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A. R. Dion

Radiation Characteristics of Loop Antennas Excited by Transients

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

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Group 61

TECHNICAL REPORT 433

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ABSTRACT

The radiation characteristics of a rectangular loop loaded at its mid-point with a resistance equal to the radiation resistance, and fed by DC pulses, are derived and compared with measurements. In particular, the time variation of the electromagnetic pulse radiated by this antenna, and also of the voltage pulse induced at the terminals of a similar receiving antenna, is derived. The relationships between the characteristics of these pulses and the loop parameters are stressed.

Accepted for the Air Force
Franklin C. Hudson
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RADIATION CHARACTERISTICS OF LOOP ANTENNAS EXCITED BY TRANSIENTS

I. INTRODUCTION

Special-purpose pulse radars proposed for very high range resolution involve operation in the 100- to 1000-MHz range and pulse lengths of only a few nanoseconds. Such pulses last for only a few RF cycles and therefore have a very broad frequency spectrum. It is apparent that these pulses consist principally of the transient response of a circuit, i.e., they are free oscillations and can be generated by exciting the circuit with transients such as DC pulses or impulses.

The radiation characteristics of an antenna driven by a transient generator, particularly the time variation of the radiated pulse (or of the induced pulse for reception), are of fundamental importance in the design of the radar system. In this report, these characteristics are derived for a practical antenna. The results of experimental verifications of some of the antenna properties supplement the analysis.

In particular, it will be necessary to derive the time variation of the voltage induced at the terminals of an antenna when it is placed in the field of another antenna periodically excited with video pulses. Since a video pulse consists of the sum of two step impulses, of opposite polarity and delayed with respect to one another by the pulse length, it is more convenient (as an intermediate step) to derive the time variation of the induced voltage for step impulse excitation.

The analysis begins with a description of the current wave observed in a radiator when it is excited with an impulse. A convenient radiator, a rectangular loop loaded at its mid-point with an impedance equal to the radiating impedance, emerges from this description. The radiation properties of this loop, principally the radiated (and induced) pulse shape and the radiation pattern, are next derived and the fundamental relations between these properties and the loop constituents are stressed. A discussion of the modified properties of the loop antenna when it is in close proximity to the ground, for the purpose of transmitting energy within this medium, concludes the report.

II. EXCITATION OF RADIATORS BY TRANSIENTS

Consider a linear antenna balanced-fed by a transmission line and connected to a generator delivering short video pulses. When a pulse reaches the feed point of the antenna, part is reflected and part is transmitted to the antenna, the amount of each part being related to the effective radiation impedance of the antenna and the characteristic impedance of the line. As the transmitted pulse propagates down each branch of the antenna, it is attenuated because of radiation. At the tip of the antenna, it is reflected back toward the feed end, yielding additional radiation and attenuation. Arriving back at the feed point, some energy is transmitted to the

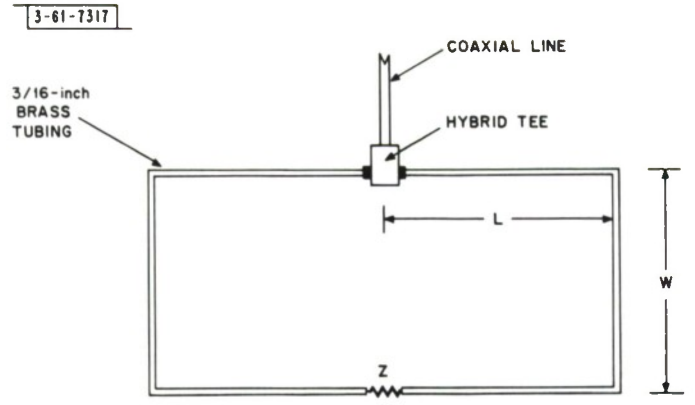

Fig. 1. Configuration of loop antenna.

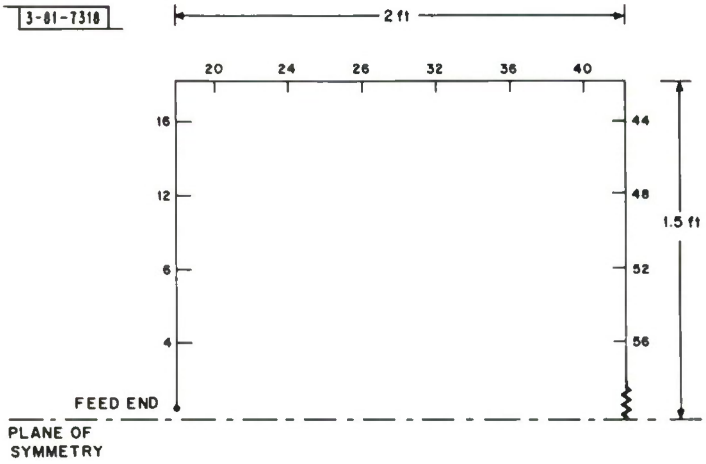

Fig. 2. Locations at which current wave was probed.

transmission line and some is reflected in the antenna where the previous process repeats. Thus, the pulse travels back and forth along the linear antenna exhibiting a progressively decreasing amplitude as a function of time. Also, because radiation takes place more effectively at the high-frequency components of the pulse, its rise time increases progressively with time.

The case where the radiator is a base-driven vertical wire above ground has been investigated by King and Schmitt,* who have shown that the amplitude of the initial reflection occurring at the feed point indicates an effective antenna impedance of about 300 ohms. These authors also verified that this impedance corresponds to the value obtained by averaging the impedances of the infinitely long antenna at the component frequencies of the exciting pulse, up to an upper limit determined by the rise time of the pulse. Since the initial reflection that occurs at the feed point of an antenna is necessarily independent of the antenna length, it is not surprising that the frequency-domain analysis involves only the infinitely long antenna.

Based on the above results, the impedance of the balanced-fed, center-driven linear antenna is about 600 ohms. Using a transmission line with a characteristic impedance of 600 ohms to feed this center-driven antenna, a pulse from a matched generator is transmitted to the antenna without reflection at the feed point. At the ends of the antenna, the pulse, modified by radiation effects, is reflected back toward the feed where it is entirely transmitted back into the transmission line and dissipated in the generator's impedance. Thus, the wave consists of one outgoing pulse and one incoming pulse, and no multiple reflections (or ringing) occur in the antenna. A similar effect is obtained by bending the two arms of the linear antenna to form a loop, and by terminating the two ends in a matching load. Again, no ringing occurs in the antenna even when the transmission line is not matched to the radiation impedance of the antenna.

Several loops of rectangular shape and of various sizes were constructed to investigate their responses to transients. The loops were balanced-fed using commercial broadband hybrid junctions. The current wave excited in these antennas was studied by probing, with a very small loop, the magnetic field close to the antenna conductors. This magnetic probe was about $\frac{1}{2}$ inch in diameter and was also balanced-fed by means of a broadband hybrid junction. The necessity for balanced excitation of the loop antennas and the magnetic probe was clearly demonstrated by the large current excited on the outer conductor of a coaxial transmission line when the latter was terminated directly on either of these radiators.

The hybrid junctions used have a pass band of 20 to 200 MHz and thus transform a step impulse into a pulse having a rise time of about 1 nsec and a decay time of about 100 nsec. Since the decay time is very large with respect to the rise time, this pulse can be considered as an impulse with a finite rise time. The general configuration of the loops tested is shown in Fig. 1. Positions along the loop antenna at which measurements were taken are given in inches from the feed point and correspond to positions along the antenna as shown in Fig. 2. Since the probe responds to the time variation of the magnetic field, its output is a measure of the time derivative of the current flowing in the antenna. The response of a small loop in close proximity to a conductor depends on the conductor geometry; but, for straight conductors of length several times larger than the probe diameter, the response is independent of length. Thus, the amplitude

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* R. W. P. King and H. J. Schmitt, "The Transient Response of Linear Antennas and Loops," Trans. IRE, PGAP AP-10, 222 (1962).

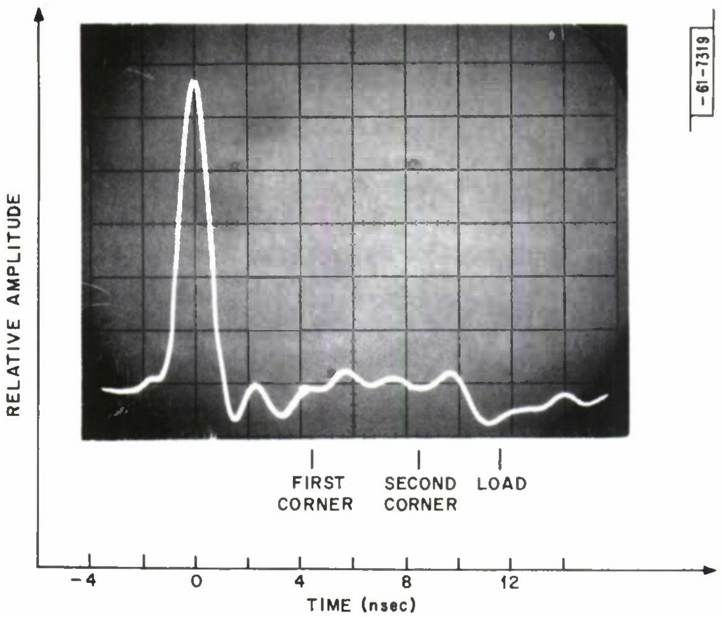

Fig. 3. Probe measurement at input of antenna.

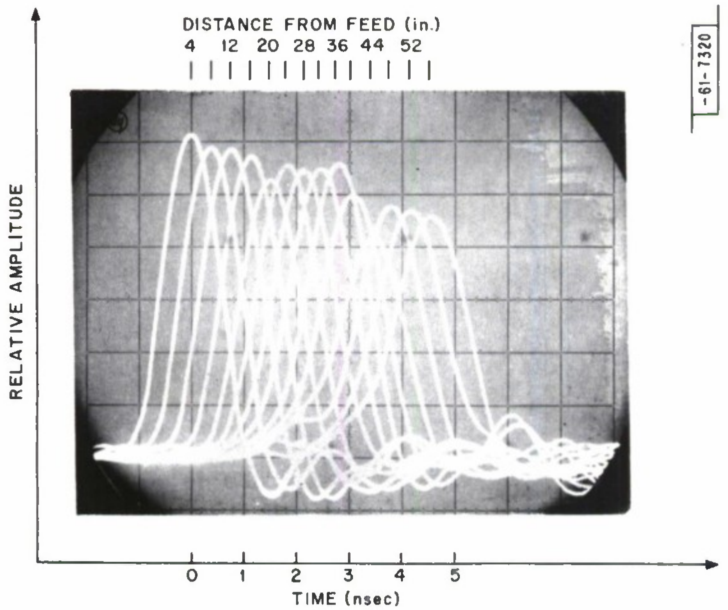

Fig. 4. Probe measurements at incremental distances along the loop.

of the probe response is indicative of the relative variation of the current in the antenna except near physical disturbances such as at the feed, at the bends, and at the load ends of the loop antenna. Examples of probe outputs as displayed on a sampling scope are given in Figs. 3 to 5. The probe output at a distance 4 inches from the feed point of a loop 3 feet long by 2 feet wide is displayed in Fig. 3.[*] This trace first shows the electric disturbance observed as the current impulse passes by the probe. Then follow reflections caused by the bends, by the load, and also (toward the end of the trace) by objects located nearby. The largest reflection corresponds to a coefficient of reflection of about 0.15. The variation of probe current as a function of position along the loop is illustrated by the multiple exposures shown in Fig. 4.[*] The different response expected close to the corners of the loop is well manifested. The appreciable drop of amplitude observed at the position 40 inches away from the feed point was expected, since at that position the probe orientation with respect to the conductor was incorrectly set. The pulse velocity computed from these data is about 5 percent less than the speed of light in vacuum. The decreasing amplitude of the probe output as a function of position reflects the increase of the impulse rise time as it propagates along the antenna. This is also reflected by the increase of the width of the probe output pulse as a function of distance from the feed. The amplitude of the probe voltage is inversely proportional to the impulse rise time; therefore, the total amplitude decrement observed in Fig. 4 corresponds to a rise-time increase of about 25 percent, or to about 5 percent per foot.

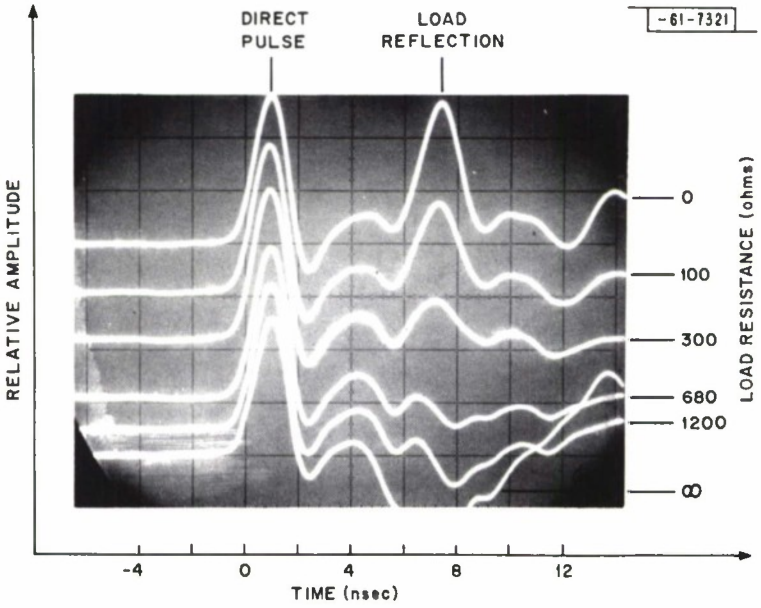

Fig. 5. Probe measurements with load resistance as a parameter.

The reflection that occurs at the load terminating the loop antenna is illustrated in Fig. 5 for different values of the terminating resistance. These measurements, performed on a loop having a half-length and width both equal to 1 foot, were taken with the magnetic probe located close to the feed. Notice the smaller reflection associated with a load resistor in the neighborhood of 600 ohms.

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[*] These measurements were carried out with a mid-point load of 680 ohms.

III. RADIATION CHARACTERISTICS

Radiation characteristics of the loop antenna are obtained by integrating the effect produced by each infinitesimal component of the antenna. The radiated field is computed under the following assumptions.

(a) Reflections occurring at the corner bends and at the load ends are negligible.

(b) Rise time of the current impulse propagating in the antenna is constant.

(c) Interactions between the branches of the loop are negligible.

Let the loop be oriented in a rectangular coordinate system as shown in Fig. 6. The antenna with its feed at the origin is located in the XY-plane, and its feed and load arms are parallel to the Y-axis. It is necessary to compute the amplitude and shape of the pulse radiated in a direction φ, Θ, at a distance R that is large compared with the dimensions of the antenna. The electric field due to an element of length ds located a distance s from the feed has only a component polarized in the direction of the element and is (after some distinct manipulations)*

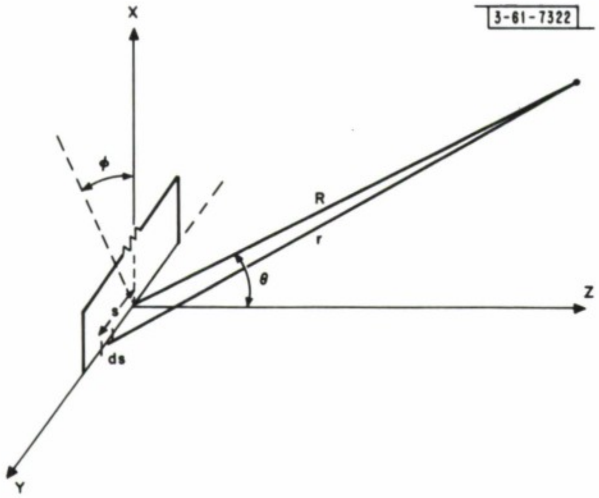

Fig. 6. Coordinate system.

$$dE(\Theta, \varphi, t) = \frac{\zeta_m \sin\psi \, ds}{4\pi R v_m} \, \frac{dI\,[t - (s/v_a) - (r/v_m)]}{dt} \tag{1}$$

$$= f\,[t - (s/v_a) - (r/v_m)] \tag{2}$$

where

ζ_m = characteristic impedance of the medium (120π in free space),

v_m = wave velocity in the medium (~1 ft/nsec in free space),

v_a = wave velocity in the antenna,

r = distance from element ds to observation point,

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* J. D. Krauss, Antennas (McGraw-Hill, New York, 1950), p. 132.

ψ = angle between element ds and radius vector to observation point,

$I\,[t - (s/v_a)]$ = current wave at a distance s from the feed point,

$I\,[t - (s/v_a) - (r/v_m)]$ = retarded current associated with element ds.

The distance r from an element of the antenna to a far-distant point is

$$r = R - (x \cos\varphi + y \sin\varphi)\sin\Theta \tag{3}$$

where x and y are the coordinates of the element, while the angle ψ obeys the relation

$$\sin\psi = (1 - \sin^2\Theta \sin^2\varphi)^{1/2} \tag{4}$$

The step voltage applied across the antenna terminals induces charges of opposite polarity in opposite arms of the loop. On the arms parallel to the Y-axis, these charges move in opposite directions. On the arms parallel to the X-axis, the charges move in the same direction; therefore, no X-component of the electric field is generated in a direction normal to the loop. However, in other directions an X-component may be expected. Only the Y-component of the field need be evaluated here; therefore, only integration along the branches of the loop parallel to the Y-axis is required. The field produced by these branches is, from Eq. (2),

$$E(\Theta, \varphi, t) = \int_{-L_T}^{L_T} \left[f\left(t - \frac{|y|}{v_a} - \frac{r}{v_m}\right) - f\left(t + \frac{|y| - 2L_T - W_T}{v_a} - \frac{r}{v_m}\right)\right] dy \tag{5}$$

where L_T and W_T are, respectively, the half-length and width of the transmitting loop antenna.

The radiated field comprises two components: the first results from the outgoing current wave in the feed arm; the second results from the current wave, moving in the opposite direction, in the load arm of the loop. Each of these components is, in turn, the sum of two terms (one for each of the two opposite branches making an arm), and these terms are different except in a direction normal to the plane of the loop. The mathematical expression of each term is of the same form, the difference between terms is the retarded time, and therefore it is necessary only to compute the integral for one of them. The field produced by the positive branch of the feed arm is

$$E_1(\Theta, \varphi, t) = \frac{\zeta_m \sin\psi}{4\pi R v_m} \int_0^L \frac{dI\left[t - \dfrac{y}{v_a} - \dfrac{(R - y \sin\varphi \sin\Theta)}{v_m}\right]}{dt}\, dy \quad . \tag{6}$$

Let

$t' = t - (R/v_m)$, the retarded time corresponding to the distance from the origin to the point of observation,

$t_y = [(1/v_a) - (\sin\varphi \sin\Theta/v_m)]\, y$, the delay associated with radiation originating from an infinitesimal element at a distance y,

$t_L = [(1/v_a) - (\sin\varphi \sin\Theta/v_m)]\, L_T$, the delay associated with radiation originating from the infinitesimal element at the end of a branch,

and the expression for the field becomes

$$E_1(\Theta, \varphi, t) = \frac{\zeta_m L_T \sin\psi}{4\pi R v_m t_L} \int_0^{t_L} \frac{dI(t' - t_y)}{dt'}\, dt_y \tag{7}$$

thus yielding

$$E_1(\Theta, \varphi, t) = -\frac{\zeta_m L_T \sin\psi}{4\pi R v_m t_L} \left[I(t') - I(t' - t_L)\right] \tag{8}$$

Thus, the time variation of the radiated field is the difference between two functions, each identical to the time variation of the current wave traveling in the loop. These functions are delayed with respect to one another by a time equal to the difference between the retarded time delay of the two rays coming from the origin and the end of a branch, respectively. As an example, consider the case where the loop is excited by a step impulse and observation is confined to the direction normal to the plane of the loop. The time variation of the radiated field is then as shown in Fig. 7; the first pulse is produced by the receding current wave in the feed arm of the loop as given by Eq. (8), while the second pulse, delayed by the time of propagation of the current wave to the beginning of the load arm, results from the approaching wave in this arm. The radiated field expression, it will be noticed, becomes indeterminate when $t_L = 0$. However, it can readily be verified that the ratio $[I(t') - I(t' - t_L)]/t_L$ remains finite for all values of t_L.

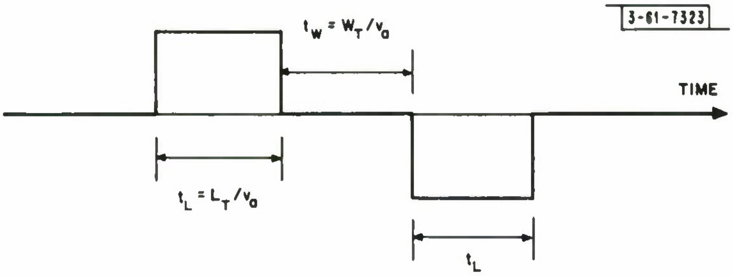

Fig. 7. Time variation of radiated field.

Next, it is necessary to compute the voltage developed at the terminals of a loop antenna when it is placed in the field of a similar antenna driven by a transient generator. The separation between the two antennas will be large compared with the antenna dimensions, and the receiving antenna will be oriented so that its plane is normal to the radius vector joining the two antennas and its polarization identical to that of the transmitting antenna. A matched receiver is across the terminals of the receiving antenna.

The electric field E parallel to an element ds at a distance s from the terminals induces an emf dV given by

$$dV = E\,ds \tag{9}$$

At the terminal, this emf generates an infinitesimal current that is delayed by a time s/v_a, and a corresponding infinitesimal voltage is developed across the matching terminal impedance. The total voltage developed across the load of the receiving antenna is then

$$V_R = \frac{1}{2}\int_0^{L_R} \left[E\left(t - \frac{y}{v_a}\right) - E\left(t - \frac{W_R + 2L_R}{v_a} + \frac{y}{v_a}\right)\right] dy \tag{10}$$

where L_R and W_R are, respectively, the half-length and width of the receiving loop antenna.

The voltage induced across the antenna terminals is the difference between two similar responses delayed with respect to one another by the time required for the wave induced in the load arm to travel to the terminals.

Expressing the electric field by its Fourier series representation,

$$E[t-(y/v_a)] = \sum_{n=-\infty}^{\infty} c_n \exp\{jn\omega\,[t+(y/v_a)]\} \tag{11}$$

where v_a is the velocity of the impulse in the antenna (about 1 ft/nsec when in free space), the terminal voltage resulting from induction in the feed arm of the loop becomes

$$V_{R1} = -\frac{1}{2}\sum_{n=-\infty}^{\infty} \frac{v_a c_n}{jn\omega}\left(\exp[jn\omega t] - \exp\{jn\omega\,[t+(L_R/v_a)]\}\right) \tag{12}$$

which may be transformed to

$$V_{R1} = \frac{L_R}{2}\sum_{n=-\infty}^{\infty} c_n \frac{\sin\left(\frac{n\omega L_R}{2v_a}\right)}{\frac{n\omega L_R}{2v_a}} \exp\{jn\omega\,[t+(L_R/2v_a)]\} \tag{13}$$

The amplitude of the terminal voltage is proportional to the length of the loop, and its frequency spectrum is the product of the incident field spectrum modified by a $\sin X/X$ function that is dependent on the time of propagation in the antenna. As an example, consider the case of propagation at normal incidence between two identical antennas, one of which is driven by a step impulse generator. The radiated field is then as shown in Fig. 7. The integration of Eq. (10) is straightforward, the result being the triangular wave pictured in Fig. 8(a) which applies to the case where the half-length and width of each loop are equal. If the driving transients are pulses of length τ, the time variation of the received pulses is obtained by subtracting from the response given in Fig. 8(a) a similar response displaced by a time τ. Maximum amplitude is thus obtained with a pulse length equal to twice the travel time of the current wave along one arm of the antenna and is as shown in Fig. 8(b). The received waveform consists of two cycles at a frequency $f = 1/2\tau$ and of amplitude progressively increasing over the first half of a pulse and decreasing in a similar manner over the second half. With driving pulses of finite rise and decay times, similar results would be obtained but the induced voltage variation would resemble more closely a sine-wave variation. An estimate of the frequency spectrum of the received pulse may then be obtained by considering the amplitude constant, thus obtaining the spectrum (Fig. 9) of an RF wave modulated by periodic pulses. The spectrum centered at a frequency equal to $1/2\tau$ has a bandwidth, measured between the first nulls, also equal to $1/2\tau$.

The case where transmission off the normal to the antenna is considered, or when driving impulses of finite rise time are applied, is not easily manageable by the previous analysis but is readily adaptable to digital computer solutions. The operations defined by Eqs. (1) and (10) were programmed for digital computation, and the results were submitted to experimental verifications. Figure 10 applies to the case where two similar antennas, of half-length and width equal to 1 foot, are used for transmission in a direction normal to the plane of the antennas and

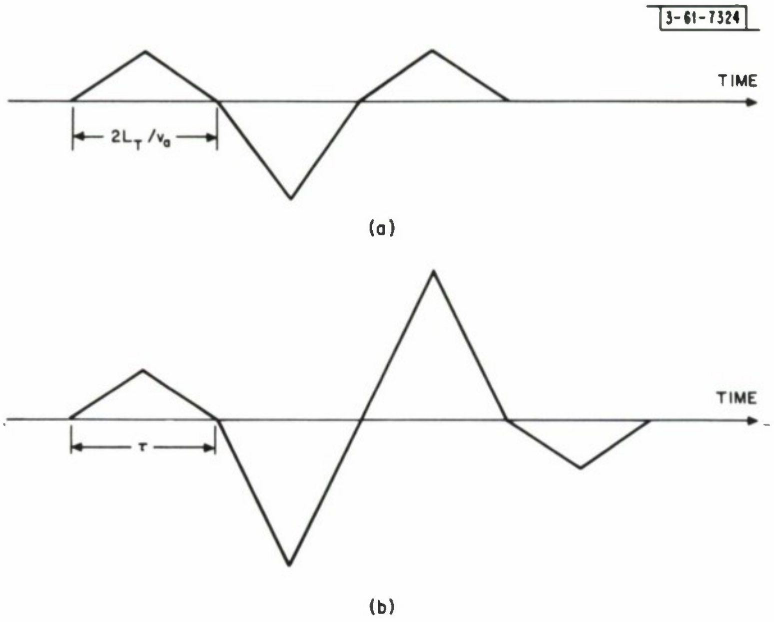

Fig. 8. Induced voltage for excitation with (a) impulse, and (b) pulse with $\tau = 2L_T/v_o$.

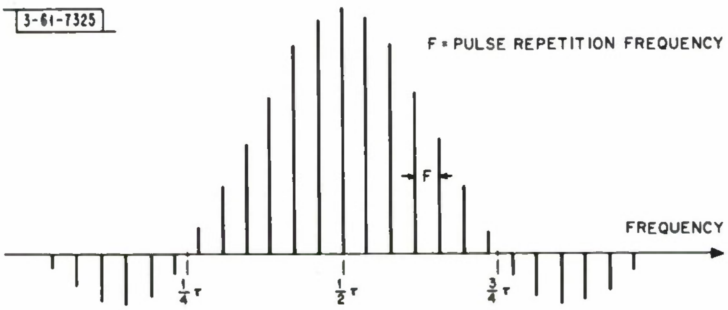

Fig. 9. Approximate frequency spectrum of received pulse.

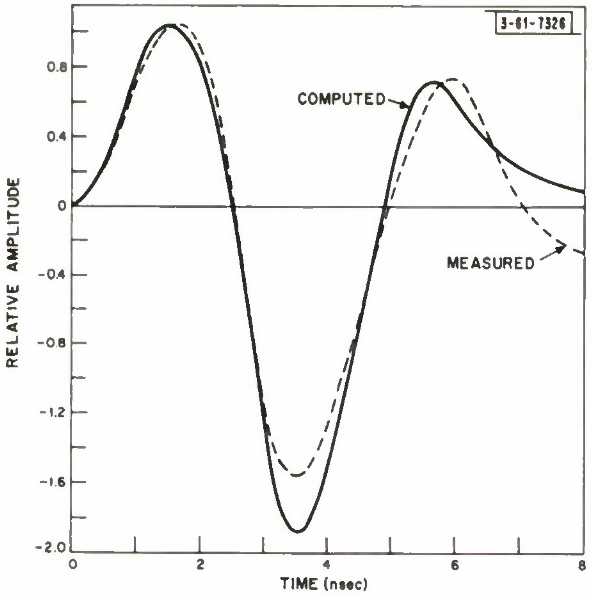

Fig. 10. Computed and measured time variation of received pulse.

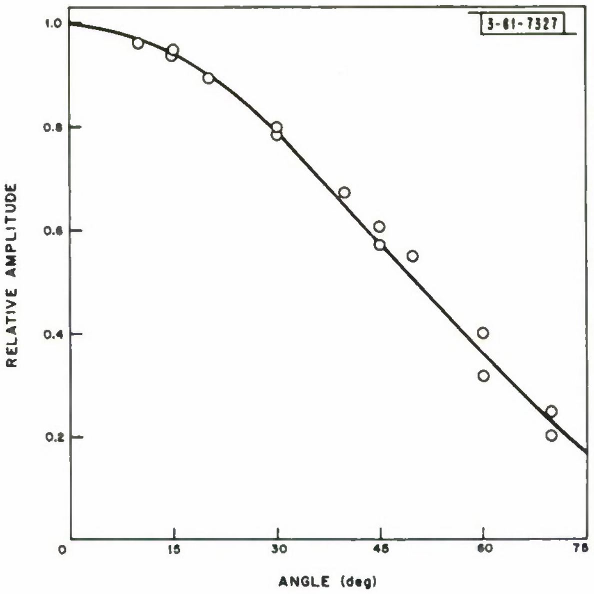

Fig. 11. Computed (solid line) and measured (circles) E-plane pattern.

where the driving impulse has a rise time of 1 nsec. The measurements were conducted outdoors using a transmission path 21 feet long. Some reflections from the ground and nearby walls were observed and contribute to the different response seen toward the end of the pulse.

As the radiated field is observed at angles off broadside, both the amplitude of the induced pulse and its shape change. However, for observations made in the E-plane (φ = 90° or 270°), little changes of the pulse shape are discerned. The amplitude decreases as a function of angle as shown in Fig. 11 for free-space transmission. Good agreement with measurements performed inside an anechoic room is observed.

In the H-plane (φ = 0° or 180°), the amplitude of the induced pulse does not decrease significantly; the pattern is nearly isotropic. The radiation pattern of the loop is thus similar to that of a half-wave electric dipole parallel to the feed arm of the loop, i.e., a toroid. However, in the H-plane, the response is not symmetrical with respect to the bisecting plane because the loop is fed asymmetrically and, therefore, the field contributed by the load arm suffers different delay in opposite direction of this plane. For instance, the pulse shape is quite different at the extreme directions given by $\varphi = 0$, $\Theta = 90°$ (endfire), and $\varphi = 180°$, $\Theta = 90°$ (backfire) as shown in Figs. 12(a) and (b). The pulse length observed in the direction opposite to the direction of propagation of the current in the side arms of the loop is 40 percent larger than that observed in the direction of propagation. The agreement with measured data is quite satisfactory.

A convenient equation for computing the amplitude of the received pulse is obtained from Eqs. (6) and (10). The ratio of the amplitude of the first peak of the induced voltage V_R to the amplitude of the driving impulse voltage V_T is for free-space transmission:

$$\frac{V_R}{V_T} = \frac{30 L_R \eta}{RZ} \qquad (14)$$

where

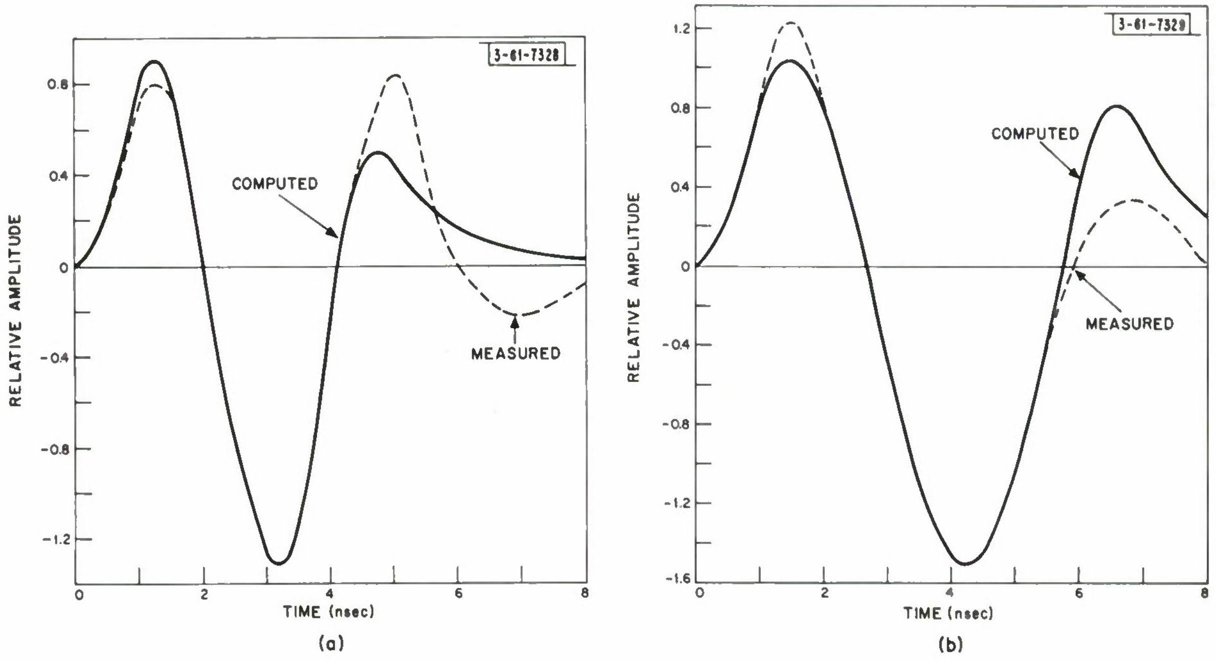

Fig. 12. Transmissions in plane of loop: (a) endfire direction; (b) backfire direction.

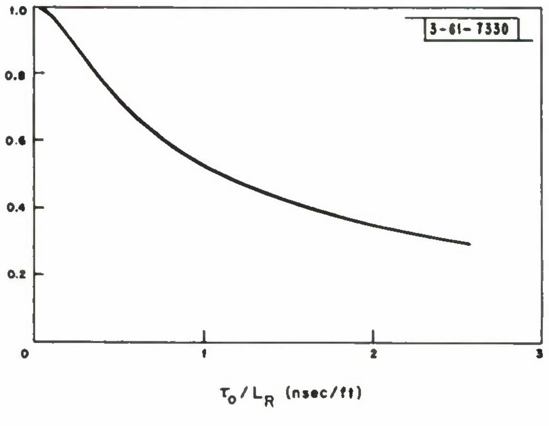

Fig. 13. Transmission coefficient vs τ_o/L_R.

Z = radiation impedance of the loop antennas in ohms (about 600 ohms),

R = separation between antennas in feet,

L_R = length of the receiving antenna in feet,

and η is a function having the dimension of velocity and depending on the respective sizes of the transmitting and receiving antennas and on the rise time τ_o of the driving impulse. The behavior of η for identical transmitting and receiving rectangular loops with half-lengths equal to their widths is illustrated in Fig. 13 as a function of τ_o/L_R. Equation (14) was verified using two similar antennas with half-lengths and widths both equal to 1 foot, a driving impulse with a 1-nsec rise time, and a 21-ft separation between antennas. The value of η for this case is 0.54, and the power ratio corresponding to the voltage ratio of Eq. (14) is – 57.8 db. A measured value of – 60 db was obtained; the discrepancy can be accounted for by impedance mismatches and by losses in the hybrid junctions used to feed the loop antennas. The transient response of these junctions was not determined accurately enough to permit a closer verification of the formula.

The study of transmission of transients between loop antennas has been made for loops of rectangular geometry. However, since their essential characteristics result from an outgoing wave in one conductor (the feed arm) and from the returning wave in another conductor (the load arm), it is clear that variations from a rectangular shape will not alter these characteristics appreciably. When used in a radar system, the shape of the received pulse will, in general, be affected by the properties of the target, particularly for large targets in the near field of the antenna.

The loop antenna has a doughnut-shaped radiation pattern. A unidirectional pattern would result by placing a flat reflector behind the antenna at a distance corresponding to one quarter-cycle of the radiated pulse. The width of the received pulse would, of course, be increased by one half-cycle. To obtain still greater directivity, the techniques used for transmission under steady-state conditions are evidently applicable.

It is interesting to consider the effect of slowing down the current wave in the loop, for example, by periodically loading it with physically small inductances. Referring to Eq. (7), it is observed that the amplitude of the field radiated along the normal to the loop is directly proportional to the velocity of propagation v_a of the current wave in the antenna. On the other hand, the radiated pulse length is proportional to the time of propagation in the loop. Therefore, the power radiated by a loaded antenna is v_a/c^* times the power radiated by a similar but unloaded antenna when excited with the same current. However, the total power radiated is a function of the feed-to-load path length only, and therefore is unchanged by inductive loading. Consequently, for conservation of energy, the current in the loaded loop has to be larger than the current in the unloaded loop by a ratio equal to $\sqrt{c/v_a}$. Correspondingly, the loaded-loop impedance has to be smaller by the same ratio.

IV. TRANSMISSION INTO ANOTHER MEDIUM

Let the loop antenna be placed parallel and in close proximity to the plane boundary between air and a dielectric medium (for example, the ground) for the purpose of transmitting energy within this medium. The characteristics of the wave transmitted within the medium may be derived by integrating the effect of each infinitesimal element of a current-carrying conductor parallel to an interface as suggested in Fig. 14. The element of electric field radiated in a

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*c is the wave velocity in the unloaded antenna.

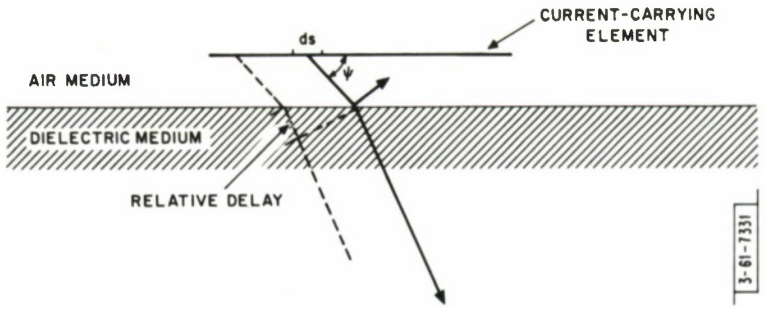

Fig. 14. Geometry of conductor above dielectric.

direction ψ from the conductor is again as given in Eq. (1). At the interface, part of this field is transmitted and part is reflected according to Snell's laws. The amplitude of the transmitted field varies in a complex manner with angle of incidence, but the retarded time to a far-distant point is the same as though the current-carrying conductor was entirely embedded in the medium. The velocity of a current pulse in the loop antenna may be expected to be affected by the close proximity of a high-dielectric medium. This effect was evaluated by probing the current wave in a loop for different heights of the loop above a ground of high effective dielectric constant. Measurements indicated surprisingly little change of velocity. For example, with a loop 4 feet long and 2 feet wide placed 2 inches above ground, the velocity is only 3 percent slower than in free space. The increase in rise time of the current impulse is also not appreciably different from that in free space. Thus, the wave velocity in the ground is less than the current velocity in the antenna, and this results in a radiation beam narrower in the ground than in free space. This behavior is consistent with Snell's laws of angular refraction. The beamwidth in a low-loss medium will be, to a first approximation, equal to the beamwidth in free space divided by the index of refraction and the gain, approximately equal to free-space gain times the square of this index. Exact values of gain and beamwidth are dependent upon the transmission coefficient at the interface. This coefficient varies in such a manner as to expect a larger beamwidth in the E-plane than in the H-plane because of the larger transmission at the Brewster's angle.

The proximity of the ground to the loop, it was mentioned, does not affect appreciably the current wave velocity in the antenna. However, it does affect the antenna input impedance, reducing it by a factor which depends on height and which is about one-half for a height above ground of 2 inches.

V. CONCLUSIONS

The field radiated by an antenna excited by transients corresponds to the free oscillations of the antenna. Loop antennas loaded at their mid-point with a resistance equal to the radiation impedance, to avoid ringing, are suitable radiators for transmission of transients. When two similar loop antennas are used in a transmission system – one of which is excited by an impulse – the voltage induced at the terminals of the other antenna is an amplitude-varying RF pulse whose period is roughly equal to the time of propagation of the impulse in a loop. For a given antenna size (or, correspondingly, for a given center frequency of the received-pulse spectrum), optimum pulse transmission occurs with an exciting pulse whose length is equal to one-half of the RF period and whose rise time is instantaneous. The radiation pattern of the loop is independent of its dimensions, and nearly similar to the pattern of an electric dipole parallel to the feed arm of the loop.

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13. ABSTRACT

The radiation characteristics of a rectangular loop loaded at its mid-point with a resistance equal to the radiation resistance, and fed by DC pulses, are derived and compared with measurements. In particular, the time variation of the electromagnetic pulse radiated by this antenna, and also of the voltage pulse induced at the terminals of a similar receiving antenna, is derived. The relationships between the characteristics of these pulses and the loop parameters are stressed.

14. KEY WORDS

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