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**ELECTROMAGNETIC IMPULSE TRANSMISSION
AND RECEPTION USING A WIDE BAND ANTENNA**

by

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ABSTRACT

An interesting method for transmitting and receiving electromagnetic pulses of small time duration over a limited distance is the use of the transient response function of a wide band antenna system. Tests were conducted with one type of wide band antenna: the disccone antenna. Although the method is very inefficient compared with the conventional modulated carrier wave transmission system, there does exist the possibility of measuring the time between several pulses to a high precision. Impulses of 10^7 watts peak power applied to a 2.75 meter disccone antenna radiated 10^6 watt transient pulses of the order of 5×10^{-8} sec long, which were received over local areas and over 23 kilometers of sea water. A directional receiver employing separated disccone antennas whose signals were mixed in a simple coincidence system is also discussed.

ACKNOWLEDGMENTS

The antenna testing, although simple in principle, could not have been accomplished without the excellent cooperation and skills of a number of people in Group J-13 of Los Alamos Scientific Laboratory. The author would like to express his appreciation and thanks to F. B. Harrison, J. E. Allen and E. J. Montoya for construction of the discone antennas and preliminary testing; to R. W. Engle and J. H. Warren for arranging transportation and communication facilities at Eniwetok; and finally to J. T. Marlow and Mrs. Amie Smith, who supplied valuable secretarial assistance.

I. INTRODUCTION

It has been suggested by many people who are acquainted with nuclear bomb testing procedures that some measurements would be easier and less expensive if a versatile fast-time radio relay system could be used. Because the bomb explodes "just once" and in rather a short time, the sampling of any data by a relay system must be done at a tremendous rate and with a time accuracy, in some cases, bordering on $\pm 10^{-9}$ sec. The distance to be covered by a relay system should be about 32 kilometers, for at this distance blast and thermal radiation effects are small enough to require only a simple shelter for any recording equipment. Also, over such a short path, line of sight can be realized, with consequent good transmission fidelity.

Microwave transmission, with its large bandwidths in terms of cycles per second and with its highly directive antenna systems, is probably the most logical choice for a fast relay unit. In fact, a microwave system using frequency modulation, with bandwidths from 40 to 250 Mc, has been involved since 1955 in field test work.¹ In the laboratory, amplitude modulation of milliwatt microwave power for times of the order of 10^{-8} to 10^{-9} sec has been accomplished in several ways,²⁻⁶ and hundreds of kilowatts have been obtained from magnetrons in times of 10^{-8} sec.⁷ High power klystrons in the megawatt power range with bandwidths of 10% are commercially available.⁸ Wide band receivers using traveling wave tube amplifiers and direct crystal detector demodulation or using the super heterodyne principle with wide band intermediate frequency amplifiers⁶ seem to be no problem.

A fair question to be raised at this point is "Why, in view of the highly developed microwave techniques, should one be interested in an impulse system?" The answers are: "Its simplicity, its turn-on and -off accuracy, and the availability of parts in the nonmicrowave laboratory are factors which may outweigh the disadvantages of inefficiency and lack of propagation range." The possibilities of an impulse system have been explored so very little that the author has not been able to find any reference to previous work wherein pulses have been applied to antenna systems directly, without a radio frequency carrier, and received at any distance.

Historically, of course, spark transmitters which supplied a damped oscillatory wave to the transmitting antenna were among the earliest forms of radio frequency generators. The impulse system, which implies a critically damped waveform, is therefore related to the early spark systems, and differs only in the details of the damping factor and of the methods for generation of high power pulses of short time duration.

A more difficult problem to be solved for any high speed data relay system is the translation of the desired data into a form which can be transmitted by the relay link. The encoder machinery design thus depends upon the particular wave form to be sampled, its time response, its dynamic range, and desired recorded detail. The encoder design is a problem common to all relay systems and will be considered a separate topic and not discussed here.

In the following we shall assume that a pulse has been provided by an encoder system, and the problem to be solved is (a) to radiate the maximum amount of the pulse energy in the shortest possible time and (b) to receive the radiated pulse with the maximum amount of receiver sensitivity in order to maximize the range of propagation.

II. ANTENNA BANDWIDTH AND TRANSIENT CONSIDERATIONS

The antenna may be considered⁹ as a transformer placed between the end of the coaxial line and free space, whose purpose is to radiate as efficiently as possible the energy flowing in the line. Ideally, in the case of an electrical pulse, the energy resolved into its various frequency components is expected to flow through the antenna and into free space unchanged in amplitude or relative phase. Although antennas can be designed to radiate a single frequency with good efficiency, it is difficult to design a system to radiate over a wide range of frequencies, and still more difficult is the radiation of the Fourier frequencies of a pulse so that the pulse shape is preserved. Wide band antenna design is still in the developmental stage, and one usually finds that certain characteristics are emphasized by the designer. The disccone antenna¹⁰ has a constant input impedance over a wide (10 to 1) range of frequencies, with a radiation pattern similar to a dipole. The fishbone traveling wave antennas^{11,12} have useful directivity and operate over a narrower band width (2 to 1 to 3 to 1). In the experimental stage is a class of antennas whose dimensions are specified by angles rather than length.^{13,14} They yield remarkably constant input impedance and dipole type radiation pattern over a 10 to 1 frequency range. The helical antenna can be shaped¹⁵ to produce a moderate bandwidth with some gain.

Electrically, a wide band antenna has bandpass filter characteristics. The transient response of an idealized bandpass filter,¹⁶ when excited by a band of frequencies which in general lie outside the bandpass, is an oscillation with a frequency at the center of the bandpass; the build-up and decay rates of the oscillation are inversely proportional to the bandwidth; the amplitude of the oscillation is proportional to the bandwidth. The mathematical analysis of a real filter usually becomes exceedingly difficult and one can indicate only in a general manner the method of procedure. Mathematical

aids provided by the Fourier and LaPlace transforms methods are often used.

Let

$e_1(t)$ = the voltage waveform incident upon the filter

$e_2(t)$ = the voltage waveform output from the filter

If $e_1(t)$ is integrable over the time region $-\infty < t < +\infty$, the frequency spectrum $g_1(\omega)$ occupied by $e_1(t)$ is given by the Fourier transform $\mathcal{F}e_1(t)$

$$\mathcal{F}e_1(t) = g_1(\omega) = \int_{-\infty}^{+\infty} e_1(t) e^{-j\omega t} dt \quad (1)$$

where ω = the angular frequency = $2\pi f$, and j indicates complex number notation. The action of the filter is to modify the amplitude and phase distribution of the waves in the frequency spectrum $g_1(\omega)$, to yield a new distribution $g_2(\omega)$. In network analysis, the filter action is mathematically described by a transfer function $A(\omega)$, such that

$$g_2(\omega) = A(\omega) g_1(\omega) \quad (2)$$

The output voltage $e_2(t)$ can now be computed by the inverse Fourier transform of $g_2(\omega)$

$$e_2(t) = \mathcal{F}^{-1} g_2(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} A(\omega) g_1(\omega) e^{j\omega t} d\omega \quad (3)$$

Ideal transmission is the case where $A(\omega) = 1$, over the infinite bandwidth $-\infty < \omega < +\infty$, in which case $e_2(t) = e_1(t)$. In the measurement of a filter's response to an impulse of voltage one tries to make $g_1(\omega)$ a very slowly changing function of ω , compared to $A(\omega)$, and thus bring $g_1(\omega)$ out of the integral as a constant. The ideal unit impulse of voltage is a spike infinitely high and infinitely small in time so that the frequency distribution is "flat"

[$g(\omega) = 1$]. The experimenter could in principle measure $e_2(t)$, for an impulse input, and then estimate $A(\omega)$, since by Eq. (2)

$$g_2(\omega) = A(\omega)(1)$$

and by definition

$$g_2(\omega) = \int_{-\infty}^{+\infty} e_2(t) e^{-j\omega t} dt \quad (4)$$

It should be anticipated that because $e_2(t)$ is very sensitive to the phase characteristics of the system, the effective bandwidth of so-called wide band antennas will be moderately narrow. If the impulse transmission system is to have $\pm 10^{-9}$ sec resolution, one should have an antenna center frequency of about 100 Mc, and sufficient bandwidth and phase response so that not more than one cycle would be radiated.

III. PEAK PULSE POWER REQUIREMENT

In the usual efficient carrier modulated wave system, the high voltage at the transmitting antenna is obtained by a resonant transformer placed between the antenna and the final power stage of transmitter. The sharpness of resonance is described by the quantity Q . One definition of Q is that $Q = f/\Delta f$, where f is the center frequency and Δf is the system bandwidth. In a series RLC circuit, if E is the voltage applied to the circuit, the voltage across L or C is (EQ) . In the impulse system one desires a Q of the order of unity in order that the impulse will be formed and will die out quickly. This requires that the high voltage be supplied to the antenna directly from the transmitting switch tubes.

An estimate of the voltage and current which one demands from the transmitter may be determined from the following factors. We assume that

the quality of the received pulses, and hence the ability to distinguish the arrival times of these pulses, will be impaired by noise modulation. An estimate of the noise spectrum¹⁷ (principally due to man-made sources, external to the receiver amplifiers) adjusted for 100 Mc bandwidth indicates that at 100 Mc the maximum noise level is about 2×10^{-3} volt/meter, or about 10^{-8} watt/meter². Obviously, an unshielded gasoline engine running under the antenna could seriously modify the so-called noise spectrum. The noise level on a 3 meter², 50 ohm receiving antenna will be about 10^{-3} volt. A 100 Mc wide amplifier has an expected noise level of about 10^{-5} volt, which is considerably less than the "atmospheric noise" just described.

If we arbitrarily demand that only 2% of the received pulse height be noise modulated, then a field strength of 0.1 volt/meter must be generated at whatever receiving distance is of interest. An isotropic radiator in free space will generate a power density P at a distance R according to $P = P_t / 4\pi R^2$ watts/meter², where P_t is the transmitted power. The field strength E is given by

$$E = \sqrt{Z_0 P} \text{ volts/meter}$$

where Z_0 is the resistance of free space ($Z_0 = 120\pi$ ohms). If $E = 0.1$ volt/meter, then

$$P_t = 3.33 \times 10^{-4} R^2 \text{ watts}$$

where R is in meters. For convenience, a plot of transmitted power versus meters from the source is given in Fig. 1.

Antenna inefficiency and the absence of true free space conditions will probably demand a peak power from the switch tubes of 10 to 50 P_t . The hydrogen thyratron 5C22 tube was chosen for test purposes to develop about 10^7 watts into a 50 ohm line for short times. Figure 2 is a schematic

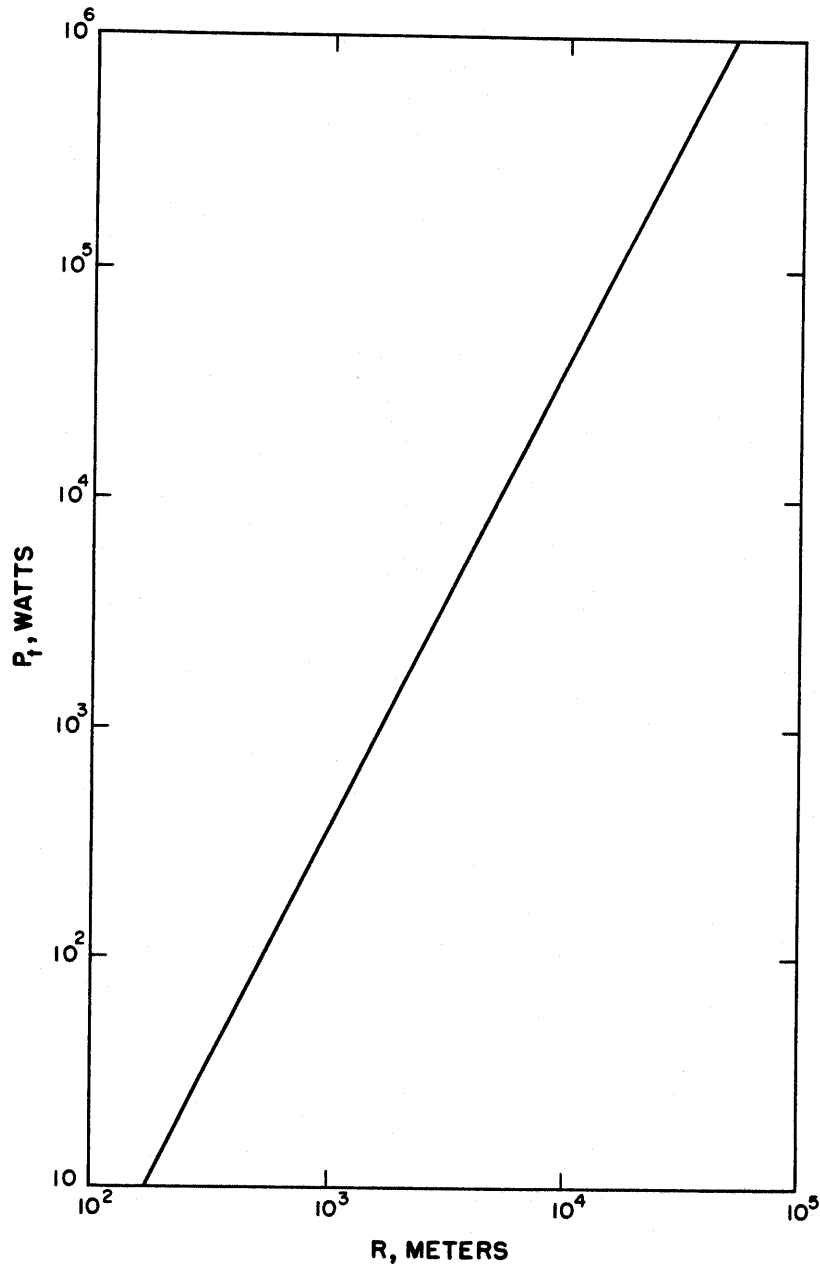


Fig. 1 Transmitted power P_t to create 0.1 volt meter at distance R meters.
 $P_t = 3.33 \times 10^{-4} R^2$ watts.

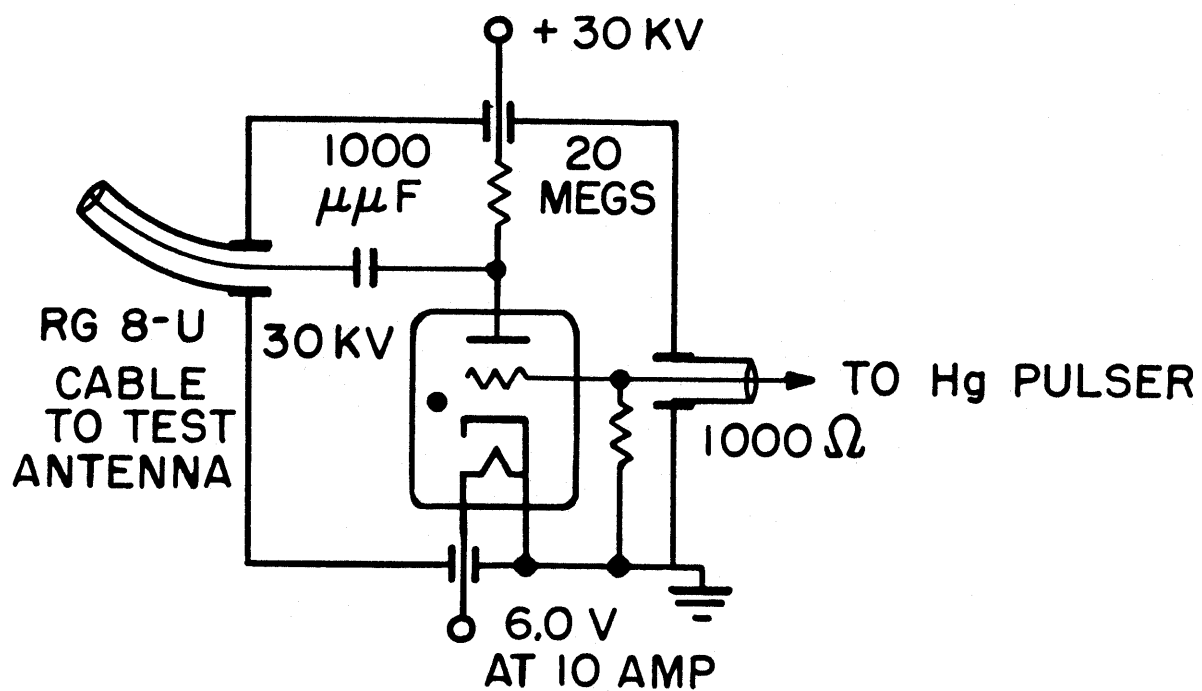


Fig. 2 5C22 hydrogen thyratron test pulser.

diagram of the 5C22 pulser. The drawing also indicates the mounting procedure for the tube to ensure a low inductance path into the output cable. A standard mercury relay pulser was used to trigger the 5C22 at a low repetition rate. For small test pulses, the mercury pulser was connected to the antenna line. In a practical pulse system where two or more pulses would be radiated independently in time in a small time interval, hard switch tubes such as the Eimac 4PR60A would be used. Laboratory tests indicate that the Eimac tube can develop 100 amp in a minimum time of 7×10^{-9} sec into a 50 ohm load, when driven by a source such as the 3E29 dual tetrode. A more desirable load for the hard tube pulser would be a 300 ohm antenna line system, where about 10^6 watts could be developed per tube. A more rugged thyatron tube for test purposes is the new EG&G¹⁸ hydrogen thyatron type 1802, constructed in a ceramic-metal envelope. This tube should deliver 2000 amp into a 15 ohm load or 6×10^7 watts.

IV. EXPERIMENT WITH DISCONE ANTENNA

A. Construction Details

The discone antenna,¹⁰ which is one solution to the flared coaxial line radiator, was chosen for the first impulse transmission tests for several reasons:

- (1) Its low standing wave ratio versus frequency characteristic, as well as a fairly constant shaped field pattern, promised some degree of radiation efficiency over a broad frequency range.
- (2) Construction is simple, and the cone shape allows the support to be a pole (nonconducting pole).
- (3) It is fed by a coaxial line (50 ohms) and can be well insulated to withstand the high pulse voltages.

The radiation pattern is similar to the elementary vertical electric

dipole, which is symmetrical about the vertical axis, has its electric field falling to zero along the vertical axis, and, in general, produces vertically polarized radiation in the horizontal plane. As mentioned before, we unfortunately did not know the phase characteristics of this antenna and therefore did not know what pulse shape would be transmitted. A general cross sectional view and the compromise design parameters as given by Nail¹⁰ are shown in Fig. 3. Low frequency (f_0) cutoff occurs when $\lambda_0 = c/f_0 = 4L$, where L is the slant height of the cone, and $c = 3 \times 10^8$ m/sec. The cone angle was set at 60° . We chose L as equal to 2.75 meters or $f_0 = 27$ Mc.

In order to make the joint between the top of the cone and the center of the top disc mechanically strong and to provide insulation, a small disc was made of brass sheet. The construction details are shown in Fig. 4. An insulated tube was placed around the top and the inside space was filled with a beeswax and rosin mixture. Mechanical strength was obtained from the screws holding the disc to the tube and the cone to the tube. The RG-9U cable braid was soldered to the top of the cone and the center conductor with its insulation was brought up through a hole in the disc and soldered. No difficulty in sparking for dc voltages up to 25 kilovolts was experienced. The cone and disc were extended to their respective dimensions of 2.75 meters and 1.9 meters by a lightweight, open mesh aluminum screen. Bolts were used to clamp the wire mesh to the more rigid brass disc. The completed structure was rather wobbly but adequately served for test purposes. Three of these antenna were constructed; one for transmitting and two for a time coincidence receiver.

Preliminary pulse tests indicated that in order to obtain a single transient response it was necessary to mount the antenna on an insulated support such as the ground or on wooden poles. Apparently a metal supporting arrangement, such as a steel pole which makes contact with the underside of

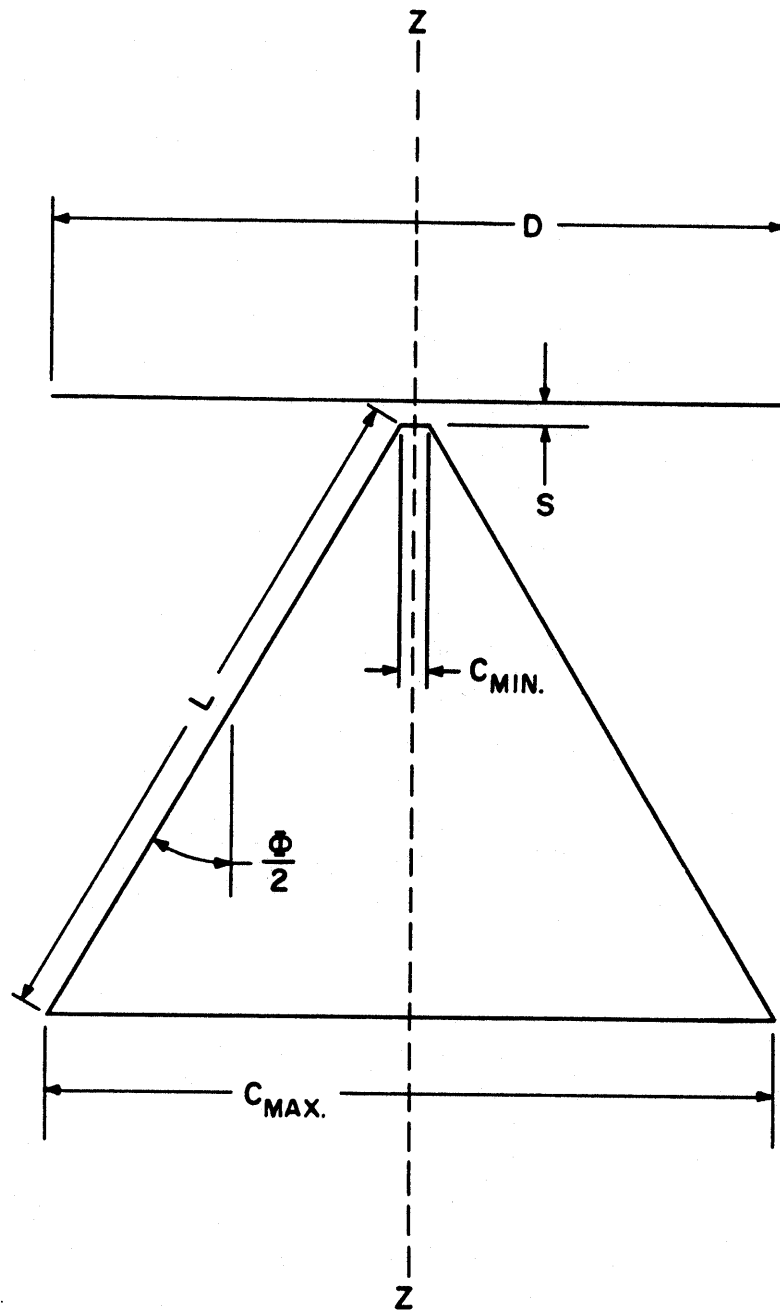


Fig. 3 Discone antenna parameters: $\Phi = 60^\circ$, $\lambda_0 = 4L =$ cutoff wavelength, $D = 0.7C_{\max} = 0.7L$, $S = 0.3C_{\min}$, $C_{\min} \approx$ external dimension of coaxial feed line. (Reprinted by permission from the August 1953 issue of Electronics, a McGraw-Hill publication, copyright 1953).

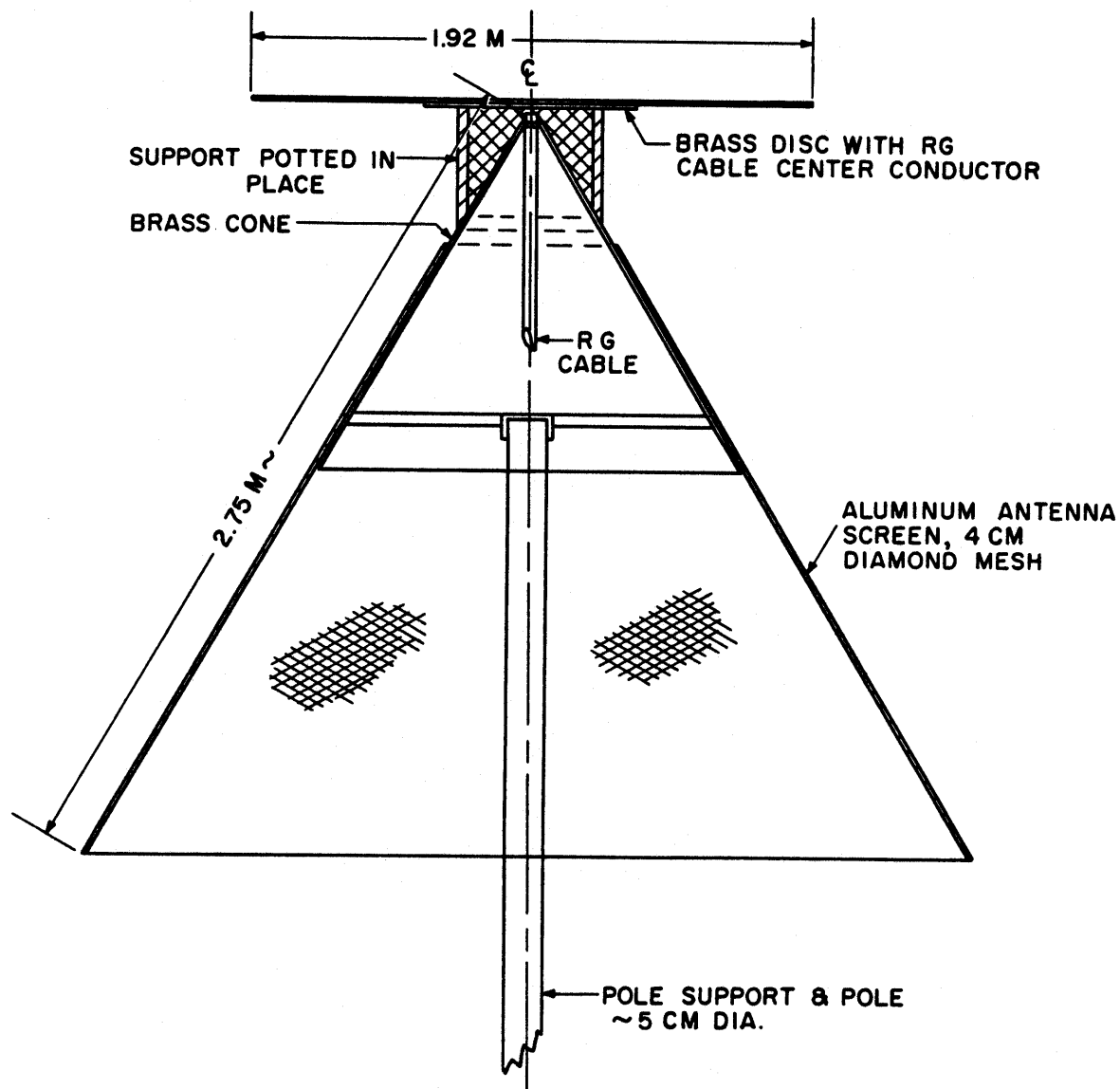


Fig. 4 Discone mechanical details. The center conductor was soldered at the middle of the top disc and the RG cable shield was soldered at the C_{min} opening of the brass cone. The antenna was fabricated of material with sufficient gauge thickness to be self-supporting.

the antenna, will be shock excited into a slowly damped resonance frequency of its own, and the energy of radiation will be comparable to the impulse energy from the discone.

B. Pulse Receiver

Basically, a pulse receiver is simply an antenna feeding an amplifier (either a bandpass or a video pulse type) and a recorder such as an oscilloscope. One difficulty with a simple broadband pulse receiver is that it can be particularly susceptible to either continuous wave jamming or pulse jamming. Rather sharp discrimination in favor of a desired pulse can be obtained by two expedencies. First, two or more antennas can be arranged in a spatial distribution such that a time coincidence among them yields a desired directivity. This is the interferometer principle which is applied in radioastronomy and in certain pulse navigation schemes, such as Loran. Second, high Q filters can be placed across the receiving cables to remove any particular continuous wave signal. The effect of the filter on the pulse shape can usually be ignored.

As a practical example of the interferometer method, suppose that the coincidence circuitry is sensitive to a change of $\pm 1 \times 10^{-9}$ sec, then two receiving antennas placed 30 meters apart on a line perpendicular to a distant source will have an angular resolution of $\pm 10^{-2}$ radian. A third antenna placed along the line to the source and mixed in a triple coincidence circuit would determine the direction unambiguously. Conversely, if the source position were unknown, it could be located by measuring the arrival time of the pulse on the separate antennas. A further refinement in pulse selectivity would be realized by using the two separated negative portions of a single impulse to actuate a coincidence circuit. Thus, a received pulse would need the correct shape, as well as the correct arrival time, in order to be registered.

For long range test purposes, we employed two disccone receiving antennas. Each signal was amplified by one or more video distributed amplifiers (Hewlett-Packard type 460A and 460B), and the signals were mixed in a double coincidence circuit. The output of the coincidence circuit triggered the sweep of a Tektronix 517 oscilloscope and a fraction of one of the antenna signals was viewed through the oscilloscope amplifier. In this way, signals which were almost in the background noise could be selected and viewed reliably. The general arrangement is shown in Fig. 5, and the coincidence circuit details are shown in Fig. 6. We expected the bandwidth of the system to be about 50 Mc, centered at 50 Mc, the lower limit being set by the antenna and the upper limit by the amplifiers.

C. Short Range Tests, Waveshapes, Energy Efficiency, and Antenna Cross Section

Pulse reflection tests, waveshape recording, and the conservation of energy principle are useful tools in estimating the pulse radiation efficiency of the transmitting antenna and the cross-sectional area of the receiving antenna. Accordingly, one of the first tests was to send a square wave from the mercury pulser down the cable to the disccone antenna and observe the incident and reflected pulses. In the case of 100% transmission through the antenna, there would be, of course, no reflected energy.

At the antenna, let

E_o = the incident energy

E_r = the reflected energy

E_t = the transmitted energy

then

$$E_o = E_t + E_r$$

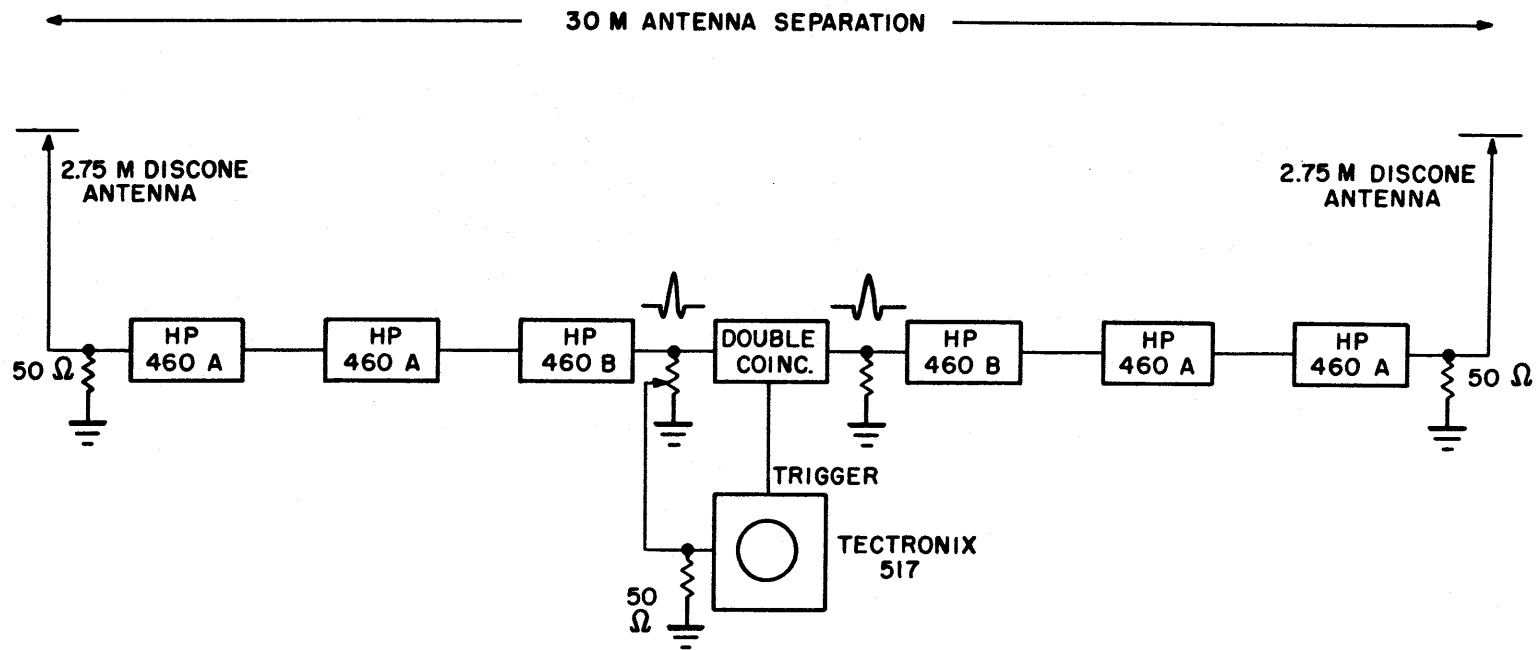


Fig. 5 Time coincidence receiver for impulse detection.

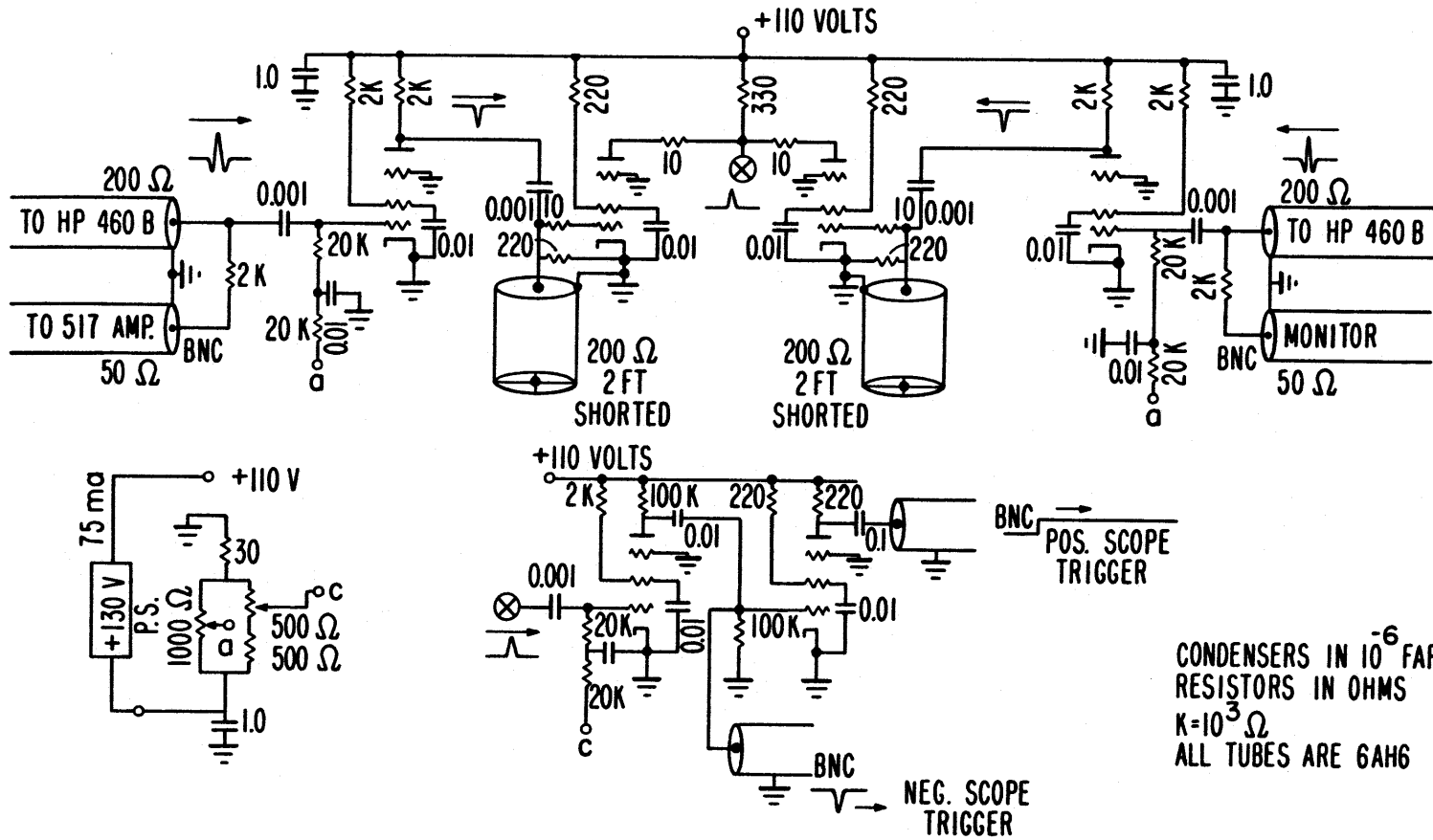


Fig. 6 Double coincidence circuit.

The antenna transmitting efficiency ϵ can be described as

$$\epsilon = \frac{E_t}{E_o} = 1 - \frac{E_r}{E_o} \quad (5)$$

In order to compute E_r and E_o , we must record the pulse shapes and amplitudes. Let

$e(t)$ = the pulse voltage (recorded as a function of time)

R = the impedance viewed by $e(t)$

Then the energy E in the pulse is

$$E = \int_{-\infty}^{+\infty} \frac{e^2(t)}{R} dt \text{ watt sec} \quad (6)$$

Experimentally, the arrangement shown in Fig. 7 was used. The pulses were photographed, plotted on graph paper, and numerically integrated. If we have a zero loss transmission line, then E_o and E_r are the same whether viewed at the generator or at the antenna. If a poor transmission line is used and the loss is relatively independent for small changes in pulse shape, the ratios of the reflected energies will be unaffected. Let the cable attenuation constant for the length in question be α , where $0 < \alpha < 1$. Then an energy E_g must leave the generator to produce E_o at the antenna, or

$$E_o = \alpha E_g \quad (7)$$

At the generator one sees a reflected pulse E'_r , where

$$E'_r = \alpha E_r \quad (8)$$

If the antenna is removed from the end of the cable, E_o is 100% reflected and appears as E'_o at the generator, so

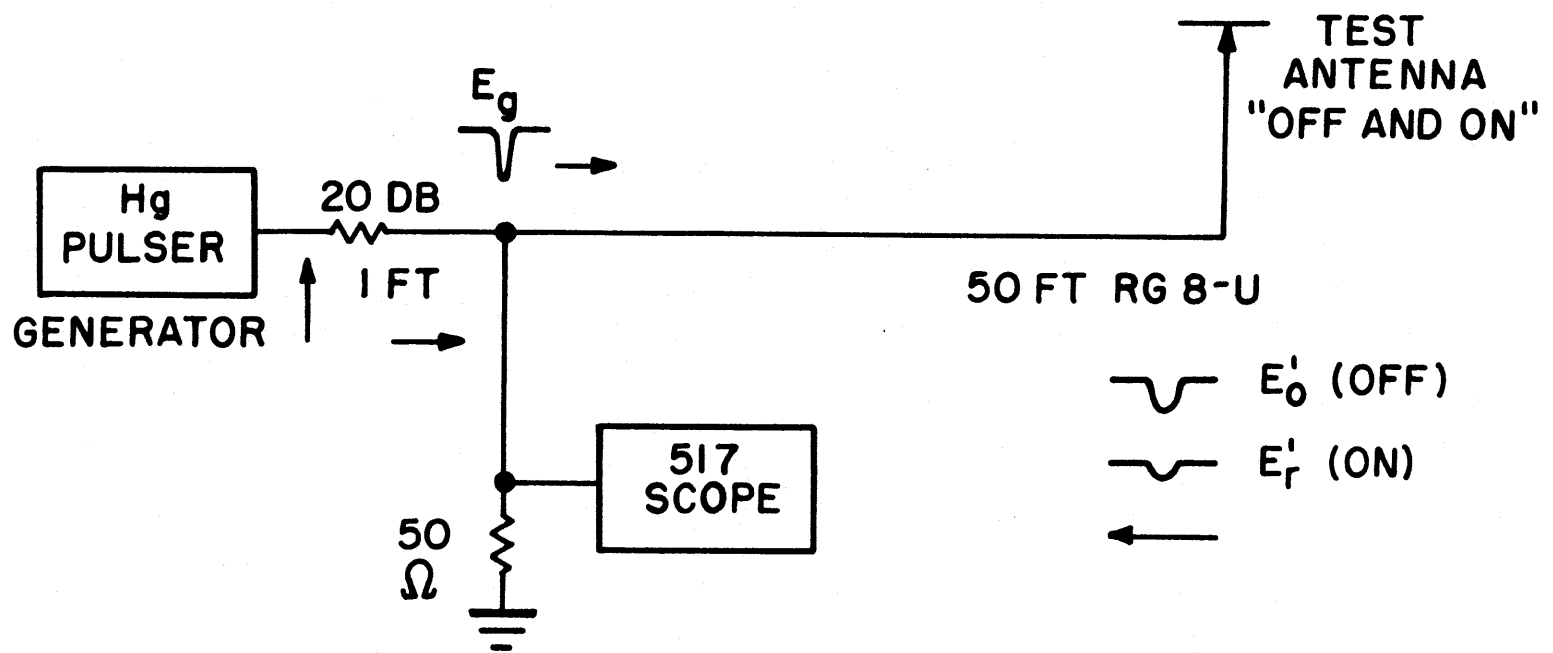


Fig. 7 Measurement of antenna energy transmission by pulse reflection technique.

$$E'_0 = \alpha E_0 \quad (9)$$

Combining Eqs. 5, 8, and 9 gives

$$\epsilon = 1 - \frac{E_r}{E_0} = 1 - \frac{E'_r}{\alpha E_0} = 1 - \frac{E'_r}{E'_0}$$

Finally

$$\epsilon = 1 - \left(\frac{\text{energy reflected with antenna "on"}}{\text{energy reflected with antenna "off"}} \right) \quad (10)$$

One expects the efficiency to approach zero for long pulses, as indeed it does. Figures 8 through 11 are time-correlated tracings of the reflected energies E'_r and E'_0 for square wave pulse input lengths ranging from 0.5 to 5.0×10^{-8} sec. A plot of the efficiency versus pulse length is shown in Fig. 12. For a pulse length of 10^{-8} sec approximately 20% of the energy is radiated. Figure 8 is interesting because it shows that the antenna is a progressive inductive mismatch throughout its length with a reflection at the edge of the cone. The peaks of E'_0 and E'_r are separated by 1.9×10^{-8} sec or 5.7 meters in free space, which is about twice the cone length.

The pulse shape of the transmitted energy was examined by placing another discone antenna of the same size (2.75 m) on the ground 33 meters from the first discone. We assume that the received pulse shape is not significantly different than the transmitted pulse, although one expects the received pulse to be broadened by $\sqrt{2}$. Figures 13 and 14 show the voltage pulse from the receiver discone when a 0.15 μ sec square pulse and the thyatron pulse are applied to the transmitting discone. One notes that the received pulse shape is approximately independent of the exciting pulse, the antenna responding only to the rapidly changing currents. Thus a true impulse driving voltage would be expected to produce roughly the same antenna

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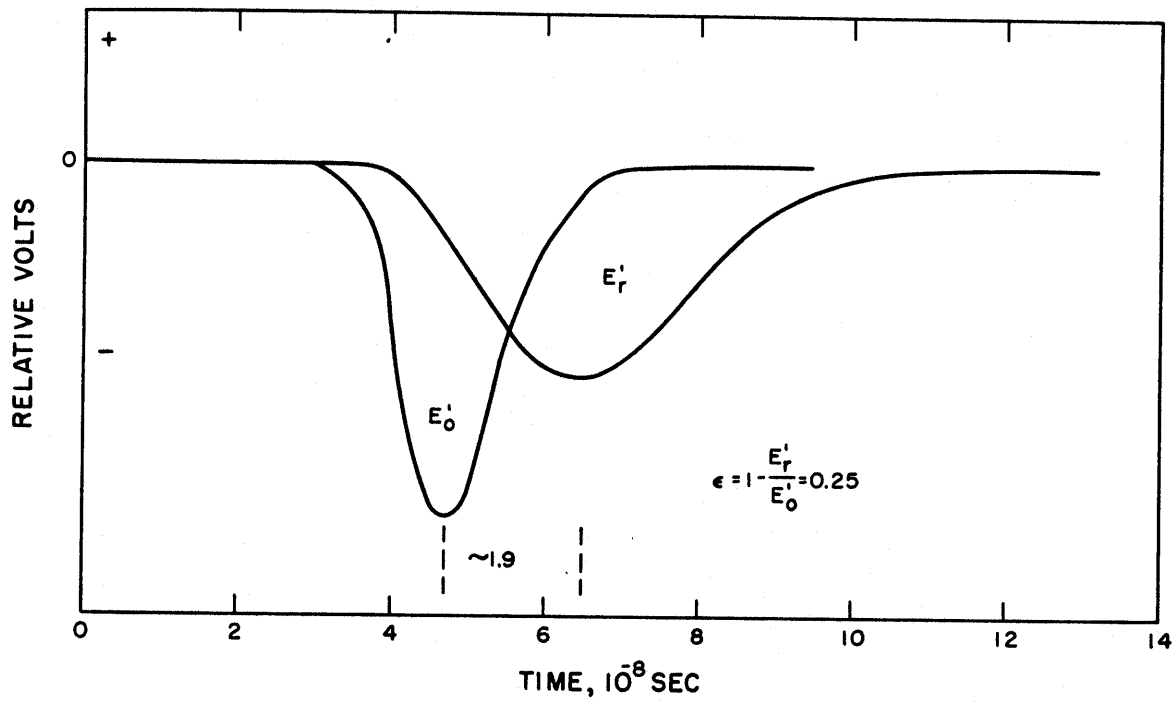


Fig. 8 Pulse reflection measurement for 2.75 meter disccone and 0.5×10^{-8} sec input pulse.

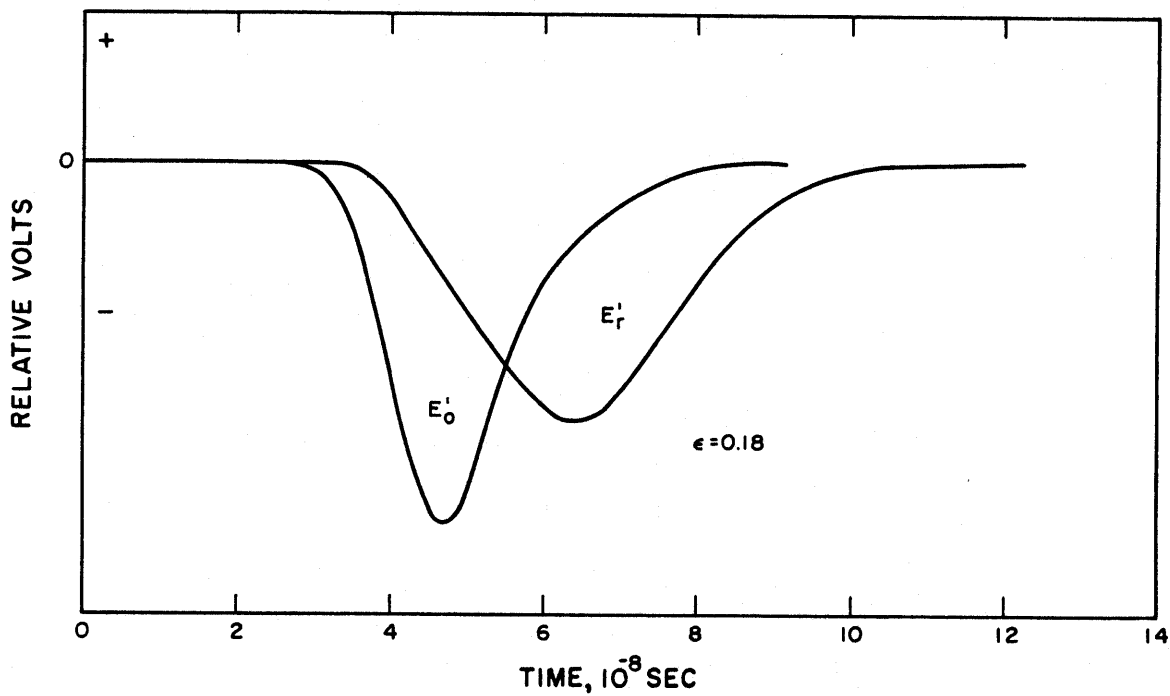


Fig. 9 1.0×10^{-8} sec input pulse.

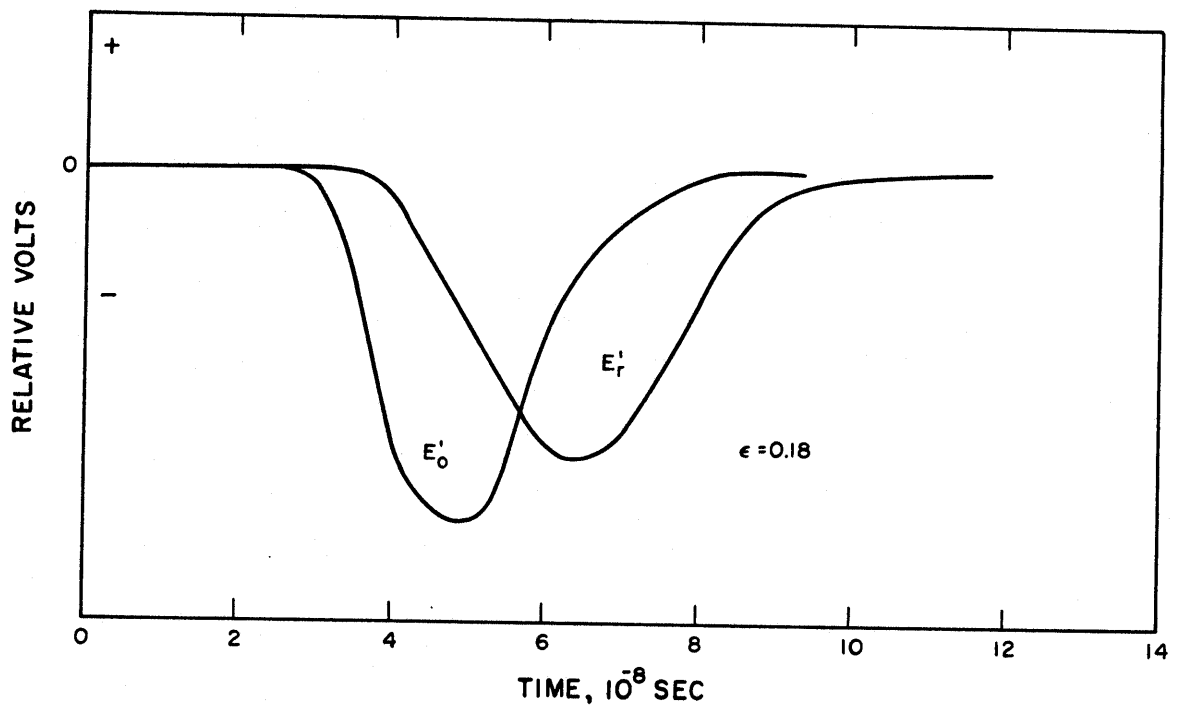


Fig. 10 2.0×10^{-8} sec input pulse.

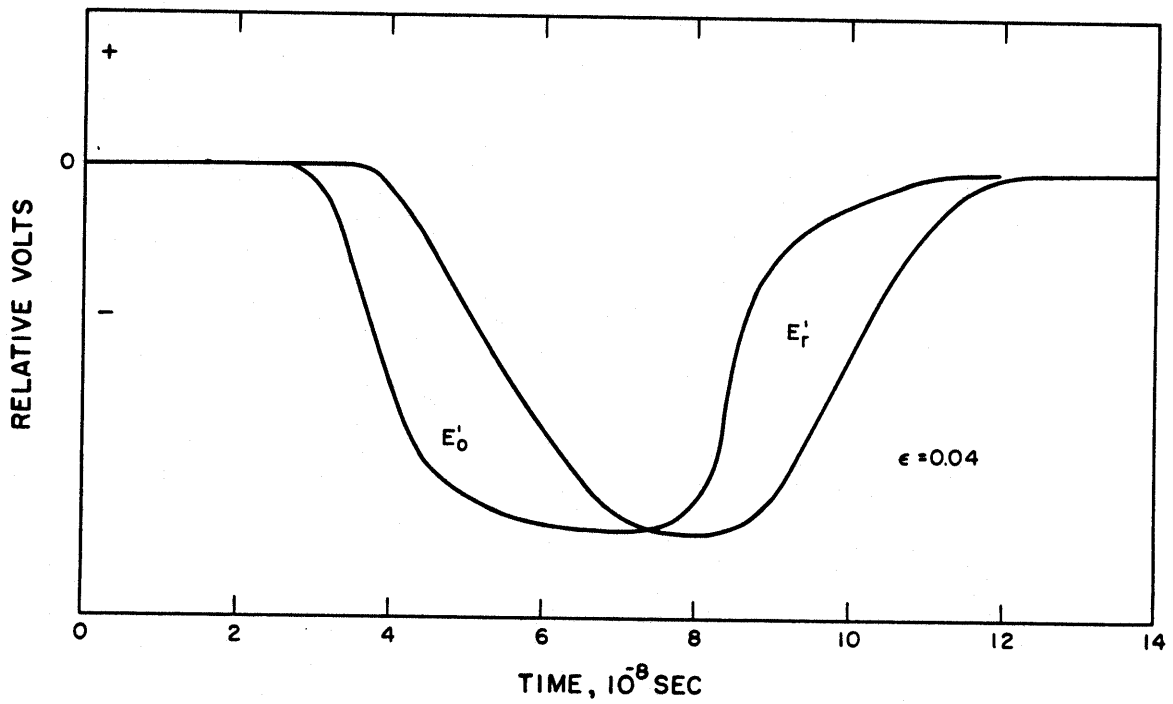


Fig. 11 5.0×10^{-8} sec input pulse.

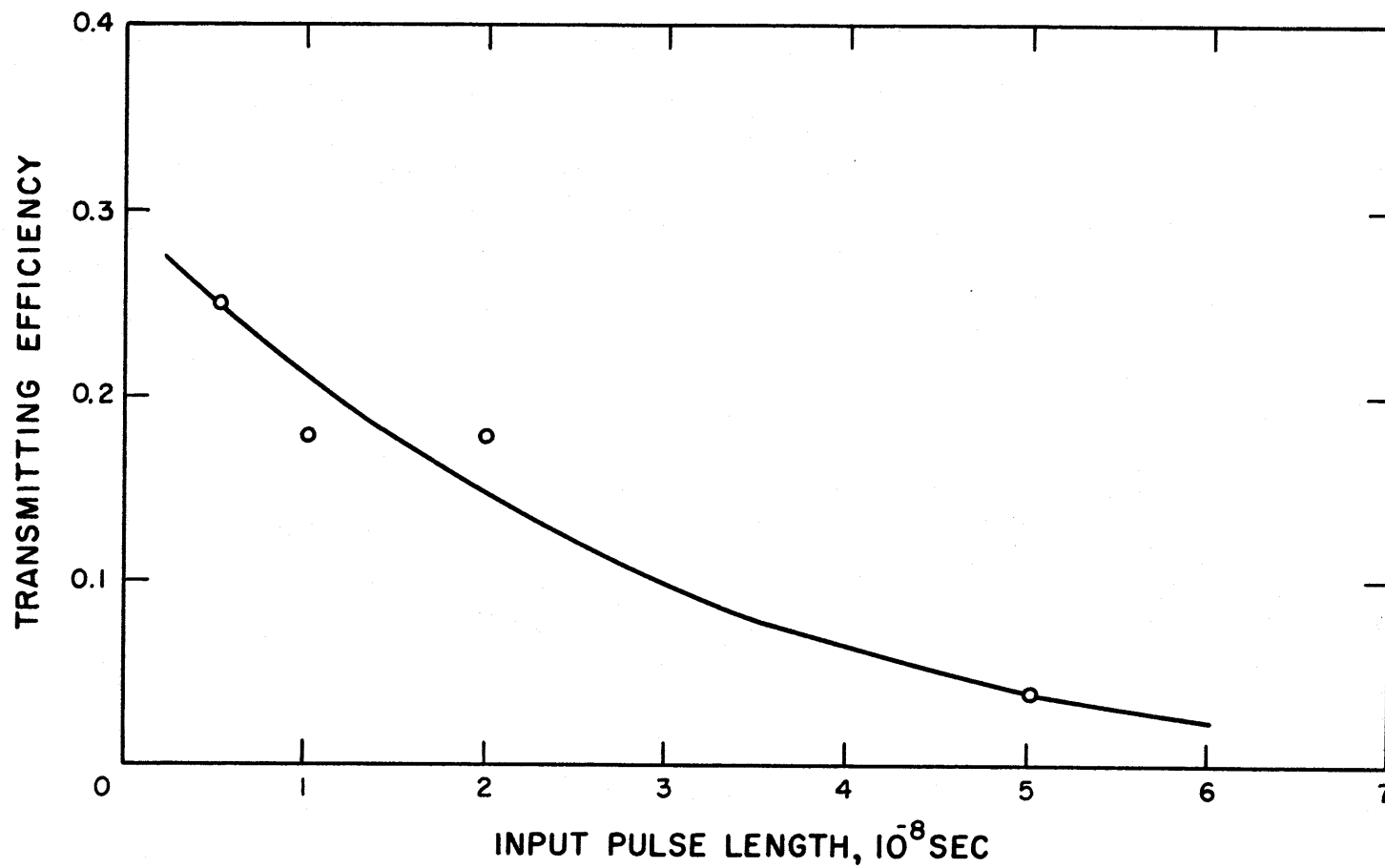


Fig. 12 Discone transmitting efficiency for 2.75 meter discone. Experimental points are based on pulse reflection energy. For 100% efficiency $\epsilon = 1$.

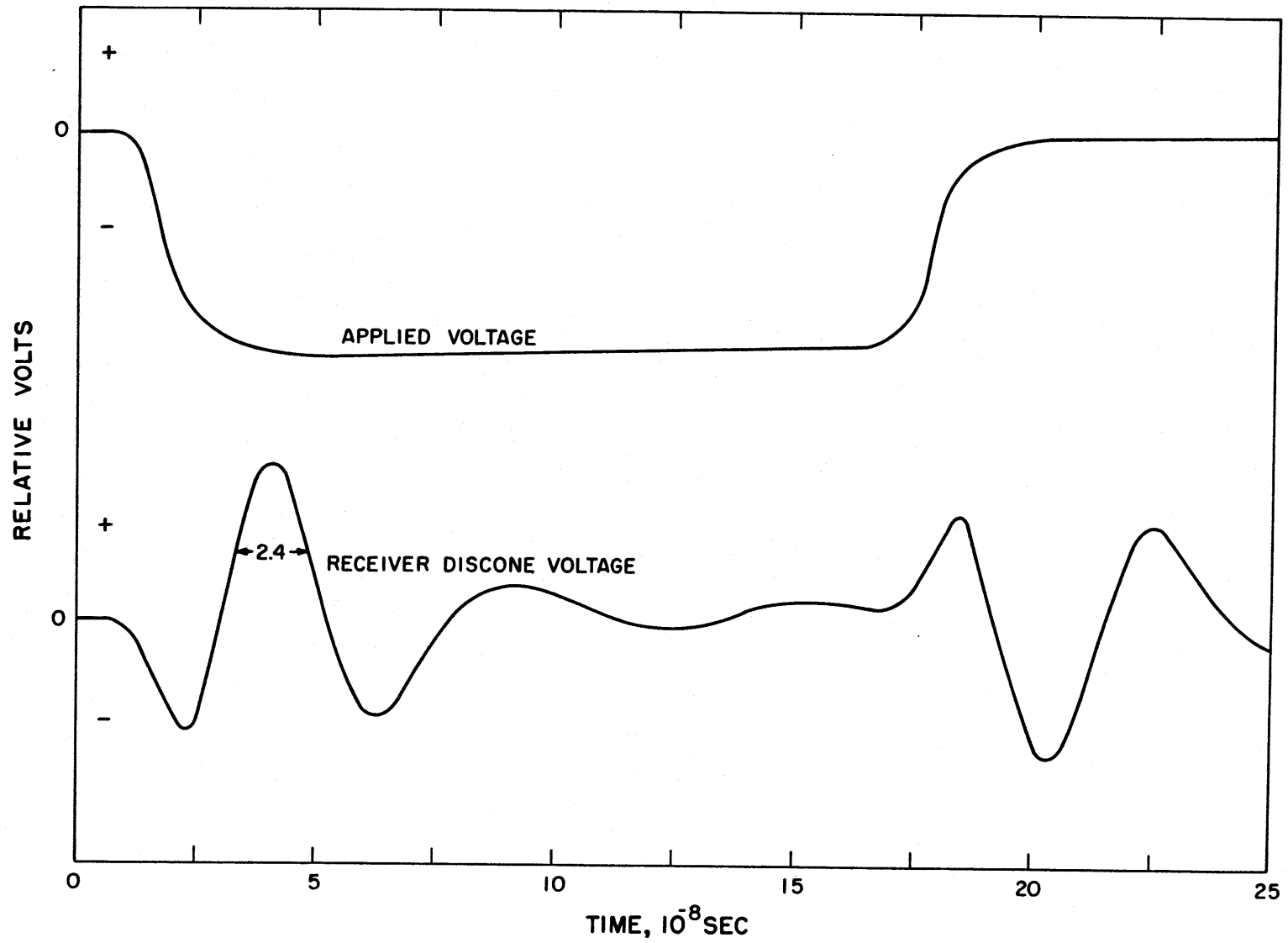


Fig. 13 Voltage response of 2.75 meter discones to a square wave.

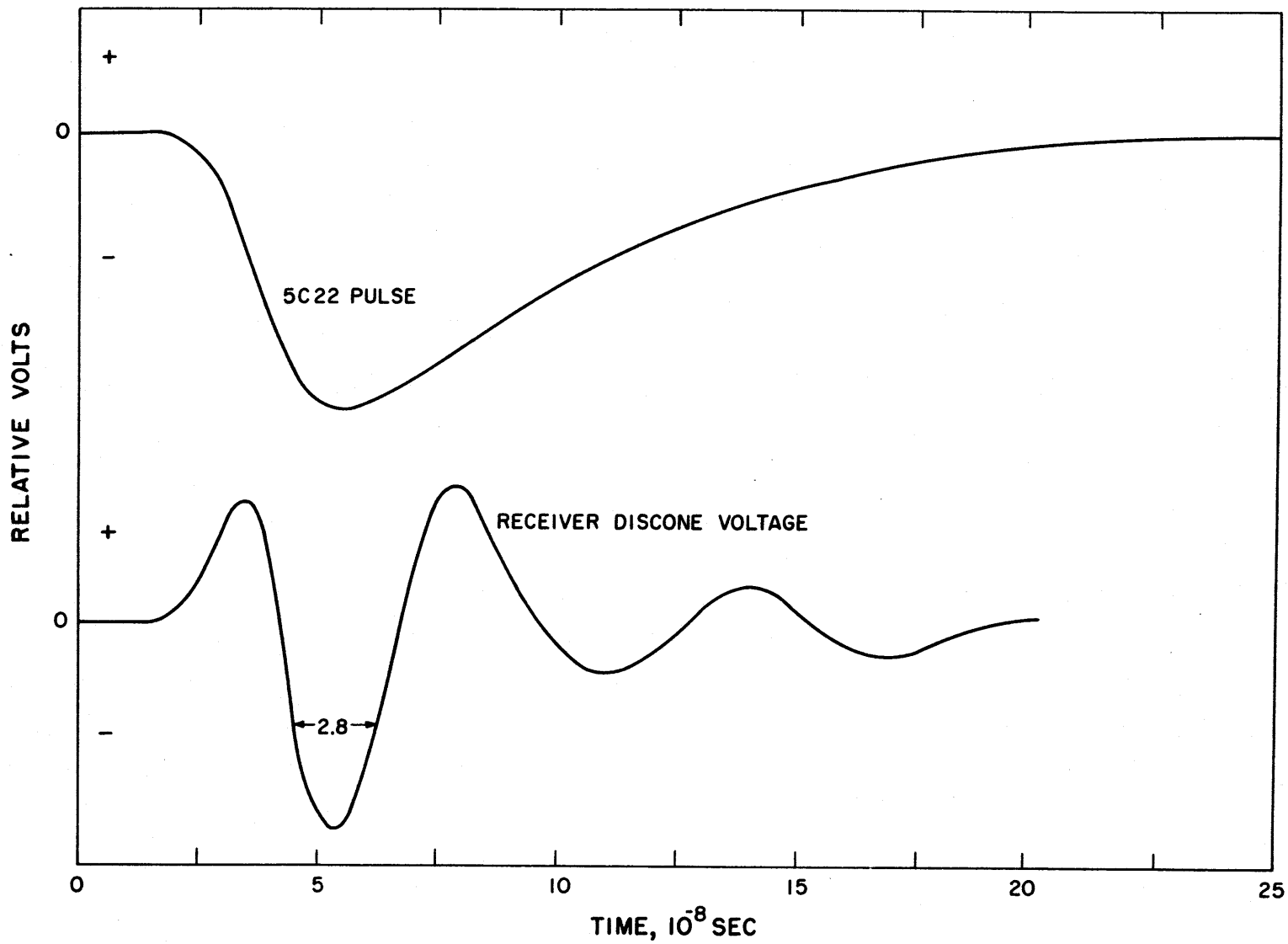


Fig. 14 Voltage response of 2.75 meter discones to the 5C22 pulse.

transient pulse. For the 5C22 pulse and the transmitted pulse we assumed peak powers of 10^7 and 10^6 watts, respectively, and numerically integrated the curve for the pulse energies. The results are given in Table I.

TABLE I
PEAK AND INTEGRATED POWER

	Peak Power, watts	Energy (Integrated Power), watt sec	Half-Power Time Width, μ sec
5C22	10^7	0.5	0.05
Transmitted pulse	10^6	0.02	0.01

The pulse length is difficult to define, since it takes several cycles for the transient to die out. If we perhaps unfairly take the positive half of the transient in Fig. 13, or the negative half of Fig. 14, as being a useful pulse, then the total width at half voltage ranges from 2.4 to 2.8×10^{-8} sec. The half power width is described by the 0.7 voltage points and is about 1×10^{-8} sec. The arrival time between two unrelated pulses, such as caused by two separately triggered 5C22 pulsers, could probably be measured to an accuracy of ± 0.1 the "pulse width" or $\pm 2.5 \times 10^{-9}$ sec. The "resonant" frequency of the antennas, which indicates the center of the passband is about 20 Mc which is about a factor of 5 lower than we would like to see. The radiation energy efficiency for a pulse 5×10^{-8} sec long was determined as 0.04 (Fig. 12). Therefore our assumptions concerning the ratio of applied to transmitted peak powers is at least self-consistent within the accuracy of the efficiency measurements described above.

At 33 meters and with the 5C22 pulser at 10^7 watts, we observed 100 peak volts on the terminated 50 ohm receiving cable. The receiving antenna

cross-sectional area was determined as follows.

Let

P = the power density in free space at the antenna

A = antenna cross-sectional area for receiving the pulse energy

e = the observed voltage on the antenna cable = 100 volts

Z = the cable impedance = 50 ohms

P_t = transmitted power = 10^6 watts

Then

$$PA = \frac{e^2}{Z}$$

$$\therefore A = \frac{e^2}{Z} \frac{1}{P} = \frac{e^2}{Z} \frac{4\pi R^2}{P_t}$$

$$= \frac{(100)^2}{50} \frac{4\pi(33)^2}{10^6} = 2.8 \text{ meters}^2$$

The receiving area is about the same as the geometrical cross section, but appears rather small from a wavelength point of view. For example, a dipole whose dimensions are small compared to a wavelength¹⁹ will intercept energy over a radius of about 0.2λ . If we take 15 meters as our average received wavelength, then an area of 9π meters² should have been observed.

D. Distance Tests, Waveshapes, and 1/R Law

Propagation of an impulse signal over sea water was performed at the Eniwetok Atoll during odd moments of the 1958 tests. The receiving station consisted of two 2.75 meter discons mounted on 15 meter high wooden telephone poles, separated by about 30 meters. The receiver location was the small island, Aniyaanii. A trailer housed the amplifiers, coincidence circuitry,

and oscilloscope. Signals were radiated by a third discone, driven by a 5C22 pulser, from the north end of Parry and from Igurin. Figure 15 shows the relative distances and locations. The transmitting discone and its 30 meter supporting mast were made portable with the help of a winch-equipped weapons carrier vehicle. The antenna heights were not sufficient to satisfy the Fresnel zone criterion for clearance distance. For free space propagation the path difference between the reflected path and the direct path should be $\lambda/4$ or greater. If L = the clearance distance, D = the direct path distance, and the antenna heights are equal, one can show that

$$L = \frac{1}{2} (\lambda D)^{1/2}$$

If $\lambda = 15$ meters and $D = 15$ kilometers, then L should be about 240 meters. When L is less than the first Fresnel zone, one would observe, in the case of monochromatic frequency transmission, large fluctuations in the received signal as the distance is varied. In the case of pulse transmission, one might observe some changes in pulse shape with distance. However, photographs of the received pulses do not show any appreciable changes in shape with location of the transmitter, provided that large metal objects such as ships, oil storage tanks, and buildings, were not in direct line of sight. As the transmitting distance was increased, the received signal decreased faster than the $1/R$ law for free space conditions would predict. Table II shows the peak pulse voltage e received at several distances, and the voltage e' predicted by $1/R$ dependence. The estimated radiated power was 10^6 watts peak and the voltages were measured on a 50 ohm terminated cable.

At 23 kilometers, about $1/3$ the expected voltage was received. The transmitting antenna was raised and lowered in each of the locations, and there was no noticeable effect either on pulse shape or amplitude. When $e = 0.05$ volt, the signal shape was slightly modulated with atmospheric noise,

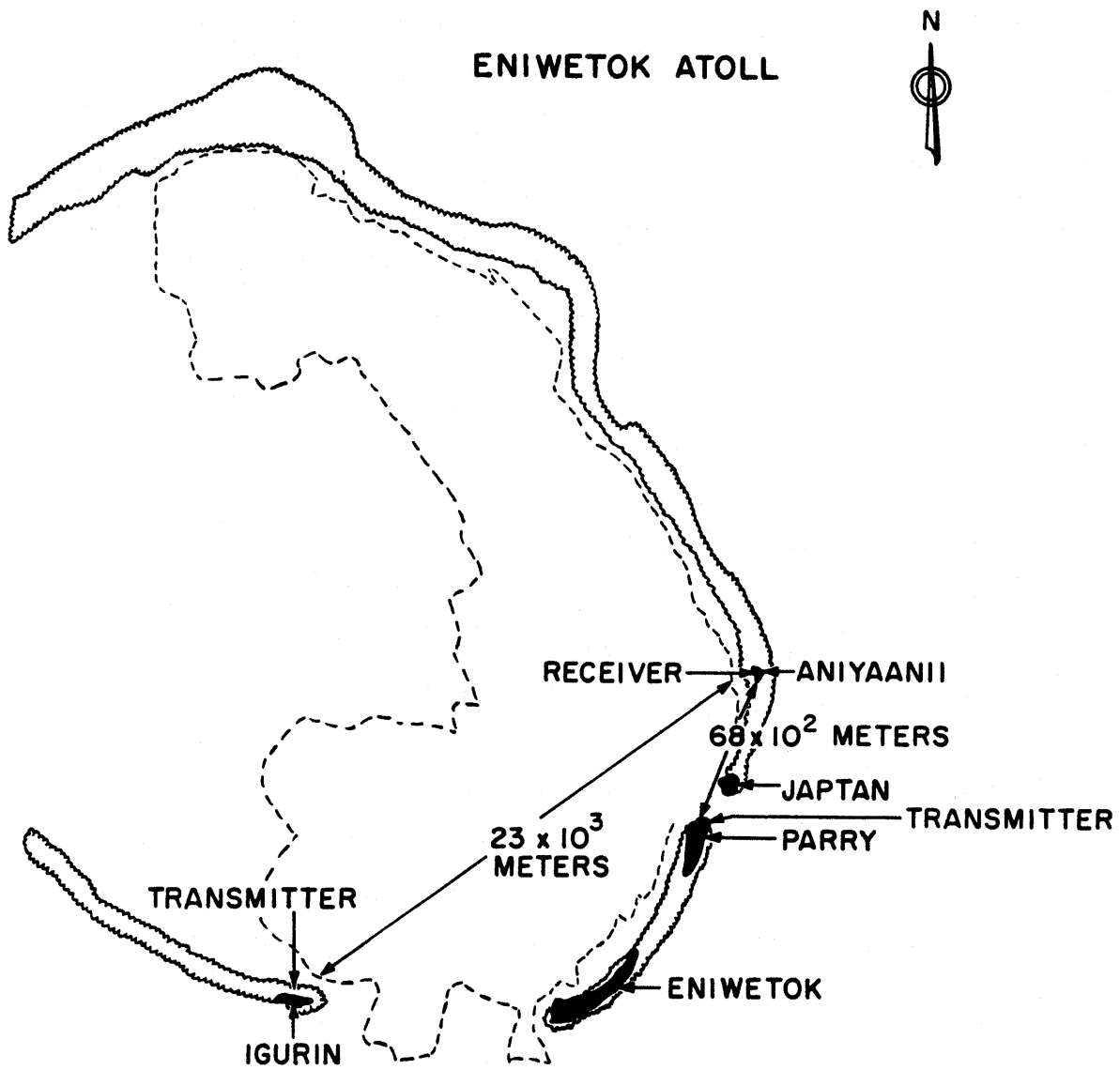


Fig. 15 Impulse transmission paths at Eniwetok Atoll.

TABLE II
RECEIVED AND PREDICTED PEAK VOLTAGES
WITH 10^6 WATTS PEAK RADIATED POWER

Transmitter Location	Distance to Receiver, meters	Peak Volts Received (e)	Predicted Volts (e')	$\frac{e}{e'}$
Local	34	100	100	1.0
Parry	68×10^2	0.3	0.5	3/5
Igurin	23×10^3	0.05	0.15	1/3

as expected, but was useable. We thought that at 32 kilometers (about 20 miles) we would have been able to detect the pulse; however, noise modulation would have been a definite problem.

E. Estimate of Antenna Bandpass Parameters

The disccone antenna does not have, probably because of phase dispersion, a very wide frequency range in terms of the requirements for pulse transmission. In order to give some interpretation to the experimental results in a simple manner, we will compare the data with the transient response of the idealized bandpass filter. In the appendix it is shown that a filter subjected to an impulse voltage $e_1(t)$ has a response $e_2(t)$ given by

$$e_2(t) = \frac{Ga}{\pi} \Delta\omega \cos \omega_0 \tau \frac{\sin \Phi}{\Phi} \quad (11)$$

where

$$\Phi = \frac{\Delta\omega}{2} \tau$$

$$\Delta\omega = \text{filter bandwidth} = \omega_2 - \omega_1 = 2\pi(f_2 - f_1) = 2\pi\Delta f$$

$$f_2 = \text{upper frequency cutoff in cps}$$

f_1 = lower frequency cutoff in cps

$\tau = t - t_d$, sec

t = time variable in sec

t_d = filter delay in sec

$$\omega_0 = 2\pi(\text{center frequency}) = \frac{\omega_2 + \omega_1}{2}$$

G and a are constants of the impulse and filter spectrums, respectively.

Plots of Eq. 11 are made with τ as the relative time variable because t_d is left unspecified. It is seen that the filter oscillates with a frequency f_0 with an amplitude proportional to $\Delta\omega$, and with a damping factor $\sin \Phi/\Phi$. A very narrow band filter has a relatively small amplitude response to an impulse voltage and will oscillate many cycles. In order to demonstrate the effect of bandwidth, Eq. 11 has been plotted in Fig. 16 for three cases; namely, $Q = 1/2, 1$ and 2 , where

$$Q = \frac{f_0}{\Delta f} = \frac{\omega_0}{\Delta\omega}$$

A constant ω_0 is assumed and the abscissa is $\omega_0 \tau$ radians. Although the relative amplitude for $Q = 1/2$ is four times larger than the amplitude for $Q = 2$, we have shown them the same size in order to emphasize the waveshapes. A value of $Q = 1/2$, indicates a low pass filter, capable of passing zero frequencies ($\omega_1 = 0$), a situation obviously impossible with finite antenna size. The response for $Q = 2$ does not damp as quickly as experimentally observed. A compromise of $Q = 1$ has been fitted to the experimental transient, in Fig. 17, when $f_0 = 2 \times 10^7$ cps. Since $Q = 1$, $f_1 = 10^7$, $f_2 = 3 \times 10^7$, and $f = 2 \times 10^7$ cps.

A smaller disccone would have a higher resonant frequency, therefore a larger bandwidth, and a larger amplitude response. However, a smaller

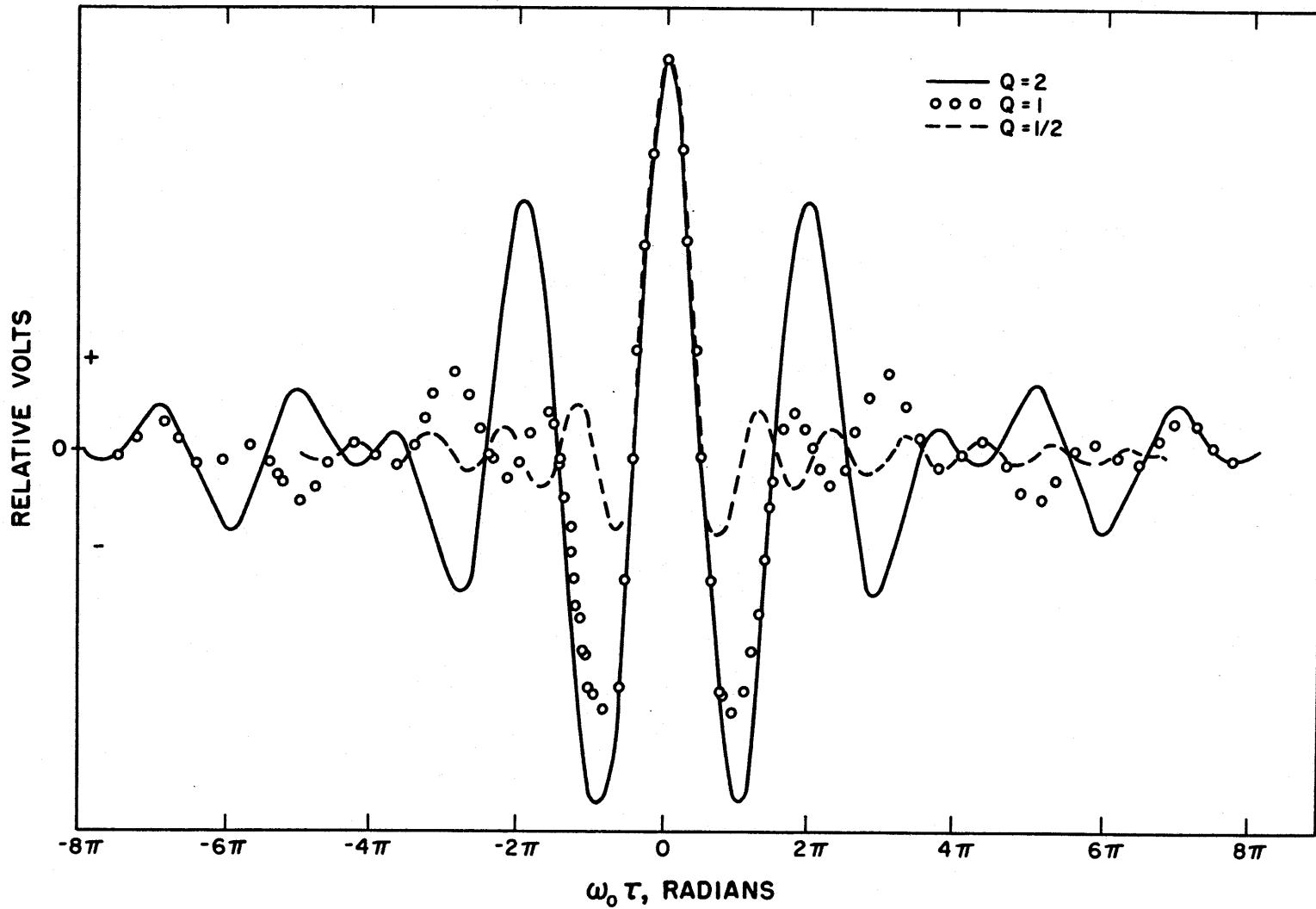


Fig. 16 Transient response of idealized filter.

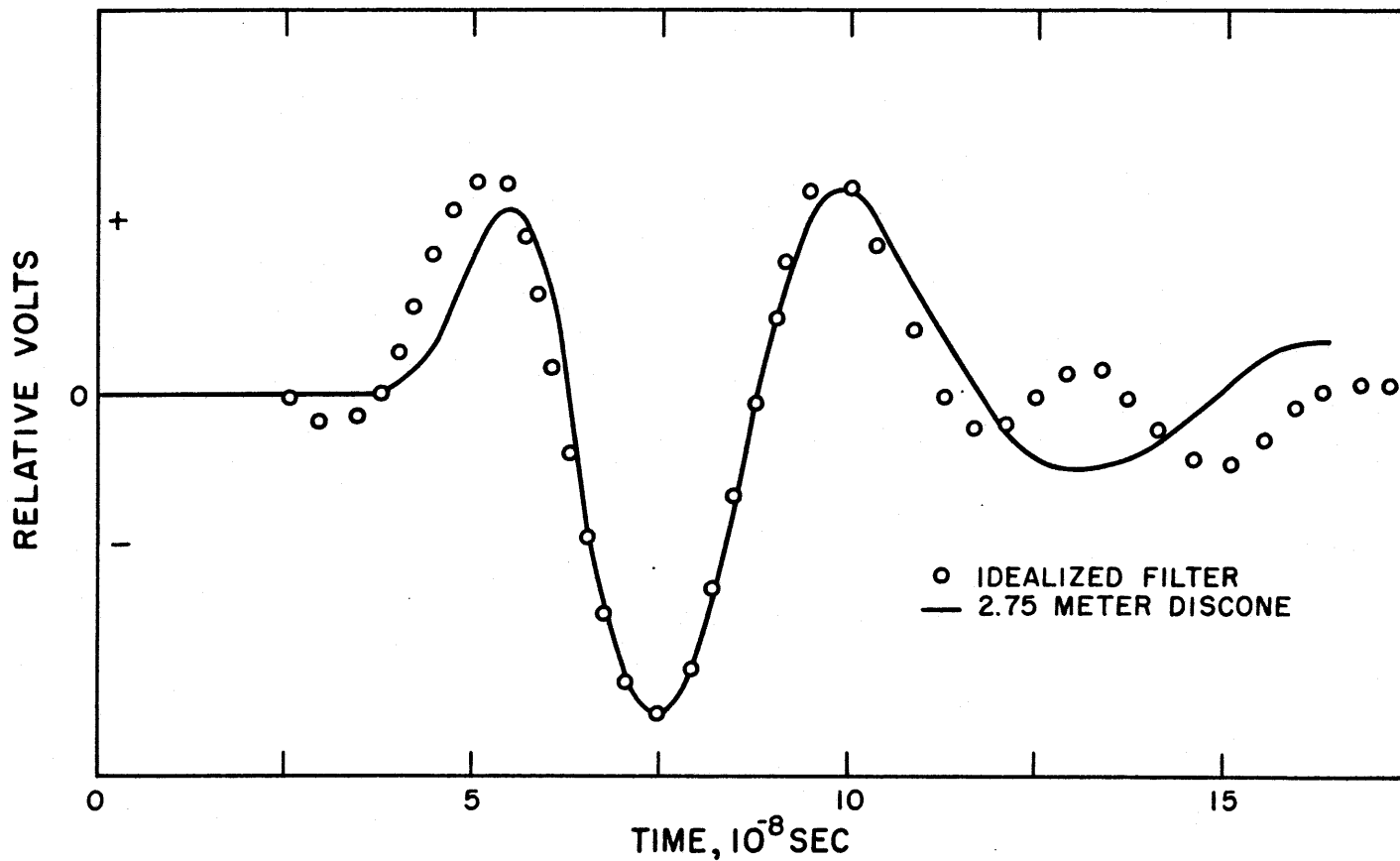


Fig. 17 Transient response of idealized filter ($Q = 1$) fitted to observed response of disccone antenna.

discone also has less cross-sectional area and therefore intercepts less power flow. To obtain the same voltage as received with the larger discone, a number of smaller discoses could be arranged in parallel with the signals adding in phase in a mixing amplifier circuit. For simplicity, however, a single antenna is desirable. It is not unusual that the experimenter must decide upon the best compromise.

V. CONCLUSIONS

Actual experience in transmitting impulses with discone antennas proved encouraging in several respects:

- A. The pulse is moderately damped and the arrival time could be determined within $\pm 2 \times 10^{-9}$ sec or better depending upon antenna and circuitry refinements.
- B. The pulse shape is relatively independent of distance and antenna location providing line of sight is provided between the transmitter and receiver.
- C. The coincident receiver technique was of major help in selecting the pulses from a background of radio signals.
- D. Transmissions up to 32 kilometers over sea water with relatively low antenna heights should be possible with only a small amount of development work.

Our curiosity has been stirred regarding the impulse response of other forms of "broadband" antennas, which we did not have time to investigate. Particularly interesting are those which might have better phase response and some directivity, such as the traveling wave types. These would include the broadband helix and the fishbone antenna.

Appendix

ESTIMATE OF ANTENNA BANDWIDTH

The transient performance of the discone antenna as measured (Figs. 13 and 14) can be compared with the response of an idealized bandpass filter, subjected to an impulse of voltage. Although we do not expect agreement in the details of the waveform, the general information, such as bandwidth and the center frequency (ω_0) is useful.

The amplitude and phase response of the idealized bandpass filter, as discussed in several textbooks,^{16, 20} are shown in Fig. A.1.

The band acceptance region is rectangular with edges specified by ω_1 and ω_2 , where $\omega = 2\pi f$ and f is the frequency in cps. Waves entering the filter will have their phase shifted by an amount $\Theta(\omega) = \omega t_d$, where t_d is the time delay of the filter. The transfer function for the filter, $A(\omega)$, expressed in polar form is

$$A(\omega) = a(\omega) e^{-j\Theta(\omega)}$$

Within the bandpass region

$$A(\omega) = a e^{-j\omega t_d} \quad \begin{array}{l} \omega_1 < \omega < \omega_2 \\ -\omega_1 < -\omega < -\omega_2 \end{array}$$

and outside the bandpass region

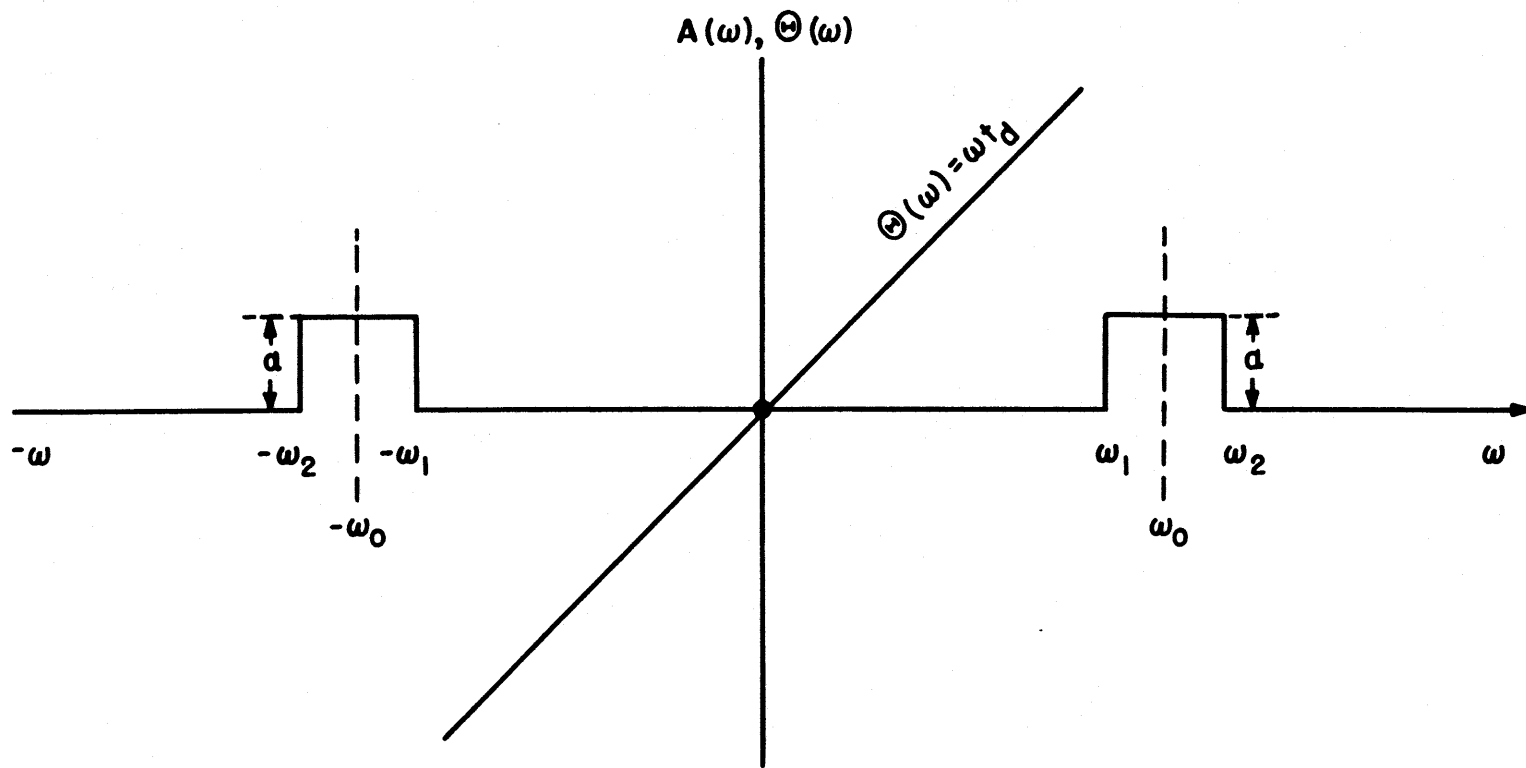


Fig. A.1 Amplitude and phase response of idealized bandpass filter.

$$A(\omega) = 0$$

The voltage response of the filter $e_2(t)$ to a wave form $e_1(t)$ is

$$e_2(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} A(\omega) g_1(\omega) e^{j\omega t} d\omega$$

where

$$g_1(\omega) = \int_{-\infty}^{+\infty} e_1(t) e^{-j\omega t} dt$$

If $e_1(t)$ is a unit impulse function, then $g_1(\omega) = 1$. In actual measurements one tries to make $g_1(\omega)$ a slowly varying function over the range of frequencies accepted by the filter. Let $g_1(\omega) = G$. Then

$$e_2(t) = (G) \frac{1}{2\pi} \int_{-\infty}^{+\infty} A(\omega) e^{j\omega t} d\omega$$

For the idealized filter above

$$e_2(t) = \frac{Ga}{2\pi} \left[\int_{-\omega_2}^{-\omega_1} e^{-j\omega t} e^{j\omega t} d\omega + \int_{\omega_1}^{\omega_2} e^{-j\omega t} e^{j\omega t} d\omega \right] \quad (\text{A.1})$$

The integration is made symmetrical about ω_0 by a change of variables. In the negative region let

$$\omega = \omega' - \omega_0$$

and in the positive region, let

$$\omega = \omega' + \omega_0, \quad d\omega = d\omega'$$

where

$$\omega_0 = \frac{\omega_1 + \omega_2}{2}$$

We define the filter bandwidth as $\Delta\omega$, where

$$\Delta\omega = \omega_2 - \omega_1$$

$$-\Delta\omega = -\omega_2 + \omega_1$$

Also if we let $\tau = t - t_d$, then Eq. 1 becomes

$$e_2(t) = \frac{Ga}{2\pi} \left[e^{-j\omega_0\tau} \int_{-\Delta\omega/2}^{+\Delta\omega/2} e^{-j\omega'\tau} d\omega' + e^{+j\omega_0\tau} \int_{-\Delta\omega/2}^{+\Delta\omega/2} e^{j\omega'\tau} d\omega' \right]$$

and finally, the transient response of the filter is

$$e_2(\tau) = \frac{Ga}{\pi} \Delta\omega \cos \omega_0\tau \frac{\sin (\Delta\omega/2) \tau}{(\Delta\omega/2) \tau}$$

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