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An Introduction to Impulse Radar

MERRILL I. SKOLNIK

Radar Division

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An impulse radar is one whose waveform is a single-cycle sinewave. Its most distinctive characteristic is its very wide relative-bandwidth. Much has been said and claimed for such a radar, as compared to conventional narrowband radar; but there is very little written about what it is, what it can and cannot do, and what is required to achieve such radars in practice. This report begins with a description of the spectrum of an impulse radar as compared to the more usual short-pulse radar. The requirements, problems, and current technology of the various subsystems that make up an impulse radar (transmitters, receivers, and antennas) are discussed. All three of these major subsystems for an impulse radar are presently far from adequate for practical applications (other than for probing underground). A number of problem areas are reviewed, including electromagnetic compatibility, target scattering, the radar equation, and the analysis of wideband signals. The relationship of impulse radar to Harmuth's nonsinusoidal radar is discussed and the differences noted. Several potential applications are briefly reviewed, including target-to-clutter enhancement, target recognition, resolution of low-altitude multipath, and target scattering enhancement, as well as its successful use for underground probing. Currently, the claims made for many of the proposed applications have not been justified, but the major differences between the impulse radar and conventional radar provide interesting technical challenges that would be worthy of fundamental investigation and understanding. (RH)

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AN INTRODUCTION TO IMPULSE RADAR

1. INTRODUCTION

An impulse radar is quite different from other radars in that its waveform is a single-cycle sinewave. Consequently, its spectral extent is much greater than the relatively narrow spectral width of conventional radar waveforms. A single-cycle sinewave has approximately 100 percent bandwidth, where percent bandwidth (also called relative bandwidth) is defined as 100 times the absolute bandwidth divided by the center frequency. This means that the spectral width of an impulse radar is approximately equal to its carrier frequency. Impulse radars resemble short-pulse radars, but the latter seldom have relative bandwidths greater than 5 or 10 percent. The extremely wide spectral width of the impulse radar is why it is of interest and is the reason its characteristics and operation are different from more conventional systems. Its unusually wide bandwidth offers interesting and difficult technical challenges to the radar systems engineer who is more accustomed to narrowband technology and concepts.*

The impulse radar dates back many years, at least to the early 1960s. The first published reference to this type of radar seems to be the 1960 paper by John C. Cook.[1] He proposed a single-cycle VHF radar for measuring the thickness of ice, detailing the contours of the rock underlying the polar ice caps, and for determining the extent and thickness of permafrost. Impulse radar was investigated in the early 60s by the U.S. Department of Defense as a possible method for detecting underground tunnels in Viet Nam. Later it was explored by those interested in remote sensing of natural underground formations, buried objects, and ice. Following this it was successfully applied commercially as a sensor for detecting buried utility cables, pipes, and other scatterers a few meters below the surface. Considerable investigation of the technology of high-power impulse radars was undertaken in the 1970s by Paul Van Etten and his colleagues at the U.S. Air Force Rome Air Development Center, Rome, N.Y. Van Etten's short 1977 paper on this subject summarizes what was done up to that time at RADC and provides references to previous work.[2]

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*A conventional radar might have a wide absolute bandwidth and still be narrowband in the relative sense. For example, a short-pulse X-band (10 GHz) radar with 500 MHz bandwidth (2 ns pulse width) is "narrowband" in that its bandwidth is small compared to the center frequency (5%). However, a 500 MHz bandwidth radar at UHF (500 MHz) has a wide relative bandwidth (100%).

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There are several reasons why impulse radar is of interest and is worthy of further investigation:

(1) Its single-cycle sinewave waveform makes it the ultimate short-pulse radar. It might be applied for those applications where short-pulse radars have been considered in the past.

(2) Its extremely wide bandwidth makes it of interest for target recognition, similar to those methods investigated by Ohio State University and others, which require larger relative bandwidth than usually found in radar.

(3) The impulse radar is well suited for studying transient scattering, where the pulse width is less than the target dimensions. (The commercial Time Domain Reflectometer is an example of the application of impulse radar concepts to low-power instrumentation.) A conventional radar observes scattering from a target as a steady-state phenomenon; but the very short duration of an impulse radar means that the waveform duration is less than the transit time across the target.

(4) If for no other reason, the impulse radar would be worthy of investigation and understanding because of its widely accepted use as a tool for underground probing. Improvements to an important existing application are always welcome.

(5) There have been claims made for potential applications that are not available with conventional narrowband radar, but at present these are mostly unsubstantiated. Some of these more interesting claims should be verified.

(6) Finally, much of the interest in impulse radar is that it represents a challenge. It has not been fully explored and it requires innovative technology not found in other types of radars. There is always the hope that with better understanding of its capabilities and characteristics, it will yield new and important areas of application.

Except for underground probing, there has not been much published about impulse radar. The paper by Paul Van Etten has already been mentioned.[2] There was a review prepared as an independent research project by E.C. Kisenwether, a Johns Hopkins University graduate student[3]. Unfortunately, neither of these references are readily available. The entire August 1988 issue of the IEE Proceedings, a UK publication, was devoted to the ground probing, or subsurface, radar.[4] The papers in this special issue describe the design and equipment for such radars as well as various applications. A recent Soviet publication[5] is on the subject of very wideband radar and covers many of the basic aspects of radiation, scattering, and reception for this type of signal. Much of the work on time-domain electromagnetics is applicable to impulse radar, and the collection of chapters edited by E.K. Miller is an excellent introduction to the subject.[6]

The present report attempts to provide an introduction to impulse radar and to review what is now known. It is hoped it can provide a basis for further exploration of radars with 100% bandwidth. Impulse radar is certainly not a closed subject. Its technology for applications other than underground probing is still primitive, and it cannot be said that its potential is completely understood.

After a brief review of the spectral characteristics of an impulse radar, this report reviews the available and proposed technology for impulse radar transmitters, antennas, and receivers. This is followed by a discussion of other considerations relating to impulse radar, such as the radar equation, target scattering, EMC, and its relation to the so-called "carrier-free" or "nonsinusoidal" radar of Prof. Henning Harmuth. Several applications, including underground probing, are described.

A "typical" simple impulse radar available with today's technology might employ a diode switch transmitter of quite low average power, have a pulse width of perhaps a fraction of a nanosecond, a peak power of about 10 kW, employ two separate low-gain (dipole or horn) antennas for transmit and receive, and use a sampling scope as the receiver. Such a radar might be used for underground probing or experimental laboratory investigations. Its range is relatively short as compared to more conventional radars. If the potential and the promises claimed for this type of radar prove worthy of application, the range capability has to be substantially increased and a better understanding is needed of how to design wide relative-bandwidth radars as well as increase the availability of components and subsystems not usually found in other radars.

Before proceeding, a comment needs to be made about the name of this radar. There are many examples in electrical engineering where the name given to a particular phenomenon or technique can be misleading. This is likewise true of the term impulse radar. The waveform radiated by such a radar is not really an "impulse" in the strict definition. According to the IEEE Standard Dictionary,[7] an impulse is "a waveform that, from the observer's frame of reference, approximates a Dirac delta function." An impulse has a dc component, but a dc component cannot be radiated into space. Many impulse radar transmitters, however, generate a high-voltage impulse in the correct sense of the definition. When such an impulse excites an antenna, the dc and low frequency components are removed so that the radiated waveform that results resembles a single cycle. The impulse radar waveform is more like what the IEEE Standard Dictionary calls a <u>doublet impulse</u>, which has equal positive and negative peaks. Originally a radar with a single-cycle waveform was called a monocycle radar.[1] This is a descriptive name for the type of radar which is the subject of this report, but it has not been widely accepted.

The term ultrawide band (UWB) has been used to describe an impulse radar. An impulse radar is an example of a UWB system, but there are other waveforms that are also UWB. Pulse compression or stepped frequency radar are examples of UWB radar when they utilize a large relative bandwidth.

2. SPECTRUM OF AN IMPULSE RADAR

The characteristic difference between an impulse radar and other "wideband" radars is found in its spectrum, which is the subject of this section.

A time waveform s(t) has a frequency spectrum S(f) given by its Fourier transform

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi ft}\, dt \qquad (1)$$

If the signal s(t) is a pulse of sinewave of frequency f_0 and duration τ, Eq. (1) becomes

$$S(f) = \int_{-\tau/2}^{\tau/2} \sin(2\pi f_0 t) e^{-j2\pi ft}\, dt \qquad (2)$$

$$= \frac{j}{2\pi} \left[\frac{\sin \pi(f_0+f)\tau}{(f_0+f)} - \frac{\sin \pi(f_0-f)\tau}{(f_0-f)} \right] \qquad (3)$$

When the duration of the pulse contains exactly N cycles, $\tau = N/f_0$ is substituted in Eq. 3 and the magnitude of the spectrum can be written

$$|S(f)| = \frac{1}{\pi f_o} \left| \frac{\sin N\pi f/f_o}{1 - (f/f_o)^2} \right| \qquad (4)$$

The first term of Eq. 3 represents negative frequencies and the second term represents positive frequencies. Equation 4, which is derived from Eq. 3, has no explicit negative frequencies. Equation 4 and the two terms of Eq. 3 are sketched in Fig. 1 (The negative of Eq. 3 is actually plotted since it is more usual to plot the positive frequencies with positive amplitude.) An impulse radar corresponds to N=1 (one cycle). When N=1 is substituted in Eq. 4, the magnitude of the spectrum of a single-cycle sinewave is

$$|S(f)| = \frac{1}{\pi f_o} \left| \frac{\sin (\pi f/f_o)}{1 - (f/f_o)^2} \right| \qquad (5)$$

This is shown plotted in Fig. 2 for τ = 0.1 ns, which corresponds to f_o = 10 GHz.

Figure 2 shows that the spectrum is quite wide, extending from 0 to beyond $2f_o$. The spectrum is not symmetrical about the carrier frequency f_o. It has a maximum at about $0.84f_o$. The asymmetry is due to the effect of the negative frequencies. Two examples of the spectra of single-cycle waveforms with different time durations are shown in Fig. 3. The single-cycle waveform on the left is 1.7 ns in duration so that its spectrum peaks at 500 MHz. Its carrier frequency f_o is actually 595 MHz. The one on the right has its spectrum maximum at 10 GHz, but its frequency is 11.9 GHz and its duration is 0.084 ns. Figure 3 shows that an impulse radar need not be of wide absolute bandwidth if the frequency is low.

The extremely wide bandwidth makes it difficult to generate and radiate a single-cycle waveform. In practice, the inability to achieve the required bandwidth might make the waveform extend for more than one cycle in duration. However, it cannot be "many" cycles in duration, else its bandwidth is no longer "extremely wide" and it becomes more like a short-pulse radar. Table 1 lists the number of cycles contained within the pulse of several experimental and operational radars. The number of cycles in the pulse is taken here to be the carrier frequency times the pulse width. (In the case of pulse compression, the width is that of the compressed pulse.) It is also interesting

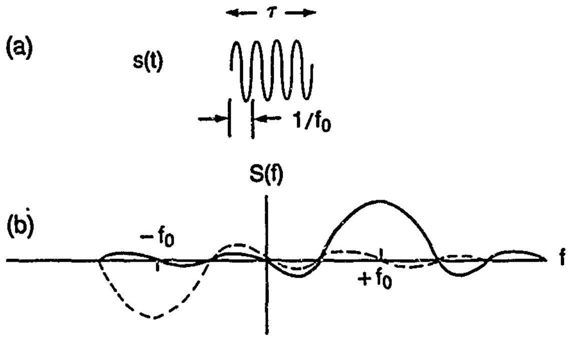
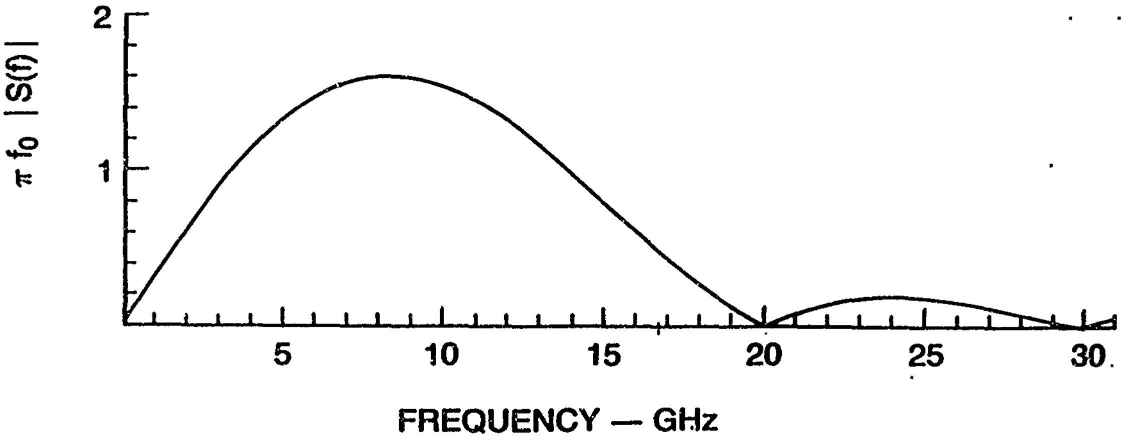


Fig. 2 — Spectrum of a single-cycle sinewave of 0.1 ns duration.



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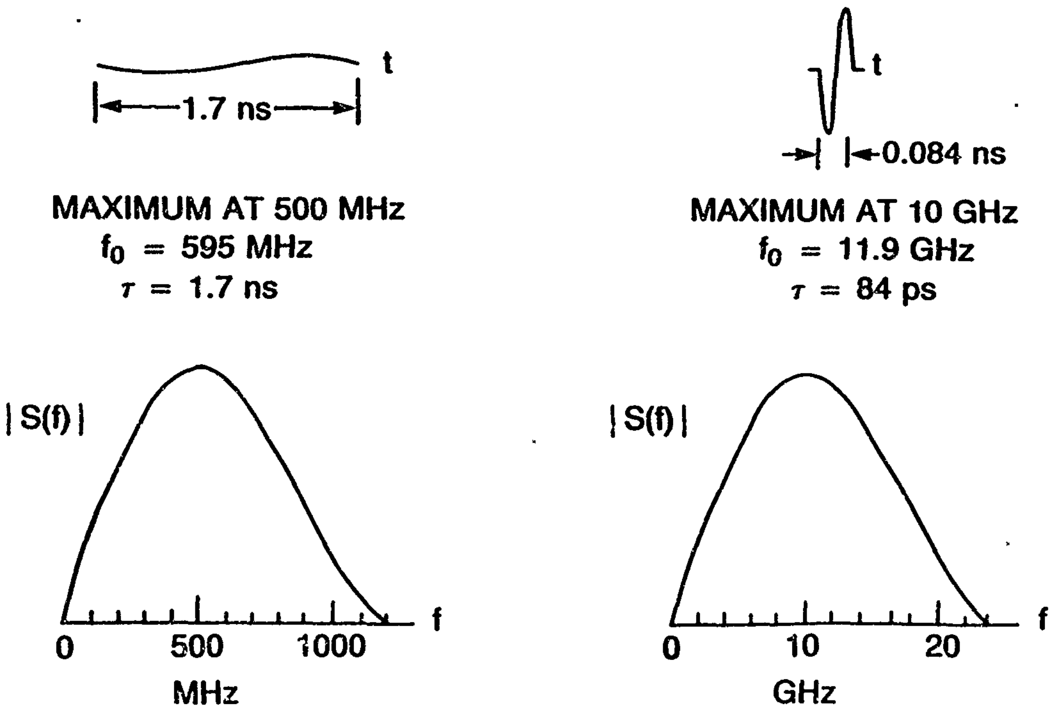


Fig. 3 — Comparison of single-cycle spectra of two different time durations.

TABLE 1

NUMBER OF CYCLES WITHIN A RADAR PULSE

RADAR	NO. OF CYCLES
L-BAND AIR-SURVEILLANCE RADAR (ARSR-3)	2600
C-BAND PRECISION TRACKER (AN/FPQ-6)	1400
X-BAND PERISCOPE DETECTION RADAR (AN/SPS-137)#	25
SHORT-PULSE LABORATORY RADARS (low power)	10
L-BAND ICBM INSTRUMENTATION RADAR (COBRA DANE)#	7
ULTRASHORT LIGHT PULSES (femtosecond)##	3-5
EXPERIMENTAL IMPULSE RADARS (low power)	1+ to 3
IDEAL IMPULSE RADAR	1

\# Pulse Compression
\## Not a radar, only a transmitter

to note in the table that pulse waveforms of only a few cycles have been achieved with lasers at optical frequencies.[8] It can be seen from this table that some short pulse and pulse compression radars have waveforms with less than ten cycles within the pulse. Thus, a radar should not be considered an impulse radar unless it has one, or perhaps two, cycles in its waveform. This also implies that it cannot be treated as a narrowband waveform, one whose bandwidth is small compared to the center frequency. Since many radar analyses assume a narrowband waveform, it should be cautioned that well-accepted analytical tools based on the narrowband assumption might not be applicable to the impulse radar.

The impulse radar can be thought of as the limiting case of a short-pulse waveform, but the extremely wide bandwidth of a single cycle makes it fundamentally different from a short pulse. Figure 4 compares the spectrum of a single cycle waveform with that of a two-cycle waveform and a short pulse consisting of ten cycles, shown on the same scale and with the same energy in the three waveforms. (At 10 GHz, a pulse one nanosecond in duration will contain ten cycles.) It is evident from the nature of the spectra in this figure that a radar with a single-cycle waveform can have different properties from that of a short-pulse radar with many cycles in its waveform. The relative bandwidth of a conventional radar, such as the FAA's ARSR-3 long-range air-traffic control radar, is only 0.04%. (Its tunable bandwidth, however, is 7.7%.) A short-pulse radar, such as the AN/APS-137 has a relative bandwidth of about 5%. Radar engineers have not usually worked with the extremely wide percentage bandwidths that characterize impulse radars.

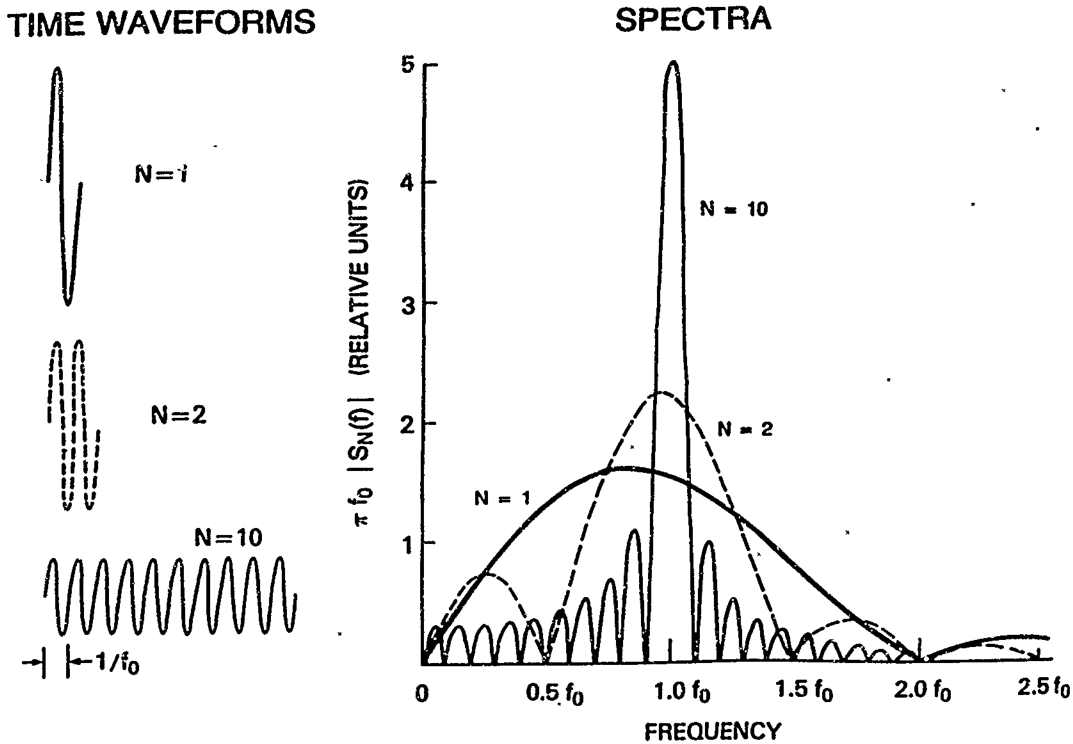


Fig. 4 — Snectra of a single-cycle waveform (dark solid line) compared with the spectrum of a two-cycle and ten-cycle waveform. Note that even with N = 10, the spectrum still shows asymmetry, indicating the effects of negative frequencies.

In the next three sections, the major subsystems of the impulse radar will be discussed to illustrate their differences from the subsystems of conventional radars.

3. TRANSMITTERS

Radar transmitters are characterized by their peak power and average power. The peak power of impulse radars must be much greater than that of ordinary radars in order to achieve the same energy on target. However, the average power and pulse energy of past experimental impulse radars have been much lower than usually found in conventional radars.

The average power or the energy are better measures of detection capability than is the peak power. The shorter the pulse, the greater must be the peak power in order to have the same energy. For example, if a one microsecond pulse has a peak power of one megawatt (this is a modest capability radar waveform, with one joule of energy), the peak power in a 0.1 nanosecond pulse with comparable energy must be 10 gigawatts (a very large value).

The classical impulse generator of Fig. 5 has been the method most often used in the past to generate the impulse. The switching device can be a diode, vacuum tube, laser-actuated semiconductor, or arc discharge. The charging impedance R_c is much larger than the load impedance R_L, and the voltage across the energy storage capacitor C builds up with time. Closing the switch allows the stored energy in the capacitor to discharge rapidly though the load. The duration of the discharge pulse is inversely proportional to the load impedance and the capacitance C.

The impulse from the generator of Fig. 5 is a video pulse. When it excites an antenna, the dc and low frequency components are removed (the antenna acts as a high-pass filter) and a waveform approximating the derivative of the pulse (which resembles a single cycle of a sinewave) is what is radiated. The efficiency of the impulse waveform can be increased by generating both a positive and a negative video pulse spaced in time so as to resemble a single-cycle waveform, without a dc component, which is then used as the waveform that excites the antenna.

<u>Diode Switch</u>: An example reported in the literature is a small, portable, battery-powered diode-actuated impulse generator for underground radar systems that is said to have a 1000 V peak amplitude pulse, 0.5 ns duration, and a spectrum from 100 MHz to 4 GHz (with ±4 dB variation).[9] The energy of the pulse, assuming a 50 ohm load, is only 10 microjoules and its average power is 0.25 mW even though its peak power is 20 kW. These values are far lower than those of conventional radars. Diode generators are suitable only for very short-range applications or as laboratory instrumentation radars.

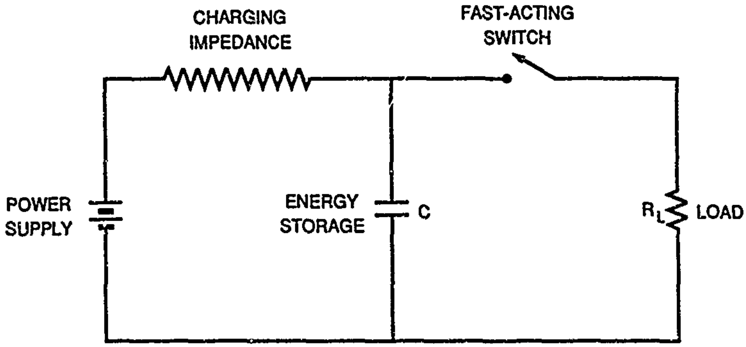


Fig. 5 — Schematic of the classical impulse generator

Laser-Actuated Semiconductor Switch. Short-pulse lasers can be used to rapidly change the impedance of photoconductive materials to provide a rapid-acting switch.[10] There has been little in the published literature from which to judge the full capabilities of this device for radar application. Both gallium arsenide and silicon have been used. The reported capability of actual devices seems to indicate current performance not much better than achieved with diode devices.[11] It has been claimed, however, that these switches can have significantly higher power than diodes and might be able to generate pulses with durations of less than a nanosecond with perhaps several hundreds of megawatts peak power. Much higher peak powers have been suggested by some proponents. The laser-actuated semiconductor switch requires more development before it can be said to be capable of delivering the high-energy short-duration pulses needed for most of the proposed impulse radar applications. The small size of an individual switch makes it unlikely that a single device can handle the large average powers (tens of kilowatts) required for high-power radar. Some form of power combining from many individual devices might be necessary. (An individual switch itself might be of small size, but a high average power transmitter might not be small.) Another problem associated with this device is the capability of the pulse laser that triggers the semiconductor switch. It needs to be of sufficient power and of short duration to produce the required switching action, and the total energy required to operate it must be accounted for when determining the overall efficiency of the power generation system. It is also necessary to operate the lasers at pulse repetition rates greater than usually employed with current lasers. The life of these switches (number of contacts before failure) is another performance factor that has not been adequately assessed.

Arc Discharge Switch. The arc discharge used as the switch in the impulse generator of Figure 5 is also known as a Hertzian generator. The pulse repetition rate is determined by the R_cC time constant in this figure. Van Etten[2] described several Hertzian generators developed by the Rome Air Development Center. He states that the best performance obtained with a simple unpressurized device with a 100 picosecond pulse width was 300 kilowatts (30 μJ). Pulse repetition rates can be 10 kHz. Pressurization can increase the power capabilities. A three-gap device operating under 85 psi pressure and an input voltage of 90 kV produced a one nanosecond pulse with 15 MW of peak power (15 mJ). RADC also obtained a 2 MW Hertzian generator with a 100 ps pulsewidth and 70 ps rise time. The pressure was 2000 psi. They stated that peak power of 100 to 200 MW might be obtained with the pressures increased to 20,000 psi. The pulse energies in the above examples are all less than the nominal one joule required of conventional air surveillance radars.

Arc discharge impulse generators also have operated with pulse repetition frequencies of several megahertz and pulsewidths of several nanoseconds or less.[12]

Conventional Devices. High-power wideband RF power generators, such as traveling-wave tubes, are usually not capable of the high peak powers required for impulse radars. Also, wideband tubes usually are not of sufficient bandwidth to achieve a single cycle of sinewave. However, it has been reported that a modified traveling-wave tube can generate "ultrashort pulses."[13] It was said that when a TWT is excited with a video pulse (of subnanosecond duration), the peak power of the generated radio waves is higher than that of the device with amplification of sinusoidal oscillations. Increasing the bandwidth of a helical slow-wave structure by replacing its central part by a drift space, further increases the peak power and decreases the pulse width.

High peak power, short duration (impulse) waveforms might be possible using relativistic RF devices, but there has been nothing reported.

Fourier Synthesis. It is well known that Fourier analysis allows a periodic waveform to be expressed as a summation of infinite-duration sine waves. Thus it might seem that it should be possible to generate a periodic train of short pulses by combining a large number of CW oscillators operating at harmonically related frequencies. Although it is easy to visualize this mathematically, it is difficult to combine CW oscillators simultaneously to obtain a periodic train of short pulses without loss. It is possible, however, to approximate the equivalent of a short pulse waveform by radiating each frequency component sequentially (pulse to pulse) and combining the received signals after the fact in a computer. (This is the basis for using a vector network analyzer to perform the equivalent of time-domain measurements.) This method of operation can be considered a form of pulse compression but is not what is usually considered to be an impulse radar. However, this pulse-to-pulse step-frequency approach has been used successfully in an impulse radar for underground exploration.[14] A question sometimes asked is whether the computer synthesis of the impulse waveform in this manner produces different results from what would be obtained if the short duration impulse waveform were radiated directly from the antenna. It has been amply demonstrated that the pulse-to-pulse step-frequency approach produces results similar to that of a short pulse occupying the same bandwidth.[15] It has also been shown by J.P. Hansen of the Naval Research Laboratory that similar results are obtained with both a single-cycle time waveform and a single-cycle waveform synthesized from a large number of (CW) sinewaves covering the same spectral extent.

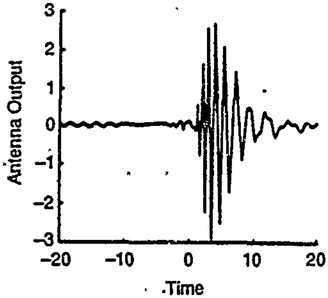
Antenna Pulse Compression. Wideband antennas such as the log periodic and the spiral are not suitable for impulse radars since their phase characteristics are not linear with frequency and therefore distortion can result. However, it is possible to excite the antenna with a waveform that will perform compression just as a matched filter will compress a long-duration waveform to a short pulse in a pulse compression radar. The dispersive properties of the antenna thus might be used to compress the generated waveform to approximate an impulse.[16] Another approach is to compress the impulse response of a dispersive antenna by employing a matched filter in the receiver, just as would be done in a pulse compression receiver. An example of this is in Figure 6, which shows the distorted signal radiated by a log-periodic antenna and its compression in time by a matched filter.[17,18]

4. RECEIVERS

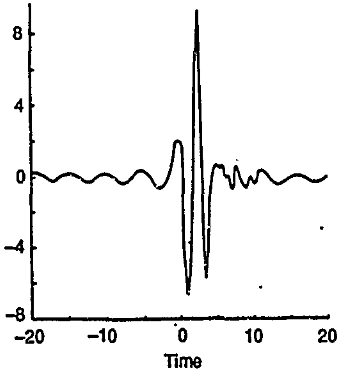
Suitable receivers, duplexers, and A/D converters for digital processing with the extremely wide bandwidth required for impulse radars are not generally available. The conventional superheterodyne receiver cannot be used with impulse radars since superheterodynes are inherently narrow band (in the relative sense). Sampling oscilloscopes have been employed as the receiver with most previous impulse radars. They are not appropriate, however, for many radar applications since they are inefficient (they do not use the full energy available in the received signal). However, they are well-suited for laboratory work or short-range applications where sensitivity is not a consideration. Commercial sampling oscilloscopes are readily available and serve the purpose for exploratory work.

An example of a sampling scope suitable for impulse radar is the Tektronix 11800 series of programmable digital sampling oscilloscopes. This is claimed to have a bandwidth of up to 20 GHz with a 1 ps timing resolution.[19] It is also capable of providing 68 multiple channels simultaneously. The Hypres PSP-1000 Picosecond signal processor is a sampling oscilloscope that uses superconducting Josephson junctions and a superconducting delay line to achieve a 70 GHz bandwidth (more than adequate for impulse radars), with a 5 ps rise time.[20]

Receivers for impulse radars will be more like extremely wideband video amplifiers. They might resemble the old TRF (tuned radio frequency) receivers or the distributed amplifier more than a superheterodyne. It is encouraging that wideband receivers have been developed for optical frequencies with the bandwidths needed for impulse radars.[21] Bandwidths up to 16 GHz have been reported, but they are operated at optical frequencies as direct detection receivers so that their sensitivity is less than what radar engineers have been accustomed to with microwave superheterodyne receivers.



(a)



(b)

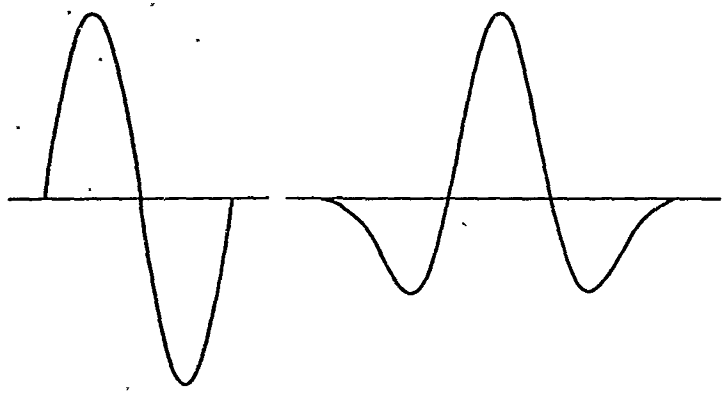
Fig. 6 — (a) The distorted output of an "impulse" from a log-periodic antenna. (b) Matched filter compensation using both phase and amplitude corrections., (From Chadhuri and Chow,[11,12])

Radar engineers design their receivers to have a matched filter characteristic. A matched filter is defined as the filter which maximizes the output signal-to-noise ratio. The matched filter frequency response theoretically is the same as the transmitted-signal spectrum. The matched filter is equivalent mathematically to taking the cross correlation between the received signal and a replica of the transmitted signal. The implementation of this mathematical relation is called a correlation receiver. The correlation receiver has been used in at least one impulse radar as a more convenient implementation, for specific experimental purposes, than a very wideband matched filter.[22]

The lack of suitable receivers for impulse radar initially, at least, should not impede progress in the exploration of impulse radar technology and applications. Many things can be demonstrated with the sampling oscilloscope as the receiver. When there are no other serious drawbacks to achieving the technology required for high-performance impulse radars and when it has been demonstrated that there are useful applications not achievable with more conventional radar, then serious effort can be concentrated on achieving suitable impulse radar receivers.

As mentioned, the radar designer employs the matched filter to maximize the output signal-to-noise ratio of the radar receiver. The waveform out of the matched filter is not the same as the input waveform. When the signal-to-noise ratio is high, the output waveform is the autocorrelation function of the transmitted signal. Figure 7a shows the output of the matched filter when the input is a single cycle of sinewave. The output is seen to be different from the input. The output (autocorrelation function) when the input is a two-cycle sinewave is shown in Figure 7b. This has to be kept in mind when judging the quality of a transmitter waveform based on observing it at the output of a receiver. The matched filter changes the waveform. If the output must be the same shape as the input, the receiver (including the transmitting and receiving antennas as well as the transmission lines) must have a uniform frequency response. Such a receiver is theoretically less sensitive than the matched filter.

The output waveforms in Figure 7 assume a point scatterer, one which reflects the same waveform as that which is incident. Practical targets of interest are complex with many independent scatterers. Thus the received waveform might be thought of as a summation of echoes from each "point" scatterer (when the target can be modeled as a collection of independent point scatterers). The interpretation of the output of a matched filter when the target is complex and with a waveform whose duration is short compared to the transit time across the target, requires the output of the matched filter to be deconvolved.



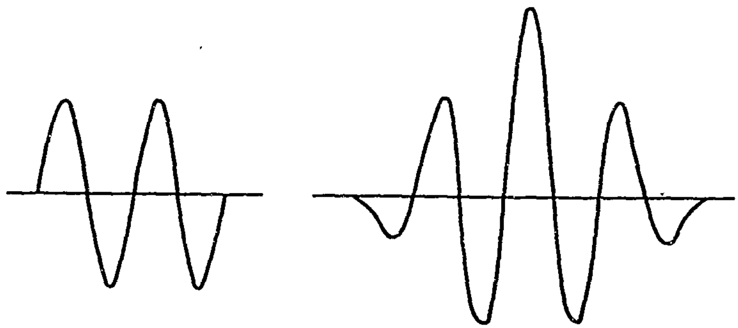


Fig. 7 — (a) Input and output of a matched filter for a single-cycle waveform. (b) Same for a two-cycle waveform.

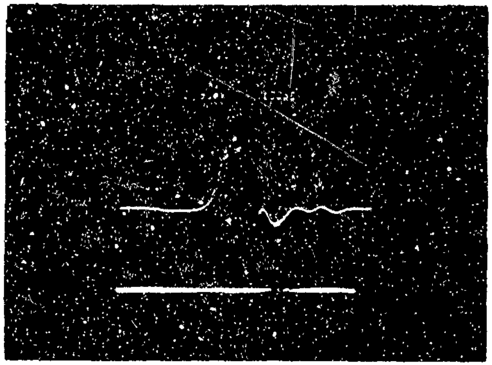
Figure 8 shows the waveforms obtained by an impulse radar built by J.P. Hansen of the NRL Radar Division. The figure on the left is the output of the transmitter (a diode impulse generator) as measured in the transmission line before radiation. The received waveform is on the right and it includes the distortion introduced by the transmit and receive antennas, both of which were short axial length broadband horns. When compared to the ideal waveform of Fig. 7, these are quite good for an inexpensive laboratory implementation. (The measured waveform of Fig. 8 is even closer to theoretical expectations when the antenna characteristics are taken into account, as described in the next section.)

The radar designer normally assumes that the target introduces little or no distortion of the incident signal on reflection. Thus conventional matched filter design assumes the received signal is the same as that which is transmitted, except for the added receiver noise. The shape of the input signal received by an impulse radar from a complex, distributed target will depend on the nature of the target. Each target produces a different echo signal. Also, the duration and composition of an echo signal received by an impulse radar will vary with the viewing aspect. Unless one knows the shape of the target and the viewing aspect, the impulse radar matched filter (if one is used) has to be designed on the basis of the transmitted signal rather than the actual echo signal which can be quite different.

Many of the suggested attributes of an impulse radar can be obtained by a conventional short-pulse radar of the same pulse duration but with many cycles within the pulse. The single-cycle of the impulse radar, however, can observe transient effects that would be missed by a conventional short-pulse radar of many cycles. Figure 9 shows the effect of a receiver whose bandwidth is matched to the transmitted waveform. A single pulse of sinewave with a number of cycles is shown in (a). The output, after passing through a matched filter, is shown in (b). Note the finite buildup time. If the receiver is to detect transient effects it must see what is happening during the first cycle. This is not possible in Fig. 9b with the matched filter. To see the first cycle, the bandwidth of the receiver must be large compared to the reciprocal of the pulse width τ, as in Fig. 9a, and it must be uniform over the spectral width of the input signal. If the usual radar condition is met that the product of the bandwidth and the pulsewidth τ is approximately unity, the pulse will build up over a time τ, and information in the leading edge will be lost. Therefore, when the impulse radar is to be used for observing transient effects, the frequency response should be flat over the spectral width of the impulse--something not easy to do.

5. ANTENNAS

The antenna of an impulse radar, just as the transmitter and



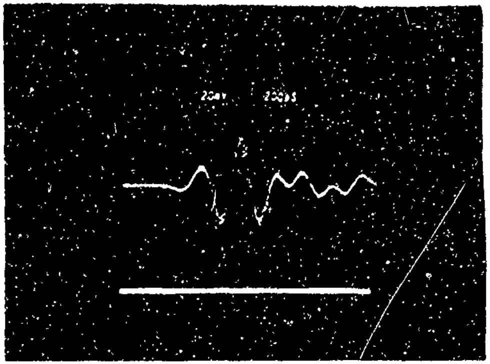


Fig. 8 — On the left is the measured waveform in the *transmission line* of *J. P. Hansen's impulse* radar. On the right is the waveform measured in the receiver. (From J. P. Hansen, Naval Research Laboratory).

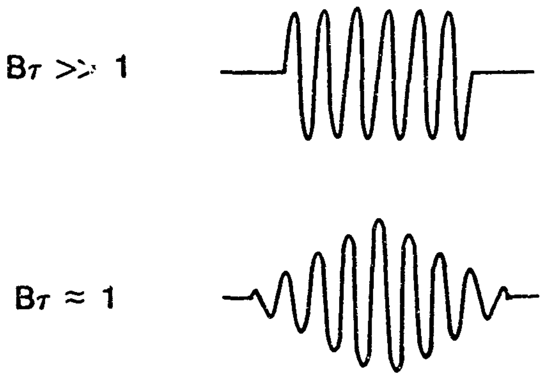


Fig. 9 — Effect of band limiting on the rise time of a sinewave pulse

receiver, is quite demanding and different from what is commonly used in a conventional broadband radar. Consider the simple radar equation

$$R^4_{max} = \frac{P_t G A_e \sigma}{(4\pi)^2 S_{min}} \qquad (6)$$

where R_{max} is the maximum range, P_t is the transmitter peak power, G is the gain of the transmit antenna, A_e is the effective aperture of the receiving antenna, σ is the target cross section, and S_{min} is the minimum detectable signal. The antenna explicitly enters in the product GA_e. Most conventional radars employ a single antenna for both transmit and receive. However, the transmit gain and receive effective aperture of an antenna are related by

$$G = 4\pi A_e/\lambda^2 \qquad (7)$$

where λ is the radar wavelength. Therefore

$$GA_e = G^2\lambda^2/4\pi = 4\pi A_e^2/\lambda^2 \qquad (8)$$

If a single antenna is used for both transmit and receive, the product of GA_e in the radar equation is not independent of frequency unless the gain varies linearly with frequency, which is equivalent to the effective aperture varying inversely with frequency.

A constant gain-aperture product can be obtained with two separate antennas, one for transmit and the other for receive. The transmit antenna should have its gain independent of frequency and the receive antenna should have an effective aperture independent of frequency (or vice-versa). A reflector antenna has a constant effective aperture (which does not vary with frequency if the feed for the antenna has a gain independent of frequency) and so might be used for the receiving antenna. The log periodic and the spiral antennas also have a gain independent of frequency, but they have poor phase characteristics and distort the signal transmitted by an impulse radar, as was illustrated in Fig. 6 for the log periodic antenna. As mentioned previously, it is possible, in theory, to transmit a phase-compensated signal that will be radiated from the antenna as an impulse; but the compensated (compressed) waveform will likely have time sidelobes. Also, it might not be easy to provide the necessary compensation in the transmitter. The biconical antenna and its variants have a gain independent of frequency and have been used for transmitting narrow pulses[23], but it is a low gain, omnidirectional antenna and is not suitable for most radar applications.

The TEM horn[24,25] is a wideband antenna with characteristics that make it more suitable than other conventional antennas for impulse radar application. It has been the antenna sometimes used for laboratory impulse radars. Unfortunately, there seems to be little published about the details and properties of these antennas. It is similar to other horn antennas, except that it has open sides (on the narrow wall). One can speculate that the open sides result in an effective aperture area that decreases with increasing frequency since one dimension (the E-plane) of the horn is fixed while the effective dimension of the H-plane appears to decrease with increasing frequency. This speculation, if correct, would make the gain-aperture product a constant.

A variant of the TEM horn is the short axial length horn.[26,27] This resembles the TEM horn in that it has open sides, but the short axial length horn is loaded with a double ridge that results in the gain being independent of frequency. Bandwidths approaching 18:1 have been claimed. These horns are commercially available from more than one supplier. The twin Alpine horn[28] is also similar to the short axial horn.

Thus there are at least three approaches to making GA_e independent of frequency: (1) one antenna can be of constant gain (such as a short axial horn) and the other can be of constant aperture (a reflector fed by a short axial horn); (2) an antenna such as the TEM horn that has a gain proportional to frequency and an aperture area inversely proportional to frequency, or (3) any other antenna combination which has its GA_e product a constant (no examples currently are known to the writer other than the TEM horn). In addition, antennas can be used with phase and amplitude compensation in either the transmitter or receiver (or both) to compensate for changes in the gain-aperture product as a function of frequency.

Antennas such as the TEM horn, the biconical antenna, and the log-periodic antenna are of low gain. Radar antennas, however, need to be of high gain. (An exception is the ground-probing impulse radar that uses crossed dipoles as the antenna.) The lack of high gain-aperture-product antennas is another factor that impedes the development of high-performance (long range) impulse radars. Low-gain antennas can be combined as a phased array to result in high gain. Phased arrays, however, generally have poor sidelobes when operated over wide bandwidth. The dispersive nature of the phased array that "distorts" the spatial characteristics of a broadband radar signal can, in principle, be used to advantage with impulse radar. At broadside, the signals from each radiating element add coherently, just as with any phased array. The sidelobe radiation, however, is quite different. The radiated signals in a direction off broadside are not coincident in time. Thus the waveform radiated is a function of angle. Clifford Temes of the NRL Search Radar Branch has suggested that it should be possible to determine the direction to the target from an examination of the detailed structure of the echo signal received by a phased array antenna or interferometer.[29]

Even if an antenna (other than a phased array) could be obtained with a constant and large gain-aperture product, there is another complication which arises in impulse radar that is different from narrowband radars. The transmit and receive beamwidths might be different (and differ in the orthogonal planes in each antenna) and the two-way beamwidth will not be constant with frequency so that the number of hits received and the nature of the echo signal will depend on the frequency even if the target cross section is independent of frequency. In a wideband impulse radar, therefore, the pulse train received as the antenna scans by a target will be quite different from that of the familiar narrowband radar. Only on boresight will targets be illuminated uniformly over the full frequency range. As will be illustrated below for a dipole antenna, the echo signal returned from a target illuminated by an impulse radar will depend on the angle of the target off boresight. (This might be used to provide the angle of the target without the need to scan the antenna.)

Before leaving the subject of antennas, there are some results to mention regarding the impulse response of a dipole. Theoretically, the radiated signal from a short dipole is the derivative of the input waveform. Thus when the input is a dc impulse the radiated waveform is like a doublet impulse and resembles a single cycle. Short dipoles, however, are not used for radar because of their poor efficiency and impedance matching. The conventional half-wave dipole does not have the limitations of the short dipole but it is usually considered a narrowband antenna. It also has not been of major interest for impulse radars (except for ground-probing applications) since it is of low gain. However, its impulse response has been examined and helps explain the operation of an antenna when the input is an impulse.

A calculation was performed by S. Samaddar of the waveform radiated by a single-cycle input to a half-wave dipole.[30] The half-wave dipole is a good antenna for a long-duration sinewave, so the motivation here was to see how the dipole responded to a single cycle (or the first few cycles of a sinewave of many cycles). The dipole, of course, does not know how many cycles are in the waveform when the leading edge of the waveform is first incident from the transmission line.

Figure 10 is the plot of the electric field radiated from a half-wave dipole as a function of time when the input to the dipole is a single cycle. The angle θ is such that $\theta = 90$ degrees is broadside to the dipole and $\theta = 0$ degrees is in the direction of the dipole. The length of the dipole is $h = \lambda/2$. The time 2h/c, where c = velocity of propagation, corresponds to one wavelength, or the duration of a cycle. There are two interesting aspects of the radiated field: (1) the radiated waveform lasts for one and a half cycles when the impulse is only one cycle and (2) the times between zero crossing are not equal (the spacings are 0.65h/c, 0.85 h/c, 0.85 h/c and 0.65h/c) and they are not equal to the half wavelength (1.0 h/c) of the incident waveform. Note also that the shape of the radiated signal is a function of the angle θ.

This problem was solved analytically rather than numerically on a computer; hence, it was possible to determine what was happening physically. There were four terms to the radiated field. One represents the field radiated when the input signal is at the discontinuity formed by the junction of the transmission line to the dipole. In Fig. 10 this is the time from 0 to 0.5 h/c (a quarter wavelength). The second and third terms represent the signal radiated from the ends of the dipole, which occurs at 0.5 h/c. The fourth term arises when the signals reflected at the ends return to the discontinuity at the center, at a time h/c. The summation of these four components is what gives rise to the waveforms of Fig. 10. In this calculation there were no additional reflections (and radiations) at the junction of the dipole and the transmission line since it was assumed that there was a perfect match between transmission line and dipole antenna.

Figure 11 shows the extension of this analysis for a perfect sinewave of longer duration. It will be noted that after one cycle the waveform is that of a sinewave, and there is a half cycle of transient response after the termination of the waveform because of the transit time along the half-wave dipole. This type of behavior is seldom found in practical antennas because, as was shown in Fig. 9b, the bandwidth must be quite large in order to have a perfect sinewave rather than the build up and build down shown in the waveform in the lower part of that figure, which is more usually found in radar.

This type of analysis explains why resistivity loaded antennas, especially dipoles much longer than a half wavelength, have good transient response. The components radiated from the ends of the antenna are highly attenuated and have less effect than in the above example. It also indicates that an antenna with good transient response might be one like a V-dipole, but with a smooth transition at the transmission line so that the major discontinuity is at the end of the V, something like an exponentially tapered V, flared notch, or twin Alpine horn.[27]

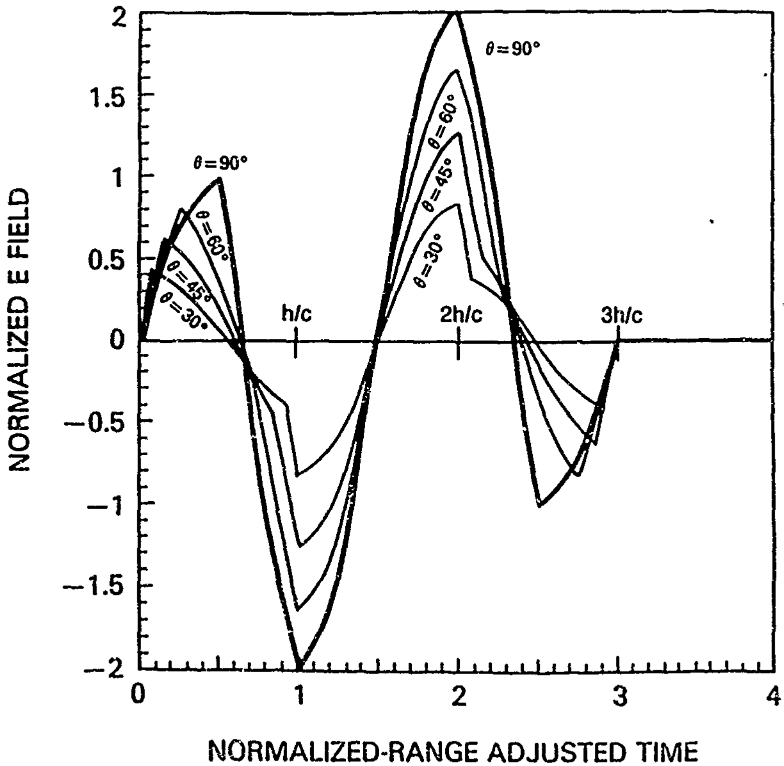


Fig. 10 — Calculated electric field as a function of time from a half-wave dipole when the input is a single cycle of duration 2 h/c, where h = length of dipole (half wavelength) and c = velocity of propagation. θ = angle measured from the plane of the dipole. (From S. N. Samaddar, Ref. 29).

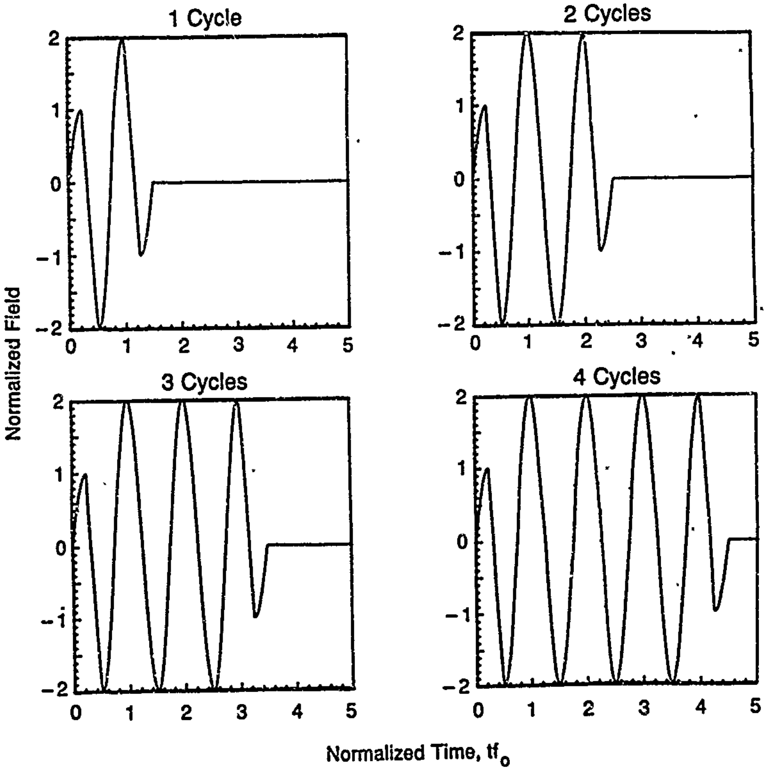


Fig. 11 — Calculated electric field as a function of time from a half-wave dipole for 1, 2, 3, and 4 cycles. Abscessa is normalized time tf_o, where t = time and f_0 = frequency of the sinewave. (From S. N. Samaddar).

The signal received in the far field by an identical, co-planar half-wave dipole when a single cycle excites the transmitting dipole was also calculated by Dr. Samaddar. The result is shown in Fig. 12. A single cycle when radiated by a half-wave dipole extends to a duration of one and a half cycles, as was shown in Fig. 10. On reception, the duration is further extended to two cycles. It is encouraging to note that the behavior shown in Fig. 12 is similar to the experimental impulse radar waveform measured by J. P. Hansen, shown in Fig. 8 (except it is inverted). Hansen, however, did not use half-wave dipoles. His antennas were (ridge-loaded) short axial length broadband horns, but it seems they behaved similar to what would be expected for half-wave dipoles.

The distance between zero crossings in Fig. 12 is not uniform (a normalized time of approximately 0.41, 0.365, 0.44, 0.365, 0.41) and is not the half wavelength spacing of the original sinewave. There are 2 1/2 cycles in a time equal to two cycles of the original signal frequency.

The calculated spectrum of the single-cycle sinewave is compared in Fig. 13 to the spectrum of the received signal (the waveform of Fig. 12). Note there is a frequency translation upward (by a factor of 1.4) due to the frequency response of the antenna. If the receiver were designed as a matched filter (one which maximizes the signal-to-noise ratio), it can be seen that the matched filter frequency response function (which is proportional to the complex conjugate of the signal spectrum) will be different from that designed on the basis of the single-cycle sinewave generated by the transmitter. Thus, the matched filter for the received signal should be centered at a higher frequency than that of a single-cycle sinewave.

6. REVIEW OF PROBLEM AREAS IN IMPULSE RADAR

The previous discussion of the subsystems required for impulse radar indicated that there were problem areas that need to be addressed before an impulse radar can be considered both practical and useful. These, and other technical challenges are summarized below:

Transmitter. The high-power transmitter technology needed to provide the large pulse energies (about one joule or more) for modest radar applications has yet to be demonstrated. The laser-actuated photoconductive switch is claimed to have promise of high peak power, but it is not yet a practical radar transmitter. Ten gigawatts with a 100 picosecond pulse width (which is one joule of energy) can be quite demanding. Some radar applications will require even more power (and pulse energy). Voltage breakdown is a concern with the high peak powers of impulse radar, as is the problem of dissipating the heat generated by the large average power. The life of such devices is also unknown. The laser that actuates the photoconductive switch can be a

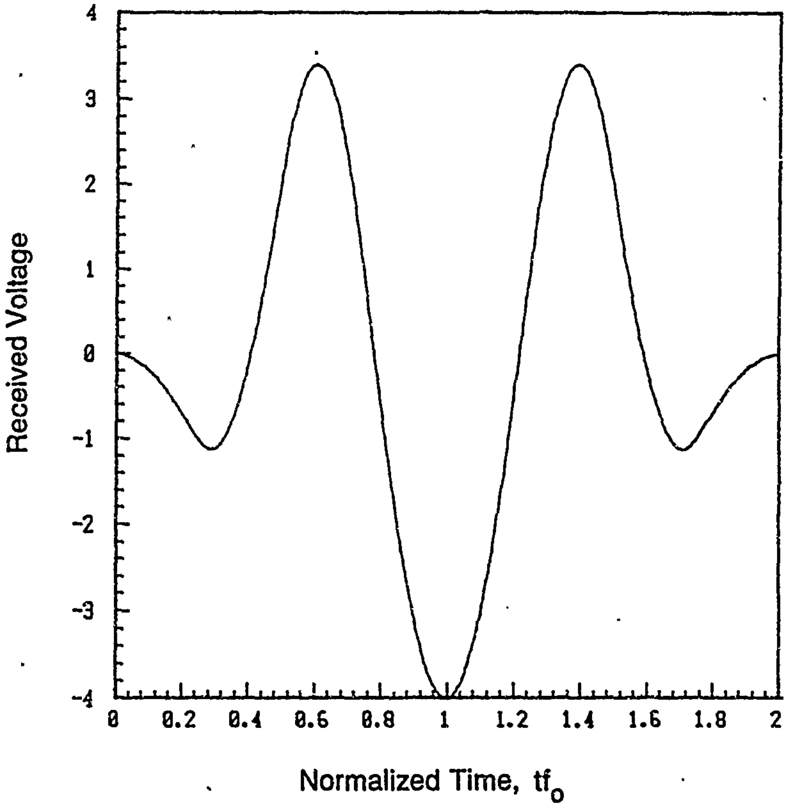


Fig. 12 — Waveform received by a half-wave dipole when a single cycle is transmitted. (From S. N. Samaddar)

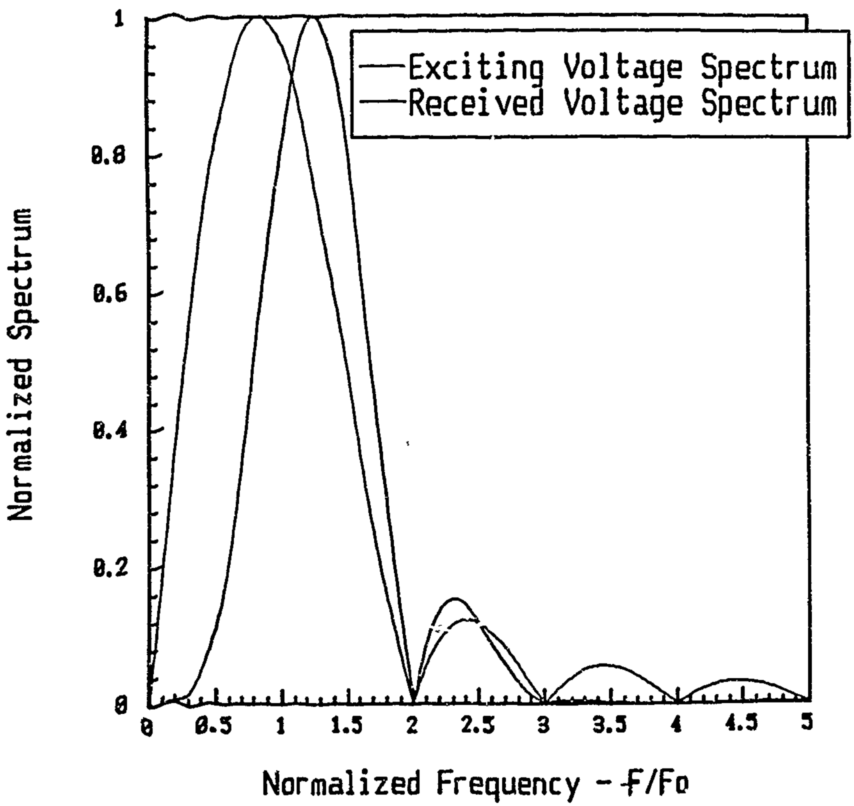


Fig. 13 — Spectrum of a single-cycle sinewave compared to the spectrum after transmission and reception by half-wave dipoles. (From S. N. Samaddar).

limitation and might require significant prime power to operate. It is not obvious at present that the laser-actuated photoconductive switch will be able to do the job required for many of the proposed impulse radar applications. More work needs to be done with this device before its capabilities and limitations are fully understood. It would also be prudent to investigate methods other than the laser-actuated switch for generating high-energy, short-duration impulses.

Receiver The very wide bandwidth receivers already employed for optical-frequency applications might be the initial approach to this problem. Large dynamic range over wide bandwidth can also be a challenge. Analog signal processing might have to be employed until very wideband A/D converters (sampling rates approaching 10 GHz) have a glimmer of reality.

Antenna. Antennas that have been used for impulse radars are of low gain (approximately 10 to 15 dB), but radar antennas have to be of high gain (typically 30 to 40 dB). There has been some progress in understanding the antenna, but much more progress needs to be made in achieving the high gain needed for radar applications. The characteristics of large phased arrays with ultrawide band signals should be better understood.

Transmission Lines and RF Components. Two of the major demands made of the transmission lines and other RF components are that they be of very broad bandwidth (as required for an impulse radar) and that they be capable of handling high peak power (gigawatts, or greater). Broad bandwidth (with no frequency dispersion) and high peak power tend to be difficult to achieve simultaneously. There are no obvious high-power transmission lines fully suited for impulse radar.

Duplexer. Separate antennas for transmit and receive can be used if a wideband duplexer is not available. Even with a large antenna separation, there may be problems, however, in preventing receiver burnout at the high peak power and pulse energy levels required for radar.

Electromagnetic Compatibility (EMC). EMC can be a severe problem. As can be seen from Fig. 2, an impulse radar receiver for a pulse width of 0.1 ns, for example, will be sensitive to all signals within the microwave portion of the spectrum (and to strong signals outside the microwave region). There is no inherent filtering to exclude unwanted signals as there is in radar receivers for conventional applications. Even if filtering is accomplished, there can be a serious dynamic range problem in attempting to handle all the unwanted signals that might be present within the receiver passband. The broadband energy radiated by an impulse radar will interfere with microwave receivers. Also, the signals from each of the impulse radars operating within this band will be similar. An impulse radar cannot discriminate between its own signal and that from other impulse radars by conventional selective filters. Frequency allocation as practiced with narrowband signals has no meaning with impulse radars, each of which occupies most of the available spectrum.

Current impulse radars used for underground probing are not limited by the above EMC problems since they are of low power and their energy is directed into the ground rather than radiated into space. Other applications of impulse radars, however, will have to confront the need for compatibility with other users of the electromagnetic spectrum.

There are some things that might be considered to relieve the EMC problem. Wideband interference to narrow-band receivers might be reduced by a Dicke-fix type of filtering. This is a well-known means for eliminating impulse interference by employing a wideband filter, followed by a hard limiter, which is followed by the conventional narrow-band matched filter. One difficulty with this approach is that some radars, such as MTI, degrade if preceded by a hard limiter. Interference from conventional narrow-band signals might be reduced by selective notch rejection-filters in the impulse radar receiver. This might cause some degradation in the received impulse signal if there are too many notches required. (Also it might not be easy to notch out all the signals that can be on the air simultaneously within the bandwidth of an impulse radar receiver). Recognition of one's own signal from all the other impulse radar signals might be attempted by pulse-width discrimination. Thus time-duration selection might be used rather than frequency filtering. This would require an impulse radar to have a different and precise pulse width in order to discriminate one signal from another. EMC can be a "show stopper", along with many other aspects of impulse radar; but there are at least some plausible places at which to start to address the problem.

Vulnerability to ECM. If EMC is a problem then so will deliberate countermeasures (ECM) be a problem to military impulse radars. A wide-open receiver covering the entire microwave frequency region can be subjected to severe jamming. Selective adaptive notch rejection-filtering would be necessary; but unless the filtering is done at RF, there might be a problem in overloading the receiver because the dynamic range could be exceeded with heavy jamming before filtering of the desired signals is accomplished. Spoofing with false signals can be accomplished with an impulse radar transmitter used as a jammer. One advantage of the impulse radar in ECM is that its high range resolution will reduce the effectiveness of chaff.

Clutter. As with chaff, the short duration of the impulse radar signal will reduce the effects of distributed clutter. A 0.1 ns impulse should see 40 dB less clutter than a radar with a 1.0 μs pulse width. Doppler filtering however, is not readily applicable to impulse radar. If greater clutter attenuation is required, area MTI would have to be used rather than conventional doppler MTI.[31] However, the echo characteristics (including statistical fluctuations) from land, sea, and weather clutter are likely to be quite different with impulse radar than with conventional radar. Thus the clutter characteristics as seen by impulse radar need to be better understood.

Target Scattering. The wide bandwidth of an impulse radar makes it difficult to compute the scattering from targets by standard methods since the solution to Maxwell's equations is generally carried out differently in different frequency regimes.

In conventional radar scattering analysis, the target is usually considered completely illuminated by a long-duration incident radar pulse. It is basically a narrow band (CW) approach. However, when a short-duration impulse is incident on a distributed target, reflection initially takes place from the forward edge of the target without any affect from other parts of the target. As the impulse travels over the distributed target, echoes will be obtained from any discontinuities in the target shape, including changes in slope and the discontinuity at the end of the target. Thus the echo signal reflected from a distributed target when illuminated by an impulse radar will be different from the echo reflected from a long (CW) pulse that illuminates the entire target.[32]

It might be said that impulse radar generates a "sequential" signature rather than a "simultaneous" signature as in a conventional narrow-band radar. The cross section "signature" of a target as seen by impulse radar will change with target aspect. In a narrow-band radar the change in cross section with angle is mainly a change in amplitude. With impulse radar, the time duration and nature of the cross section are aspect dependent. As indicated previously, this raises havoc with the concept of matched filter detection that is the basis for conventional radar design.

Fourier analysis allows the echo seen by an impulse radar to be calculated from the echoes received when the target is illuminated by a large number of CW or long-pulse frequencies that cover the same spectral range as that of the impulse waveform. This implies that whatever is found by an impulse radar can be duplicated by a radar that transmits sequentially many CW signals of different frequencies and combines the echo signals in a signal processor to synthesize the effect of an impulse (as prescribed by Fourier analysis). Arguments can be made for the equivalence of these two approaches.

Radar Equation. The usual radar equation is derived on the basis of a narrow-band (CW) signal. The radar equation is useful not only for predicting the range of a radar, but it also shows the relationship among the various parameters of a radar as required for purposes of design. One form of the radar equation is

$$R^4_{max} = \frac{P_{av} G A_e \sigma N_{eff}}{(4\pi)^2 k T_o F_n (B\tau) f_p (S/N)_{min}} \qquad (9)$$

where R_{max} = maximum range, P_{av} = average transmitter power, G = antenna gain, A_e = effective receiving aperture, σ = target cross section, n_{eff} = effective number of pulses integrated, kT_oF_n = receiver noise power per unit bandwidth, F_n = receiver noise figure, B = receiver bandwidth, τ = pulse width, f_p = pulse repetition frequency, and $(S/N)_{min}$ is the minimum detectable signal-to-noise ratio. In this equation the antenna parameters GA_e usually vary with frequency, as mentioned previously. The target cross section σ also can vary with frequency. If the impulse radar antenna were to scan past a target, the effective number of received pulses is different from that of a conventional radar since the two-way beamwidth of the antenna is frequency dependent (beamwidth = k λ/D, where k is a constant of the order of unity, λ = radar wavelength, and D = antenna dimension). Thus the usual forms of the radar equation need proper interpretation and/or modification in order to properly predict radar performance.

Wideband Analysis. It has been noted previously in this report, but worth repeating, that one must be cautious in using prior analysis methods and standard "rules of thumb" since they might not be applicable to the impulse radar with 100% bandwidth.

The use of Fourier analysis has been questioned when applied to impulse radar, although no one has shown that it is not applicable. For several reasons, doubts can arise in the application of Fourier analysis to real-world problems: (1) a finite time waveform has an infinite Fourier spectrum and vice versa; (2) negative frequencies are produced in the mathematics of the Fourier transform, and (3) there is not a good physical explanation for negative frequencies as being reality. One cannot buy a negative frequency generator, nor a generator of exp[j2πft]. A time waveform is a reality in that one can go to the laboratory and build a device to generate it. A spectrum, however, is a mathematical concept that cannot be similarly generated. (The spectrum measured by a spectrum analyzer is a derived quantity and is not "real" in the sense that the time waveform is real.)

It is known that pulse compression produces results similar to that of a short pulse. The successful use of pulse-to-pulse stepped frequency waveforms is an example of the application of the principles of Fourier analysis to synthesize the effect of a short-duration pulse, as long as the target does not change too much during the measurement interval. This technique has been applied to a ground probing radar with success, but it apparently has not been fully demonstrated for synthesizing a single cycle. If this principle is valid, then the behavior of an impulse (single cycle) can be determined by examining the behavior of a CW or long-pulse radar that is sequentially tuned over the same frequency band as the impulse radar. Thus for impulse radar to offer something unique that is not now known, it should be demonstrated that something different is obtained when all the frequencies are radiated simultaneously (as in an impulse radar) as compared to when the frequencies are radiated sequentially in time (as in a pulse-to-pulse stepped frequency radar).

Another issue concerning impulse radar analysis is the assertion of Prof. Henning Harmuth that Maxwell's equations, as used in the past, might not be valid for ultrawide band waveforms. Thus far there has been little concurrence by others that Maxwell's equations are invalid for impulse radar, and no one has yet suggested a definitive experiment to demonstrate that Maxwell's theory yields incorrect predictions.

7. RELATIONSHIP OF IMPULSE RADAR TO NONSINUSOIDAL RADAR

As has been noted, the impulse radar is of much wider bandwidth than conventional radars. The nonsinusoidal radar[33] as described by Prof. Henning Harmuth, is also of very wide band and has sometimes been considered a "cousin" to the impulse radar. There are significant differences, however. Nonsinusoidal radar has also been called carrier-free radar and baseband radar. An impulse radar, however, does not have to be a nonsinsoidal radar and it is inappropriate to call it a carrier-free radar.

Figure 14a shows (once again) a sketch of the waveform and spectrum of an impulse (single-cycle) radar. An example of a nonsinusoidal waveform is the rectangular signal. Figure 14b shows a single rectangular pulse and its spectrum. This waveform cannot radiate, however, since it has a dc component. Figure 14c is a modification of the rectangular pulse that has no dc component so that it can in theory be radiated from an antenna. The waveform of Fig. 14c has sometimes been used by Prof. Harmuth as an example of a nonsinusoidal waveform.

The property of a radar waveform that characterizes its ability to resolve echoes is its effective bandwidth[34] as defined by

$$\beta^2 = \frac{(2\pi)^2 \int_{-\infty}^{\infty} f^2 |S(f)|^2 df}{\int_{-\infty}^{\infty} |S(f)|^2 df} \qquad (10)$$

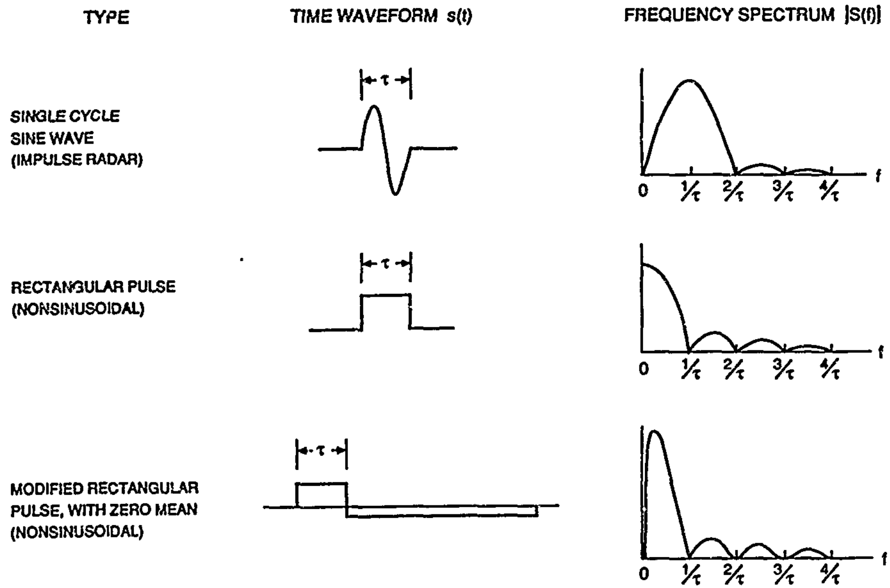


Fig. 14 — Waveform and spectrum of an impulse (single cycle), a single rectangular pulse, and a "rectangular" pulse without a dc component

where S(f) is the spectrum of the signal. The ability of a conventional radar or a radar with a nonsinusoidal waveform to perform such radar functions as the resolution of two targets, the recognition of one target from another based on the measurement of the range profile, the separation of a low-altitude target echo from its image reflected from the ground, the ineffectiveness of absorbers, and several of the other claims sometimes made for nonsinusoidal radar are all determined by the effective bandwidth. It is therefore S(f) that determines the resolution properties of a radar. In practice, the spectral bandwidth available to the radar designer will be limited by nature or by legal agreements. Thus there is no special attribute of nonsinusoidal radar that makes it different from other waveforms that have similar spectra.

The chief characteristic of the nonsinusoidal waveform that gives rise to many of the claims made for it, is the rapid rise time of the rectangular pulse. In theoretical analyses, the rise time is often taken to be zero. A zero rise time, however, is not realizable since it requires infinite bandwidth. Bandwidth is an important commodity in radar. Hence, a nonsinusoidal radar that has an infinite bandwidth can do a lot of things -- on paper. In practice, a nonsinusoidal radar has to be of finite bandwidth. A conventional radar waveform of the same bandwidth as the nonsinusoidal waveform should be able to do whatever it is claimed a nonsinusoidal waveform can do.

An ideal impulse radar radiates a sinewave, not a nonsinusoidal waveform. The term carrier-free sometimes used to describe Prof. Harmuth's radar, is of little significance in radar engineering. A carrier is a concept more appropriate for communications than for radar. Therefore, as mentioned previously, the impulse radar need not be a nonsinusoidal radar nor a carrier-free radar, but usually is a sinusoidal waveform radar (unless distorted unintentionally by the limited bandwidth of the radar).

In addition to the terms nonsinusoidal and carrier-free, Prof. Harmuth and his colleagues have sometimes referred to this type of radar as large relative bandwidth radar.[35] It does have a large relative bandwidth, but as indicated in this report there can be other waveforms with large relative bandwidth that can provide capabilities not available with conventional narrow-band signals.

As far as is known to the writer, Prof. Harmuth has never published a description of the engineering design of a nonsinusoidal radar that includes descriptions of the various subsystems (antennas, transmitters, receivers, and signal processors) suitable for performing some specific radar application. Such a description would be helpful in comparing the technology required of nonsinusoidal radar with the technology of a single-cycle (impulse) radar or with a conventional radar designed to accomplish the same purpose. In his 1981 book (Reference 32, Section 1.6) Prof. Harmuth offers the "into-the-ground radar" (here called ground-probing radar) as an example of the successful application of nonsinusoidal radar. The ground-probing radar is a fine example of an important radar with large relative bandwidth, but it is more like a single-cycle radar as described in this report and does not use the nonsinusoidal waveforms mentioned in the previous publications of Prof. Harmuth.

8. APPLICATIONS

The applications of impulse radar may be grouped into at least three categories: (1) those based on high-range resolution, (2) ground probing (below surface propagation) that takes advantage of high resolution and reduced attenuation at the lower frequencies, and (3) those involving some unique characteristic of single-cycle target scattering.

8.1 High Range Resolution Applications

Since the impulse radar waveform is a single cycle, it can be of very short duration so that all of the applications that have been considered for short pulse radar can be considered for impulse radar. There are many good uses for high resolution in radar. Table 2 lists the applications of high resolution radar that have been demonstrated or which have been seriously proposed. A conventional high range resolution radar is assumed here to be either one with a short pulse or with pulse compression that obtains the resolution of a short pulse. There is no standard definition for a high range resolution radar, but an example might be the Navy's AN/APS-137 X-band pulse compression radar with a compressed pulse width of 2.5 nanoseconds giving a range resolution of about 1.3 feet when its full 500 MHz bandwidth is used. As was indicated in Table 1, there are about 25 cycles in this waveform. Generally, high resolution radars are found at the higher microwave frequencies, such as X band. However, the Cobra Dane radar uses a 200 MHz bandwidth at L band and the Stretch pulse compression technique to give a range resolution of about 4 ft. It contains about 7 cycles in its compressed waveform. Both of these radars represent what can be achieved with high range resolution, but they are not the one-cycle waveform of an impulse radar and can be considered "narrow band" (as measured by their relative bandwidths).

The effectiveness of these high range resolution applications depends more on the absolute bandwidth (which affects resolution) rather than the relative bandwidth (which determines the number of cycles in the waveform and the rise time). None of the applications in Table 2 require a single cycle. However, if the application required a time resolution of 0.1 ns (corresponding to a range resolution of 1.5 cm) it would be difficult to obtain this at microwave frequencies, since a bandwidth of 10 GHz is required. A radar with 10% relative

Table 2

Uses of High Range Resolution in Radar

Accurate range measurement

Resolution of multiple targets; raid count

Enhancement of target-to-clutter ratio

Target range profile and size

Target classification (range-only, SAR, ISAR)

Recognition and avoidance of deception ECM

Reduction of glint (in angle measurement)

Resolution of multipath and low-altitude track

Target height by multipath

Area MTI

Angle measurement by time-difference of arrival

Interclutter visibility (for MTI and land clutter)

Tolerance to doppler frequency shift

Measurement of range rate without doppler

bandwidth would have to operate at a frequency of 100 GHz, which is usually not acceptable because of the high propagation attenuation at this frequency as well as other serious limitations. Thus when very high range resolution is required by the nature of the application, the impulse radar can be considered. (In the above example, the impulse radar spectrum might occupy the frequency region from 1 to 11 GHz.) If no more than a 10% bandwidth is allowed at X band, the bandwidth would be about 1 GHz, corresponding to a theoretical resolution of 7.5 cm. There are few applications where greater range resolution is necessary.

A number of the applications in Table 2 have been proposed for impulse radar. In what follows, several of these will be addressed.

Target-to-Clutter Enhancement. The shorter the pulse, the greater the target-to-clutter ratio. This is the basic principle used in the AN/APS-137 radar for periscope detection. There is a limit, however, in how much range resolution can be used for this purpose. In the case of sea clutter, the clutter echo statistics change (for the worse) with high resolution and complicate the detection process. Also, resolution less than the target size is not always useful for detection (although it is for recognition). If X band is a suitable radar frequency, there seems little incentive to improve the resolution already achieved with operational radars in order to improve target-to-clutter ratio. However, target enhancement with respect to clutter is important for ground probing radar, which is the major current application of impulse radar.

Target Recognition. High-resolution radar technology at X band is capable of providing better than one-foot range resolution. It is not clear than better resolution would be helpful for target recognition. This assumes that target recognition is based on the radial profile of the target. When the method of natural resonances is used for target recognition, a large relative bandwidth is necessary; but it can consist of discrete frequency components of long duration, rather than the continuous spectrum of an impulse.

Resolution of Low-Altitude Multipath. With sufficient time (range) resolution, the pulse that travels directly from radar to target and back can be separated from the pulse that travels to target and back via reflection from the surface. Assuming a flat earth, the time delay t_D (seconds) between the multipath signals is

$$t_D = 2\ h_a h_t / cR \qquad (11)$$

where h_a = antenna height (m), h_t = target height (m), c = velocity of propagation (m/s), and R = range (m). If we take h_a = 25 m (a typical shipboard antenna height), h_t = 2 m (altitude of an Exocet), and R = 15 km, or 8 nmi (the range at which an Exocet might be put into track after it crosses the radar horizon), the time delay t_d is 0.022 ns. If we make the conservative assumption that the direct and surface scattered pulse must be separated by this amount, than the bandwidth must be 45 GHz, which is too great for microwave radar. Having to completely separate the two pulses might be too rigid a criterion, however. A lesser separation might be suitable, so that a pulse an order of magnitude wider (0.22 ns) might be used (with a bandwidth of 4.5 GHz).

In general, if the high range resolution applications discussed above were the only applications for impulse radar, there would probably be little interest in this subject. Likewise, there seem to be few applications listed in Table 2 that would make impulse radar a major application, but it would be desirable to take a more serious look at some of the more promising ones.

8.2 Ground Probing Radar

A number of companies in the US and in other countries manufacture radars that penetrate the surface of the earth and reflect from underground objects. They are of relatively short range compared to other radars. A few meters range is common. Longer ranges are possible in low-loss soils and with higher power equipments. These radars generally operate on the surface, but they have also been flown in helicopters at low altitudes. They need to be of wide bandwidth in order to resolve closely spaced scatterers, and they have to be at low frequency in order to propagate in the earth without excessive loss. Propagation loss increases with increasing frequency and might vary from 10 to 30 dB/m.

It was mentioned previously [Sec. 1] that the impulse radar was first proposed (as a monocycle radar) for ground probing in 1960, followed by its exploration by the military for the detection of underground tunnels. It was applied to the observation of natural scatterers such as ice and stratifications of the earth. It is now used by utility companies for finding buried pipe and cable, as well as for inspection of road surfaces. Table 3 is a list of its various applications that have been reported in the literature. One of the indications of the degree of interest in this application is the publication of a special issue on subsurface radar by the IEE Proceedings (UK).[4] Table 4 gives an example of an impulse radar used for ground probing.

Ground probing impulse radar can be flown in orbit around the moon and planets to explore beneath the surface in a manner not currently practical by any other means. Penetration of the lunar surface by HF and VHF signals was demonstrated on the Apollo-17 lunar mission.[36]

The many potential problems listed in Sec. 6 that limit the application of impulse radar are not as important in its application to ground probing. The low transmitter power of current impulse devices is sufficient for the applications of Table 3 since the ranges are very short. Similarly, the low antenna gain is not a serious matter. High attenuation in the ground limits the signals received from angles far from broadside so that the wide antenna beamwidth of a dipole is narrowed when propagating into the earth. It has already been mentioned that the low transmitter power and the fact that its energy is coupled into the ground rather than radiate into free space avoids serious EMC problems. It might not have the dollar value of some other radar applications, but ground-probing radar has been a successful commercial venture.

8.3 Target Scattering

Most of the theoretical and experimental work on electro-

Table 3. Ground-Probing Radar Applications

Detection of buried gas pipes, water pipes and utility cables

Tunnel detection

Military nonmetallic mine detection

Profiling of the subsurface soil

Geophysical prospecting

Measurement of ice thickness and permafrost

Monitoring of subsurface conditions of highways and bridges

Soundings in fresh water

Archeological mapping

Coal mining (probing for hazards, measurement of seam thickness, measurement of permeability and conductivity of coal).

Detection of buried organic material (by law enforcement agencies).

Related application: penetration of walls and detection of hidden objects in walls.

Table 4. Characteristics of an Impulse Ground-Probing Radar*

Transmitter waveform: 1000-volt peak pulse, 250 picosecond (half-power) width, with 250 pulses per second repetition rate. Amplitude spectrum is essentially flat below 1 GHz.

Antenna: Two 6-ft orthogonal transmit and receive broad-band bow-tie dipoles. Antennas are on the surface and are well matched to the soil or rock. Orthogonal dipole arrangement minimizes reflections from horizontal stratifications and the earth-air interface.

Receiver: Sampling oscilloscope

Alternative mode: Two orthogonal 24-ft bow-tie dipoles with a 50-volt peak, 45 nanosecond pulse width, variable from 10 to 1000 pulses per second. Used for deeper depths.

Capability: In soft rock such as limestone or dolomite the radar is said to be able to detect a lithologic contrast at a depth of 55 ft. A limestone void is detectable at 35 ft. The depth of penetration in hard rock should be greater by a factor of three or four.

*D.L. Moffatt and R.J. Puskar, "A Subsurface Electromagnetic Pulse Radar," Geophysics, vol. 41, No. 3, pp. 506-518, June 1976.

magnetic (radar) scattering from targets has been narrow-band, or even CW. The assumption is usually made that there is a steady state illumination of the entire target by a sine wave of a particular frequency. The effect of broad bandwidth is examined by determining the (CW) scattering as a function of frequency and using the inverse Fourier transform to determine the time-domain signal. An impulse waveform is generally of duration much less than the transit time across the target. Thus the echo obtained with an impulse radar will indicate the various scattering discontinuities that make up the target which is what is needed for target recognition. It has been suggested that the different scattering response from a target when illuminated by an impulse radar might enhance the scattering from targets designed to have low cross section. Whether obtained by shaping or absorbers, however, low-observable targets can be made of low cross section over a very wide bandwidth. If an impulse radar has a spectral bandwidth greater than the bandwidth over which the target is of reduced scattering, there will be reflected energy. However, it can be argued that it would be better to concentrate the radar signal energy at the frequencies outside the frequency range over which the target cross section is low rather than expend energy at frequencies where the target has low response.

Even though the transient response of an impulse radar waveform when reflected from a target is different from the narrowband (CW) response, it is not obvious that it will or will not be better than the sum of the CW responses obtained across the frequency band occupied by the impulse waveform. As mentioned previously, Fourier analysis states that any time-waveform can be represented by its frequency spectrum and that theoretically the same results can be obtained by examining the response in the frequency domain as the response obtained in the time domain. If Fourier analysis applies, then it would indicate that the combined response from a number of long duration CW waveforms should provide the same information as a single short-duration impulse waveform. Thus from an intuitive point of view it might be thought that the transient response with an impulse waveform might have some advantage, but on the basis of Fourier analysis it might be thought that whatever is obtained in the time domain can be achieved in the frequency domain.

The transient response of a target, therefore, is a subject of interest not only because it is different from conventional narrowband scattering, but also because it is important for understanding target recognition and to determine whether there is target scattering enhancement.

8.4 Other Considerations

There have been other, more speculative, applications proposed which are claimed by their proponents to be better suited to solution with impulse radar than with conventional radar. Discussion of these will be given elsewhere.

9. DISCUSSION

There has been much interest in impulse radar for other than ground-probing radar. There are some who believe that impulse radar is revolutionary and that it can find useful application where other radars or other sensors cannot. It has been mentioned in the trade journals and has been said in the press to be the answer to stealth. However, statements or claims made in the press about the attributes of impulse radars for applications other than ground probing have not included justification that substantiates what is being claimed.

The impulse radar is certainly different from other radars. Its technology creates an exciting challenge to the innovative engineer. It would be a fascinating subject for a thorough investigation of its basic research and exploratory development aspects. Even if there were no other reason than intellectual curiosity, pursuit should be made of the understanding of the capabilities and limitations of impulse radar, its technology, phenomenology (mainly target and clutter scattering), and to clearly define and evaluate its potential applications.

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