, I_0^2}{\pi a_1 b_1 I_t^2} \int_0^\pi \left\{ \sum_{n=0}^\infty \Delta_n \frac{(\cos kd - \cos N_1 d)^2}{k^2 - N_1^2} \right.$$

$$\left. \times \sum_{mo} \frac{1}{\Gamma_{mn}^{(1)}} \cos(M_1 t \cos \theta) e^{-\Gamma_{mn}^{(1)} t \sin \theta} \right\} d\theta \qquad \text{(b-15)}$$

where we have noted that the theta integration is symmetric about π. Let us now consider the sum over m

$$S_n(\theta) = \sum_{mo} \frac{1}{\Gamma_{mn}^{(1)}} \cos(M_1 t \cos \theta) e^{-\Gamma_{mn}^{(1)} t \sin \theta} \qquad \text{(b-16)}$$

The dominant series will be for $n = 0$. $S_0(\theta)$ may be expressed as follows.

$$S_0(\theta) = \text{Re} \sum_{mo} \frac{e^{iM_1 t \cos \theta} \, e^{-\Gamma_{mn}^{(1)} t \sin \theta}}{\Gamma_{mn}^{(1)}} \Bigg|_{n=0} \qquad \text{(b-17)}$$

For large m we see that $\Gamma_{mo}^{(1)} \sim M_1$. Adding and subtracting the asymptotic form of the summand will thus give

$$S_0(\theta) = \text{Re} \sum_{mo} \frac{e^{M_1 t(i \cos \theta - \sin \theta)}}{M_1}$$

$$+ \text{Re} \sum_{mo} e^{iM_1 t \cos \theta} \left[\frac{e^{-\Gamma_{mn}^{(1)} t \sin \theta}}{\Gamma_{mn}^{(1)}} - \frac{e^{-M_1 t \sin \theta}}{M_1} \right]_{n=0} \qquad \text{(b-18)}$$

where the first series represents the major contribution. The first series may be summed

$$\sum_{mo} \frac{e^{iM_1 t(e^{i\theta})}}{M_1} = \frac{-a_1}{\pi} \ln \left[\tan\left(\frac{\pi t e^{i\theta}}{4a_1}\right)\right] + \frac{ia_1}{2} \tag{b-19}$$

We now assume that the probe is thin, $\pi t/4a_1 \ll 1$, which allows us to replace the tangent by its argument

$$\ln\left[\tan\left(\frac{\pi t e^{i\theta}}{4a_1}\right)\right] \approx \ln\left(\frac{\pi t}{4a_1} e^{i\theta}\right) = \ln\left(\frac{\pi t}{4a_1}\right) + i\theta \tag{b-20}$$

If we now take the real part of the first sum in (b-18) we see that

$$S_0(\theta) = \frac{a_1}{\pi} \ln\left(\frac{4a_1}{\pi t}\right) + \mathrm{Re} \sum_{mo} e^{iM_1 t \cos\theta} \left[\frac{e^{-\Gamma_{mn}^{(1)} t \sin\theta}}{\Gamma_{mn}^{(1)}} - \frac{e^{-M_1 t \sin}}{M_1}\right]_{n=0} \tag{b-21}$$

The correction series will be considered next. Again consider $\Gamma_{mo}^{(1)}$

$$\Gamma_{mo}^{(1)} = M_1(1 - k^2/M_1^2)^{\frac{1}{2}} \approx M_1(1 - k^2/2M_1^2) = M_1(1 - \varepsilon) \tag{b-22}$$

where $\varepsilon = k^2/2M_1^2$ is assumed to be small. The correction series may be written

$$\sum_{mo} \frac{e^{M_1 t(i \cos\theta - \sin\theta)}}{M_1} \left[\frac{e^{M_1 t \varepsilon \sin\theta}}{1 - \varepsilon} - 1\right] \tag{b-23}$$

For ε small, we have $(1 - \varepsilon)^{-1} \approx 1 + \varepsilon$. This series converges very rapidly, thus only a few significant terms may be considered. Because $\pi t/2a_1 \ll 1$ for these few terms, the exponents may be replaced by unity with little error giving

$$\sum_{mo} \frac{\varepsilon}{M_1} = \frac{k^2}{2} \sum_{mo} \frac{1}{M_1^3} = \frac{4a_1^3 k^2}{\pi^3} \sum_{mo} \frac{1}{m^3} \tag{b-24}$$

The sum of the inverse cube over odd m may be done in terms of the Riemann Zeta function. Recalling that

$$\zeta(s) = \sum_{k=1}^{\infty} k^{-s} \tag{b-25}$$

For $\mathrm{Re}(s) > 1$, we see that our expression may be written

$$\sum_{mo} \frac{1}{m^3} = \sum_{m=1}^{\infty} \frac{1}{m^3} - \sum_{m=1}^{\infty} \frac{1}{(2m)^3} = \frac{7}{8} \zeta(3) \tag{b-26}$$

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The Riemann-Zeta function is well tabulated, and from [6] we find

$$\zeta(3) \approx 1.20205 \tag{b-27}$$

Collecting these results we have the following for the dominant series $S_0(\theta)$

$$S_0(\theta) \approx \frac{a_1}{\pi} \ln\left(\frac{4a_1}{\pi t}\right) + \frac{a_1^3 k^2}{\pi^3} (4.207175) \tag{b-28}$$

The remaining series $S_n(\theta)$ for $n \geq 1$ will be summed in a manner similar to that used by Collin [3] in treating the probe excitation of a rectangular waveguide. We will make use of the following Poisson summation formula: if $f(x)$ is a square integrable function, then

$$\sum_{n=-\infty}^{\infty} f(n\alpha) = \frac{1}{\alpha} \sum_{n=-\infty}^{\infty} F\left(\frac{2\pi n}{\alpha}\right) \tag{b-29}$$

where $F(\omega)$ is the Fourier-transform of $f(x)$ defined by

$$F(\omega) = \int_{-\infty}^{\infty} f(x) e^{i\omega x} dx \tag{b-30}$$

Our particular problem involves the function $f(x)$ defined by

$$f(x) = e^{ixt \cos\theta - \Gamma_{mn}^{(1)}(x) t \sin\theta} / \Gamma_{mn}^{(1)}(x) \tag{b-31}$$

$$\Gamma_{mn}^{(1)}(x) = [x^2 + N_1^2 - k^2]^{\frac{1}{2}} \tag{b-32}$$

This function is clearly L_2 so Poisson's summation formula applies. The Fourier transform is given by

$$F(\omega) = \int_{-\infty}^{\infty} \frac{e^{-\Gamma_{mn}^{(1)}(x) t \sin\theta}}{\Gamma_{mn}^{(1)}(x)} e^{ix(t \cos\theta + \omega)} dx \tag{b-33}$$

If we now rewrite the complex exponential, and notice that $\Gamma_{mn}^{(1)}(x)$ is even in x, then $F(\omega)$ takes the form

$$F(\omega) = 2\int_{0}^{\infty} \frac{e^{-\Gamma_{mn}^{(1)}(x) t \sin\theta}}{\Gamma_{mn}^{(1)}(x)} \cos((t \cos\theta + \omega)x) dx \tag{b-34}$$

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This integral may be evaluated in terms of the modified Bessel function K_0 [7] with the result

$$F(\omega) = 2K_0 [(N_1^2 - k^2)^{\frac{1}{2}} (t^2 \sin^2\theta + (t \cos\theta + \omega)^2)^{\frac{1}{2}}] \qquad (b-35)$$

If we now return to the definition of $S_n(\theta)$ we see that

$$S_n(\theta) = \frac{1}{2} \sum_{m_0 = -\infty}^{+\infty} f(\frac{m\pi}{2a_1}) = \frac{1}{2} \sum_{m = -\infty}^{\infty} \left\{ f(\frac{m\pi}{2a_1}) - f(\frac{m\pi}{a_1}) \right\} \qquad (b-36)$$

Thus applying Poisson's summation formula we have

$$S_n(\theta) = \frac{1}{2} \sum_{m = -\infty}^{\infty} \left\{ \frac{2a_1}{\pi} F(4a_1 m) - \frac{a_1}{\pi} F(2a_1 m) \right\} \qquad (b-37)$$

which in terms of modified Bessel functions K_0 becomes

$$S_n(\theta) = \frac{a_1}{\pi} \sum_{m = -\infty}^{\infty} \left\{ 2K_0 [(N_1^2 - K^2)^{\frac{1}{2}} ((4a_1 m)^2 + 8a_1 mt \cos\theta + t^2)^{\frac{1}{2}}] \right.$$
$$\left. - K_0 [(N_1^2 - k^2)^{\frac{1}{2}} ((2a_1 m)^2 + 4a_1 mt \cos\theta + t^2)^{\frac{1}{2}}] \right\} \qquad (b-38)$$

The modified Bessel function decays very rapidly so the only significant contribution comes from $m = 0$. Thus

$$S_n(\theta) \approx \frac{a_1}{\pi} K_0 [(N_1^2 - k^2)^{\frac{1}{2}} t] \qquad (n \geq 1) \qquad (b-39)$$

Returning to the integral for Z_1 in (b-15) we have the following

$$Z_1 \approx \frac{i\omega\mu I_0^2}{\pi a_1 b_1 I_t^2} \int_0^\pi \left\{ \frac{(1 - \cos kd)^2}{2k^2} S_0(\theta) + \sum_{n=1}^{\infty} \frac{(\cos kd - \cos N_1 d)^2}{k^2 - N_1^2} S_n(\theta) \right\} d\theta \qquad (b-40)$$

Note that the approximate form for $S_n(\theta)$ in (b-39) is now independent of θ. Thus combining all these results, we have

$$Z_1 \approx \frac{i\omega\mu I_0^2}{2\pi b_1 k^2 I_t^2} (1 - \cos kd)^2 \left\{ \ln(\frac{4a_1}{\pi t}) + \frac{a_1^2 k^2}{\pi^2} (4.207175) \right.$$
$$\left. - 2k^2 \sum_{n=1}^{\infty} \left(1 - \frac{\sin^2 N_1 d/2}{\sin^2 kd/2} \right)^2 \frac{K_0 [t(N_1^2 - k^2)^{\frac{1}{2}}]}{N_1^2 - k^2} \right\} \qquad (b-41)$$

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Note that Z_1 given in (b-41) is approximate, based on two assumptions that the probe is thin ($\pi t/2a_1 \ll 1$) and that the frequency is not too high ($k^2 a_1^2 \ll 1$).

Finally, we note that the total current at the aperture ($y = b_1$) is given by $I_t = -I_o \sin k\, d$. Thus,

$$Z_1 \approx \frac{i\omega\mu}{2\pi b_1 k^2}\ \tan^2 \frac{kd}{2}\left\{ \ln\left(\frac{4a_1}{\pi t}\right) + \frac{a_1^2 k^2}{\pi^2}(4.207175)\right.$$

$$\left. - 2k^2 \sum_{n=1}^{\infty} \left(1 - \frac{\sin^2 N_1\, d/2}{\sin^2 kd/2}\right)^2\ \frac{K_o[t(N_1^2 - k^2)^{\frac{1}{2}}]}{N_1^2 - k^2}\right\}.$$

(b-42)

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APPENDIX C

EVALUATION OF Z_2

The integral defined for Z_2 in (13) is to be evaluated.

$$Z_2 = \frac{-1}{2\pi I_t^2} \int\limits_{S} \int\limits_{S'} J(\bar{x}) \int\limits_{-\infty}^{\infty} \tilde{K}_2^{(1)} (\bar{x}_t, \bar{x}_t') e^{i\alpha z} J(\bar{x}') d\alpha \, ds' \, ds \qquad \text{(c-1)}$$

where

$$\tilde{K}_2^{(1)} (\bar{x}_t, \bar{x}_t') = \frac{i\omega\mu\pi}{2a_1^2\zeta} L(\alpha) f_1(\bar{x}_t) f_1(\bar{x}_t') \qquad \text{(c-2)}$$

$$L(\alpha) = \left\{ \ln\left(\frac{8\sqrt{a_1 a_2}}{\pi g}\right) + \frac{\pi}{2} \sum_{j=1}^{2} \frac{1}{a_j} \sum_{mo} \left[\frac{\cot K_m^{(j)} b_j}{K_m^{(j)}} + \frac{1}{M_j} \right] \right\}^{-1} \qquad \text{(c-3)}$$

and

$$f_1(\bar{x}_t) = \sum_{mo} \frac{M_1 \cos K_m^{(1)}(b_1 - y)}{K_m^{(1)} \sin K_m^{(1)} b_1} \sin \frac{m\pi}{2} \cos M_1 x \, J_0(M_1 g) \qquad \text{(c-4)}$$

If we define two integrals I_4 and I_5 via

$$I_4 = \int\limits_{S'} J(\bar{x}') \, f_1(\bar{x}_t') ds' \qquad \text{(c-5)}$$

$$I_5 = \int\limits_{S} J(\bar{x}) \, f_1(\bar{x}_t) e^{i\alpha z} ds \qquad \text{(c-6)}$$

and interchange the α- and surface integrations, we may write Z_2 in the following form

$$Z_2 = \frac{-i\omega\mu}{4a_1^2 I_t^2} \int\limits_{-\infty}^{\infty} \frac{L(\alpha)}{\zeta^2} I_4 \, I_5 \, d\alpha \qquad \text{(c-7)}$$

The integrals I_4 and I_5 now need to be evaluated.

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The assumed current distribution is given by (2). Therefore I_4 becomes

$$I_4 = I_0 \sum_{mo} \frac{M_1 \sin \frac{m\pi}{2} J_0(M_1 g)}{K_m^{(1)} \sin K_m^{(1)} b_1} \int_{b_1-d}^{b_1} \sin k(b_1 - d - y') \cos K_m^{(1)}(b_1 - y') dy' \qquad \text{(c-8)}$$

Performing the y-integration gives

$$I_4 = kI_0 \sum_{mo} \frac{M_1 \sin \frac{m\pi}{2} J_0(M_1 g)}{K_m^{(1)} \sin K_m^{(1)} b_1} \cdot \frac{(\cos kd - \cos K_m^{(1)} d)}{M_1^2 + \alpha^2} \qquad \text{(c-9)}$$

The integral I_5 is similar to I_4 except that an additional azimuthal integration around a probe must be performed. The y-integration is the same as in I_4 so I_5 becomes

$$I_5 = \frac{kI_0}{2\pi t} \sum_{mo} \frac{M_1 \sin \frac{m\pi}{2} J_0(M_1 g)}{K_m^{(1)} \sin K_m^{(1)} b_1} \frac{(\cos kd - \cos K_m^{(1)} d)}{M_1^2 + \alpha^2}$$

$$\times \int_0^{2\pi} \cos(M_1 t \cos \theta) e^{i\alpha t \sin\theta} t \, d\theta \qquad \text{(c-10)}$$

If we designate the theta integration by $H_m(t)$, then letting $\theta \rightarrow 2\pi - \theta$ in the interval $[\pi, 2\pi]$ allows $H_m(t)$ to be written

$$H_m(t) = 2t \int_0^\pi \cos(M_1 t \cos \theta) \cos(\alpha t \sin \theta) d\theta \qquad \text{(c-11)}$$

The second cosine term may be expanded in terms of Bessel functions [7]

$$\cos(\alpha t \sin \theta) = J_0(\alpha t) + 2 \sum_{k=1}^\infty J_{2k}(\alpha t) \cos 2k\theta \qquad \text{(c-12)}$$

Interchanging the sum and integral gives

$$H_m(t) = 2t \left\{ J_0(\alpha t) \int_0^\pi \cos(M_1 t \cos\theta) d\theta \right.$$

$$\left. + 2 \sum_{k=1}^\infty J_{2k}(\alpha t) \int_0^\pi \cos 2k\theta \cos(M_1 t \cos \theta) d\theta \right\} \qquad \text{(c-13)}$$

Again consulting [7] allows us to evaluate these integrals with the result that

$$H_m(t) = 2\pi t \left\{ J_0(\alpha t) J_0(M_1 t) + 2 \sum_{k=1}^\infty (-1)^k J_{2k}(\alpha t) J_{2k}(M_1 t) \right\} \qquad \text{(c-14)}$$

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This is of the form described by Gegenbauer's Addition Theorem [6], which for the special case that the function being expanded is a zero th order Bessel function, becomes

$$J_0(pR) = J_0(pq)J_0(pr) + \sum_{k=1}^{\infty} \cos k\phi \, J_k(pq)J_k(pr) \tag{c-15}$$

where $R = [q^2 + r^2 - 2qr \cos \phi]^{\frac{1}{2}}$. If we let $p = t$, $q = \alpha$, $r = M_1$, and $\phi = \frac{\pi}{2}$, we find

$$R = [\alpha^2 + M_1^2]^{\frac{1}{2}} \tag{c-16}$$

Therefore, $H_m(t)$ in (c-14) becomes

$$H_m(t) = 2\pi t J_0[t(\alpha^2 + M_1^2)^{\frac{1}{2}}] \tag{c-17}$$

If for simplicity, we define the following quantity

$$h_m(\alpha,d) = \frac{M_1 \sin \frac{m\pi}{2} J_0(M_1 g)}{K_m^{(1)} \sin K_m^{(1)} b_1} \cdot \frac{(\cos kd - \cos K_{md}^{(1)})}{M_1^2 + \alpha^2} \tag{c-18}$$

the above results for I_4 and I_5 combine to give Z_2 as

$$Z_2 = \frac{-i\omega\mu k^2 I_0^2}{4a_1^2 I_t^2} \int_{-\infty}^{\infty} \left\{ \frac{L(\alpha)}{\zeta^2} \sum_{mo}' h_{m'}(\alpha,d) \sum_{mo} h_m(\alpha,d) J_0[t(\alpha^2+M_1^2)^{\frac{1}{2}}] \right\} d\alpha \tag{c-19}$$

If we now recall that I_t, the total current at the aperture, is given by $-I_0 \sin kd$, Z_2 becomes

$$Z_2 = \frac{-i\omega\mu k^2}{4a_1^2} \csc^2 kd \int_{-\infty}^{\infty} \left\{ \frac{L(\alpha)}{\zeta^2} \sum_{mo} h_{m'}(\alpha,d) \sum_{mo} h_m(\alpha,d) J_0[t(\alpha^2+M_1^2)^{\frac{1}{2}}] \right\} d\alpha \tag{c-20}$$

Unfortunately, the α-integration is sufficiently complex that some numerical approach has to be used in evaluating this integral. Notice that for large m, since $d < b_1$, $h_m(\alpha,d)$ will contain an exponential decay according to $\exp(-\alpha(b_1-d))$. Therefore, the integrand will decay rapidly with α and a numerical routine should not prove time consuming.

APPENDIX D

CHECKS OF R AND Z_1

This appendix will detail checks of two of the impedance contributions.
First, the radiation resistance will be checked against a result given by
Tippet [1], and second, Z_1 will be compared to the rectangular waveguide
result given by Collin [3]. The radiation resistance R_e' of an electric
dipole inside a TEM cell due to the TEM mode, as given by Tippet [1], is

$$R_e' = \frac{2Z_c}{|I|^2} \left(d\ell \, \frac{IE_o \cos\theta}{2V}\right)^2 \tag{d-1}$$

where Z_c is the characteristic impedance of an RCTL, I is the magnitude
of the current, $d\ell$ is the effective length of the dipole, E_o is the TEM
mode electric field distribution, θ is the angle between the dipole direction
and the y axis, (for a vertical dipole $\theta = 0$), and V is the voltage asso-
ciated with the TEM mode. Because the probe is an electrically short mono-
pole ($kd \ll 1$) the radiation resistance should be nearly that of a dipole
with the same current distribution. Expression (d-1) assumes an elementary
dipole, however. We may replace $IE_o d\ell$ with an effective value defined by

$$(IE_o d\ell)_{eff} = \int_{b_1-d}^{b_1} I(y)E(y)dy \tag{d-2}$$

where $I(y) = \sin k(b_1-d-y)$, and $E(y)$, for a centrally located dipole, is
found in [4] to be

$$E(y) = \frac{2V}{a} \sum_{mo} \frac{\cosh M(b_1-y)}{\sinh Mb_1} \sin\frac{m\pi}{2} \, J_o(Mg) \tag{d-3}$$

Integrating yields the following

$$(IE_o d\ell)_{eff} = \frac{2Vk}{a} \sum_{mo} \frac{(\cos kd - \cosh Md)}{\sinh Mb_1} \sin\frac{m\pi}{2} \, J_o(mg) \tag{d-4}$$

which, if we recall the definition of $h_m(\alpha,d)$, may be written

$$(IE_o d\ell)_{eff} = \frac{-2Vk}{a} \sum_{mo} h_m(k,d) \tag{d-5}$$

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If we now normalize by the magnitude of the current, $|I| = \sin kd$, we find R_e' becomes

$$R_e' = \frac{2Z_c k^2}{a^2} \csc^2 kd \left(\sum_{mo} h_m(k,d) \right)^2 \tag{d-6}$$

This may be compared to the radiation resistance R due to the TEM mode given by

$$R = \frac{2Z_c k^2}{a^2} \csc^2 kd \sum_{mo} h_{m'}(k,d) \sum_{mo} h_m(k,d) J_0 \left[t(k^2 + M^2)^{\frac{1}{2}} \right] \tag{d-7}$$

The term $h_m(k,d)$ has a strong decay in M according to

$$h_m(k,d) \sim \frac{1}{M^2} e^{-M(b_1 - d)} \tag{d-8}$$

Only a few terms will be significant. For these few terms J_0 will remain near unity since we have assumed that $\pi t/2a \ll 1$. Thus, the radiation resistance may be approximated by

$$R \approx \frac{2Z_c k^2}{a^2} \csc^2 kd \left(\sum_{mo} h_m(k,d) \right)^2 = R_e' \tag{d-9}$$

and the results indeed do check.

Next the case of no gap will be considered. As $g \to 0$, $L(\alpha) \to 0$ so only Z_1 contributes. Collin discusses a rectangular waveguide with a short circuit at a distance ℓ from the probe [3]. Thus we need to modify his result by letting $\ell \to \infty$. Making the appropriate changes, the radiation resistance for a probe in a rectangular waveguide becomes

$$R = \frac{\eta_0}{2ab\, \beta_{10} k} \tan^2 \frac{kd}{2} \tag{d-10}$$

The equivalent reactance is given by

$$X = \frac{\eta_0}{2\pi bk} \tan^2 \frac{kd}{2} \left\{ \ell n\left(\frac{4a}{\pi t}\right) + \frac{k^2 a^2}{\pi^2} (.2072) - 2\left(1 - \frac{t}{a}\right) \right.$$
$$\left. - 2k^2 \sum_{n=1} \left(1 - \frac{\sin^2 N_1 d/2}{\sin^2 kd/2}\right) \frac{K_0\left[t(N_1^2 - k^2)^{\frac{1}{2}}\right]}{N_1^2 - k^2} \right\} \tag{d-11}$$

In order to compare our expression to that of Collin, we must return to Appendix B (b-4) and let k be larger than M ($a_1 = a_2 = a$). This will create a pole on the real axis when $\alpha = \beta_{10}$. Thus I_2 becomes

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$$I_2 = \frac{-\pi i k^2}{2\beta_{10}} g_{10}(\overline{x}_t, \overline{x}_t')e^{i\beta_{10}|z|} + \pi \sum_{m,n=0}' \Delta_n \frac{k^2 - N_1^2}{\Gamma_{mn}^{(1)}} g_{mn}(\overline{x}_t, \overline{x}_t')e^{-\Gamma_{mn}^{(1)}|z|},$$

(d-12)

where the primed summation indicates that the term $m = 1$, $n = 0$ is missing. Performing the current integrations yields

$$Z_1 = \frac{i\omega\mu\, I_o^2}{\pi ab\, I_t^2} \int_o^\pi \left\{ \frac{(1 - \cos kd)^2}{2ik^2\beta_{10}} \cos\left(\frac{\pi t}{2a} \cos\theta\right)e^{i\beta_{10}t\sin\theta} \right.$$

$$\left. + \sum_{mo,n=0}^\infty {}' \Delta_n \frac{(\cos kd - \cos N_1 d)^2}{k^2 - N_1^2} \frac{1}{\Gamma_{mn}^{(1)}}\cos(Mt\cos\theta)e^{-\Gamma_{mn}^{(1)}t\sin\theta} \right\} d\theta$$

(d-13)

The sum over m and n is precisely that encountered by Collin [3] with the result that

$$\sum_{mo,n=0}^\infty {}' \Delta_n \frac{(\cos kd - \cos N_1 d)}{k^2 - N_1^2} \frac{1}{\Gamma_{mn}^{(1)}} \cos(Mt\cos\theta)e^{-\Gamma_{mn}^{(1)}t\sin\theta}$$

$$= \frac{(1 - \cos kd)^2}{2k^2} \frac{a}{\pi}\left[\ell n\left(\frac{4a}{\pi t}\right) + \frac{k^2 a^2}{2}(.2072) - 2\left(1 - \frac{t}{a}\right)\right]$$

$$+ \frac{a}{\pi} \sum_{n=1}^\infty \frac{(\cos kd - \cos N_1 d)^2}{k^2 - N_1^2} K_o\left[t(N_1^2 - k^2)^{\frac{1}{2}}\right]$$

(d-14)

The significant contribution for $\pi t/2a \ll 1$ may be approximated via

$$\cos\left(\frac{\pi t}{2a} \cos\theta\right)e^{i\beta_{10}t\sin\theta} \approx 1$$

(d-15)

Combining these results and integrating over θ, which simply introduces a factor of π, yields

$$Z_1 \approx \frac{i\omega\mu\, I_o^2}{\pi ab\, I_t^2} \left\{ \frac{(1 - \cos kd)^2}{2ik^2\beta_{10}} \pi + \frac{a(1 - \cos kd)^2}{2k^2}\left[\ell n\left(\frac{4a}{\pi t}\right) + \frac{k^2 a^2}{\pi^2}(.2072) \right.\right.$$

$$\left.\left. -2\left(1 - \frac{t}{a}\right)\right] + a \sum_{n=1}^\infty \frac{(\cos kd - \cos N_1 d)^2}{k^2 - N_1^2} K_o\left[t(N_1^2 - k^2)^{\frac{1}{2}}\right] \right\}$$

(d-16)

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Finally, letting $I_t = -I_o \sin kd$, and separating Z_1 into real and imaginary parts R and X respectively, we obtain

$$R = \frac{\eta_o}{2abk\beta_{10}} \tan^2 \frac{kd}{2} \tag{d-17}$$

$$X = \frac{\eta_o}{2\pi bk} \tan^2 \frac{kd}{2} \left\{ \ln(\frac{4a}{\pi t}) + \frac{k^2 a^2}{\pi^2}(.2072) - 2(1 - \frac{t}{a}) \right.$$

$$\left. - 2k^2 \sum_{n=1}^{\infty} \left(1 - \frac{\sin^2 N_1 d/2}{\sin^2 kd/2}\right)^2 \frac{K_o[t(N_1^2 - k^2)^{\frac{1}{2}}]}{N_1^2 - k^2} \right\} \tag{d-18}$$

which are the precise results found by Collin in (d-10) and (d-11).

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APPENDIX E

SUBROUTINE ZIN

SUBROUTINE ZIN is used to compute the input impedance Z of a probe inserted into a TEM cell. ZIN calls upon four major subroutines. These are (1) SUBROUTINE ZC which computes the characteristic impedance of a section of RCTL according to (18); (2) SUBROUTINE HMSUM which sums $h_m(\alpha,d)$, and $h_m(\alpha,d)J_0[t(\alpha^2 + M_1^2)^{1/2}]$; (3) SUBROUTINE XSUM which finds the reactance X given by (20), and (4) SUBROUTINE INTEGR which integrates a complex function over the real axis. INTEGR is called twice in order to evaluate the principal value integral defined by (21). The input to ZIN is mostly via a common block PARAM which contains the cell dimensions a_1, a_2, b_1, b_2, and g, the probe dimensions d and t, the constant π, and the TEM mode propagation constant k. Figure 6 gives a flow chart of SUBROUTINE ZIN. The only direct input to ZIN is ε which sets the desired accuracy. ZIN outputs Z_c, R, X, and δX as well as the total impedance Z.

The constant ε is used to set the upper summation limit in the various sums evaluated by the subroutines. The infinite integral in δX is also truncated according to ε. There are three basic sums; the sums inherent in $L(\alpha)$ and X, and the summation of the $h_m(\alpha,d)$. We will begin with the last. For large m, that is $M_1^2 \gg k^2 - \alpha^2$, we have $K_m^{(1)} \sim iM_1$, and

$$h_m(\alpha,d) \sim \frac{\sin \frac{m\pi}{2} \cosh M_1 d}{M_1^2 \sinh M_1 b_1} \approx \frac{\sin \frac{m\pi}{2}}{M_1^2} e^{-M_1(b_1-d)} \qquad (e-1)$$

We wish to truncate the summation so that the remainder is less than ε. Thus we need to look at the remainder sum

$$\sum_{m=K}^{\infty} \frac{4a_1^2(-1)^m}{(2m-1)^2\pi^2} e^{-(2m-1)\pi(b_1-d)/2a_1} < \varepsilon \qquad (e-2)$$

Clearly the sum is dominated by the following much simpler sum.

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$$R_K(x) = \sum_{m=K}^{\infty} (-1)^m e^{-(2m-1)x} \tag{e-3}$$

so we will set M by requiring that

$$\frac{4a_1^2}{\pi^2} R_K \left(\frac{\pi(b_1-d)}{2a_1} \right) < \varepsilon \tag{e-4}$$

Summing $R_K(x)$ is straightforward and yields

$$R_K(x) = \frac{2e^{-2(K-1)x}}{\cosh x} \tag{e-5}$$

Thus inserting this result into (e-4) and solving for K we find

$$K > \frac{a_1}{\pi(b_1-d)} \ln \left[\frac{8a_1^2}{\varepsilon\pi \cosh \frac{\pi(b_1-d)}{2a_1}} \right] + 1 \tag{e-6}$$

This condition will be used to truncate the $h_m(\alpha,d)$ summation.

Next consider the summation in $L(\alpha)$ given by

$$\frac{1}{a_j} \sum_{mo} \left[\frac{\cot K_m^{(j)}}{K_m^{(j)}} + \frac{1}{M_j} \right] \tag{e-7}$$

For large m the remainder will behave according to

$$\frac{2}{\pi} \sum_{m=K_j}^{\infty} \frac{1}{(2m-1)} \left(1 - \coth \frac{(2m-1)\pi b_j}{2a_j} \right) \tag{e-8}$$

Again we choose a simpler dominating sum. For large m, such that $(2m-1)\pi b_j/2aj >> 1$, the coth term may be replaced by

$$\coth \frac{(2m-1)\pi b_j}{2a_j} \approx 1 + 2e^{-(2m-1)\pi b_j/a_j} \tag{e-9}$$

Therefore we need to consider

$$\frac{4}{\pi} \sum_{m=K_j}^{\infty} \frac{1}{2m-1} e^{-(2m-1)\pi b_j/a_j} \tag{e-10}$$

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Clearly we have

$$\frac{4}{\pi} \sum_{m=K_j}^{\infty} \frac{1}{2m-1} e^{-(2m-1)\pi b_j/a_j} < \frac{4}{\pi} \sum_{m=K_j}^{\infty} e^{-(2m-1)\pi b_j/a_j} \qquad (e\text{-}11)$$

Summing the R.H.S. and requiring that the result is less than $\varepsilon/2$ yields

$$K_j > \frac{a_j}{2\pi b_j} \ln \left[\frac{16}{\varepsilon\pi \sinh \frac{\pi b_j}{a_j}} \right] + 1 \qquad (e\text{-}12)$$

This condition will be checked for both $j = 1$ and 2, and the maximum value K_j chosen.

We next consider the series contained in X. Because both kd and kt are small, the decay of the series will be primarily due to the N_1^2 in the denominator. Thus, we will consider the remainder series dominated by

$$\sum_{n=N}^{\infty} \frac{1}{N_1^2} , \qquad (N_1 = n\pi/b_1) \qquad (e\text{-}13)$$

This series in turn may be bounded by a simple integral

$$\sum_{n=N}^{\infty} \frac{1}{N_1^2} < \left(\frac{b_1}{\pi}\right)^2 \int_{N-1}^{\infty} \frac{dx}{x^2} = \left(\frac{b_1}{\pi}\right)^2 \frac{1}{N-1} \qquad (e\text{-}14)$$

So requiring that the R.H.S. be bounded by ε implies that

$$N > \frac{b_1^2}{\varepsilon\pi} + 1 \qquad (e\text{-}15)$$

What remains is to bound the truncation of the principal value integral. In terms of α we see $h_m(\alpha,d)$ behaving roughly as α^{-2}. Therefore, the total integrand behaves approximately as α^{-6}. Thus, the truncation gives a remainder integral similar to

$$C \int_X^{\infty} \alpha^{-6} d\alpha = \frac{C}{5} x^{-5} \qquad (e\text{-}16)$$

where $C = -\omega\mu k^2 \csc^2 kd/4a_1^2$. If we bound this result by $\varepsilon/2$, x must satisfy

$$x > (2C/5\varepsilon)^{1/5} , \qquad (e\text{-}17)$$

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which is the criterion used to set the upper limit of integration.

A listing of the subroutines follows. They were run at the University of Colorado using the MNF compiler, Version 5.4. It should be stressed that ε sets a percentage error rather than an absolute error. That is $\varepsilon = 0.01$ implies 1% error rather than accuracy to two digits beyond the decimal point.

MNF.

```
 1.    000000B        COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,KO
 2.    002131B        REAL PI,KO
 3.    002131B        COMPLEX Z
 4.    002131B        A1=1.0
 5.    002133B        A2=1.0
 6.    002134B        B1=1.0
 7.    002135B        B2=1.0
 8.    002136B        G=0.2
 9.    002136B        T=0.001
10.    002140B        PI=4.0*ATAN(1.0)
11.    002143B        F=3.0E+06
12.    002145B        C=2.99793E+08
13.    002146B        KO=2.0*PI*F/C
14.    002151B        EPS=0.01
15.    002152B        DO 10 M=34,39
16.    002155B        D=FLOAT(M)/40.0
17.    002156B        CALL ZIN(EPS,ZC,ZR,ZI,DELZI,Z)
18.    002162B  10    CONTINUE
19.    002164B        END
```

```
 1.    000000B        SUBROUTINE ZIN(EPS,ZC,ZR,ZI,DELZI,Z)
 2.    000000B  C
                      C     SUBROUTINE ZIN COMPUTES THE INPUT IMPEDANCE Z OF A PROBE
                      C     IN A TEM CELL. THE ONLY DIRECT INPUT TO ZIN IS EPS (LESS THAN
                      C     ONE), THE DESIRED ACCURACY. THE GUIDE PARAMETERS ARE PASSED
                      C     INTO ZIN VIA THE COMMON BLOCK PARAM WHICH CONTAINS THE FOLLOWING
                      C        A1,A2 THE UPPER AND LOWER CHAMBER HALF-WIDTHS
                      C        B1,B2 THE UPPER AND LOWER CHAMBER HEIGHTS
                      C        D THE PROBE LENGTH
                      C        G THE GAP WIDTH
                      C        T THE PROBE RADIUS
                      C        PI THE SIXTEENTH LETTER OF THE GREEK ALPHABET
                      C        KO THE TEM MODE PROPAGATION CONSTANT
                      C     THE OUTPUTS ARE
                      C        ZC THE CHARACTERISTIC IMPEDANCE OF THE RCTL SECTION
                      C        ZR THE REAL RADIATION RESISTANCE (19)
                      C        ZI THE ORDINARY WAVEGUIDE REACTANCE (20)
                      C        DELZI THE GAP PERTURBATION REACTANCE (21)
                      C        Z THE TOTAL IMPEDANCE, Z=R+J*(ZI+DELZI)
```

```
 3.    000000B        COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,KO
 4.    000000B        COMMON/CPARAM/ZERO,UNITY,J
 5.    000000B        REAL PI,KO
 6.    000000B        COMPLEX ZERO,UNITY,J,HM,HMBJ,VAL1,VAL2,Z
 7.    000000B        LOGICAL GG
 8.    000000B        EXTERNAL XOFA
 9.    000000B        ZERO =(0.0,0.0)
10.    000011B        UNITY=(1.0,0.0)
11.    000014B        J=(0.0,1.0)
12.    000016B        NSTEP=1024
13.    000020B        XO=30.0*PI*KO*((KO/A1/SIN(KO*D))**2.0)
14.    000030B        X1=0.0
15.    000031B        X2=KO-EPS
16.    000032B        X3=KO+EPS
```

```
18.   000033B     X4=(2.0*X0/EPS/5.0)**0.2
19.   000041B     CALL ZONORM(EPS,ZC)
20.   000045B     CALL HMSUM(K0,HM,HMBJ,EPS)
21.   000050B     CALL XSUM(EPS,ZI)
22.   000054B     CALL INTEGR(X1,X2,EPS,NSTEP,XOFA,VAL1,X,XRELTV,K,GG)
23.   000057B     CALL INTEGR(X3,X4,EPS,NSTEP,XOFA,VAL2,X,XRELTV,K,GG)
24.   000062B     ST1=K0/A1/SIN(K0*D)
25.   000067B     ZR=ST1*ST1*ZC*REAL(HM*HMBJ)
26.   000077B     DELZI=REAL(VAL1+VAL2)
27.   000113B     Z=UNITY*ZR+J*(ZI+DELZI)
28.   000113B     PRINT 10,A1,A2,B1,B2,G
29.   000125B  10 FORMAT(1X,*THE GUIDE DIMENSIONS ARE AS FOLLOWS*/,1X,*      A1=  *
                 1F12.6/,1X,*        A2= *F12.6/,1X,*      B1= *F12.6/,1X,*      B2=  *
                 2F12.6/,1X,*        G= *F12.6//)
30.   000125B     PRINT 11,D,T
31.   000132B  11 FORMAT(1X,* THE PROBE DIMENSIONS ARE AS FOLLOWS*/,1X,*      D=  *
                 1F12.6/,1X,*        T= *F12.6//)
32.   000132B     PRINT 12,ZC,ZR,ZI,DELZI,Z
33.   000142B  12 FORMAT(1X,*THE RESULTING IMPEDANCES ARE AS FOLLOWS*/,1X,*      ZC=
                 1*F12.6/,1X,*        ZR= *F12.6/,1X,*      ZI= *F12.6/,1X,*      DELZI=
                 2*F12.6//,1X,*      THE TOTAL IMPEDANCE Z= *F12.6,* +J *F12.6,5/)
34.   000142B     RETURN
35.   000144B     END

1.    000000B     SUBROUTINE ZONORM(EPS,X)
2.    000000B     COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,K0
3.    000000B     REAL PI,K0,KM1,KM2,Q0,L1,L2,LIM
4.    000000B     Q0=0.0
5.    000006B     X1=PI*B1/A1
6.    000011B     X2=PI*B2/A2
7.    000013B     X3=(EXP(X1)-EXP(-X1))/2.0
8.    000022B     X4=(EXP(X2)-EXP(-X2))/2.0
9.    000032B     L1=1.0+ALOG(16.0/EPS/PI/X3)/X3/2.0
10.   000043B     L2=1.0+ALOG(16.0/EPS/PI/X4)/X4/2.0
11.   000053B     LIM=AMAX1(L1,L2)
12.   000055B     MLIM=INT(LIM)+1
13.   000057B     DO 10 M=1,MLIM
14.   000061B     KM1=(2.0*M-1.0)*PI/2.0/A1
15.   000065B     KM2=(2.0*M-1.0)*PI/2.0/A2
16.   000070B     ST1=KM1*B1
17.   000072B     ST2=KM2*B2
18.   000073B     ST3=1.0-1.0/TANH(ST1)
19.   000100B     ST4=1.0-1.0/TANH(ST2)
20.   000104B     ST5=FLOAT(2*M-1)
21.   000106B     Q0=Q0+(ST3+ST4)/ST5
22.   000112B  10 CONTINUE
23.   000114B     ST6=8.0*SQRT(A1*A2)/PI/G
24.   000122B     ST7=ALOG(ST6)+Q0
25.   000126B     X=120.0*PI*PI/ST7/8.0
26.   000131B     RETURN
27.   000133B     END

1.    000000B     SUBROUTINE BJ0(X,BJ)
2.    000000B     T=X/3.
3.    000001B     Z=3./X
4.    000002B     Y=T*T
5.    000003B     IF (X.GE.3.) GO TO 10
6.    000004B     BJ=1.-Y*(2.2499997-Y*(1.2656208-Y*(.3163866-Y*(.0444479-
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7.   000015B        1Y*(.0039444-Y*.0002100)))))
8.   000020B        RETURN
9.   000023B        W=SQRT(X)
           10    AF=.79788456-Z*(.00000077+Z*(.00552740+Z*(.00009512-Z*(.00137237
                 1-Z*(.00072805-Z*.00014476)))))
10.  000034B        THETA=X-.78539816-Z*(.04166397+Z*(.00003954-Z*(.00262573
                 1-Z*(.00054125+Z*(.0002933-Z*.00013558)))))
11.  000047B        BJ=AF*COS(THETA)/W
12.  000053B        RETURN
13.  000056B        END

1.   000000B        SUBROUTINE HMSUM(ALPHA,HM,HMBJ,EPS)
2.   000000B        COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,KO
3.   000000B        COMMON/CPARAM/ZERO,UNITY,J
4.   000000B        REAL PI,KO,M1,LIM
5.   000000B        COMPLEX ZERO,UNITY,J,HM,HMBJ,KM1,ST2,ST3
6.   000000B        HM=ZERO
7.   000011B        HMBJ=ZERO
8.   000013B        X1=PI*(B1-D)/2.0/A1
9.   000017B        X2=(EXP(X1)+EXP(-X1))/2.0
10.  000026B        X3=8.0*A1*A1/EPS/PI/X2
11.  000032B        LIM=1.0+ALOG(X3)/X1/2.0
12.  000037B        MLIM=INT(LIM)+1
13.  000041B        DO 10 M=1,MLIM
14.  000043B        M1=(2.0*M-1.0)*PI/2.0/A1
15.  000047B        ST1=ALPHA*ALPHA+M1*M1
16.  000051B        KM1=CSQRT(UNITY*(KO*KO-ST1))
17.  000061B        ST2=M1*SIN(M1*A1)*(UNITY*COS(KO*D)-CCOS(KM1*D))
18.  000107B        ST3=KM1*CSIN(KM1*B1)*ST1
19.  000121B        ST4=M1*G
20.  000123B        ST5=SQRT(ST1)*T
21.  000126B        CALL BJO(ST4,BJG)
22.  000131B        CALL BJO(ST5,BJT)
23.  000133B        HM=HM+ST2*BJG/ST3
24.  000150B        HMBJ=HMBJ+ST2*BJG*BJT/ST3
25.  000167B     10 CONTINUE
26.  000172B        RETURN
27.  000174B        END

1.   000000B        SUBROUTINE BJKO(X,Y)
2.   000000B        IF (X.GE.2.0) GO TO 10
3.   000002B        Z=X/2.0
4.   000003B        V=Z*Z
5.   000004B        T=X/3.75
6.   000005B        W=T*T
7.   000006B        U=1.0+W*(3.5156229+W*(3.0899424+W*(1.2067492+W*(0.2659732+
                 1W*(0.0360768+W*0.0045813)))))
8.   000017B        Y=-ALOG(Z)*U-0.57721566+V*(0.42278420+V*(0.23069756+V*(0.0348859+
                 1V*(0.00262698+V*(0.0001075+V*0.0000074)))))
9.   000036B     10 Z=2.0/X
10.  000040B        RETURN
11.  000041B        U=1.25331414-Z*(0.07832358-Z*(0.02189568-Z*(0.01062446-Z*(
                 10.00587872-Z*(0.0025154-Z*(0.0005328)))))
12.  000053B        Y=U/SQRT(X)/EXP(X)
13.  000062B        RETURN
14.  000065B        END
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000000B      1.    SUBROUTINE XSUM(EPS,X)
000000B      2.    COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,KO
000000B      3.    REAL PI,KO,N1,LIM
000002B      4.    SUM=0.0
000006B      5.    LIM=1.0+B1/EPS/PI
000010B      6.    NLIM=INT(LIM)+1
000012B      7.    DO 10 N=1,NLIM
000014B      8.    N1=FLOAT(N)*PI/B1
000030B      9.    ST1=SIN(N1*D/2.0)/SIN(KO*D/2.0)
000033B     10.    ST2=(1.0-ST1*ST1)**2.0
000036B     11.    ST3=N1*N1-KO*KO
000041B     12.    ST4=SQRT(ST3)*T
000044B     13.    CALL BJKO(ST4,BKT)
000047B     14.    SUM=SUM+ST2*BKT/ST3
000052B     15. 10 CONTINUE
000055B     16.    ST5=4.0*A1/PI/T
000057B     17.    ST6=A1*KO/PI
000065B     18.    ST7=ALOG(ST5)+ST6*ST6*4.207175-2.0*KO*KO*SUM
000072B     19.    ST8=TAN(KO*D/2.0)
000076B     20.    X=30.0*ST8*ST8*ST7/B1/KO
000100B     21.    RETURN
            22.    END

000000B      1.    SUBROUTINE LALPHA(ALPHA,X,EPS)
000000B      2.    COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,KO
000000B      3.    COMMON/CPARAM/ZERO,UNITY,J
000000B      4.    REAL PI,KO,M1,M2,L1,L2,LIM
000020B      5.    COMPLEX ZERO,UNITY,J,KM1,KM2,SUM,ST1,ST2,X
000023B      6.    SUM=ZERO
000026B      7.    ZETA2=KO*KO-ALPHA*ALPHA
000030B      8.    X1=PI*B1/A1
000040B      9.    X2=PI*B2/A2
000050B     10.    X3=(EXP(X1)-EXP(-X1))/2.0
000061B     11.    X4=(EXP(X2)-EXP(-X2))/2.0
000071B     12.    L1=1.0+ALOG(16.0/EPS/PI/X3)/X3/2.0
000073B     13.    L2=1.0+ALOG(16.0/EPS/PI/X4)/X4/2.0
000075B     14.    LIM=AMAX1(L1,L2)
000077B     15.    MLIM=INT(LIM)+1
000102B     16.    DO 10 M=1,MLIM
000104B     17.    M1=FLOAT(M)*PI/2.0/A1
000115B     18.    M2=FLOAT(M)*PI/2.0/A2
000125B     19.    KM1=CSQRT(UNITY*(ZETA2-M1*M1))
000163B     20.    KM2=CSQRT(UNITY*(ZETA2-M2*M2))
000222B     21.    ST1=CCOS(KM1*B1)/CSIN(KM1*B1)/KM1+UNITY/M1
000234B     22.    ST2=CCOS(KM2*B2)/CSIN(KM2*B2)/KM2+UNITY/M2
000240B     23.    SUM=SUM+ST1/A1+ST2/A2
000246B     24. 10 CONTINUE
000271B     25.    ST3=8.0*SQRT(A1*A2)/PI/G
000275B     26.    X=UNITY/(UNITY*ALOG(ST3)+PI*SUM/2.0)
            27.    RETURN
            28.    END

000000B      1.    SUBROUTINE XOFA(ALPHA,Y,EPS)
000000B      2.    COMMON/PARAM/A1,A2,B1,B2,D,G,T,PI,KO
000000B      3.    REAL PI,KO
000000B      4.    COMPLEX LA,HM,HMBJ,Y
000010B      5.    ZETA2=KO*KO-ALPHA*ALPHA
             6.    CALL LALPHA(ALPHA,LA,EPS)
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000014B      7.    CALL HMSUM(ALPHA,HM,HMBJ,EPS)
000020B      8.    ST1=K0/A1/SIN(K0*D)
000025B      9.    ST2=-60.0*PI*K0*ST1*ST1
000031B     10.    Y=LA*HM*HMBJ*ST2/ZETA2
000042B     11.    RETURN
000045B     12.    END

000000B      1.       SUBROUTINE INTEGR(A,B,EPS,NSTEP,F,VALUE,X,XRELTV,K,G)
000000B      2.       COMPLEX FCNA,FCNB,FCNXI,T,SUM,QX1,QX2,VALUE,Q(16)
000000B      3.       LOGICAL G
000056B      4.       QX1=0.0
000060B      5.       QX2=0.0
000060B      6.       H=B-A
000062B      7.       CALL F(A,FCNA,EPS)
000067B      8.       CALL F(B,FCNB,EPS)
000073B      9.       T=(FCNA+FCNB)*H/2.0
000100B     10.       NX=1
000101B     11.       N=1
000102B     12.  10   K=2**N
000104B     13.       H=H/2.0
000106B     14.       SUM=(0.0,0.0)
000107B     15.       DO 20 I=1,NX
000112B     16.       XI=2.0*FLOAT(I)-1.0
000114B     17.       XA=A+XI*H
000116B     18.       CALL F(XA,FCNXI,EPS)
000122B     19.       SUM=SUM+FCNXI
000125B     20.  20   CONTINUE
000130B     21.       T=T/2.0+H*SUM
000137B     22.       Q(N)=(T+H*SUM)*2.0/3.0
000145B     23.       IF (N-2) 100,30,30
000151B     24.  30   FX=4.0
000152B     25.       DO 40  J=2,N
000155B     26.       I=N+1-J
000156B     27.       FX=FX*4.0
000160B     28.       Q(I)=Q(I+1)+(Q(I+1)-Q(I))/(FX-1.0)
000171B     29.  40   CONTINUE
000173B     30.       IF (N-3) 90,50,50
000174B     31.  50   X=0.0
000175B     32.       XRELTV=0.0
000175B     33.       XREAL=ABS(REAL(Q(1)-QX2)+ABS(REAL(QX2-QX1))
000206B     34.       XIMAG=ABS(AIMAG(Q(1)-QX2)+ABS(AIMAG(QX2-QX1))
000217B     35.       CR=CABS(Q(1))
000223B     36.       IF (CR.EQ.0.0) GO TO 60
000227B     37.       XR=AMAX1(XREAL,XIMAG)/CR
000230B     38.       GO TO 70
000230B     39.  60   XR=0.0
000230B     40.  70   XRELTV=AMAX1(XR,XRELTV)
000233B     41.       X=AMAX1(X,XREAL,XIMAG)
000237B     42.       COMPA=X-3.0*EPS
000242B     43.       COMPR=XRELTV-3.0*EPS
000244B     44.       IF (COMPA.LE.0.0.OR.COMPR.LE.0.0) 110,80
000247B     45.       IF (NSTEP-K) 110,110,90
000252B     46.  80   QX1=QX2
000254B     47.  90   QX2=Q(1)
000257B     48.  100  NX=NX*2
000261B     49.       N=N+1
000262B     50.       GO TO 10
000263B     51.  110  VALUE=Q(1)
000265B     52.       G=NSTEP.LT.K
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53.     000270B      RETURN
54.     000273B      END

THE GUIDE DIMENSIONS ARE AS FOLLOWS
    A1=    1.000000
    A2=    1.000000
    B1=    1.000000
    B2=    1.000000
    G=     .200000

THE PROBE DIMENSIONS ARE AS FOLLOWS
    D=     .850000
    T=     .001000

THE RESULTING IMPEDANCES ARE AS FOLLOWS
    ZC=    62.640845
    ZR=    2.289899
    ZI= -3132.962182
    DELZI=  -.122230

    THE TOTAL IMPEDANCE Z=     2.289899 +J -3133.084413


THE GUIDE DIMENSIONS ARE AS FOLLOWS
    A1=    1.000000
    A2=    1.000000
    B1=    1.000000
    B2=    1.000000
    G=     .200000

THE PROBE DIMENSIONS ARE AS FOLLOWS
    D=     .875000
    T=     .001000

THE RESULTING IMPEDANCES ARE AS FOLLOWS
    ZC=    62.640845
    ZR=    2.447836
    ZI= -3049.147672
    DELZI=  -.130126

    THE TOTAL IMPEDANCE Z=     2.447836 +J -3049.277799


THE GUIDE DIMENSIONS ARE AS FOLLOWS
    A1=    1.000000
    A2=    1.000000
    B1=    1.000000
    B2=    1.000000
    G=     .200000
```

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Figure 1. An NBS TEM Cell

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Figure 2. A RCTL with coaxial-line probe
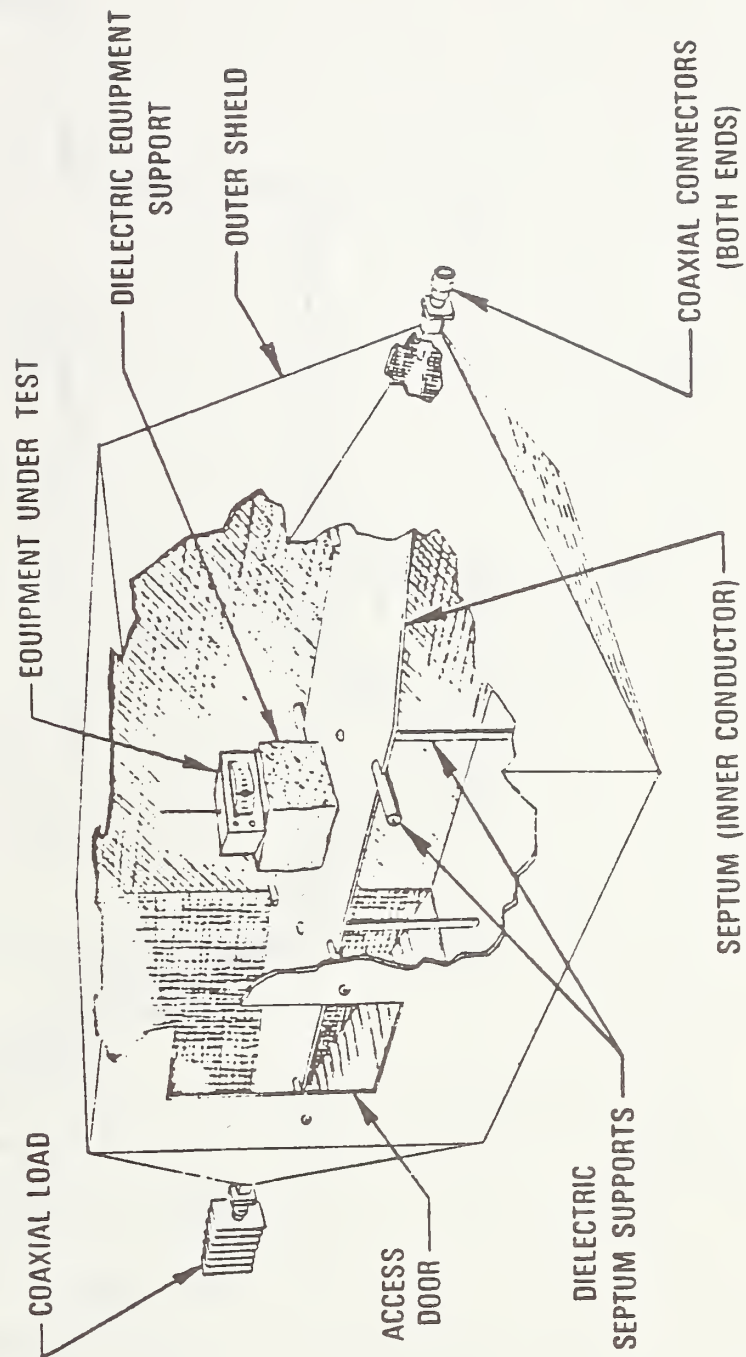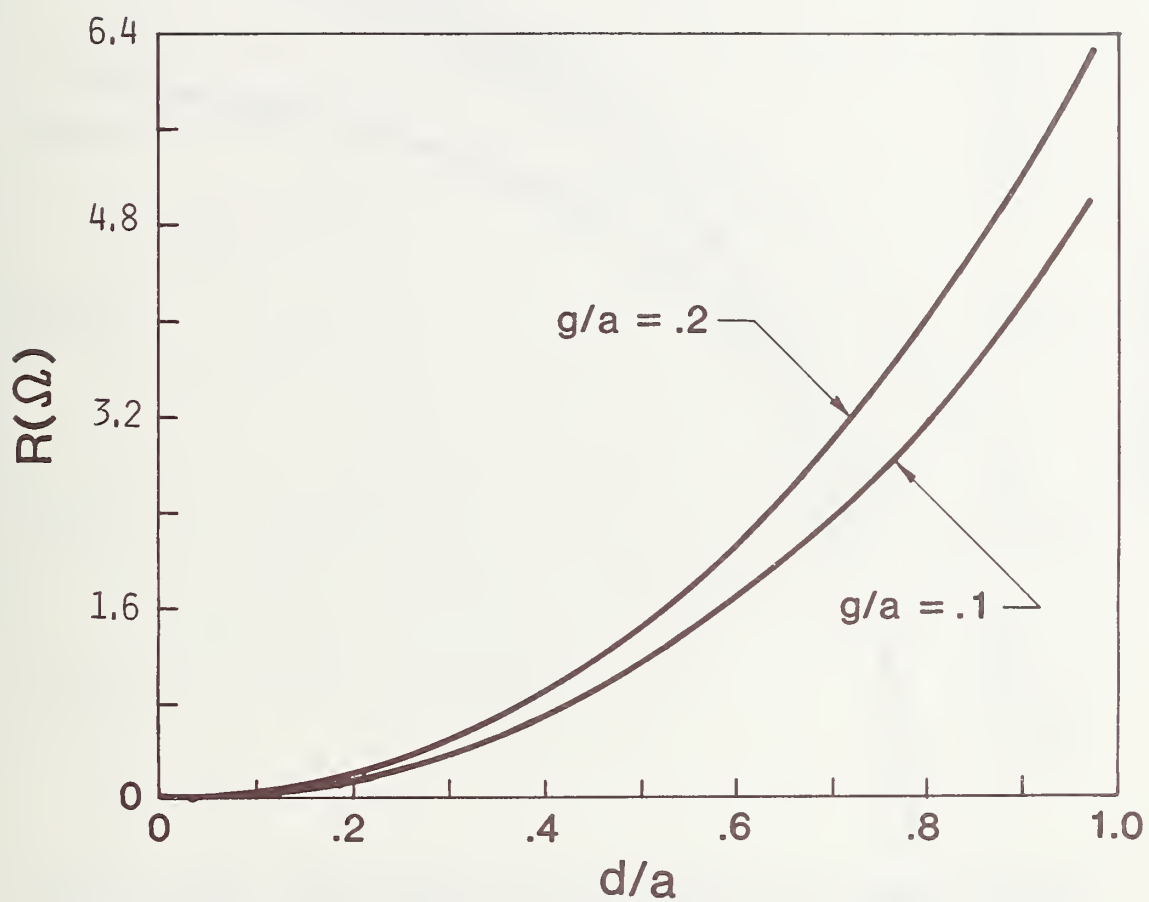
Figure 3.   Radiation resistance for $a_1 = a_2 = b_1 = b_2 = 1$ m,
t = 1 mm, and f = 1 MHz
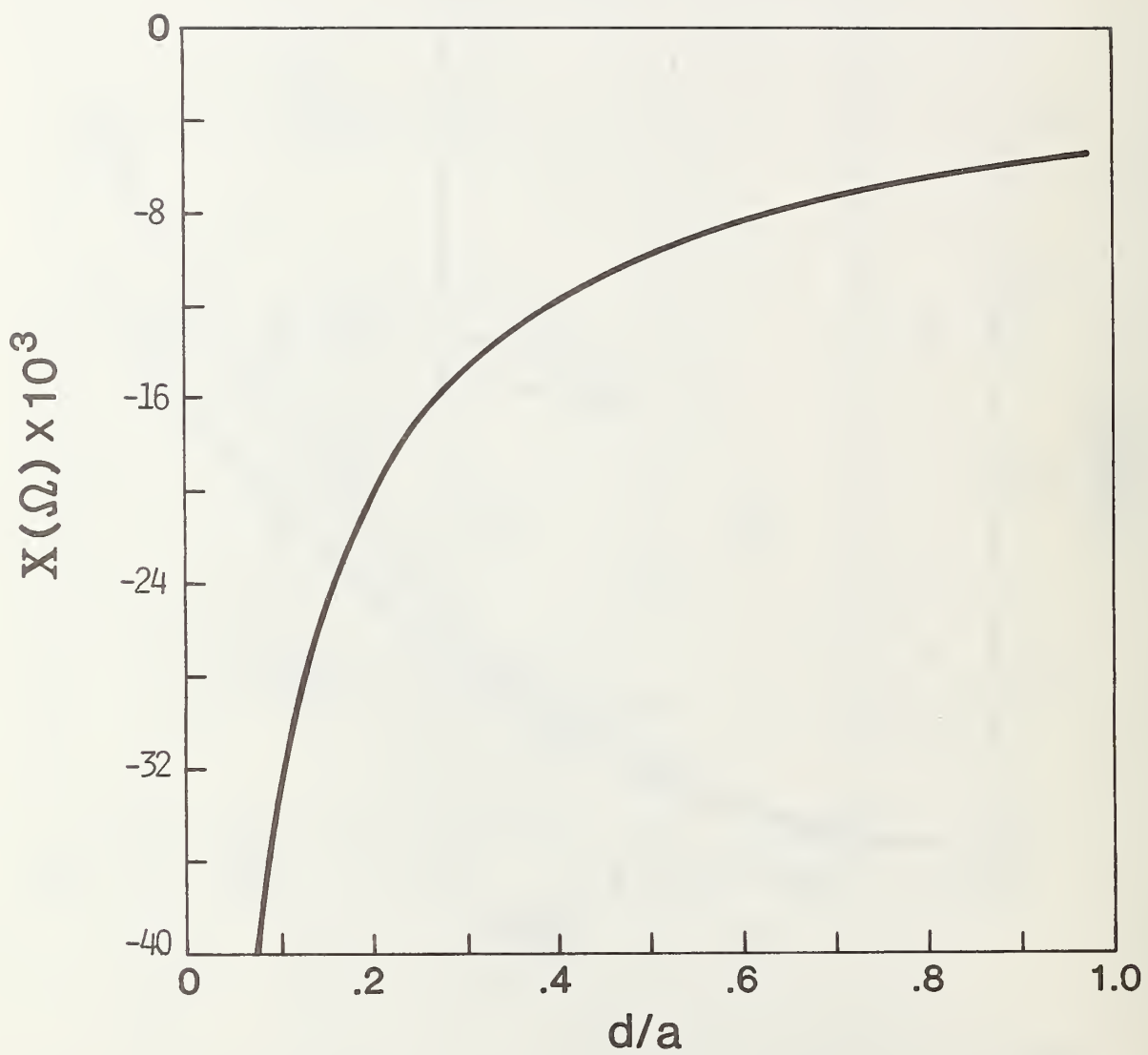
Figure 4.   Reactance for $a_1 = a_2 = b_1 = b_2 = 1$ m, $t = 1$ mm, and $f = 1$ MHz
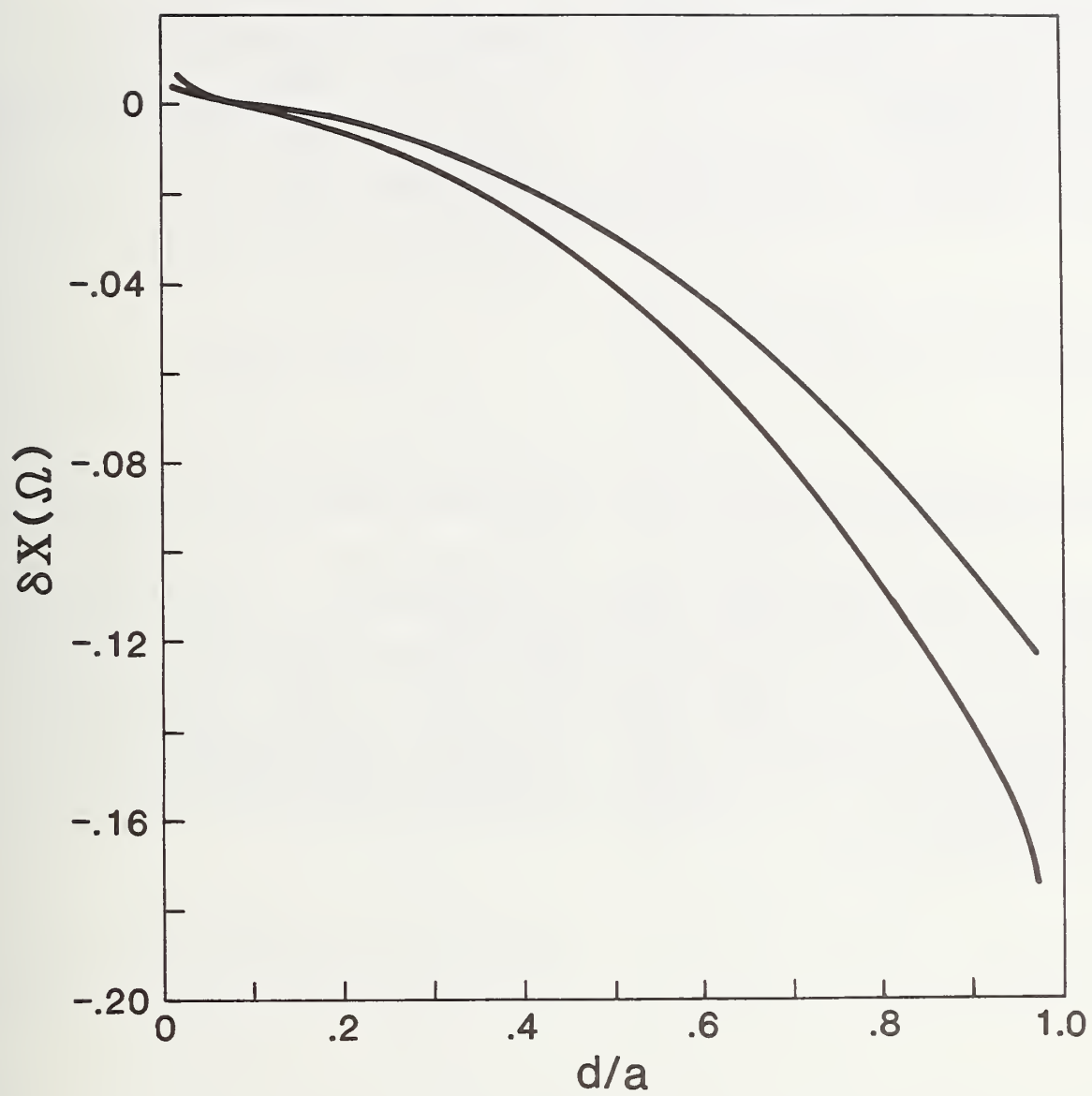
Figure 5. Perturbation reactance for $a_1 = a_2 = b_1 = b_2 = 1$ m,
$t = 1$ mm, and $f = 1$ MHz

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The input impedance of a probe antenna exciting a transverse electromagnetic (TEM) transmission line cell is formulated by a variational approach. The formulation also utilizes the results from a previous work on the field distribution inside a TEM cell excited by a vertical electrical Hertzian dipole. The final result of impedance is shown to consist of two distinct terms, which are respectively contributed by the ordinary rectangular waveguide and the gap perturbation. Numerical results for both the real and imaginary parts of the impedance are given. The resistive part is found to be proportional to the square of the probe length, and the reactive part largely capacitive.

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