IMR-168/1

COPY NO. 54 OF 60 COPIES

APPROVED FOR RELEASE. [signature]

INTERNAL MEMORANDUM

RELEASABLE

THE JUNGLE AS A COMMUNICATION NETWORK

by

B. A. Lippmann

Revised September 1965
(Supersedes Sept. 1964 edition)

DEFENSE RESEARCH CORPORATION
6300 Hollister Avenue
P.O. BOX 3587 • SANTA BARBARA, CALIFORNIA • 93105

This work supported by
Advanced Research Projects Agency

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

Elementary arguments and a simple model are used to clarify the dominant features of radio transmission through jungles.

Part I represents the jungle as a plane uniform slab of constant conductivity and permittivity. A critical frequency is defined; below this frequency the slab behaves like a conductor; above it, it behaves like a dielectric. From these two limiting cases an upper limit on attenuation, which holds independently of the operating frequency, is derived.

The model is applied to Herbstreit's experiments in the Panama jungle. Reasonable assumptions regarding the dielectric constant and density of the jungle lead to values between .02 and .04 mhos/m for the conductivity of the vegetation, which corresponds quite well with that of moist earth.

Part II discusses the applicability of the uniform dielectric model employed in Part I. Equivalent circuit concepts are used to analyze the jungle as a four-terminal network. The model of Part I is shown to be strictly applicable only to a uniform--or at least a symmetrical--jungle.

The determination of the network parameters for the equivalent circuit representing the jungle is discussed. The relation between the complex propagation constant and the amplitude of the forward scattered field is given. The results of using the Born approximation, and a rough first correction to it, to solve the field problem are also stated.

INTRODUCTION

The aim of this work is to use elementary arguments and simple models to clarify the dominent features of radio transmission through jungles.

The analysis is in two parts. Part I represents the jungle as a plane uniform slab of constant conductivity and permittivity; rough, quantitative calculations are made with this model and are related to Herbstreit's World War II measurements.[1] Part II discusses the theoretical justification for representing the jungle as a uniform, dissipative, dielectric. The conditions that limit the usefulness of this model are discussed in some detail. Thus, Part I is essentially a numerical study of an easily calculated special case, while Part II is a rigorous theoretical discussion of the approximations that the use of the simple model implies.

The cont nt of the paper s summarized in the Abstract.

I. THE JUNGLE AS A UNIFORM DIELECTRIC SLAB

A. THE UNIFORM DIELECTRIC MEDIUM

In this section we discuss some of the transmission properties of a uniform dielectric. The limitations on the use of this as a model for jungle vegetation will be discussed in Part II. We use MKS units and we follow the convention of putting $\mu = \mu_o = 4\pi \times 10^{-7}$ henries/meter. Thus, only the dielectric constant, ε, and the conductivity, σ, remain to be specified. We shall specify these latter quantities by noting that the dielectric slab is a model for a mixture of two kinds of propagation media--air and vegetation--and the constants for the equivalent uniform medium have to be determined.

The dielectric properties of mixtures have been considered since Rayleigh's time, at least. According to the Encyclopedia of Physics,[2] if the elements of a mixture have dielectric constants ε_1, ε_2, . . . ε_n, and they occupy fractions of the total volume $v_1, v_2, \ldots v_n$, then the mean dielectric constant, ε_m, is bounded by

$$\bar{\varepsilon}_m > \varepsilon_m > \underline{\varepsilon_m} , \tag{1}$$

where

$$\bar{\varepsilon}_m = \sum_{i=1}^{n} \varepsilon_i v_i , \tag{2}$$

and

$$\frac{1}{\underline{\varepsilon_m}} = \sum_{i=1}^{n} \frac{v_i}{\varepsilon_i} . \tag{3}$$

With the replacement $\varepsilon \to \sigma$, similar considerations apply to conductivity. However, in the jungle case, one of the constituents of the mixture is air, with zero conductivity. Hence, we now find only an upper limit on σ_m, the lower limit being the trivial value zero; that is,

$$\bar{\sigma}_m > \sigma_m > 0, \tag{4}$$

where

$$\bar{\sigma}_m = \sum_{i=1}^{n} \sigma_i v_i . \tag{5}$$

B. CRITICAL FREQUENCY

The complex dielectric constant is, assuming time dependence $e^{-i\omega t}$ in Maxwell's equations,

$$\varepsilon + i \frac{\sigma}{\omega} = \varepsilon' + i \varepsilon'' \tag{6}$$

If the vegetation has permittivity 80 (very wet) and occupies a fraction d of the total volume (d << 1), we find ($\epsilon_o = 10^{-9}/36\pi$):

$$1 + 79\, d > \frac{\epsilon_m}{\epsilon_o} > 1 \qquad (7)$$

If σ_v is the conductivity of the vegetation

$$\sigma_v\, d > \sigma_m > 0 \,. \qquad (8)$$

Using the symbol $\bar{\sigma}$ for $\sigma_v d$ we have:

$$\left.\begin{aligned} \epsilon' &\simeq \epsilon_o\,(1 + 79\, d) \\ \epsilon'' &= \frac{\bar{\sigma}}{\omega} \quad . \end{aligned}\right\} \qquad (9)$$

A critical frequency, $\bar{f}$, may be defined as that frequency for which $\epsilon' = \epsilon''$. We then find (assuming $d \sim 10^{-3}$)

$$\bar{f}_{mc} = \bar{\sigma}\left(2 \times 10^4\right). \qquad (10)$$

A set of values of $\bar{f}$ are given in Table I.

TABLE I

d	.001	.001	.001	.001
σ_v	1	10^{-1}	10^{-2}	10^{-3}
$\bar{\sigma}$	10^{-3}	10^{-4}	10^{-5}	10^{-6}
$\bar{f}_{mc}$	20	2	.2	.02

The usefulness of the critical frequency arises from the relation:

$$\frac{\epsilon'}{\epsilon''} = \frac{f}{\bar{f}} \quad . \qquad (11)$$

C. ATTENUATION

Consider a plane wave, propagating as $e^{i(\alpha + i\beta)x}$ in the x-direction. To determine α and β, we note that

$$(\alpha + i\beta)^2 = \omega^2 \mu_o (\varepsilon' + i\varepsilon'') \tag{12}$$

Or,

$$\left.\begin{aligned} \alpha^2 &= \frac{1}{2}\omega^2 \mu_o \left\{ \sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon' \right\} \\ \beta^2 &= \frac{1}{2}\omega^2 \mu_o \left\{ \sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon' \right\} \end{aligned}\right\} \tag{13}$$

We consider two limiting cases:

<u>Case 1.</u> $\frac{\varepsilon'}{\varepsilon''} = \frac{f}{\bar{f}} >> 1$ (slab ∿ dielectric)

$$\alpha \approx \frac{2\pi}{\lambda_o} \sqrt{1 + 79\, d}$$

$$\beta = \frac{\bar{\sigma}}{2}\sqrt{\frac{\mu_o}{\varepsilon'}} = \frac{\bar{\sigma}}{2}\sqrt{\frac{\mu_o}{\varepsilon_o}}\,\frac{1}{\sqrt{1+79\, d}} \tag{14}$$

For $\bar{f}$ = 2 mc/sec, we find

$$\text{attenuation} = .2 \text{ db/m} \tag{15}$$

In the above, we have taken $\varepsilon'/\varepsilon_o = 1 + 79\, d$, and $\bar{f}$ = 2 mc/sec. The general expression, for arbitrary ε' and $\bar{f}$, is

$$\left.\begin{aligned} \text{attenuation} &= 1.64 \times 10^3\, \bar{\sigma} \sqrt{\frac{\varepsilon_o}{\varepsilon'}} \text{ db/m} \\ &= .091\, \bar{f} \sqrt{\frac{\varepsilon'}{\varepsilon_o}} \text{ db/m} \end{aligned}\right\} \tag{16}$$

Case 2. $\frac{\varepsilon'}{\varepsilon''} = \frac{f}{\bar{f}} << 1$. (slab ∿ conductor)

$$\beta \approx \alpha \approx \sqrt{\frac{\bar{\sigma}\,\mu_o\,\omega}{2}} \tag{17}$$

$$\left.\begin{aligned} \text{attenuation} &= 17.4\sqrt{\bar{\sigma}\ f_{mc}} \quad \text{db/m} \\ &\lesssim 17.4\sqrt{\bar{\sigma}\ \bar{f}_{mc}} \quad \text{db/m} \end{aligned}\right\} \tag{18}$$

For $\bar{f}$ = 2mc/sec, therefore,

$$\text{attenuation} < .25 \text{ db/m} \tag{19}$$

If we join the two limiting cases, (15) and (19), smoothly, we deduce an upper limit to the attenuation; namely, (for $\bar{f}$ ∿ 2 mc/sec)

$$\text{attenuation} \lesssim .3 \text{ db/m} \tag{20}$$

for <u>any</u> frequency.

This may be expressed in a more general form by using (16) and substituting $\bar{f} = 2\,\bar{\sigma} \times 10^4$ mc/sec in (18). We thereby deduce as the upper limit on attenuation:

$$\text{attenuation} \lesssim .1\,\bar{f}_{mc} = 2\,\bar{\sigma} \times 10^3 \text{ db/m.} \tag{21}$$

The relation $\bar{f} = 2\,\bar{\sigma} \times 10^4$ mc/sec assumes that $\varepsilon' \approx \varepsilon_o$. If this is not so, we must replace (10) by

$$\bar{f} = 1.8 \times 10^4\,\bar{\sigma}\left(\frac{\varepsilon_o}{\varepsilon'}\right) \text{ mc/sec.} \tag{22}$$

The inequality (18) becomes

$$\text{attenuation} \lesssim .13\ \bar{f}\ \sqrt{\frac{\varepsilon'}{\varepsilon_o}}\ \text{db/m}, \tag{23}$$

and (21) takes the form of (23) or, equivalently,

$$\text{attenuation} \lesssim 2.3 \times 10^3\ \bar{\sigma}\ \sqrt{\frac{\varepsilon_o}{\varepsilon'}}\ \text{db/m}. \tag{24}$$

The inequalities (23) and (24) are the general forms that replace (21) when $\varepsilon' \neq \varepsilon_o$.

D. APPLICATION TO EXPERIMENT

Herbstreit[1] measured the field strength, at various frequencies, as a function of distance, in both the Panama jungle and over a golf course adjacent to the jungle. We have analyzed his data by computing the attenuation of the jungle field strengths,* relative to those over the golf course, at various distances up to one mile from the transmitter. The results are plotted in Figs. 1, 2, and 3. Figure 1 and Fig. 2 exhibit the same data, the rate of attenuation (db/meter) vs distance (miles) for each of the frequencies used. All curves are for vertical polarization except the ones labeled "100 h." Figure 2 differs from Fig. 1 in that a log-log plot was used in place of linear scales.

An effective conductivity may be deduced from these curves and Eq. (16). For example, taking the rate of attenuation to vary between .03 - .08 db/m, Eq. (16) yields .02 - .05 as the value of $10^3\ \bar{\sigma}\ \sqrt{\frac{\varepsilon_o}{\varepsilon'}}$. Taking $\varepsilon' = \varepsilon_o$, recalling that $\bar{\sigma} = \sigma_v d$, and taking $d \sim 10^{-3}$ we deduce that Herbstreit's data leads to the range .02 - .05 mhos/m for the conductivity of the vegetation. This corresponds to the conductivity of wet earth and therefore does not seem at all unreasonable.

---

* We have used the smoothed jungle data (dotted in Herbstreit's figures) where the unsmoothed data fluctuated widely.

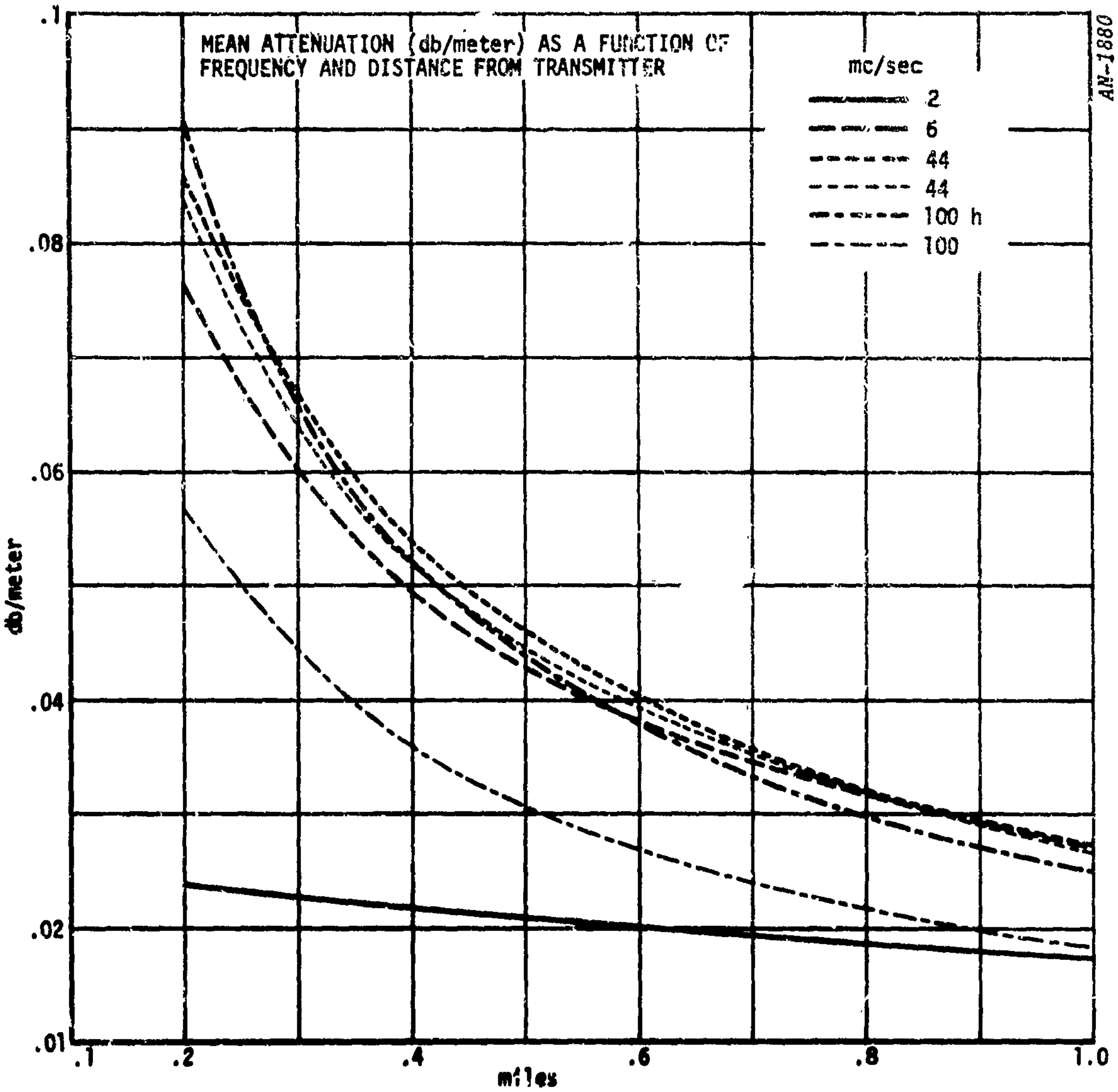

Figure 1. Rate of Att. (db/meter) vs Distance (miles) for Fixed Freq. (mc/sec.)

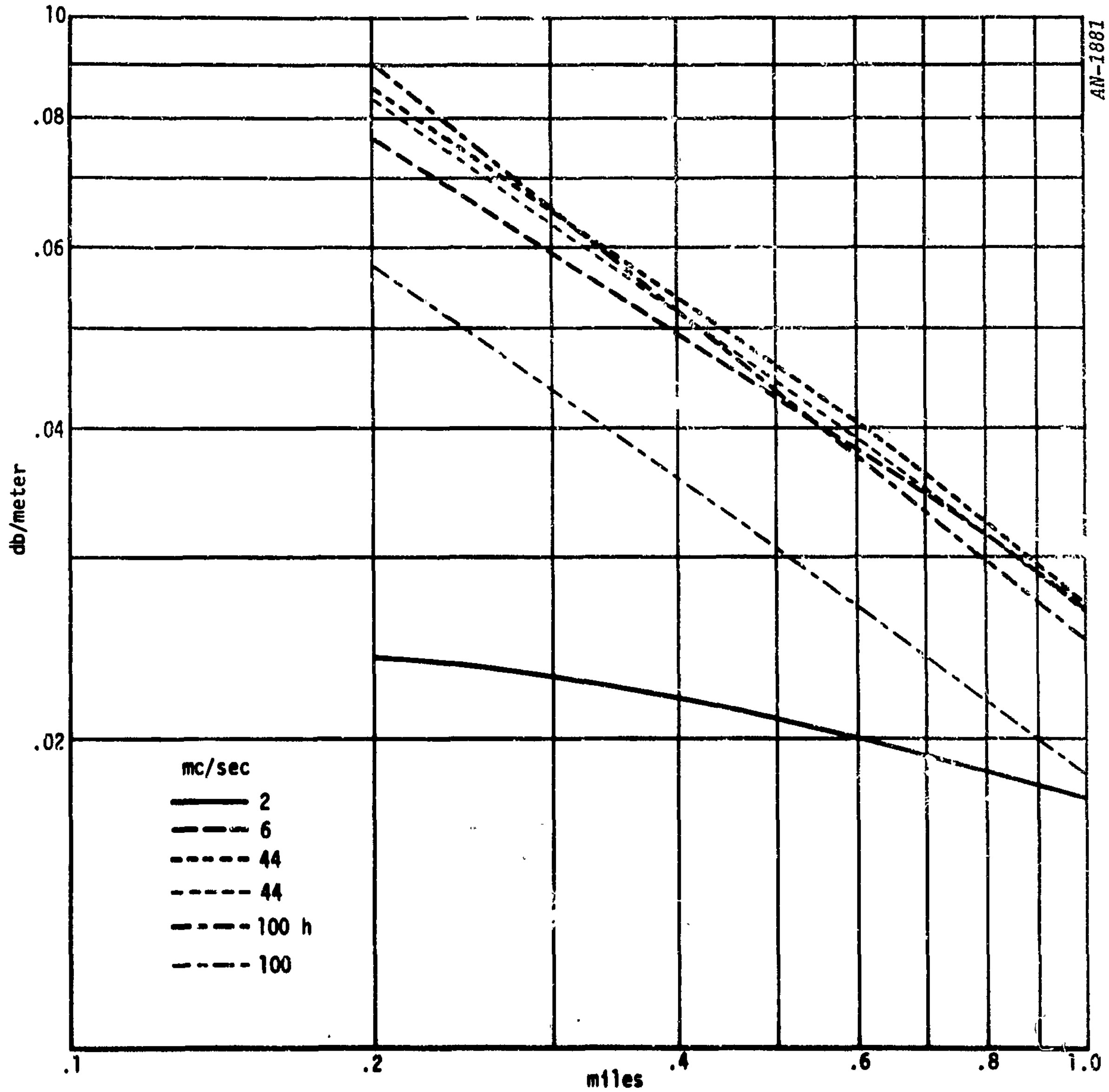

Figure 2. Rate of Att. (db/meter) vs Distance (miles) for Fixed Freq. (mc/sec.)

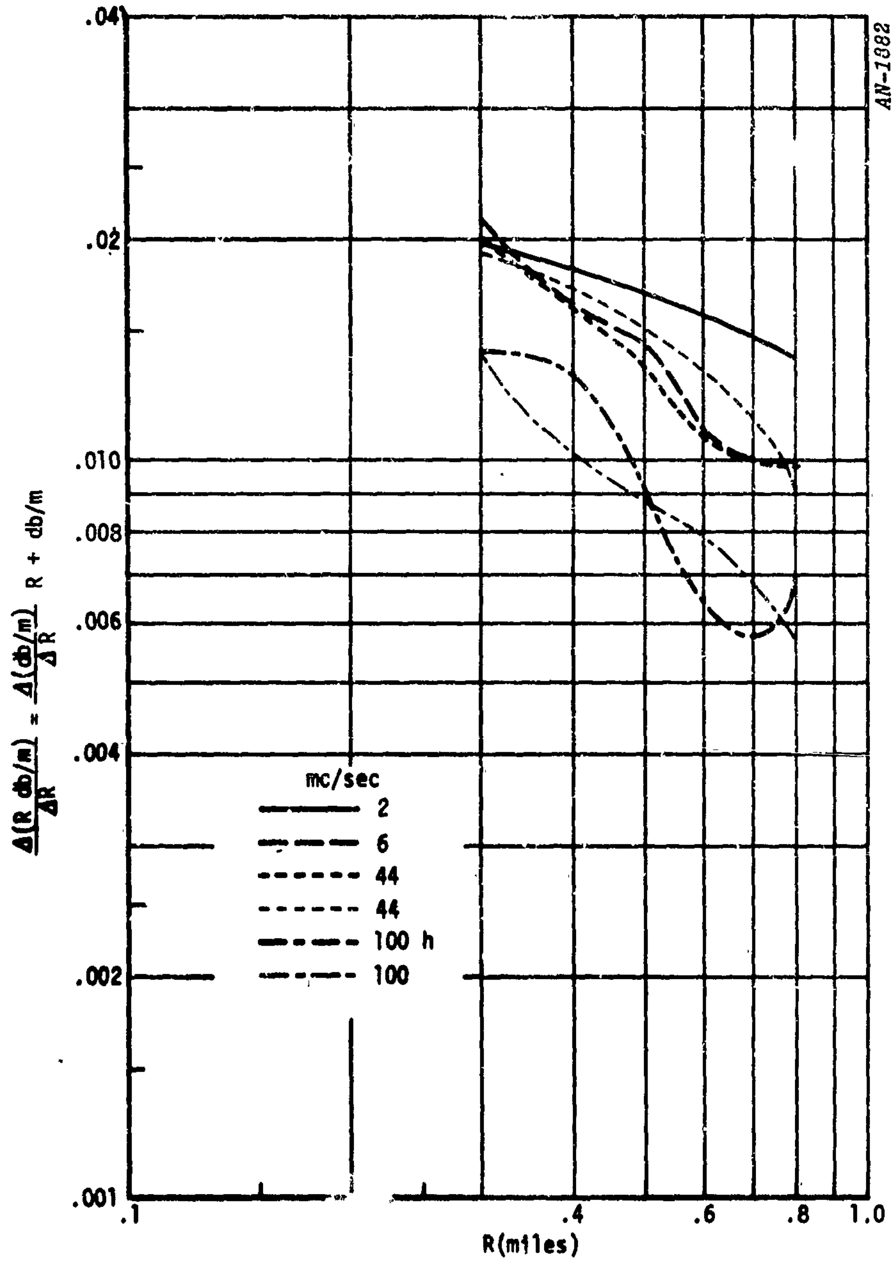

Figure 3. Rate of Incremental Attenuation (db/meter) as a Function of Frequency and Distance from Transmitter

In Figs. 1 and 2, the total attenuation in db's between two fixed points has been divided by the distance between the two points. In Fig. 3, what is plotted is the incremental attenuation in db/meter referred to a given distance from the transmitter. It is not clear whether the erratic behavior of the curve labeled "100 h" is due to inaccuracies in the data or not. In general, these curves seem fairly well behaved.

II. THE JUNGLE AS AN EQUIVALENT CIRCUIT

A. EQUIVALENT CIRCUITS FOR JUNGLES

In this part, we wish to qualify the applicability of the uniform dielectric model employed in Part I to represent the transmission properties of jungles. We shall do this by applying equivalent circuit techniques, using the approach that is familiar in connection with the analysis of microwave junctions.

The equivalent circuit approach[3] analyzes the transmission problem in two stages: first, the form of the equivalent network that couples input to output terminals is determined--using general circuit theorems; then, the values of the elements of the equivalent circuit are evaluated by solving the electromagnetic field problem that the transmission process presents.

Here, we shall make some brief comments on the appropriate form of the equivalent circuit for a jungle, and we shall follow this with a rough, approximate analysis of the field problem.

B. THE JUNGLE AS A FOUR-TERMINAL NETWORK

Applying equivalent circuit concepts to the jungle communication problem, we note that, if we define a pair of terminals connected to the transmitting antenna and another pair of terminals connected to the receiving antenna, everything in between can be replaced by a "black box."

Whatever may be the complexity of the propagation medium between the two pairs of terminals, the structure within the box that is equivalent to it is a four-terminal network. The general network theorems therefore may be applied. For example, if the communication process is linear and if the presence of magnetic fields can be ignored, reciprocity holds: namely, the transmission coefficient from one pair of terminals to the other is independent of the direction of transmission.

The network, as defined in terms of the medium between the transmitting and receiving terminals, is a lossy four-terminal network. However, the objects that absorb energy--trees, vegetation, etc.--may be surrounded by boundary surfaces. What remains after the material within the bounding surfaces is removed is a lossless network. Thus, the lossy material may be considered to be connected by its own terminals, to a lossless network, which has more than four terminals. In this way, everything between the transmitter and receiver may be represented in terms of a lossy four-terminal network, or as a lossless network of more than four terminals, with the lossy structures connected to the additional terminals.

From this point of view it is clear that the dissipative elements may be identified, and the lossy network may be replaced by a lossless network. Conservation of energy, reciprocity, and the usual time reversal theorems then apply.

To fix the parameters of the equivalent circuit, a theoretical calculation, or a set of measurements, must be made relating the coupling between the input and output terminals. The number of independent measurements necessary is equal to the number of independent parameters in the network. In general, a four-terminal network requires three complex (or six real) parameters to specify it completely. On the other hand, a symmetrical four-terminal network requires only two complex (or four real) parameters.

C. THE SYMMETRICAL JUNGLE; THE UNIFORM JUNGLE

A symmetrical network can be used to represent the jungle only if the jungle also has the same type of symmetry; thus, a symmetrical network requires a symmetrical jungle--namely, a jungle which has the same electrical properties when reflected in a plane through the mid-point between transmitter and receiver.

A further specialization over the symmetrical jungle is the "uniform jungle." Here it is implied that each section of the jungle has the same transmission characteristics as any other section.

Such uniformity will generally not be encountered. When this is so, one may often resolve the complex physical structure into its component elements. These may be analyzed individually and the results combined to represent the original, complex structure.

For example, one type of uniform medium may be used to represent a section of jungle, another type to represent a clearing. The combination of the two is represented by connecting the two representations (networks or slabs) in series. In the general case, another network will be required at the point of connection to represent the "junction effect." In the simple case we shall consider, however, junction effects will be absent.

A more complex situation occurs when one of the components, transmitter or receiver, is located above the jungle and the other within it. The simple four-terminal network, or slab model, must be modified to deal with this case. The modification is easily obtained although we shall not discuss it here. Instead of treating the general case, we shall turn at once to the simplest possible case, namely that where the transmitter and receiver are both within the jungle, which in turn may be described by a uniform slab.

In the analysis of Part I, we have considered plane waves propagating through the slab; hence the slab was implicitly assumed either infinite in the direction transverse to the propagation direction, or half-infinite, say with one boundary being the earth, assumed to be perfectly conducting. Clearly, a real jungle can be represented by a slab of this type only if the propagation is essentially along a horizontal path through the jungle. When this is not so, the simple, uniform slab model must be replaced by a more complicated equivalent circuit.

D. DETERMINATION OF THE CIRCUIT PARAMETERS

The upper and lower bounds on ε and σ given in Section 1.1 are strictly applicable only in the case of zero frequency. At any non-zero frequencies, the use of these values is an approximation ("static approximation"); the more accurate determination requires a solution of the scattering problem that the actual set of jungle obstacles presents.

Without giving a detailed proof, we note that, if f(o) is the forward scattered amplitude, the complex propagation constant of Section I.C. is given by

$$\alpha + i\,\beta = N\,\lambda\,f(o), \qquad (25)$$

where N is the density of scattering elements.

If the volume per scatterer is V, and the partial volume of the scatterers is d = NV, (this is the same d as in Section 1.2), then (25) leads to ("Im" means "imaginary part of"):

$$\text{attenuation} = 8.686\ \frac{d\lambda}{V}\left\{\text{Im } f(o)\right\}\ \text{db/m.} \qquad (26)$$

E. BORN APPROXIMATION; ROUGH CORRECTION

For a scatterer having dimensions << λ, we may calculate f(o) simply be using the Born approximation. Here, we merely quote the result:

$$\text{Im } f(o) = \frac{\pi}{\lambda^2}\ \frac{\sigma}{\omega\varepsilon_o}\ V\ . \qquad (27)$$

When inserted in (26), this leads to:

$$\text{attenuation} = 4.34\ \sigma d \sqrt{\frac{\mu_o}{\varepsilon_o}}\ \text{db/m} \tag{28}$$

Since $\sigma d = \bar{\sigma}$, this result is the same as (14) if $\varepsilon' = \varepsilon_o$.

This calculation assumes that the field inside the obstacle is the same as that outside. A rough correction follows by adjusting the amplitude of the inside field by a factor corresponding to the transmission coefficient

$$\frac{2}{1 + \sqrt{\frac{\varepsilon'}{\varepsilon_o}}} \tag{29}$$

which governs the transmission from free space into a dielectric slab of dielectric constant ε'. If the scatterer is a sphere of radius a, we find that the result (28) must be multiplied by the factor ($k = 2\pi/\lambda$)

$$\left(\frac{2}{1 + \sqrt{\frac{\varepsilon'}{\varepsilon_o}}}\right)\left(\frac{3}{\left(ka\sqrt{\frac{\varepsilon'}{\varepsilon_o}}\right)^2}\right)\left(\frac{\sin ka\sqrt{\frac{\varepsilon'}{\varepsilon_o}}}{ka\sqrt{\frac{\varepsilon'}{\varepsilon_o}}} - \cos ka\sqrt{\frac{\varepsilon'}{\varepsilon_o}}\right) \tag{30}$$

In the limit $ka\sqrt{\frac{\varepsilon'}{\varepsilon_o}} \to 0$, (28) must be multiplied by (29) alone, since the remaining two factors of (30) approach unity.

REFERENCES

1. Jack W. Herbstreit and W. O. Crichlow, "Measurement of the Attenuation of Radio Signals by Jungles," J. Res. Natl. Bur. Std., Section D, (Radio Science), 68D, 903 (August 1964).

2. Vol. 16, pg. 706, Springer (1958).

3. Marcuvitz, Waveguide Handbook, MIT Radiation Laboratory Series, McGraw-Hill Book Company, Inc., New York, pp. 101-413.