ESD-TDR-63-166 TM-3494

# DISTORTION AND REGENERATION OF ELECTROMAGNETIC TRANSIENTS AFTER THEIR PROPAGATION AS GROUND WAVES

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-63-166

May 1963

W. J. Albersheim

Prepared for

477L SYSTEM PROGRAM OFFICE

ELECTRONIC SYSTEMS DIVISION

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

L. G. Hanscom Field, Bedford, Massachusetts

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THE MITRE CORPORATION
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ABSTRACT

The transmission characteristics of 200 and 500 statute mile ground wave propagation over land are simulated by simple networks and the responses of these networks to impulse and step functions are computed and plotted. The simulators serve as regenerative equalizers when placed in the return loop of stabilized feedback amplifiers.

## 1. Introduction

It is required to discriminate between electromagnetic signals caused by distant sferics and signals due to man-made pulses, by means of their transient behavior.

However, the transients are modified by the transient response of the long range wave propagation.

The present paper has a double objective:

1) To describe analytically and graphically the distortions and blunting effect of propagation over representative distances of dry land.
2) To devise equalizing circuits that minimize the transient distortion.

The computation is limited to ground wave propagation. This excludes:

a. Line-of-sight radiation which is nearly undistorted and, in its limited range, outweighs other modes of propagation.
b. Sky waves, that is reflections from the ionosphere. The arrival of the first sky wave is delayed by an interval which is slightly affected by the altitude of the source but which is mainly a function of range and of the altitude of the reflecting layer[1]. This function is derived in Section 2.2

Note: Although it is excluded from the transient analysis of this paper, the sky wave may be utilized. If the altitude of the reflecting layer is known, the delay of the first sky wave pulse is a measure of range and thus aids in selecting the proper regenerating equalizer.

## 2. Analysis

### 2.1 Line-of-sight Exclusion

The distance to the horizon is:

$$D_h = \sqrt{(R_e+h_1)^2-h_1^2} + \sqrt{(R_e+h)^2-h^2} \qquad 1\text{-}1$$

where $R_e$ = effective radius of the earth.
$h_1$ = antenna height.
$h$ = source altitude.

For low antennas one may approximate

$$D_h \doteq \sqrt{2R_eh} \qquad 1\text{-}2$$

where the effective earth radius for electromagnetic radiation is 4/3 the actual radius or 4600 nautical miles. Hence

$$D_h \doteq 96\sqrt{h} \qquad 1\text{-}3$$

1. See Reference 1, Figure 2.

when D and h are measured in nautical miles. Assuming that man-made pulses requiring electromagnetic analysis do not originate higher than 2 n. M., neglect of free space radiation is justified for source distances

$$D_h \geq 130 \text{ nM}$$

## 2.2 Sky Wave Utilization and Exclusion

The difference between the direct distance D over curved earth and the single reflection path to a reflecting layer at altitude h and down to the receiver is

$$\Delta D = 2\sqrt{h^2 + 4(R^2 + hR)\sin^2 \frac{D}{4R}} - D \qquad \text{2-1}$$

Assuming that both the ground wave and the sky wave are propagated very nearly with the speed of light,

$$c = 162{,}000 \text{ nM/sec}, \qquad \text{2-2}$$

the sky wave delay is

$$\Delta t \doteq \frac{\Delta D}{c} . \qquad \text{2-3}$$

In the range between 130 and 500 nM, one may approximate

$$\Delta t \doteq \frac{h}{c}\left(\frac{2h}{D} + \frac{D}{2R} - +\right) \qquad \text{2-4}$$

and
$$D \doteq R\,(x+x^3-+), \text{ with } x = \frac{2h^2}{Rc\Delta t} \qquad \text{2-5}$$

In this equation, R is the true Earth radius and R, D, and h are measured in nautical miles.

Since it is possible to measure h, the height of the reflecting layer, by conventional local tests, one may utilize the onset of the first sky wave as a measure of range, provided that it is clearly distinguishable from the ground wave signal.

Typical values of sky wave delay, found either from Figure 2 of Reference 1 or from Equation 2-5, are tabulated below:

Table 1.

| Range (n. M.) | Height of reflecting layer (n. M.) | Sky wave delay (micro/sec) |
|---|---|---|
| 200 | 50 | 163 |
| 400 | 50 | 95 |
| 500 | 30 | 36 |

For range computation, the observation time should be 200 to 300μ seconds to include short range signals and high altitude of the ionized layer. Of these, only the initial 35 may be useable for source identification, if the source is distant and the ionization altitude is low.

The computations given in the following sections indicate that this time may be sufficient for discrimination between sferics and man-made pulses.

## 2.3 Ground Wave Transfer Characteristic

The following analysis is based on a paper by J. R. Johler of the National Bureau of Standards. (Reference 1) This paper derives a highly complicated equation for the transfer constant, as a function of the conductivity and dielectric constant of a level ground surface.
Numerical solutions for typical dry soil are graphed in Figures 7 and 8 of Reference 1.
The curves for 200 and for 500 statute miles (174 and 435 n. M.) are used as examples for detailed computation.

### 2.3.1 200 Mile Transfer Characteristic

Numerical values of relative amplitude and phase for 200 mile range are given in Table 2 below.

Table 2.

| Frequency (kilocycles/sec) | Amplitude nanovolts/m | Relative level db | Phase, Johler Radians | Simulation (denominator) |
|---|---|---|---|---|
| 0.1 | 0.4 | 0 | 2.3 | 0 |
| 1 | 4 | 20 | 0.2 | 0 |
| 3.2 | 12 | 30 | 0.15 | 0.04 |
| 10 | 40 | 40 | 0.2 | 0.14 |
| 100 | 250 | 58 | 1.5 | 1.4 |
| 180 | 330 | 59 | 2.3 | 2.4 |
| 500 | 80 | 46 | 4.0 | 3.9 |
| 1000 | 20 | 34 | 4.5 | 4.3 |

#### 2.3.1.1 200 Mile Simulating Network

The design of a simple simulator network for this range is carried out step by step to illustrate the technique.
Johler's curve has a low frequency asymptotic gain slope of 6 db/octave, and a high frequency slope of -12db/octave. This requires an energy density polynomial of the form

$$E = \frac{kw^2}{1 + C_2 w^2 + C_4 w^4 + C_6 w^6} \qquad 3\text{-}1$$

A close fit is obtained by making

$$E = \frac{kn^2}{1 + 0.5 n^2 + 0.04 n^4} \qquad 3\text{-}2$$

with $n = \frac{w}{w_0}$ ; $w_0 = 2\pi \cdot 10^5$ radians/second.
To make this physically realizable, one must make

$$e = \frac{k_2 n}{1 + ajn - bn^2 - cjn^3} \qquad 3\text{-}3$$

This has the power density

$$E = \frac{kn^2}{1 + (a^2 - 2b)n^2 + (b^2 - 2ac)\, n^4 + c^2 n^4} \qquad 3\text{-}4$$

By equating the denominators of 3-2 and 3-4 term by term one finds

$$a = 1.412 \quad 3\text{-}5$$
$$b = 0.751 \quad 3\text{-}6$$
$$c = 0.2 \quad 3\text{-}7$$

Two equivalent circuits producing this type of polynomial are shown as Figures 1a and 1b. The circuit per 1b, being the simpler one, was selected.
The circuit has five elements and since equations 3-5 specify only three parameters, it was arbitrarily decided that

$$r_1 = r_2 = 200 \text{ ohm}. \quad 3\text{-}8$$

This determines

$$C_1 = 0.0144 \text{ micro farad} \quad 3\text{-}9$$
$$C_3 = 0.025 \text{ micro farad} \quad 3\text{-}10$$
$$L_2 = 225 \text{ micro henry} \quad 3\text{-}11$$

The amplitude characteristic of this simulator matches Johler's curve to within the accuracy of curve reading, that is to within less than 1 db.
The phase characteristic of the denominator alone agrees with Johler's curve between 1 and 1000 kc. The numerator contributes a fixed phase shift of $-0.5\pi$ which does not affect the group velocity characteristic.
The low frequency phase reversal of Johler's curve could be simulated by the type of admittance in parallel with $C_1$ shown in dotted lines in Figure 1a. It was omitted from 1b because it does not noticeably affect the transient behavior during the first 50 microseconds.

### 2.3.1.2 200 Mile Equalizing Circuit

It is possible to design a passive network that inverts and thus equalizes the 200 mile transfer characteristic in a limited frequency range. However, it is simpler to make use of active circuits and to use the simulator itself as the "$\beta$" or loss part of a stabilized feedback loop.
Input and output of the simulator may be buffered by cathode followers or by equivalent transistor circuits. The skirt gain and phase of the amplifier are shaped to insure stability. If the maximum gain correction is chosen as 25db, the overall characteristic can be made constant in gain and phase from about 6 kc. to 1 Mc. This would reduce transient distortion to about 1 microsecond.

### 2.3.1.3 Transient Response of 200 Mile Ground Wave Propagation

The distorting effect of ground wave propagation on any given source wave form is found as follows:
The simulator is substituted for the actual propagation. The Fourier transform of the simulator is its response to an impulse. The response to a step function is the time integral of the impulse response. It can also be directly derived as the Fourier transform of the network characteristic divided by $p = jw$.
If desired, one can also derive the transient response to a ramp function by a second integration of the impulse response, or by a second division by $p$ before taking the Fourier transform. It is easy to approximate any given source function as a sum of shifted impulses, steps and ramps (linear slopes).
The inverse process, that of reconstructing a source signal from the distorted signal received after ground wave propagation over known terrain and known distance, has been discussed by Dr. J. W. F. Ye[2].

2. See Reference 2.

It is quite laborious, therefore it is preferable to carry it out electrically, in real time by means of the equalizer or inverted simulator as described above.

The transient responses to impulses and to unit steps are derived below, in this section. They are plotted, as curves A and B, respectively, in Figure 4. The Fourier transformations are based on Campbell and Foster's tables[3].

Equation 3-3 is adapted to the form used in reference 3 by writing

$$E = \frac{kp}{p^3 + a_1p^2 + a_2p + a_3} \qquad \text{4-1}$$

If $p$ is measured in radians per microsecond one has

$$a_1 = 2.36 \qquad \text{4-2}$$
$$a_2 = 2.82 \qquad \text{4-3}$$
$$a_2 = 1.42 \qquad \text{4-4}$$

This is factorized into

$$E = \frac{kp}{(p + b_1)\ (p^2 + b_2p + b_3)} \qquad \text{4-5}$$

with

$$b_1 = 0.81$$
$$b_2 = 1.55$$
$$b_3 = 1.53$$

## 2.3.1.3.1. Impulse Response

One may write

$$\frac{p}{(p+b_1)\ (p^2+b_2p+b_3)} = \frac{1}{(p+\beta)^2+\lambda^2} - \frac{b_1}{(p+b_1)[(p+\beta)^2+\lambda^2]} \qquad \text{5-1}$$

with

$$\beta = 0.5b_2 = 0.775 \qquad \text{5-2}$$

$$\lambda = \sqrt{b_3 - 0.25b_2{}^2} = 0.964 \qquad \text{5-3}$$

The first term of 5-1 is of the form listed in Reference 3, Table 1, Number 448.1. Its transform is

$$\ell_{1(t)} = \frac{1}{\lambda} \sin\lambda t \exp(-\beta t) \ (t \text{ in microseconds}) \qquad \text{5-4}$$

The second form of 5-1 must again be factorized into

$$\frac{-b_1}{(p+b_1)[(p+\beta)^2+\lambda^2]} = \frac{-k_1}{p+b_1} + \frac{k\ p+k}{(p+\beta)^2+\lambda^2}, \qquad \text{5-5}$$

with

$$k_1 = 0.87 \qquad \text{5-6}$$
$$k_2 = 0.644 \qquad \text{5-7}$$

---

3. See reference 3.

The first term on the right hand side of 5-5 corresponds to Reference 3, Table 1, Number 438, with the transform

$$\ell_{2(t)} = -k_1 \exp(-b_1 t) \qquad 5\text{-}8$$

The second term corresponds to Table 1, Numbers 448.1 and 449.1, with the transform

$$\ell_{3(t)} = [k_1 \cos\lambda t + \frac{k_2 - k_1\beta}{\lambda} \sin\lambda t] \exp(-\beta t), \qquad 5\text{-}9$$

Summing $\ell_1$, $\ell_2$ and $\ell_3$ and dividing by $k$, one obtains

$$\ell_{(t)} = -\exp(-b_1 t) + [\cos\lambda t + \frac{1+k_1-k_1\beta}{k_1 \ \lambda} \sin\lambda t]\exp(-\beta t) \qquad 5\text{-}10$$

substituting the numerical values,

$$\ell_{(t)} = -\exp(-0.81t) + (\cos 0.964t + 1.15 \sin 0.964t)\exp(-0.775t) \qquad 5\text{-}11$$

This is curve A of Figure 4.

2.3.1.3.2 Step Response

Dividing 4-5 by $p$ one obtains

$$E_{(p)} = \frac{k}{(p+b_1)(p^2+b_2+b_3)} \qquad 6\text{-}1$$

This has the form of the second term of 5-1, with negative sign. By using the transforms listed in Section 2.3.1.3.1 one finds

$$E_{(t)} = \exp(-b_1 t) - [\cos\lambda t + \frac{k_2-k_1\beta}{k_1 \ \lambda} \sin\lambda t]\exp(-\beta t) \qquad 6\text{-}2$$

and numerically

$$E_{(t)} = \exp(-0.81t) - (\cos 0.964t - 0.034 \sin 0.964t)\exp(-0.775t) \qquad 6\text{-}3$$

This is curve B of Figure 4.

Note: One can verify that

$$E_{(t)} = k\int e_{(t)} dt \qquad 6\text{-}4$$

or

$$k\, e_{(t)} = \frac{d}{dt} E_{(t)} \qquad 6\text{-}5$$

in agreement with the fact that a unit step is the time integral of a unit impulse.

### 2.3.2 500 Mile Transfer Characteristic

Amplitude and phase of the 500 mile transfer characteristic according to Reference 1 are given in Table 3 below.

TABLE 3.

| Frequency kc | Amplitude nanovolts/m | Gain db | Phase radians |
|---|---|---|---|
| 1 | 2 | 0 | 0.2 |
| 10 | 20 | 20 | 0.4 |
| 32 | 40 | 26 | 0.9 |
| 100 | 50 | 28 | 3 |
| 180 | 30 | 23.5 | 4.5 |
| 500 | 1.6 | -2 | 6 |
| 1000 | 0.1 | -26 | 7.5 |

#### 2.3.2.1 200 to 500 Mile Simulating Network

It is possible to design a single network simulating the entire 500 mile transfer characteristic. But, just as the actual propagation proceeds mile by mile, it is simpler to design a supplemental network simulating the difference, in db and in radians, between the 200 mile and the 500 mile transfer characteristics. This reduces the number of elements and the loss in each partial network and makes it possible to equalize in steps, with each partial simulator in a separate feedback loop.

By comparing the characteristics of Tables 2 and 3 one arrives at the following table.

Table 4: 200 to 500 mile transfer characteristic.

| | Incremental Characteristic | | Simulator Characteristic | |
|---|---|---|---|---|
| Frequency kc | Loss db | Phase radians | Loss db | Phase radians |
| 1 | 0 | 0 | 0 | 0 |
| 10 | 0 | .2 | 0 | 0 |
| 32 | 2 | .3 | 1.8 | .2 |
| 100 | 8 | 1.4 | 8.5 | 1.6 |
| 180 | 15 | 2.0 | 14.5 | 2.1 |
| 500 | 28 | 2.7 | 29 | 2.7 |
| 1000 | 40 | 3 | 40 | 2.9 |

The last two columns refer to the simulator derived below. The 200 to 500 mile loss has a zero low-frequency slope and a 12 db per octave high frequency slope. The phase difference is zero at low frequencies and about $\pi$ at high frequencies. These requirements are met by the networks per Figures 3a and 3b.

The network per Figure 3b was chosen because it is simpler. The power loss characteristic corresponding to column 4 of Table 4, is

$$\frac{P_{(in)}}{P_{(out)}} = 1 + 5\,n^2 + n^4 \quad \text{with } n \text{ defined as in 3-2} \qquad \text{7-1}$$

This is realized by the complex amplitude response

$$\frac{E_{(in)}}{E_{(out)}} = (1 + 2.19jn)\ (1 + 0.46jn) \qquad 7\text{-}2$$

The phase characteristic

$$\Delta\phi = \tan^{-1} 2.19n + \tan^{-1} 0.46n \qquad 7\text{-}3$$

### 2.3.2.2 200 t0 500 Mile Equalizing Circuit

It is recommended to obtain incremental equalization by placing the simulator per Figure 3b as feedback loss into the loop of a stabilized feedback circuit similar to that of Figure 2.

The two feedback circuits connected in cascade will equalize the 500 mile groundwave transfer characteristic. If the gain is limited to 25db, the equalized band will extend from 6 kc to 400 kc.

### 2.3.2.3 Transient Response of 500 Mile Circuit

The transient response is found by the combined Fourier transform of the networks per Figures 1b and 3b, connected in cascade.

#### 2.3.2.3.1 Impulse Response

The incremental response per 7-2 is brought into a form suitable for Reference 3 by writing:

$$\frac{E_{(in)}}{E\ (out)} = (p+g_1)\ (p+g_2) \qquad 8\text{-}1$$

with

$$g_1 = 0.29 \qquad 8\text{-}2$$

$$g_2 = 1.375 \qquad 8\text{-}3$$

According to 5-1 and 5-5, the 200 mile characteristic is

$$\frac{E_{(out)}}{E_{(in)}} = -\frac{k}{p+b} + \frac{k_1 p+(1+k_2)}{p^2+b_2 p+b_3} \qquad 8\text{-}4$$

Combining 8-1 with 8-4 and dividing by $k_1$ the overall response is

$$e_p = \frac{-1}{(p+b_1)(p+g_1)(p+g_2)} + \frac{p + \frac{1+k_2}{k_1}}{(p^2+b_2p+b_3)[p^2+(g_1+g_2)p+g_1g_2]} \qquad 8\text{-}5$$

Factorizing these terms and utilizing Fourier integrals Numbers 452, 448 and 449 of Reference 3 one obtains

$$e_{(t)} = 3.4\exp(-0.81t) - 0.51\exp(-0.29t) - 2.01\exp(-1.375t) - (0.88\cos 0.964t + 0.875\sin 0.964t)\exp(-0.775t) \qquad 8\text{-}6$$

This is curve A of Figure 5.

2.3.2.3.2. Step Response

Since the step function is the time integral of the impulse, one can derive the step response by integrating 8-6 with regard to time. One finds

$$E_{(t)} = -4.2 \exp(0.81t) + 1.75 \exp(-0.29t) + 1.45 \exp(-1.375t) + (\cos 0.964t - \sin 0.964t) \exp(-0.775t) \quad 8\text{-}7$$

This is curve B of Figure 5.

## 3. Summary and Conclusions

It has been shown that

1. The distance of a signal source can be computed from the altitude of the ionized reflection layer and from the interval bebetween ground wave and first sky wave. For distances between 150 and 500 miles, the sky wave delay is between 35 and 150 microseconds.

2. The ground wave transfer characteristic over ground of known conductivity and dielectric constant can be simulated quite closely by one simple lumped-constant, minimum-phase network, or by two such networks in cascade.

3. When the simulator networks are used as loss circuits in the return loops of stabilized feedback networks, they produce equalizers that flatten the amplitude and phase transfer characteristic from 6 kc to above 400 kc.

4. The transient response of the unequalized ground wave propagation over 500 miles to both impulse and step functions is practically finished in less than 15 microseconds.

From the above one may conclude that the onset of the sky wave will be recognizable for all but the slowest of source signals. Hence it is feasible to recognize the source range and pick the correct amount of equalization for a good regeneration of the source signal.

The transient response to step functions has no zero crossings in the initial 50 to 100 microseconds. The transient response to impulse signals has one downward zero crossing, 2 to 15 microseconds after the signal onset. It resembles the actual long range records.

This makes it likely that the source signals resemble impulses rather than step functions and that the first 35 microseconds may suffice to bring out the differences between single sferics and manmade pulses.

The transient response curves plotted in this report may serve as a reminder that some features of records taken at long range are characteristic of the transmission path rather than of the source.

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Attachments: Figures 1 - 5
List of References
Distribution List

## FIGURE 1: 200 STATUTE MILE SIMULATORS

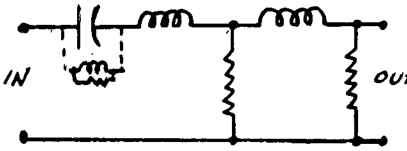
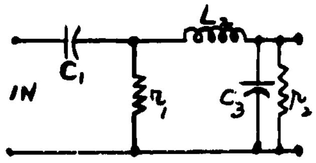


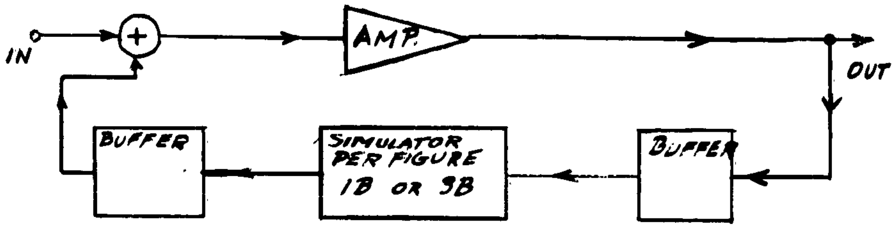

FIG. 1A: 2½ SECTIONS



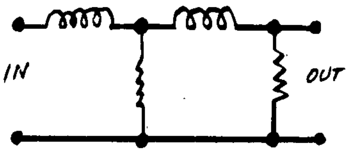

$C_1$ = 14,400 pf
$L_2$ = 225 μh
$C_3$ = 25,000 pf
$r_1$ = 200 Ω
$r_2$ = 200 Ω

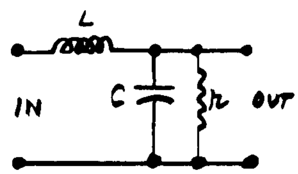
FIG. 1B: 1½ SECTIONS

## FIGURE 2: FEEDBACK EQUALIZER CIRCUIT




## FIGURE 3: 200 TO 500 MILE INCREMENTAL SIMULATOR




C = 6000 pf
L = 421 μh
r = 100 Ω

FIG. 3A: 1½ SECTIONS

FIG. 3B: ½ SECTION

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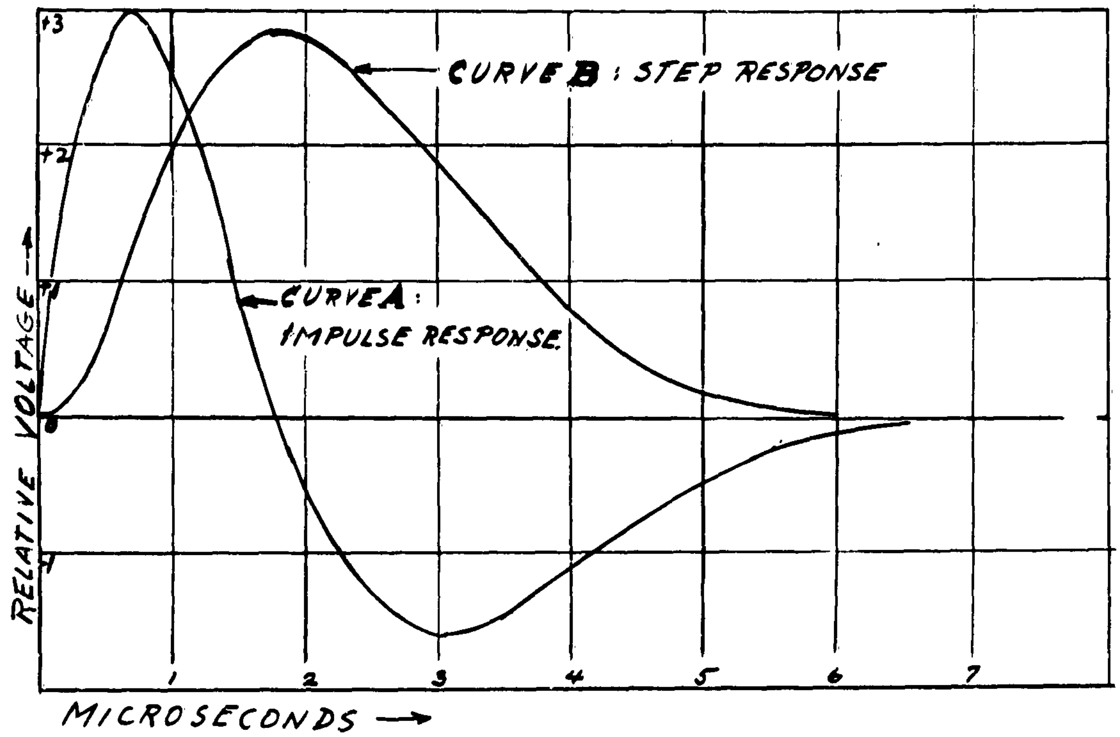
FIGURE 4 TM-3494

TRANSIENT RESPONSE OF 200 MILE GROUND WAVE SIMULATOR

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# FIGURE 5

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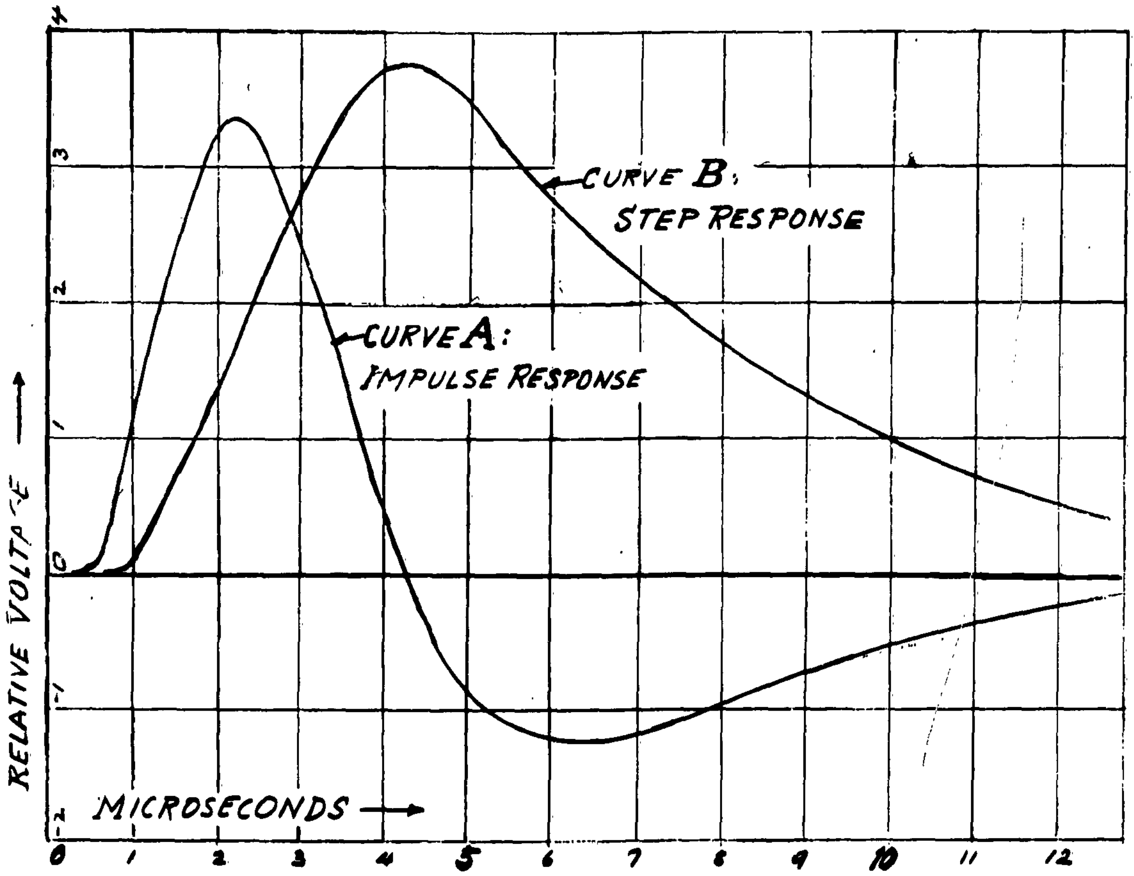
TRANSIENT RESPONSE OF 500 MILE GROUND WAVE SIMULATOR

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