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THE EFFECTS OF A NEARBY BIOLOGICAL BODY ON THE
PARAMETERS OF A SMALL HAND-HELD RADIO OPERATING
IN THE H.F. BAND (3 MHz-30 MHz)

A Thesis Presented to
The Faculty of the College of Engineering and Technology
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

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CHAPTER 1

Introduction

1.1 General Overview

The use of small portable hand-held radios has been a common means of communication for quite some time now in such areas as the military and law enforcement. The operation and performance of the radio itself is well known and documented in many texts on fundamental electromagnetics or antenna theory. However, there is a common difference the above mentioned areas have with the manner the radio is characterized in the literature. All of the parameters for the radio, such as radiation pattern and current distribution on the antenna, are formulated with the assumption that the radio exists in homogeneous free space, or over a perfectly conducting ground plane at best. However, in actual practice, the radio is in the presence of the body of the operator.

The goal of this investigation is to determine how the presence of a biological body affects the parameters, such as radiation pattern and efficiency, of a small hand-held radio. Previous investigations[1-6] of this problem have followed a different approach than what will be done in this report. One popular technique used to model three-dimensional lossy bodies is to approximate the shape of the body with impedance patches. In this method, the unknown volume current density is replaced with an equivalent unknown surface current density. A general-purpose computer

code known quite appropriately as "PATCH" has been developed for this impedance patch technique. The PATCH code allows the user to model three-dimensional shapes with interlocking planar triangular patches. A previous investigation used this PATCH program to model a PVC pipe filled with a saline solution, which was to be used to model a biological body. However, that investigation focused on the frequency band of 450 - 470 MHz, whereas this report limits itself to the H.F. band of 3 - 30 MHz. The H.F. band (3-30 MHz) is currently receiving renewed interest due to such factors as the use of a skywave and the crowding of channels in the higher spectrum is increasing. Other earlier investigations of this problem have been purely experimental in nature, due primarily to the lack of computer sophistication at the time. Still other solutions to similar problems, such as scattering from infinite dielectric cylinders with arbitrary cross sections[7-8] and scattering from inhomogeneous bodies of revolution[9-10] have been offered.

1.2 Historical Background

To better facilitate the understanding of the analysis of the 'man with radio' problem, a knowledge of the methods and techniques historically used to solve these types of problems would be beneficial. As stated previously, the literature contains the analysis of electromagnetic problems, such as radiation and scattering, that is limited to simple canonical geometries residing in a well-behaved medium. There is good reason for this limitation. Only for these simple shapes and media is it possible to formulate closed-form solutions to the equations that describe the systems. Once a departure is made from these simplistic situations, it rapidly becomes impossible to formulate descriptive equations, much less solve them. To wit: a complex shape might be impossible to describe with closed form function or a definite integral might not yield to any known methods. So the situation has remained for many years. The theory was understood but the mathematical complexity formed a seemingly impenetrable barrier against any advancement or application. However, one momentous event would effectively demolish this barrier.

The development of the microprocessor, which eventually led to powerful, high-speed digital computers, opened up a whole new realm for the antenna designer. Complex structures could now be modeled and analyzed to an arbitrary degree of accuracy, limited only by the storage capacity and precision of the computer being used. Complementing and

utilizing the raw number crunching power of the digital computer is a mathematical technique called the "Method of Moments," or simply MoM[11]. The theory and application of MoM will be explained and exemplified in a subsequent section of this report. In the most crude sense, what MoM does is to approximate an unknown function as a linear combination of known independent functions. A system of equations is then generated to solve for expansion coefficients associated with the known independent functions. The system of equations is then solved by applying traditional matrix methods. As the approximations made by MoM become more and more representative of the actual system, the number of unknowns, computer storage requirements and computational time tends to increase geometrically.

In short, the development of the digital computer has given rise to an entirely new field of study commonly referred to "computational electromagnetics." Nearly all of work done today in fields such as antenna design involves using a computer to solve equations generated by MoM or some similar method, such as physical optics, the geometrical theory of diffraction, finite element, or the finite-difference-time-domain technique. More specifically, the main goal of most problems in computational electromagnetics is to solve for an unknown current distribution once the geometry of the structure and the excitation has been specified. Once the currents on a structure have been

determined, it is a relatively straightforward procedure to solve for such parameters as radiation patterns or the efficiency of a radiating structure. However, it should be noted that there are other approaches used in computational electromagnetics. High frequency techniques will ignore current distributions altogether and essentially trace rays to find scattered fields.

1.3 Specific Approach

There are several commercial software programs available that vary in complexity and abilities. One of the most powerful programs is the Numerical Electromagnetics Code, or NEC. NEC is capable of such tasks as the modeling of complex antenna structures and incorporating such obstacles as a ground plane or cliffs into the antenna environment. NEC will be discussed in more detail later, as it has been implemented in different sections of this investigation.

A commonly solved in computational electromagnetics is the scattering properties of an obstacle when illuminated by an wave of arbitrary type and polarization. Initially, this appears to be a perfect match for the solution to the 'man with radio' problem. However, there is an assumption made by the programs which compute this scattering data that the 'man with radio' problem violates. In the existing programs, the source of the incident wave is assumed to be far enough away from the scattering object that it is not influenced by the scattered fields. In other words, the current distribution of the source is not perturbed by the scattered field. Such is not the case with a person holding a radio. The antenna of the radio and the operator are so close to one another that the normal current distribution of the antenna will be perturbed to some degree by the scattered field radiated from the biological body. Now that the current distribution on the antenna is changed, the

incident field has also changed. Effectively, the close proximity of the radio and the biological body creates two unknown current distributions: the currents on the antenna and the currents induced in the biological body. Clearly this coupling between the body and radio considerably complicates the analysis of the problem.

However, due to the nature of this particular problem, more specifically the electrical size of the radio and biological body, this coupling by the biological body on the antenna is minimal and may be neglected. The electrical size of an object is its size when compared to the wavelength at the operating frequency. In the frequency band of this investigation (3-30 MHz), the operating wavelength ranges from 10 to 100 meters. It will be demonstrated later that it is the excessively small electrical size of the man-radio system that allows for the coupling effect of the biological body on the antenna to be neglected. The current distribution on the antenna of the radio remains virtually unperturbed for this particular system. The problem is simplified to determining the currents induced in the biological body. Once these currents are determined, all other desired parameters will easily follow.

One problem that remains is determining the incident field. The proximity of the body to the radio does not permit the usual simplification of the incident field being a plane wave in the far-zone of the source. However, one of

the abilities of NEC is to determine the values of the electric and magnetic fields in the near-zone of the source. In summary, NEC will be used to model the radio and antenna and to supply the near-zone incident field values. A program based on MoM[12] will be used to compute the currents induced in the biological body. The investigation will begin with a derivation of the necessary integral equations to be solved.

CHAPTER 2

Derivation of 3-D Integral Equations

2.1 Descriptive Geometry

Figure 2-1 illustrates the geometry and terms used throughout this report.

Figure 2-1 : Descriptive Geometry and Terms

The position vectors $\mathbf{r}$ and $\mathbf{r}'$ denote free-space and source coordinates respectively. V represents the volume occupied by the biological body. Note that the biological body is inhomogeneous with respect to permittivity and conductivity. Define $\mathbf{E}$ as the total electric field throughout all space and $\mathbf{E}^S$ as the scattered electric field that is radiated from the induced currents in the biological body when illuminated by the incident field. It is this induced current distribution in the biological body that is the unknown

function to be determined. $\mathbf{E}^i$ is defined to be the incident field radiated by the current distribution on the radio.

2.2 Volume Equivalence Theorem

One of the fundamental theorems upon which the volume integral equations are constructed is the volume equivalence theorem[12]. The volume equivalence theorem states that an isotropic inhomogeneous penetrable body may be removed and replaced with an equivalent current density. This theory is necessary due to the fact, as will be shown later, that the integral equations to be solved are formed in conjunction with the dyadic Green's function. The expression for the dyadic Green's function is derived with the assumption that the source is in homogeneous free space. Therefore, for the integral equations to retain validity, the actual physical biological body must be removed and replaced with an equivalent volume current density existing in free space. Figure 2-2 illustrates this concept.

FIGURE 2-2 : Volume Equivalence Theorem

In Figure 2-2, $\mathbf{E}^i$ represents the incident field generated by the antenna of the radio. $\mathbf{E}$ represents the total electric field throughout space. It should be noted that throughout this entire investigation, the relative permeability of all media is set to unity ($\mu=\mu_0$). The equivalent current density in case b is represented by $\mathbf{J}$. The volume equivalence theorem results from a fairly simple derivation. In case a, the following Maxwell equation must be true:

$$\nabla \times \mathbf{H} = j\omega \epsilon \mathbf{E} \quad (2-1)$$

In case b, the following Maxwell equation must be true:

$$\nabla \times \mathbf{H} = j\omega \epsilon \mathbf{E} + \mathbf{J} \quad (2-2)$$

The term equivalence implies that the total fields in space will be identical. With this implication, the curl of the $\mathbf{H}$ -field must be the same in both cases and equations (2-1) and (2-2) may be equated in order to express the equivalent current in terms of the total electric field in space. This leads to:

$$\mathbf{J}(\mathbf{r}) = j\omega[\epsilon(\mathbf{r}) - \epsilon_0]\mathbf{E}(\mathbf{r}) \quad (2-3)$$

The functional variable $\mathbf{r}$ denotes the position vector from the origin. This important relationship permits the body occupying the volume $\mathbf{V}$ to be replaced by the equivalent current density $\mathbf{J}(\mathbf{r})$.

2.3 Volume Integral Equations

As stated previously, $\mathbf{E}$ is the total electric field in space. This total field is actually the sum of the incident and scattered fields:

$$\mathbf{E} = \mathbf{E}^i + \mathbf{E}^s \quad (2-4)$$

From appendix A, the scattered field due to the currents induced in the biological body is given by:

$$\mathbf{E}^s = -j\omega\mu_0 \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}_{eq}(\mathbf{r}') d\mathbf{v}' \quad (2-5)$$

Substituting (2-5) into (2-4) gives the following integral equation:

$$\mathbf{E} = \mathbf{E}^i - j\omega\mu_0 \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}_{eq}(\mathbf{r}') d\mathbf{v}' \quad \text{in } V \quad (2-6)$$

Now the result from appendix B is used to circumvent the singularity of the dyadic Green's function in the source region:

$$\mathbf{E}(\mathbf{r}) = -j\omega\mu_0 \text{PV} \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}_{eq}(\mathbf{r}') d\mathbf{v}' - \frac{\mathbf{J}(\mathbf{r})}{3j\omega\epsilon(\mathbf{r})} \quad (2-7)$$

where the PV represents principle value integration.

Finally, the volume equivalence theorem is used to replace the total field with equivalent currents. After a few steps of simplification, the following expression is obtained[13]:

$$j\omega\mu_0 \text{PV} \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}_{eq}(\mathbf{r}') d\mathbf{v}' + \frac{(\epsilon_r(\mathbf{r}) + 2)\mathbf{J}_{eq}(\mathbf{r})}{3j\omega[\epsilon_r(\mathbf{r}) - \epsilon_o]} = \mathbf{E}^i(\mathbf{r}) \quad \mathbf{r} \in V \quad (2-8)$$

Equation (2-8) is the crux of this investigation. This is the integral equation to be solved by the Method of Moments.

2.4 Validation of the Unperturbed Current Assumption

As mentioned in the first chapter, the initial current distribution on the antenna of the radio will be perturbed to some extent by the close proximity of the biological body. However, it has been assumed that, for this particular investigation, this perturbation is negligible and may be disregarded. A simple procedure is used to validate this assumption. NEC was used to determine the current distribution on both an electrically long and short dipole antenna. The two dipoles were both modeled in free space and above an infinite half space. The parameters of the half space were selected to simulate an actual biological medium: $\epsilon_r=81.0$ and $\sigma=0.75$ mhos/meter. It is assumed that the infinite half space is the limiting case with respect to degree of perturbation. In other words, under identical conditions, the current distribution on the antenna receives the maximum influence when the scattering object is an infinite half space. Any perturbation due to a finite body will be of a lesser extent.

Figure 2-3 shows the magnitude of the current distribution for a relatively long dipole of one wavelength. Figure 2-4 shows the same dipole in the presence of the infinite half space. It can be seen from the two graphs that the current distribution is noticeably perturbed from its free space distribution.

Figure 2-5 shows the magnitude of the current distribution for a relatively short dipole of $1/10$ of a

wavelength. The reason these values were chosen is that the physical length of the dipole will be no longer than $1/10$ of a wavelength. Figure 2-6 shows the same dipole in the presence of the infinite half space. It can be seen from the two graphs that there is no noticeable perturbation of the current distribution from its free space distribution.

Figure 2-3 : long dipole in free space

Figure 2-4 : long dipole above an infinite half space

Figure 2-5 : short dipole in free space

Figure 2-6 : short dipole above an infinite half space

CHAPTER 3

The Method of Moments

3.1 Mathematical Background

To better interpret the application of MoM to the solution of the electromagnetics integral equations[7], MoM will be explained from a purely mathematical perspective. This should help to generalize MoM to disciplines other than computational electromagnetics and to better understand the terms and definitions used in MoM.

Let any functional equation to be solved be of the form:

$$L(f) = g \quad (3-1)$$

Here, L represents a linear operator, g represents a known forcing function and f represents the unknown function that is to be determined. With respect to the electromagnetics integral equations, L represents the integral operator, g represents the incident field and f represents the unknown current distribution that is to be determined. Let the unknown function f be represented by the linear combination of a set of N predetermined functions in the domain of L :

$$f = \sum_j^N \alpha_j f_j \quad (3-2)$$

The α_j represent expansion coefficients that are to be determined. The f_j represent the known expansion functions, which are sometimes called basis functions. The summation variable, j , ranges from one to the number of expansion

functions used to approximate the function f . In general, the higher N is, the better the approximation to the actual function. By the linearity of the operator L , equation (3-1) may be restated as:

$$\sum_j^N \alpha_j L(f_j) = g \quad (3-3)$$

Equation (3-3) represents one equation with N unknowns. In order to generate a system of N equations with N unknowns, it is necessary to take the inner product (linear projection) of both sides of equation (3-3) with a predefined set of N testing functions, or sometimes called weighting functions, denoted w_m . The inner product of two functions, a and b , is denoted $\langle a, b \rangle$ and is a scalar operator, usually an integration in electromagnetic problems, that must meet the following criteria:

$$\langle a, b \rangle = \langle b, a \rangle$$

$$\langle \alpha a + \beta b, c \rangle = \alpha \langle a, c \rangle + \beta \langle b, c \rangle$$

where α and β are scalars

$$\langle a^*, a \rangle > 0 \text{ if } a \neq 0$$

$$\langle a^*, a \rangle = 0 \text{ if } a = 0$$

Taking the inner product of both sides of equation (3-3) with the testing functions w_m yields:

$$\sum_j^N \alpha_j \langle w_m, L(f_j) \rangle = \langle w_m, g \rangle \quad (3-4)$$

Equation (3-4) may now be represented in matrix form as:

$$[l_{mj}][\alpha_j] = [g_m] \quad (3-5)$$

where the elements of matrix $[l_{mj}]$ are given by:

$$[l_{mj}] = [<w_m, L(f_j)>] \quad (3-6)$$

As the subscripts range up to the number of expansion functions used to approximate the unknown function f , the matrix $[l_{mj}]$ is filled.

$$[l_{mj}] = \begin{bmatrix} <w_1, L(f_1)> & <w_1, L(f_2)> & \bullet & \bullet & <w_1, L(f_j)> \\ <w_2, L(f_1)> & & & & <w_2, L(f_j)> \\ \bullet & & & & & \bullet \\ \bullet & & & & & \bullet \\ <w_j, L(f_1)> & <w_j, L(f_2)> & \bullet & \bullet & <w_j, L(f_j)> \end{bmatrix} \quad (3-7)$$

The column vector $[\alpha_j]$ is filled as:

$$[\alpha_j] = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \bullet \\ \bullet \\ \alpha_j \end{bmatrix} \quad (3-8)$$

The column vector $[g_m]$ follows a similar procedure:

$$[g_m] = \begin{bmatrix} <w_1, g> \\ <w_2, g> \\ \bullet \\ \bullet \\ <w_j, g> \end{bmatrix} \quad (3-9)$$

The vector of unknown expansion coefficients may now be determined by:

$$[\alpha_j] = [l_{mj}]^{-1}[g_m] \quad (3-10)$$

The original unknown function f is now defined as:

$$f = [f_j][\alpha_j] \quad (3-11)$$

Equation (3-11) represents our answer. The original unknown function f is now approximated, or in a well-behaved case, represented exactly by equation (3-11).

A few words need to be said at this point about the choice of expansion and testing functions. Although there are no set rules regarding the choice of these functions, an *a priori* knowledge of the general form of the solution will enable the expansion functions to be chosen judiciously such that the solution to the function f will converge with acceptable error to the actual solution with a minimal number of expansion functions used. However, in the case of the electromagnetics integral equations, there usually is no before hand knowledge of the form the unknown current distribution will take. Thus, the expansion functions that are generally chosen in electromagnetic problems are generic unit pulses or triangle functions. With these functions, the expansion coefficients reduce to the height of the unit pulses or a simple summation of the triangles.

3.2 Example of the application of the Method of Moments

An example of the application of the Method of Moments will be given to illustrate the technique and how it is used to solve the problems to which it is applied. In this example, the Method of Moments will be used to solve a simple second order ordinary differential equation[7]. The O.D.E to be solved is:

$$\frac{d^2 f(x)}{dx^2} = 1 + 2x^2 \quad (3-12)$$

where the function f is defined in the interval $0 \leq x \leq 1$ and must adhere to the boundary conditions of $f(0)=f(1)=0$. With respect to equation (3-1), L is the second order

differential operator $\frac{d^2}{dx^2}$, f is the unknown function $f(x)$,

and g is the known function $(1 + 2x^2)$. Enforcing the initial boundary conditions yields the exact solution for $f(x)$:

$$f(x) = -\frac{2}{3}x + \frac{1}{2}x^2 + \frac{1}{6}x^4 \quad (3-13)$$

Now the Method of Moments will be employed to solve the same O.D.E. The first step is to choose appropriate basis functions. Since the form of the forcing function is of powers of x , a wise choice for the form of the basis functions is $f_j = x - x^{j+1}$. This choice of basis functions also meets the initial boundary conditions. The testing functions are chosen to be identical to the expansion functions. The procedure of letting $w_m = f_j$ is known as

Galerkin's Method. The inner product is chosen to be

$\langle a, b \rangle = \int_0^1 a(x) b(x) dx$. Now derive an expression for the elements of the $[l_{mj}]$ matrix.

$$\begin{aligned}
 l_{mj} &= \langle w_m, L(f_j) \rangle \\
 &= \int_0^1 w_m(x) L f_j(x) dx \\
 &= \int_0^1 (x - x^{m+1}) \left[\frac{d^2}{dx^2} (x - x^{j+1}) \right] dx \\
 &= -j(j+1) \int_0^1 (x^j - x^{m+j}) dx \\
 &= j(j+1) \left[\frac{x^{m+j+1}}{m+j+1} - \frac{x^{j+1}}{j+1} \right] \Big|_0^1 \\
 &= j(j+1) \left[\frac{1}{m+j+1} - \frac{1}{j+1} \right] \\
 l_{mj} &= - \frac{mj}{m+j+1} \tag{3-14}
 \end{aligned}$$

Equation (3-14) is a closed-form expression for the elements of the $[l_{mj}]$ matrix. A similar procedure is followed to obtain an expression for the elements of the g_m column vector.

$$\begin{aligned}
 g_m &= \langle w_m, g \rangle \\
 &= \int_0^1 w_m(x) g(x) dx \\
 &= \int_0^1 (x - x^{m+1}) (1 + 2x^2) dx \\
 &= \frac{1}{2} - \frac{1}{m+2} - \frac{2}{m+4} + \frac{1}{2} \\
 g_m &= \frac{m(m+3)}{(m+2)(m+4)} \tag{3-15}
 \end{aligned}$$

Equation (3-15) represents a closed-form expression for the elements of the g_m column vector.

The next step in the procedure is to choose the number of expansion functions that will be used to approximate the function f . For this specific example, N will be chosen to be 1, 2, and 3. The results for the three trials will be compared to illustrate how increasing the number of expansion functions used will decrease the error in the approximation to the actual function. It will be seen that for $N=3$, this particular example converges to the exact solution.

For $N=1$, there is only one element to determine for the $[l_{mj}]$ matrix and the $[g_m]$ vector.

$$l_{11} = -\frac{mj}{m+j+1} = -\frac{1}{3}$$

$$g_1 = \frac{m(m+3)}{(m+2)(m+4)} = \frac{4}{15}$$

The matrix equation, which for this case reduces to a scalar equation, becomes:

$$-\frac{1}{3}(\alpha_1) = \frac{4}{15}$$

Solving for α_1 yields:

$$\alpha_1 = -\frac{4}{5}$$

The unknown function f is now approximated as:

$$f \approx \sum_{j=1}^1 \alpha_j f_j = -\frac{4}{5}(x-x^2)$$

$$f(x) \approx -\frac{4}{5}x + \frac{4}{5}x^2 \quad \text{for } N=1. \quad (3-16)$$

For $N=2$, equations (3-14) and (3-15) produce the following matrix and vector elements:

$$\begin{aligned} l_{11} &= -\frac{1}{3} & l_{21} &= -\frac{1}{2} & g_1 &= \frac{4}{15} \\ l_{12} &= -\frac{1}{2} & l_{22} &= -\frac{4}{5} & g_2 &= \frac{5}{12} \end{aligned}$$

The matrix equation $[l_{mj}][\alpha_j] = [g_m]$ is now

$$\begin{bmatrix} -\frac{1}{3} & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{4}{5} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \frac{4}{15} \\ \frac{5}{12} \end{bmatrix}$$

Solving for the α vector gives:

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} -\frac{3}{10} \\ -\frac{1}{3} \end{bmatrix}$$

The function f is now approximated by:

$$\begin{aligned} f &\approx \sum_{j=1}^2 \alpha_j f_j = \alpha_1 f_1 + \alpha_2 f_2 = -\frac{3}{10}(x - x^2) - \frac{1}{3}(x - x^3) \\ f(x) &\approx -\frac{19}{30}x + \frac{3}{10}x^2 + \frac{1}{3}x^3 \quad \text{for } N=2 \end{aligned} \quad (3-17)$$

For N=3, equations (3-14) and (3-15) produce the following matrix and vector elements:

$$\begin{array}{llll} l_{11} = -\frac{1}{3} & l_{21} = -\frac{1}{2} & l_{31} = -\frac{3}{5} & g_1 = \frac{4}{15} \\ l_{12} = -\frac{1}{2} & l_{22} = -\frac{4}{5} & l_{32} = -1 & g_2 = \frac{5}{12} \\ l_{13} = -\frac{3}{5} & l_{23} = -1 & l_{33} = -\frac{9}{7} & g_3 = \frac{18}{35} \end{array}$$

The matrix equation $[l_{mj}][\alpha_j] = [g_m]$ is now

$$\begin{bmatrix} -\frac{1}{3} & -\frac{1}{2} & -\frac{3}{5} \\ \frac{1}{2} & -\frac{4}{5} & -1 \\ -\frac{3}{5} & -1 & -\frac{9}{7} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} = \begin{bmatrix} \frac{4}{15} \\ \frac{5}{12} \\ \frac{18}{35} \end{bmatrix}$$

Inverting the $[l_{mj}]$ matrix and then pre-multiplying with the $[g_m]$ vector solves for the $[\alpha_j]$ vector:

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} = \begin{bmatrix} -\frac{1}{2} \\ 0 \\ -\frac{1}{6} \end{bmatrix}$$

The function f is now approximated by:

$$\begin{aligned} f &\approx \sum_{j=1}^3 \alpha_j f_j = \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3 = -\frac{1}{2}(x-x^2) - \frac{1}{6}(x-x^4) \\ f(x) &= -\frac{2}{3}x + \frac{1}{2}x^2 + \frac{1}{6}x^4 \quad \text{for } N=3 \end{aligned} \quad (3-18)$$

Equation (3-18) is identical to the exact solution in equation (3-13), hence the equality sign. Figure 3-1 is

plot of all three versions of $f(x)$ for $N=1$, $N=2$ and $N=3$. As can be seen from the graph, the more expansion functions that are used to represent $f(x)$, the better the approximation, if not actually achieving equality.

Figure 3-1 : An example of MoM used to solve a 2nd order O.D.E.

CHAPTER 4

Solution of the Electromagnetic Volume Integral Equations

4.1 Specifics

Now that the appropriate volume integral equation has been formulated, the Method of Moments will be used to construct a solution. Actually, the v.i.e. was solved by two different techniques: the direct MoM approach and a variation of MoM, known as the Conjugate Gradient Method[14]. The Conjugate Gradient Method is an iterative technique that has certain advantages and disadvantages with respect to the direct Method of Moments. Since the Conjugate Gradient Method was not used extensively in this investigation, the description of the C.G. Method will be limited to a qualitative nature. To begin, an average size human body of 1.7 meters tall was segmented into 114 cubical cells[15]. A rather interesting illustrated book of cross-sectional human anatomy was used to determine the conductivity and the permittivity of each individual cubical cell based on the type of tissue found in that particular cell[16-17]. Appendix D contains a list of the input file that describes the sizes and parameters of the cells and a figure of the block model of the man. With respect to the Method of Moments, unit pulses were chosen for the basis functions and delta functions for the testing functions. The use of delta functions as testing functions may be interpreted as forcing an equality at the points of testing, which are the discrete cell centers. The necessary

expressions for the elements of the impedance matrix and excitation vector are formulated and the resulting system of equations is solved with traditional matrix methods.

4.2 Mathematical Details

Recall that the v.i.e. to be solved is:

$$j\omega\mu_0PV\int_V \bar{G}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_{eq}(\mathbf{r}')d\mathbf{v}' + \frac{(\epsilon_r(\mathbf{r})+2)\mathbf{J}_{eq}(\mathbf{r})}{3j\omega[\epsilon_r(\mathbf{r})-\epsilon_o]} = \mathbf{E}^i(\mathbf{r}) \quad \mathbf{r} \in V \quad (4-1)$$

Denote the basis functions by:

$$\mathbf{B}_l^i(\mathbf{r}) = \hat{u}_l \mathbf{B}_l^i(\mathbf{r}) = \hat{u}_l P_l(\mathbf{r}) \quad (4-2)$$

where:

$$P_l(\mathbf{r}) = \begin{cases} 1 & \text{for } \mathbf{r} \in v_l \\ 0 & \text{elsewhere} \end{cases} \quad (4-3)$$

u_k represents a unit vector in the x, y or z direction depending on the value of k (1, 2 or 3). The biological body has been divided into 114 discrete cells: $v_1, v_2, \dots, v_{114}$. In terms of these basis functions, the current is:

$$\mathbf{J}(\mathbf{r}) \cong \sum_{l=1}^{114} \sum_{i=1}^3 J_l^i \mathbf{B}_l^i(\mathbf{r}) \quad (4-4)$$

Using the rectangular coordinate system, (4-1) may be written as:

$$\int_V \bar{\mathbf{g}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_{eq}(\mathbf{r}')d\mathbf{v}' + \frac{(\epsilon_r(\mathbf{r})+2)\mathbf{J}_{eq}(\mathbf{r})}{3j\omega[\epsilon_r(\mathbf{r})-\epsilon_o]} = \mathbf{E}^i(\mathbf{r}) \quad \mathbf{r} \in V \quad (4-5)$$

The Green's function - current product in (4-5) can be represented in matrix form:

$$\bar{\mathbf{g}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J} = \begin{bmatrix} g^{11} & g^{12} & g^{13} \\ g^{21} & g^{22} & g^{23} \\ g^{31} & g^{32} & g^{33} \end{bmatrix} \begin{bmatrix} J_1^1 \hat{x} \\ J_1^2 \hat{y} \\ J_1^3 \hat{z} \end{bmatrix} \quad (4-6)$$

The elements of the matrix in (4-6) are given by:

$$g^{nk}(\mathbf{r}, \mathbf{r}') = j\omega\mu_0 \left(\delta_n^k + \frac{1}{k_0} \cdot \frac{\partial^2}{\partial u_n \partial u_k} \right) \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|} \quad (4-7)$$

where δ_n^k is the Kronecker delta function and $k_0 = \omega\sqrt{\mu_0\epsilon_0}$.

Substituting (4-4) into (4-1) gives:

$$\sum_{l=1}^L \sum_{k=1}^3 J_l^k \int_V \bar{\mathbf{g}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{B}_l^k(\mathbf{r}') d\mathbf{v}' + \frac{(\epsilon_r(\mathbf{r}) + 2)\mathbf{B}_l^k \hat{u}_k}{3j\omega[\epsilon_r(\mathbf{r}) - \epsilon_o]} = \mathbf{E}^i(\mathbf{r}) \quad \mathbf{r} \in V \quad (4-8)$$

where L is the number of discrete cells. To simplify further notation, define the following terms:

$$D(\mathbf{r}) = \frac{\epsilon_r(\mathbf{r}) + 2}{3j\omega[\epsilon_r(\mathbf{r}) - \epsilon_o]} \quad (4-9a)$$

$$Z_{lk} = \int_V \bar{\mathbf{g}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{B}_l^k(\mathbf{r}') d\mathbf{v}' - D(\mathbf{r})\mathbf{B}_l^k \hat{u}_k \quad (4-9b)$$

$$G11_l^k(\mathbf{r}) \equiv \int_V \mathbf{g}^{*k}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{B}_l^k(\mathbf{r}') d\mathbf{v}' \quad (4-9c)$$

$$\mathbf{Z}_{lk} = \sum_{\alpha=1}^3 Z_{lk}^{\alpha} \hat{u}_{\alpha} \quad (4-9d)$$

Equation (4-8) may now be rewritten as:

$$\sum_{l=1}^L \sum_{k=1}^3 J_l^k \sum_{\alpha=1}^3 Z_{lk}^{\alpha} \hat{u}_{\alpha} \cong \sum_{\alpha=1}^3 E_{\alpha}^i(\mathbf{r}) \hat{u}_{\alpha} \quad \mathbf{r} \in V \quad (4-10)$$

Now use the delta testing function to force equalities at the centers of the discrete cells. The delta testing function may be expressed as:

$$\mathbf{W}_\rho^* = \delta(\mathbf{r} - \mathbf{r}_\rho) \hat{\mathbf{u}}_n \quad n=1,2,3; \quad \rho=1,2,\dots,L \quad (4-11)$$

This yields 3L equations:

$$\sum_{l=1}^L \sum_{k=1}^3 \mathbf{J}_l^k \mathbf{Z}_{\rho,k}^{l*} = \mathbf{V}_\rho^n \quad n=1,2,3; \quad \rho=1,2,\dots,L \quad (4-12)$$

where:

$$\begin{aligned} \mathbf{Z}_{\rho,k}^{l*} &= \langle \mathbf{W}_\rho^n, \mathbf{Z}_{l,k}^n \hat{\mathbf{u}}_n \rangle \\ &= G \mathbf{I}_l^{nk}(\mathbf{r}_\rho) + D(\mathbf{r}_\rho) \delta_k^n \delta_\rho^n \end{aligned} \quad (4-13)$$

and:

$$\begin{aligned} \mathbf{V}_\rho^n &= \langle \mathbf{W}_\rho^n, \mathbf{E}_n^i(\mathbf{r}) \hat{\mathbf{u}}_n \rangle \\ &= \mathbf{E}_n^i(\mathbf{r}_\rho) \end{aligned} \quad (4-14)$$

Equations (4-13) and (4-14) provide expressions for the elements of the impedance matrix and excitation vector.

4.3 Computer Implementations

An existing program based on the equations of the previous section was obtained and modified to accommodate the particulars of this investigation[12]. Specifically, the excitation vector of the existing code was formed by matching points from an incident plane wave of arbitrary polarization. For this project, the code had to be modified to accept the sampled points from the near field of the dipole antenna as the elements of the excitation vector.

As stated previously, two approaches were used in solving the equations of the previous section: the direct

MoM approach and the Conjugate Gradient approach. Although computer programs for both methods were obtained[12], only the direct MoM approach was used. The reason for this limitation may be understood in light of the computational considerations involved. The matrix aspect of the direct moment method is usually the factor limiting the usefulness of this approach. Large matrices require a sizable chunk of computer memory and the chunk required tends to increase geometrically as the number of cells used to model the body increases. Even if the system's memory can accommodate the size of the matrix, the finite precision floating point processors may be unable to supply the high precision needed when inverting a large matrix, thus resulting in numerical instabilities and singularities. This is where the Conjugate Gradient approach is advantageous over the Moment Method approach.

The Conjugate Gradient method does not construct the matrices that the direct Moment Method approach does, but rather utilizes an iterative search for the solution. An initial guess, usually the incident field, to the solution is supplied and the theory of the C.G. method allows for a new guess to the solution to be computed. The algorithm continues until the difference between two successive iterations meet a predefined error limit. The lack of the matrix aspect of the C.G. method will usually allow for an order more unknowns than the direct Moment Method approach. However, the major disadvantage of the C.G. method is time.

The C.G. method takes much, much longer to solve the same problem than the direct MoM approach. The computer used in this investigation, a Sparc II Sun workstation, was able to meet the memory requirements and the ability to declare triple precision variables in the FORTRAN compiler insured numerical stability. For a comparison, this investigation used a biological model of 114 cells with 3 field components per cell for a total of 342 unknowns. The direct Moment method gave a solution in just under three minutes, whereas the Conjugate Gradient method gave the same solution in just over 5 hours!

CHAPTER 5

Program Output

5.1 Far-zone fields

For this investigation, two different man-antenna geometries were modeled. The first geometry had the antenna 0.8 meters away from the face and the second geometry placed the antenna 0.7 meters away from the face. Once the output from the modified codes was collected, a separate program was written to compute the far-zone fields in any given azimuthal or elevation angle. For each of the output files, the far-zone fields were determined in a 360 degree scan at a constant elevation angle of 90 degrees. Also, the front and back 90 degree elevation segments were scanned at a constant azimuthal angle of 0 degrees. Appendix C contains the source code for the far-zone field patterns.

Figure 5-1 shows the reference patterns for a small dipole in free space. Figures 5-2 through 5-57 show the far-zone patterns for each of the two geometries at 1 MHz increments. Note the anomalous behavior of the radiation patterns exhibited by both geometries at 3 MHz. These patterns do not follow the trend set by the higher frequencies. At the present, it is unknown if this is the actual behavior or the result of a numerical instability in the program: further investigation is required at this juncture. Figures 5-58 through 5-61 show a three-dimensional view of the two desired radiation patterns for both body geometries as the frequency is incremented. In

these four graphs, the 3 MHz patterns have been omitted. Barring the three MHz frequency, the patterns follow a definite trend with respect to frequency. The patterns scanned through the theta angles show a decrease in the overhead null as the frequency decreases. This is to be expected if the behavior of the near field of the dipole is taken into account. As the operating frequency decreases, the near electric fields of the dipole will contain more x and y field components that will in turn induce x and y current components in the biological body. these x and y current components will radiate broadside and add to the overhead null, thereby decreasing it. The results from the 360 degree scan through the phi angles differ from the expected results. The trend from the output is an increasing directivity with a decrease in frequency. This observation is in diametric agreement with the behavior of a dipole as the operating frequency increases. A dipole will become more directive as its operating frequency increases while its physical length remains constant.

5.2 Efficiency

One of the outputs from NEC when used to model the dipole antenna is the power radiated by the antenna. Given the conductivity and the induced field in the cells of the body model, the power lost in the body may be computed. From these two factors, the efficiency may be computed. The power lost in a single cell is given by:

$$\frac{1}{2} \int_v \sigma |E|^2 dv \quad (5-1)$$

Since the conductivity and field quantities are constant for a given cell, the power lost in a single cell reduces to:

$$\frac{1}{2} \sigma |E|^2 (\text{volume of the cell}) \quad (5-2)$$

The total power lost is the sum of the power lost in the individual cells. Figures 5-62 and 5-63 show the efficiency vs. frequency curves. As is expected, the fields at lower frequencies penetrate the body further and lose more power in the body and hence have a lower efficiency. Figure 5-64 is a composite of the two previous figures to better illustrate how the proximity of the dipole and the biological body will effect the efficiency of the radio.

Figure 5-1 : Small Dipole in Free Space

Figure 5-2 : Far-zone patterns for $d=0.8$ meters at 3 MHz

Figure 5-3 : Far-zone patterns for $d=0.8$ meters at 4 MHz

Figure 5-4 : Far-zone patterns for $d=0.8$ meters at 5 MHz

Figure 5-5 : Far-zone patterns for $d=0.8$ meters at 6 MHz

Figure 5-6 : Far-zone patterns for $d=0.8$ meters at 7 MHz

Figure 5-7 : Far-zone patterns for $d=0.8$ meters at 8 MHz

Figure 5-8 : Far-zone patterns for $d=0.8$ meters at 9 MHz

Figure 5-9 : Far-zone patterns for $d=0.8$ meters at 10 MHz

Figure 5-10 : Far-zone patterns for $d=.8$ meters at 11 MHz

Figure 5-11 : Far-zone patterns for $d=.8$ meters at 12 MHz

Figure 5-12 : Far-zone patterns for $d=.8$ meters at 13 MHz

Figure 5-13 : Far-zone patterns for $d=.8$ meters at 14 MHz

Figure 5-14 : Far-zone patterns for $d=.8$ meters at 15 MHz

Figure 5-15 : Far-zone patterns for $d=.8$ meters at 16 MHz

Figure 5-16 : Far-zone patterns for $d=.8$ meters at 17 MHz

Figure 5-17 : Far-zone patterns for $d=.8$ meters at 18 MHz

Figure 5-18 : Far-zone patterns for $d=.8$ meters at 19 MHz

Figure 5-19 : Far-zone patterns for $d=.8$ meters at 20 MHz

Figure 5-20 : Far-zone patterns for $d=.8$ meters at 21 MHz

Figure 5-21 : Far-zone patterns for $d=.8$ meters at 22 MHz

Figure 5-22 : Far-zone patterns for $d=.8$ meters at 23 MHz

Figure 5-23 : Far-zone patterns for $d=.8$ meters at 24 MHz

Figure 5-24 : Far-zone patterns for $d=.8$ meters at 25 MHz

Figure 5-25 : Far-zone patterns for $d=.8$ meters at 26 MHz

Figure 5-26 : Far-zone patterns for $d=.8$ meters at 27 MHz

Figure 5-27 : Far-zone patterns for $d=.8$ meters at 28 MHz

Figure 5-28 : Far-zone patterns for $d=.8$ meters at 29 MHz

Figure 5-29 : Far-zone patterns for $d=.8$ meters at 30 MHz

Figure 5-30 : Far-zone patterns for $d=0.7$ meters at 3 MHz

Figure 5-31 : Far-zone patterns for $d=0.7$ meters at 4 MHz

Figure 5-32 : Far-zone patterns for $d=0.7$ meters at 5 MHz

Figure 5-33 : Far-zone patterns for $d=0.7$ meters at 6 MHz

Figure 5-34 : Far-zone patterns for $d=0.7$ meters at 7 MHz

Figure 5-35 : Far-zone patterns for $d=0.7$ meters at 8 MHz

Figure 5-36 : Far-zone patterns for $d=0.7$ meters at 9 MHz

Figure 5-37 : Far-zone patterns for $d=.7$ meters at 10 MHz

Figure 5-38 : Far-zone patterns for $d=.7$ meters at 11 MHz

Figure 5-39 : Far-zone patterns for $d=.7$ meters at 12 MHz

Figure 5-40 : Far-zone patterns for $d=.7$ meters at 13 MHz

Figure 5-41 : Far-zone patterns for $d=.7$ meters at 14 MHz

Figure 5-42 : Far-zone patterns for $d=.7$ meters at 15 MHz

Figure 5-43 : Far-zone patterns for $d=.7$ meters at 16 MHz

Figure 5-44 : Far-zone patterns for $d=.7$ meters at 17 MHz

Figure 5-45 : Far-zone patterns for $d=.7$ meters at 18 MHz

Figure 5-46 : Far-zone patterns for $d=.7$ meters at 19 MHz

Figure 5-47 : Far-zone patterns for $d=.7$ meters at 20 MHz

Figure 5-48 : Far-zone patterns for $d=.7$ meters at 21 MHz

Figure 5-49 : Far-zone patterns for $d=.7$ meters at 22 MHz

Figure 5-50 : Far-zone patterns for $d=.7$ meters at 23 MHz

Figure 5-51 : Far-zone patterns for $d=.7$ meters at 24 MHz

Figure 5-52 : Far-zone patterns for $d=.7$ meters at 25 MHz

Figure 5-53 : Far-zone patterns for $d=.7$ meters at 26 MHz

Figure 5-54 : Far-zone patterns for $d=.7$ meters at 27 MHz

Figure 5-55 : Far-zone patterns for $d=.7$ meters at 28 MHz

Figure 5-56 : Far-zone patterns for $d=.7$ meters at 29 MHz

Figure 5-57 : Far-zone patterns for $d=.7$ meters at 30 MHz

Figure 5-58 : Theta scans at $\phi=0$ for $d=0.8$ meters

Figure 5-59 : Phi scans at $\theta=90$ for $d=0.8$ meters

Figure 5-60 : Theta scans at $\phi=0$ for $d=0.7$ meters

Figure 5-61 : Phi scans at $\theta=90$ for $d=0.7$ meters

Figure 5-62 : Efficiency of radio vs. frequency
head-to-radio = 0.8 meters

Figure 5-63 : Efficiency of radio vs. frequency
head-to-radio = 0.7 meters

Figure 5-64 : Composite of Figures 5-62 & 5-63

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

A. The biological body does lower the efficiency of the radio by dissipating a portion of the power supplied by the radio. The results indicate that as much as 45% of the supplied power may be lost due to the biological body. The location of the dipole with respect to the body also greatly effects the efficiency of the radio, as shown by figure 5-64.

B. The biological body does influence the radiation pattern of the radio. However, the influence on the horizontal-plane pattern is of such a small degree as to be considered negligible. A drop of approximately 1 dB on the radio side of the body is indicated from the results. The azimuth-plane radiation pattern remains omni-directional for all practical purposes. This is as expected when the physical size the radio and body are compared to the free space wavelength at the operating frequency. The vertical-plane patterns show a minima when the elevation angle is approximately 0 degrees. This agrees with what is expected in light of the characteristics of an electrically short dipole.

C. The current distribution on the radio antenna remains constant in spite of the presence of a biological body. Although the biological body will influence the current distribution on the antenna, it is once again the

extremely small electrical size of the antenna-body system that makes this influence negligible.

D. The maximum induced fields in the biological body tend to be in the body extremities.

6.2 Recommendations

A. Modify the existing computer programs to allow for linear, surface and volumetric current densities to be incorporated into the radio-body model. This would eliminate the need to use an external source to construct the excitation vector, and enable higher frequencies to be studied. In addition, this modification would allow for different body configurations to be constructed in an attempt to increase the efficiency of the system. As an example, a surface of highly conducting mesh woven into the operators uniform could be modeled.

B. Perform the analysis and modify the existing computer programs to include an infinite lossy, homogeneous ground plane to represent real earth. Obviously, having the known universe consist of a single radio and a biological body is somewhat of an inaccurate model. The addition of a real earth ground plane would account for such factors as ground waves and power lost by absorption in the earth.

C. Modify the existing equations such that the solutions the computer programs generate adhere more closely to real life boundary conditions. Without becoming too specific, this modification involves replacing the pulse

expansion functions used by MoM with a triangular or perhaps a high order spline expansion function.

D. Apply different numerical techniques in an attempt to accelerate the rate of convergence of the iterative solution. The rate of convergence for the iterative method of solution is a limiting factor with respect to the size and complexity of the systems being modeled. Different extrapolation techniques should be applied to try and speed up this rate of convergence.

E. Try to eliminate the use of NEC to obtain the excitation vector. Although NEC is a powerful tool in the analysis of radiating structures, there are several inherent constraints on the size and segmentation of the structure that may be modeled due to the finite precision of the computers floating point processors. Indeed, in this investigation, the model of the dipole used to represent the radio needed to be altered at the lower frequencies in order to circumvent these constraints. There are closed form expressions that describe the near-fields of an electrically short dipole, which is what the radio essentially is in the H.F. band.

F. Based on the values of the induced field in the biological body and the values of the conductivity throughout the body, find the exact 'hotspots' and 'coolspots' in the body.

G. Attempt to determine the cause of the anomalous behavior of the radiation patterns at 3 MHz. Reexamine the

computer programs for signs of numerical instability. Also, take smaller frequency increments from four to three MHz to determine exactly where and why the behavior deviates from what is expected.

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APPENDIX A

The Dyadic Green's Function for Unbounded Free Space

A.1 Introduction

Nearly all endeavors in the field of non-optical computational electromagnetics involve the process of determining field values or field patterns once the unknown current distribution has been solved. Historically, there are two methods commonly used to determine these desired field quantities.

The more traditional approach involves multiplying the currents with the free space scalar Green's function and then integrating the product over the source region to obtain a vector potential function. The vector potential function is then differentiated to obtain the fields.

The second technique involves multiplication of the currents, in vector form, with the dyadic Green's function. The product may then be integrated over the source region to directly obtain the desired fields[18]. The use of the dyadic Green's function eliminates the intermediate step involving the vector potential. The two-step procedure is more common due to the fact that the integration involved in the two-step procedure is generally more tractable than in the more direct one-step method. However, due to the nature of the Method of Moments and the services of a digital computer, the integral equations formulated in this investigation are in terms of the dyadic Green's function.

A.2 Mathematical Derivation

Maxwell's two curl equations in the frequency domain are:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H} \quad (\text{A-1})$$

$$\nabla \times \mathbf{H} = j\omega\epsilon\mathbf{E} + \mathbf{J} \quad (\text{A-2})$$

These two equations are used to form a second order uncoupled vector Helmholtz equation via direct substitution:

$$\nabla \times \nabla \times \mathbf{E} = \omega^2\mu\epsilon\mathbf{E} - j\omega\mu\mathbf{J} \quad (\text{A-3})$$

A vector identity may be used to express the second derivatives in equation (A-3) in terms of a gradient, divergence and a Laplacian of a vector:

$$\nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} - \omega^2\mu\epsilon\mathbf{E} = -j\omega\mu\mathbf{J} \quad (\text{A-4})$$

Factoring out the $\mathbf{E}$ from the dot product and introducing the unit dyad to maintain consistency yields:

$$(\nabla\nabla - \nabla^2 \bar{\mathbf{I}} - k_0^2 \bar{\mathbf{I}}) \cdot \mathbf{E} = -j\omega\mu\mathbf{J} \quad (\text{A-5})$$

where $k_0^2 = \omega^2\mu\epsilon$.

Now define the operator $\mathcal{L}$ as:

$$\mathcal{L} = (\nabla\nabla - \nabla^2 \bar{\mathbf{I}} - k_0^2 \bar{\mathbf{I}}) \quad (\text{A-6})$$

Hence, equation (A-5) may be simplified to:

$$\mathcal{L} \cdot \mathbf{E} = -j\omega\mu\mathbf{J} \quad (\text{A-7})$$

Therefore, by finding the inverse of the $\mathcal{L}$ operator, the desired fields may be obtained:

$$\mathbf{E} = -j\omega\mu \mathcal{L}^{-1} \cdot \mathbf{J} \quad (\text{A-8})$$

It is now necessary to use the sifting property of the delta function to represent the current distribution in terms of primed and unprimed coordinates. The convention being used

is that primed coordinates refer to source regions while unprimed coordinates refer to source-free regions.

$$J(\mathbf{r}) = \int_V J(\mathbf{r}') \delta(\mathbf{r} - \mathbf{r}') d^3\mathbf{r}' \quad (\text{A-9})$$

Equation (A-8) now becomes:

$$\mathcal{L}^{-1} E(\mathbf{r}) = -j\omega\mu \mathcal{L}^{-1} \cdot \int_V J(\mathbf{r}') \delta(\mathbf{r} - \mathbf{r}') d^3\mathbf{r}' \quad (\text{A-10})$$

Where V is the volume occupied by the source region. Since $\mathcal{L}^{-1}$ is an operator on unprimed coordinates it may be taken inside the integral.

$$E(\mathbf{r}) = -j\omega\mu \int_V \mathcal{L}^{-1} \cdot J(\mathbf{r}') \cdot \bar{\mathbf{I}} \delta(\mathbf{r} - \mathbf{r}') d^3\mathbf{r}' \quad (\text{A-11})$$

$$E(\mathbf{r}) = -j\omega\mu \int_V \left[\mathcal{L}^{-1} \cdot \bar{\mathbf{I}} \delta(\mathbf{r} - \mathbf{r}') \right] \cdot J(\mathbf{r}') d^3\mathbf{r}' \quad (\text{A-12})$$

$$E(\mathbf{r}) = j\omega\mu \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot J(\mathbf{r}') d^3\mathbf{r}' \quad (\text{A-13})$$

Equation (A-13) is used as the definition of the dyadic Green's function:

$$\bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') = -\mathcal{L}^{-1} \cdot \bar{\mathbf{I}} \delta(\mathbf{r}, \mathbf{r}') \quad (\text{A-14})$$

$$\mathcal{L} \cdot \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') = -\delta(\mathbf{r}, \mathbf{r}') \bar{\mathbf{I}} \quad (\text{A-15})$$

$$(\nabla\nabla - \nabla^2 \bar{\mathbf{I}} - k_0^2 \bar{\mathbf{I}}) \cdot \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') = -\delta(\mathbf{r}, \mathbf{r}') \bar{\mathbf{I}} \quad (\text{A-16})$$

The dyadic Green's function is the solution to equation (A-16). The first step in solving this equation is to represent the three-dimensional delta function in a Fourier expansion:

$$\delta(\mathbf{r}, \mathbf{r}') = \frac{1}{(2\pi)^3} \iiint_{\text{All Space}} e^{-j\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}')} d^3\mathbf{k} \quad (\text{A-17})$$

Substituting the Fourier representation of the delta function in to (A-14) yields the following for $\bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}')$:

$$\bar{G}(\mathbf{r}, \mathbf{r}') = -\frac{1}{(2\pi)^3} \int_V \mathcal{L}^1 e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} d^3k \quad (\text{A-18})$$

To proceed, apply the $\mathcal{L}$ operator to the exponential term in equation (A-18).

$$\mathcal{L} e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} = (\nabla \nabla - \nabla^2 \bar{\mathbf{I}} - k_0^2 \bar{\mathbf{I}}) e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} \quad (\text{A-19})$$

Since $\nabla e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} = -j\mathbf{k} e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')}$, equation (A-19) becomes:

$$\begin{aligned} \mathcal{L} e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} &= [(-j\mathbf{k})(-j\mathbf{k}) - (-j\mathbf{k}) \cdot (-j\mathbf{k}) \bar{\mathbf{I}} - k_0^2 \bar{\mathbf{I}}] e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} \\ \mathcal{L} e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} &= [-\mathbf{k}\mathbf{k} + (k^2 - k_0^2) \bar{\mathbf{I}}] e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} \\ \mathcal{L}^1 e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} &= [-\mathbf{k}\mathbf{k} + (k^2 - k_0^2) \bar{\mathbf{I}}]^{-1} e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} \end{aligned} \quad (\text{A-20})$$

The matrix on the right side of equation (A-20) has the form of:

$$[\alpha \bar{\mathbf{I}} + \mathbf{a}\mathbf{b}] \quad (\text{A-21})$$

The inverse of a matrix of the form of the matrix in equation (A-21) is given by:

$$[\alpha \bar{\mathbf{I}} + \mathbf{a}\mathbf{b}]^{-1} = \frac{1}{\alpha} \left[\bar{\mathbf{I}} - \frac{\mathbf{a}\mathbf{b}}{\alpha + \mathbf{a} \cdot \mathbf{b}} \right] \quad (\text{A-22})$$

Hence, equation (A-20) becomes:

$$\mathcal{L}^1 e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} = \frac{1}{k^2 - k_0^2} \left[\bar{\mathbf{I}} - \frac{1}{k_0^2} \mathbf{k}\mathbf{k} \right] e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} \quad (\text{A-23})$$

From equation (A-18), the dyadic Green's function is now:

$$\bar{G}(\mathbf{r}, \mathbf{r}') = -\frac{1}{(2\pi)^3} \int_V \frac{1}{(k^2 - k_0^2)} \left[\bar{\mathbf{I}} - \frac{1}{k_0^2} \mathbf{k}\mathbf{k} \right] e^{-j\mathbf{k} \cdot (\mathbf{r}-\mathbf{r}')} d^3k \quad (\text{A-24})$$

Perform the integration in equation (A-24) to obtain an expression for the free-space dyadic Green's function:

$$\bar{G}(\mathbf{r}, \mathbf{r}') = \frac{1}{(2\pi)^3} \left[\bar{I} - \frac{1}{k_0^2} \mathbf{k} \mathbf{k} \right] \int_V \frac{1}{(k^2 - k_0^2)} e^{-j\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}')} d^3k \quad (\text{A-23})$$

Recognizing that $\mathbf{k} \rightarrow j\nabla$, equation (A-23) may be rewritten as:

$$\bar{G}(\mathbf{r}, \mathbf{r}') = \frac{1}{(2\pi)^3} \left[\bar{I} + \frac{1}{k_0^2} \nabla \nabla \right] \int_V \frac{1}{(k^2 - k_0^2)} e^{-j\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}')} d^3k \quad (\text{A-24})$$

Using $\frac{1}{(2\pi)^3} \int_V \frac{1}{(k^2 - k_0^2)} e^{-j\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}')} d^3k$ as the definition of the scalar

Green's function in an unbounded region, the final form of the dyadic Green's function is given by:

$$\boxed{\bar{G}(\mathbf{r}, \mathbf{r}') = \left[\bar{I} + \frac{1}{k_0^2} \nabla \nabla \right] g(\mathbf{r}, \mathbf{r}')} \quad (\text{A-25})$$

where $g(\mathbf{r}, \mathbf{r}') = \int_V \frac{1}{(k^2 - k_0^2)} e^{-j\mathbf{k} \cdot (\mathbf{r} - \mathbf{r}')} d^3k$ is the scalar Green's function.

Using equation (A-25), the electric field due to a known current distribution is given by:

$$\mathbf{E} = -j\omega\mu \int_V \bar{G}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') d^3\mathbf{r}' \quad (\text{A-26})$$

APPENDIX B

Singularities of the Electric Dyadic Green's Function

B.1 Introduction

In appendix A, it is shown how the dyadic Green's function is used in conjunction with the known current distribution to compute the electric field radiated by the source. This same result is used in deriving the volume integral equations that describe the biological body. The difference between these two applications of the dyadic Green's function is the domain in which the function is desired. With respect to the scattering problem, the domain of interest is the space outside of the source. The electric fields that are desired lie outside of the source. For the volume integral equations, the domain of interest lies within the source.

For the scattering problem, there is no problem in computing the integral, numerically if need be, and solving for the electric fields. On the other hand, a strong singularity on the order of $1/R^3$ results from the dyadic Green's function when the domain of interest lies within the source. In order to overcome this singularity, the "principle-value" method of integration is used[19]. In short, an infinitesimal sphere containing the singularity is subtracted out and the integral is computed as the limit of the volume of the infinitesimal sphere goes to zero.

B.2 Mathematical Derivation

Recalling the result from appendix A that relates the electric fields to the source current:

$$\mathbf{E} = -j\omega\mu \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') d^3\mathbf{r}' \quad (\text{B-1})$$

where V is the volume occupied by the source current, and the dyadic Green's function is:

$$\bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') = \left[\bar{\mathbf{I}} + \frac{1}{k_0^2} \nabla \nabla \right] \mathbf{g}(\mathbf{r}, \mathbf{r}') \quad (\text{B-2})$$

The $\mathbf{g}(\mathbf{r}, \mathbf{r}')$ term is the scalar Green's function and is given by:

$$\mathbf{g}(\mathbf{r}, \mathbf{r}') = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|} \quad (\text{B-3})$$

Given an arbitrary source distribution, the method of retarded potentials gives an expression for the field values within the source directly:

$$\begin{aligned} \mathbf{E}(\mathbf{r}_0) = & -\nabla \frac{1}{4\pi\epsilon_0} \left[\iiint_{V'} \frac{-1}{j\omega} (\nabla \cdot \mathbf{J}) \frac{e^{-jk|\mathbf{r}-\mathbf{r}_0|}}{|\mathbf{r}-\mathbf{r}_0|} dV + \iint_S \frac{1}{j\omega} (\mathbf{J} \cdot \hat{\mathbf{n}}) \frac{e^{-jk|\mathbf{r}-\mathbf{r}_0|}}{|\mathbf{r}-\mathbf{r}_0|} ds \right] \\ & - \frac{j\omega\mu_0}{4\pi} \iiint_{V'} \mathbf{J}(\mathbf{r}) \frac{e^{-jk|\mathbf{r}-\mathbf{r}_0|}}{|\mathbf{r}-\mathbf{r}_0|} dV \end{aligned} \quad (\text{B-4})$$

In the above equation, V' represents the volume of the source with an infinitesimal sphere centered about the point of singularity, $\mathbf{r}_0$, subtracted out. S is the surface of the enclosing the source region. Taking the del operator inside the integrals yields:

$$\begin{aligned}
E(\mathbf{r}_o) = & -\frac{1}{j\omega 4\pi\epsilon_o} \iiint_{V'} (\nabla \cdot \mathbf{J}) \nabla \frac{e^{-jk|\mathbf{r}-\mathbf{r}_o|}}{|\mathbf{r}-\mathbf{r}_o|} dV + \frac{1}{j\omega 4\pi\epsilon_o} \iint_S (\mathbf{J} \cdot \hat{\mathbf{n}}) \nabla \frac{e^{-jk|\mathbf{r}-\mathbf{r}_o|}}{|\mathbf{r}-\mathbf{r}_o|} ds \\
& - \frac{j\omega\mu_o}{4\pi} \iiint_{V'} \mathbf{J}(\mathbf{r}) \frac{e^{-jk|\mathbf{r}-\mathbf{r}_o|}}{|\mathbf{r}-\mathbf{r}_o|} dV \quad (B-5)
\end{aligned}$$

The first volume integral of the above equation may be transformed to a surface integral with the following relationships:

$$\nabla \cdot (\mathbf{a}\mathbf{b}) = (\nabla \cdot \mathbf{a})\mathbf{b} + \mathbf{a} \cdot \nabla \mathbf{b} \quad (B-6)$$

$$\iiint_V \nabla \cdot (\mathbf{a}\mathbf{b}) dV = \iint_S (\hat{\mathbf{n}} \cdot \mathbf{a}) \mathbf{b} dS \quad (B-7)$$

Combining with the second integral in (B-5) gives:

$$E(\mathbf{r}_o) = \frac{1}{j\omega 4\pi\epsilon_o} \iiint_{V'} \mathbf{J} \cdot \nabla \nabla \frac{e^{-jk|\mathbf{r}-\mathbf{r}_o|}}{|\mathbf{r}-\mathbf{r}_o|} dV + \frac{1}{j\omega 4\pi\epsilon_o} \iint_{\Sigma} (\mathbf{J} \cdot \hat{\mathbf{n}}) \nabla \frac{e^{-jk|\mathbf{r}-\mathbf{r}_o|}}{|\mathbf{r}-\mathbf{r}_o|} d\Sigma \quad (B-8)$$

Σ is the surface enclosing the sphere surrounding the point of singularity. As the radius of the sphere surrounding the singularity becomes small, the gradient of the scalar Green's function approaches $-u/\eta^2$, where η is the radius of the sphere. Using spherical coordinates centered at the singularity, the surface integral in the above equation becomes $-\mathbf{J}/(3j\omega\epsilon_o)$. Equation (B-8) now takes the final form of:

$$\boxed{E(\mathbf{r}_o) = -j\omega\mu_P V \int_V \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') d^3\mathbf{r}' - \frac{\mathbf{J}(\mathbf{r})}{3j\omega\epsilon_o}} \quad (B-9)$$

The PV signifies the Principal Value integration technique. Equation (B-9) allows for the fields to be determined within

the source region and is used to derive the volume integral equations used in this investigation.

APPENDIX C

Source Code for Far-Zone Fields

```

C*****
C
C      PROGRAM : FFLD.FOR
C
C          This program uses the body geometry and the
C          currents induced in the body to compute a
C          far - zone scattered field. The field will
C          be given in dB-down.
C
C*****

C SUBPROGRAMS
    external tslice,pslice

C pslice: This subprogram determines the far-zone field with a
C          constant phi observation angle & scans through theta.
C tslice: This subprogram determines the far-zone field with a
C          constant theta observation angle & scans through phi.

C CONSTANTS
    integer max
    parameter (max=135)

C VARIABLES
    real*8   freq,center(max,3),length(max,3),angle,rho

C   freq      : The frequency of the source.
C   center     : A 2-dimensional array to hold the X,Y,Z coordinates
C                of the centers of each cell.
C   length     : A 2-dimensional array to hold the X,Y,Z dimensions
C                of each cell.
C   rho        : The observation distance in meters.

    complex*16 j(max,3)

C j: A 2-dimensional array to hold the X,Y,Z components of the
C   currents induced in each cell.

    integer cells,nn,ans

C cells: The number of cells in the body.
C   nn: A loop index.
C   ans: An answer to a question.

C*****
C          Load currents & body geometry.
C*****
    open (3,file='data.dat')
    read(3,*) freq
    read(3,*) cells
    read(3,*) rho
    read(3,*) ans
    read(3,*) angle

```

```

        read(3,*) ndivx
        read(3,*) ndivy
        read(3,*) ndivz
        do 10 nn = 1,cells
            read(3,*) j(nn,1) , j(nn,2) , j(nn,3)
10      continue
        do 20 nn = 1,cells
            read(3,*) center(nn,1) , center(nn,2) , center(nn,3)
20      continue
        do 30 nn = 1,cells
            read(3,*) length(nn,1) , length(nn,2) , length(nn,3)
30      continue
        close(unit = 3)

C*****
C      Request scan angles & compute far-zone fields.      *
C*****
        if (ans .eq. 1) then
            call pslice(cells,ndivx,ndivy,ndivz,freq,j,length,center,
+                angle,rho)
        endif
        if (ans .eq. 2) then
            call tslice(cells,ndivx,ndivy,ndivz,freq,j,length,center,
+                angle,rho)
        endif
        stop
        end

```

```

C*****
C
C      Subprogram pslice.for
C
C      Output: This subroutine will compute the far - zone field
C              in dB-down.
C*****

      SUBROUTINE pslice(cells,ndivx,ndivy,ndivz,freq,jj,length,center
+,phi,rho)
C Constants
      real*8 pi,mu,c
      integer max
      parameter (pi=3.141592659,mu=12.56637061E-7,c=299.8E6,max=135)

C Arguments

      integer cells,ndivx,ndivy,ndivz
C Cells : the number of cells in the radio-body model
C Ndivx : the number of subdivisions the cells are sectioned into in
C         the x-direction. This parameter is used in a midpoint
C         integral approximation.
C Ndivy : the number of subdivisions the cells are sectioned into in
C         the y-direction. This parameter is used in a midpoint
C         integral approximation.
C Ndivz : the number of subdivisions the cells are sectioned into in
C         the z-direction. This parameter is used in a midpoint
C         integral approximation.
C Phi   : The constant phi angle.

      real*8 freq,length(max,3),center(max,3),rho,phi
C Freq   : the frequency of operation in hertz.
C Length : the x-y-z dimensions of the discrete cells in meters.
C Center : the x-y-z coordinates of the centers of the cells in meters.
C Rho    : the observation distance from the origin in meters.

      complex*16 jj(max,3)
C JJ : the complex constant currents in the discrete cells.

C Variables
      real*8 escan(360),deltax,deltay,deltaz,beta,emax,xo,yo,zo,R
      real*8 xi,yj,zk,dvprim
      complex*16 ax,ay,az,atheta,aphi,etheta,ephi
      integer theta,i,j,k,cell
C Escan : the array of E-field magnitudes at each scan angle(1-360).
C Deltax : The finite increment in the x-direction used in the midpoint
C         definite integral approximation.
C Deltay : The finite increment in the y-direction used in the midpoint
C         definite integral approximation.
C Deltaz : The finite increment in the z-direction used in the midpoint
C         definite integral approximation.
C dvprim : The volume of the source subcells.
C Beta   : The wave number rad/meter.
C Emax   : A temp variable used in the normalization of the E-field.
C xo     : The x-coordinate of the distance from the origin.
C yo     : The y-coordinate of the distance from the origin.
C zo     : The z-coordinate of the distance from the origin.
C R      : The distance from the source to the observation point.
C xi     : The x-coordinate of the source subcell.

```

```

C yj      : The y-coordinate of the source subcell.
C zk      : The z-coordinate of the source subcell.
C ax      : The x-component of the A-vector potential.
C ay      : The y-component of the A-vector potential.
C az      : The z-component of the A-vector potential.
C atheta  : The theta component of the A-vector potential.
C aphi    : The phi component of the A-vector potential.
C etheta  : The theta component of the E-field.
C ephi    : The phi component of the E-field.
C Theta   : The theta observation angle that changes.
C i,j,k   : Loop indicies.
C cell    : Another loop index.

```

```

C*****
C                                  BEGIN                                  *
C*****
      beta=2*pi*freq/c
      do 10 theta=1,180
        xo=rho*sin((theta-1)*pi/180)*cos(phi*pi/180)
        yo=rho*sin((theta-1)*pi/180)*sin(phi*pi/180)
        zo=rho*cos((theta-1)*pi/180)
        ax=cplx(0.0,0.0)
        ay=cplx(0.0,0.0)
        az=cplx(0.0,0.0)
        do 20 cell=1,cells
          deltax=length(cell,1)/ndivx
          deltax=length(cell,2)/ndivx
          deltay=length(cell,2)/ndivy
          deltaz=length(cell,3)/ndivz
          dvprim=deltax*deltay*deltaz

          do 30 i=1,ndivx
            do 40 j=1,ndivy
              do 50 k=1,ndivz
                xi=center(cell,1)-length(cell,1)/2+deltax*(i-.5)
                yj=center(cell,2)-length(cell,2)/2+deltax*(j-.5)
                zk=center(cell,3)-length(cell,3)/2+deltax*(k-.5)

                R=sqrt((xo-xi)**2+(yo-yj)**2+(zo-zk)**2)

                ax=ax+mu*jj(cell,1)/(4*pi)*cexp(cplx(0,-beta*R))/R*dvprim
                ay=ay+mu*jj(cell,2)/(4*pi)*cexp(cplx(0,-beta*R))/R*dvprim
                az=az+mu*jj(cell,3)/(4*pi)*cexp(cplx(0,-beta*R))/R*dvprim
50          continue
40          continue
30          continue
20        continue

        atheta=cos((theta-1)*pi/180)*cos(phi*pi/180)*ax+cos((theta
+      -1)*pi/180)*sin(phi*pi/180)*ay-sin((theta-1)*pi/180)*az
        aphi=-sin(phi*pi/180)*ax+cos(phi*pi/180)*ay

        etheta=atheta*cplx(0,-2*pi*freq)
        ephi=aphi*cplx(0,-2*pi*freq)

        escan(theta)=sqrt((abs(etheta))**2+(abs(ephi))**2)
        write(6,500) (theta-1)
500      format('+', ' JUST SCANNED AT ',I4,' DEGREES')
10    continue

```



```

C*****
C    Now rotate the constant phi angle by 180 degrees and scan the    *
C    other side of the theta slice.                                  *
C*****
    phi=phi+180
    do 100 theta=180,1,-1
        xo=rho*sin(theta*pi/180)*cos(phi*pi/180)
        yo=rho*sin(theta*pi/180)*sin(phi*pi/180)
        zo=rho*cos(theta*pi/180)
        ax=cmplx(0.0,0.0)
        ay=cmplx(0.0,0.0)
        az=cmplx(0.0,0.0)
        do 110 cell=1,cells
            deltax=length(cell,1)/ndivx
            deltay=length(cell,2)/ndivy
            deltaz=length(cell,3)/ndivz
            dvprim=deltax*deltay*deltaz

            do 120 i=1,ndivx
                do 130 j=1,ndivy
                    do 140 k=1,ndivz
                        xi=center(cell,1)-length(cell,1)/2+deltax*(i-.5)
                        yj=center(cell,2)-length(cell,2)/2+deltax*(j-.5)
                        zk=center(cell,3)-length(cell,3)/2+deltax*(k-.5)

                        R=sqrt((xo-xi)**2+(yo-yj)**2+(zo-zk)**2)

                        ax=ax+mu*jj(cell,1)/(4*pi)*cexp(cmplx(0,-beta*R))/R*dvprim
                        ay=ay+mu*jj(cell,2)/(4*pi)*cexp(cmplx(0,-beta*R))/R*dvprim
                        az=az+mu*jj(cell,3)/(4*pi)*cexp(cmplx(0,-beta*R))/R*dvprim
140                    continue
130                continue
120            continue
110        continue

        atheta=cos(theta*pi/180)*cos(phi*pi/180)*ax+cos(theta
+        *pi/180)*sin(phi*pi/180)*ay-sin(theta*pi/180)*az
        aphi=-sin(phi*pi/180)*ax+cos(phi*pi/180)*ay

        etheta=atheta*cmplx(0,-2*pi*freq)
        ephi=aphi*cmplx(0,-2*pi*freq)

        escan(361-theta)=sqrt((abs(etheta))**2+(abs(ephi))**2)
        write(6,500) (theta)
100    continue
C*****
C    Normalize the Escan array    *
C*****
    emax=escan(1)
    do 60 i=2,360
        if (escan(i) .GE. emax) then
            emax=escan(i)
        endif
60    continue
    do 70 i=1,360
        escan(i)=escan(i)/emax
70    continue

```

```

C*****
C          Convert to decibels                      *
C*****
      do 80 i=1,360
        if (escan(i) .LE. 0.01) then
          escan(i)=0.01
        endif
        escan(i)=20*log10(escan(i))
80    continue

C*****
C          Write to an output file                  *
C*****
      open(3,file='scan1.mat')
      do 90 i=1,360
        write(3,*) (i-1) , escan(i)
90    continue
      close(unit=3)
      return
      end

```

```

C*****
C
C      Subprogram tslice.for
C
C      Output: This subroutine will compute the far - zone field
C              in dB-down.
C*****

      SUBROUTINE tslice(cells,ndivx,ndivy,ndivz,freq,jj,length,center
+,theta,rho)
C Constants
      real*8 pi,mu,c
      integer max
      parameter (pi=3.141592659,mu=12.56637061E-7,c=299.8E6,max=135)

C Arguments

      integer cells,ndivx,ndivy,ndivz
C Cells : the number of cells in the radio-body model
C Ndivx : the number of subdivisions the cells are sectioned into in
C         the x-direction. This parameter is used in a midpoint
C         integral approximation.
C Ndivy : the number of subdivisions the cells are sectioned into in
C         the y-direction. This parameter is used in a midpoint
C         integral approximation.
C Ndivz : the number of subdivisions the cells are sectioned into in
C         the z-direction. This parameter is used in a midpoint
C         integral approximation.
C Theta : The constant theta angle.

      real*8 freq,length(max,3),center(max,3),rho,theta
C Freq : the frequency of operation in hertz.
C Length : the x-y-z dimensions of the discrete cells in meters.
C Center : the x-y-z coordinates of the centers of the cells in meters.
C Rho : the observation distance from the origin in meters.

      complex*16 jj(max,3)
C JJ : the complex constant currents in the discrete cells.

C Variables
      real*8 escan(360),deltax,deltay,deltaz,beta,emax,xo,yo,zo,R
      real*8 xi,yj,zk,dvprim
      complex*16 ax,ay,az,atheta,aphi,etheta,ephi
      integer phi,i,j,k,cell
C Escan : the array of E-field magnitudes at each scan angle(1-360).
C Deltax : The finite increment in the x-direction used in the midpoint
C         definite integral approximation.
C Deltay : The finite increment in the y-direction used in the midpoint
C         definite integral approximation.
C Deltaz : The finite increment in the z-direction used in the midpoint
C         definite integral approximation.
C dvprim : The volume of the source subcells.
C Beta : The wave number rad/meter.
C Emax : A temp variable used in the normalization of the E-field.
C xo : The x-coordinate of the distance from the origin.
C yo : The y-coordinate of the distance from the origin.
C zo : The z-coordinate of the distance from the origin.
C R : The distance from the source to the observation point.
C xi : The x-coordinate of the source subcell.

```

```

C yj      : The y-coordinate of the source subcell.
C zk      : The z-coordinate of the source subcell.
C ax      : The x-component of the A-vector potential.
C ay      : The y-component of the A-vector potential.
C az      : The z-component of the A-vector potential.
C atheta  : The theta component of the A-vector potential.
C aphi    : The phi component of the A-vector potential.
C etheta  : The theta component of the E-field.
C ephi    : The phi component of the E-field.
C Theta   : The theta observation angle that changes.
C i,j,k   : Loop indicies.
C cell    : Another loop index.

C*****
C                                  BEGIN
C*****

      beta=2*pi*freq/c
      do 10 phi=1,360
        xo=rho*sin(theta*pi/180)*cos((phi-1)*pi/180)
        yo=rho*sin(theta*pi/180)*sin((phi-1)*pi/180)
        zo=rho*cos(theta*pi/180)
        ax=cplx(0.0,0.0)
        ay=cplx(0.0,0.0)
        az=cplx(0.0,0.0)
        do 20 cell=1,cells
          deltax=length(cell,1)/ndivx
          deltay=length(cell,2)/ndivy
          deltaz=length(cell,3)/ndivz
          dvprim=deltax*deltay*deltaz

          do 30 i=1,ndivx
            do 40 j=1,ndivy
              do 50 k=1,ndivz
                xi=center(cell,1)-length(cell,1)/2+deltax*(i-.5)
                yj=center(cell,2)-length(cell,2)/2+deltax*(j-.5)
                zk=center(cell,3)-length(cell,3)/2+deltax*(k-.5)

                R=sqrt((xo-xi)**2+(yo-yj)**2+(zo-zk)**2)

                ax=ax+mu*jj(cell,1)/(4*pi)*exp(cplx(0,-beta*R))/R*dvprim
                ay=ay+mu*jj(cell,2)/(4*pi)*exp(cplx(0,-beta*R))/R*dvprim
                az=az+mu*jj(cell,3)/(4*pi)*exp(cplx(0,-beta*R))/R*dvprim
              50          continue
            40          continue
          30          continue
        20          continue

        atheta=cos(theta*pi/180)*cos((phi-1)*pi/180)*ax+cos(
+      theta*pi/180)*sin((phi-1)*pi/180)*ay-sin(theta*pi/180)*az
        aphi=-sin((phi-1)*pi/180)*ax+cos((phi-1)*pi/180)*ay

        etheta=atheta*cplx(0,-2*pi*freq)
        ephi=aphi*cplx(0,-2*pi*freq)

        escan(phi)=sqrt((abs(etheta))**2+(abs(ephi))**2)
        write(6,500) (phi-1)
500      format(' ',' JUST SCANNED AT ',I4,' DEGREES')
10      continue

```

```

C*****
C                                     Normalize the Escan array                                     *
C*****
    emax=escan(1)
    do 60 i=2,360
        if (escan(i) .GE. emax) then
            emax=escan(i)
        endif
60    continue
    do 70 i=1,360
        escan(i)=escan(i)/emax
70    continue

C*****
C                                     Convert to decibels                                     *
C*****
    do 80 i=1,360
        if (escan(i) .LE. 0.01) then
            escan(i)=0.01
        endif
        escan(i)=20*log10(escan(i))
80    continue

C*****
C                                     Write to an output file                                     *
C*****
    open(3,file='scan2.mat')
    do 90 i=1,360
        write(3,*) (i-1) , escan(i)
90    continue
    close(unit=3)
    return
end

```

APPENDIX D

Details of the model of the biological body

D.1 Input File

The following is a listing of the input file that describes the block model of the man. The first 114 lines are the x, y and z coordinates of the centers of each cell followed by the x, y and z dimensions of each cell. The final set of 114 lines represent the dielectric constant and conductivity for each cell.

```
-----
0.05,0.05,0.65,0.1,0.1,0.1
0.05,-0.05,0.65,0.1,0.1,0.1
-0.05,0.05,0.65,0.1,0.1,0.1
-0.05,-0.05,0.65,0.1,0.1,0.1

0.05,0.05,0.55,0.1,0.1,0.1
0.05,-0.05,0.55,0.1,0.1,0.1
-0.05,0.05,0.55,0.1,0.1,0.1
-0.05,-0.05,0.55,0.1,0.1,0.1

0.025,0.025,0.475,0.05,0.05,0.05
0.025,-0.025,0.475,0.05,0.05,0.05
-0.025,0.025,0.475,0.05,0.05,0.05
-0.025,-0.025,0.475,0.05,0.05,0.05

0.025,0.025,0.425,0.05,0.05,0.05
0.025,-0.025,0.425,0.05,0.05,0.05
-0.025,0.025,0.425,0.05,0.05,0.05
-0.025,-0.025,0.425,0.05,0.05,0.05

0.0,0.25,0.35,0.1,0.1,0.1
0.05,0.15,0.35,0.1,0.1,0.1
0.05,0.05,0.35,0.1,0.1,0.1
0.05,-0.05,0.35,0.1,0.1,0.1
0.05,-0.15,0.35,0.1,0.1,0.1
0.0,-0.25,0.35,0.1,0.1,0.1
-0.05,0.15,0.35,0.1,0.1,0.1
-0.05,0.05,0.35,0.1,0.1,0.1
-0.05,-0.05,0.35,0.1,0.1,0.1
-0.05,-0.15,0.35,0.1,0.1,0.1

0.0,0.25,0.25,0.1,0.1,0.1
0.05,0.15,0.25,0.1,0.1,0.1
0.05,0.05,0.25,0.1,0.1,0.1
0.05,-0.05,0.25,0.1,0.1,0.1
0.05,-0.15,0.25,0.1,0.1,0.1
0.0,-0.25,0.25,0.1,0.1,0.1
```

-0.05,0.15,0.25,0.1,0.1,0.1
-0.05,0.05,0.25,0.1,0.1,0.1
-0.05,-0.05,0.25,0.1,0.1,0.1
-0.05,-0.15,0.25,0.1,0.1,0.1

0.0,0.25,0.16,0.08,0.08,0.08
0.045,0.135,0.155,0.09,0.09,0.09
0.045,0.045,0.155,0.09,0.09,0.09
0.045,-0.045,0.155,0.09,0.09,0.09
0.045,-0.135,0.155,0.09,0.09,0.09
0.0,-0.25,0.16,0.08,0.08,0.08
-0.045,0.135,0.155,0.09,0.09,0.09
-0.045,0.045,0.155,0.09,0.09,0.09
-0.045,-0.045,0.155,0.09,0.09,0.09
-0.045,-0.135,0.155,0.09,0.09,0.09

0.0,0.25,0.08,0.08,0.08,0.08
0.04,0.12,0.07,0.08,0.08,0.08
0.04,0.4,0.07,0.08,0.08,0.08
0.04,-0.4,0.07,0.08,0.08,0.08
0.04,-0.12,0.07,0.08,0.08,0.08
0.0,-0.25,0.08,0.08,0.08,0.08
-0.04,0.12,0.07,0.08,0.08,0.08
-0.04,0.4,0.07,0.08,0.08,0.08
-0.04,-0.4,0.07,0.08,0.08,0.08
-0.04,-0.12,0.07,0.08,0.08,0.08

-0.005,0.255,0.005,0.07,0.07,0.07
0.04,0.12,-0.01,0.08,0.08,0.08
0.04,0.04,-0.01,0.08,0.08,0.08
0.04,-0.04,-0.01,0.08,0.08,0.08
0.04,-0.12,-0.01,0.08,0.08,0.08
-0.005,-0.255,0.005,0.07,0.07,0.07
-0.04,0.12,-0.01,0.08,0.08,0.08
-0.04,0.04,-0.01,0.08,0.08,0.08
-0.04,-0.04,-0.01,0.08,0.08,0.08
-0.04,-0.12,-0.01,0.08,0.08,0.08

-0.005,0.255,-0.065,0.07,0.07,0.07
0.045,0.135,-0.095,0.09,0.09,0.09
0.045,0.045,-0.095,0.09,0.09,0.09
0.045,-0.045,-0.095,0.09,0.09,0.09
0.045,-0.135,-0.095,0.09,0.09,0.09
-0.005,-0.255,-0.065,0.07,0.07,0.07
-0.045,0.135,-0.095,0.09,0.09,0.09
-0.045,0.045,-0.095,0.09,0.09,0.09
-0.045,-0.045,-0.095,0.09,0.09,0.09
-0.045,-0.135,-0.095,0.09,0.09,0.09

0.0,0.25,-0.14,0.08,0.08,0.08
0.05,0.15,-0.19,0.1,0.1,0.1
0.05,0.05,-0.19,0.1,0.1,0.1
0.05,-0.05,-0.19,0.1,0.1,0.1
0.05,-0.15,-0.19,0.1,0.1,0.1
0.0,-0.25,-0.14,0.08,0.08,0.08
-0.05,0.15,-0.19,0.1,0.1,0.1
-0.05,0.05,-0.19,0.1,0.1,0.1
-0.05,-0.05,-0.19,0.1,0.1,0.1
-0.05,-0.15,-0.19,0.1,0.1,0.1

0.045,0.145,-0.285,0.09,0.09,0.09
0.045,0.055,-0.285,0.09,0.09,0.09
0.045,-0.055,-0.285,0.09,0.09,0.09
0.045,-0.145,-0.285,0.09,0.09,0.09
-0.045,0.145,-0.285,0.09,0.09,0.09
-0.045,0.055,-0.285,0.09,0.09,0.09
-0.045,-0.055,-0.285,0.09,0.09,0.09
-0.045,-0.145,-0.285,0.09,0.09,0.09

0.04,0.14,-0.37,0.08,0.08,0.08
0.04,0.06,-0.37,0.08,0.08,0.08
0.04,-0.06,-0.37,0.08,0.08,0.08
0.04,-0.14,-0.37,0.08,0.08,0.08
-0.04,0.14,-0.37,0.08,0.08,0.08
-0.04,0.06,-0.37,0.08,0.08,0.08
-0.04,-0.06,-0.37,0.08,0.08,0.08
-0.04,-0.14,-0.37,0.08,0.08,0.08

0.0,0.1,-0.47,0.12,0.12,0.12
0.0,-0.1,-0.47,0.12,0.12,0.12

0.0,0.1,-0.59,0.12,0.12,0.12
0.0,-0.1,-0.59,0.12,0.12,0.12

0.0,0.1,-0.7,0.1,0.1,0.1
0.0,-0.1,-0.7,0.1,0.1,0.1

0.0,0.1,-0.8,0.1,0.1,0.1
0.0,-0.1,-0.8,0.1,0.1,0.1

0.0,0.1,-0.9,0.1,0.1,0.1
0.0,-0.1,-0.9,0.1,0.1,0.1

0.0,0.1,-1.0,0.1,0.1,0.1
0.0,-0.1,-1.0,0.1,0.1,0.1

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80.0, 0.25
80.0, 0.25
80.0, 0.25

80.0, 0.25
80.0, 0.25
80.0, 0.25
80.0, 0.25

96.0, 0.25
96.0, 0.25
96.0, 0.25
96.0, 0.25

96.0, 0.25
96.0, 0.25
96.0, 0.25
96.0, 0.25

96.0, 0.08
96.0, 0.08
96.0, 0.08
96.0, 0.08

96.0, 0.08
96.0, 0.08
96.0, 0.08
96.0, 0.08
96.0, 0.08
96.0, 0.08

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100.0, 0.3

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100.0, 0.3
100.0, 0.3
70.0, 0.08
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100.0, 0.3
100.0, 0.3
100.0, 0.3

70.0, 0.08
100.0, 0.3
100.0, 0.3
100.0, 0.3
100.0, 0.3
100.0, 0.3
70.0, 0.08
100.0, 0.3
100.0, 0.3
100.0, 0.3
100.0, 0.3

70.0, 0.08
101.0, 0.25
101.0, 0.25
101.0, 0.25
101.0, 0.25
101.0, 0.25
70.0, 0.08
101.0, 0.25
101.0, 0.25
101.0, 0.25
101.0, 0.25

70.0, 0.08
101.0, 0.25
101.0, 0.25
101.0, 0.25
101.0, 0.25
101.0, 0.25
70.0, 0.08
101.0, 0.25
101.0, 0.25
101.0, 0.25

101.0, 0.25

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80.0, 0.08

80.0, 0.08

80.0, 0.08

80.0, 0.08

70.0, 0.001

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80.0, 0.08

80.0, 0.08

80.0, 0.08

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96.0, 0.2

96.0, 0.2

96.0, 0.2

96.0, 0.2

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96.0, 0.3

96.0, 0.3

96.0, 0.3

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75.0, 0.05

75.0, 0.05

75.0, 0.05

75.0, 0.05

75.0, 0.05

D.2 Illustration of the Block Model of the Body