ULTRA-WIDEBAND RADAR—POTENTIAL AND LIMITATIONS

Roger S. Vickers

SRI International, Geoscience and Engineering Center

ABSTRACT

There has been a recent awakening of interest in defense applications for ultra-wideband radar (UWB) systems. Work is in progress at a number of laboratories to establish the performance potential and limitations of such systems for target detection and identification. UWB radars differ from more conventional systems in that their bandwidth is a significant fraction of the carrier frequency. This can result in a design that gives the technique potential for identifying targets, reducing the effectiveness of low-observable treatments, and performing detection tasks that are now considered to be difficult.

The primary limitation on such systems is the lack of peak output power. Up to now, the pulse sources for these experimental radars have been either transistor impulse generators or spark gaps; both of these sources have severe limitations. With the development of OASS devices, new possibilities for extending the performance of UWB radars become available. In particular, the repeatability and fast rise time of OASS devices, while operating at high power levels, are of extreme importance to this newly emerging radar technology.

In this paper, some of the more obvious uses of a UWB radar are discussed, together with some of the problems (arising from limited source capabilities) in implementing adequate designs.

INTRODUCTION

What is UWB radar? The definition that has become commonly accepted, originating at the Ultra-Wideband Radar Conference in Los Alamos in 1990 (1), is that it is a radar whose bandwidth is 25% or more of its center frequency. In the case of a radar using an impulse as the excitation, this 25% bandwidth is the instantaneous bandwidth (as opposed to the case of an FM chirp, for example, where the signal is swept through the bandwidth at rate determined by the radar performance requirements). Much of the controversy surrounding UWB radar relates only to the impulse case, and so in this paper we will examine impulse radars specifically and show what is possible now, what the limitations are, and what is potentially achievable.

LIMITATIONS OF IMPULSE RADARS

The difficulties of building impulse radar systems are manyfold, but the principal challenges are in the design of the antennas, the power source, and the method of dealing with electromagnetic interference (EMI) in both the transmit and receive directions. A quick inspection of the radar equation shows why. The equation used here is given in terms of the received signal-to-noise ratio (SNR) for an ideal receiver, and does not include any special treatment for the impulse case:

$$R_{max}^4 = \frac{P_t G_t A_c \sigma}{(4\pi)^2 k T_o B_n (S/N)_{min}} ,$$

where the terms have their usual meanings.

Firstly, the directional gain of the antennas must be close to constant with frequency over the entire bandwidth. Because this can involve frequencies with a 3:1 ratio or higher, the design problem can be difficult. One solution, shown in Figure 1, is to use a feed horn into a parabolic reflector such that the reflector is under-illuminated at the higher frequencies and fully illuminated at the lowest frequency. The price paid for this approach is that the resulting dish size is larger than would normally be the case over much of the band. This approach is currently being used in a sea-clutter radar described later in this article. The dominant term in the equation is, of course, range. For a system that operates satisfactorily at a range of 10 km with an output power of 10 MW, for example, increasing the range to 30 km requires a dramatic increase in transmitter power to 810 MW.

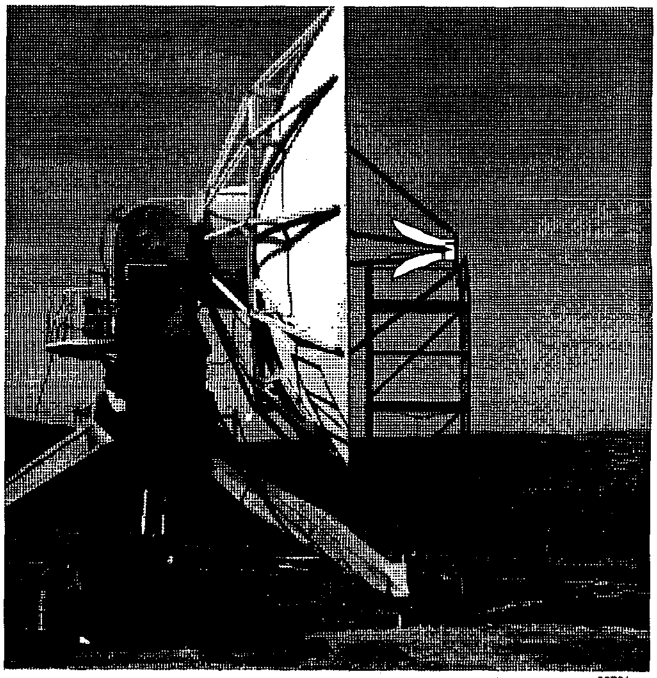

30791-c

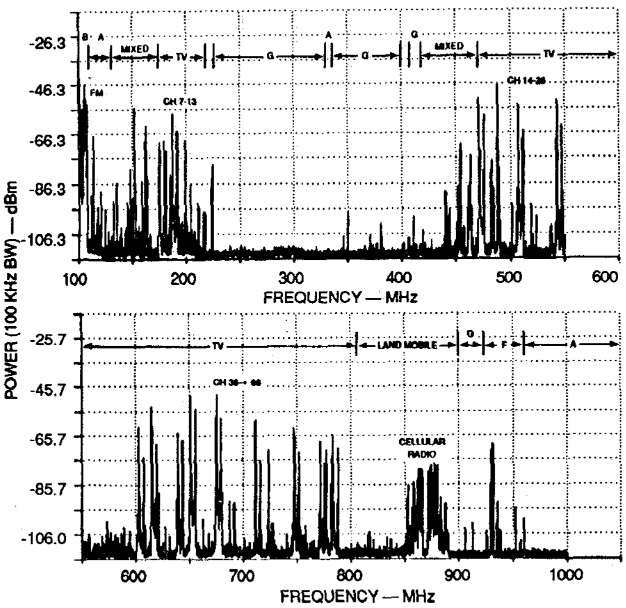
FIGURE 1 PARABOLIC HORN WITH UWB FEED

Finally, the other parameter that contributes to the high output levels required for impulse radar is the large bandwidth used. For a VHF system, for example, transmitting a 200-MHz monocycle, the spectrum extends over 200 MHz. This provides the resolution ability desired, but opens the receiver to both thermal and man-made noise. Figure 2 shows an example (taken in the San Francisco area) of how severe this noise can be in the region from 100 to 1000 MHz.

Thus, impulse radars inherit a number of design problems peculiar to their requirement for large instantaneous bandwidth. One of these is the need for very high peak output powers to achieve ranges in excess of 10 km. If this problem is solved by the evolution of optically activated switch sources, then the primary problem will be one of the specialized antenna designs necessary to handle the high field strengths at the feed and maintaining a constant beamwidth. The question of interference with other spectral users may restrict the siting of such powerful radars, although this is not a problem unique to impulse designs.

K

CH2870-4/91/0000-0371$01.00 © 1991 IEEE



30791-3b

FIGURE 2 MAN-MADE SIGNAL SPECTRUM FROM 100 -1000 MHz IN AN URBAN AREA

POTENTIAL APPLICATIONS

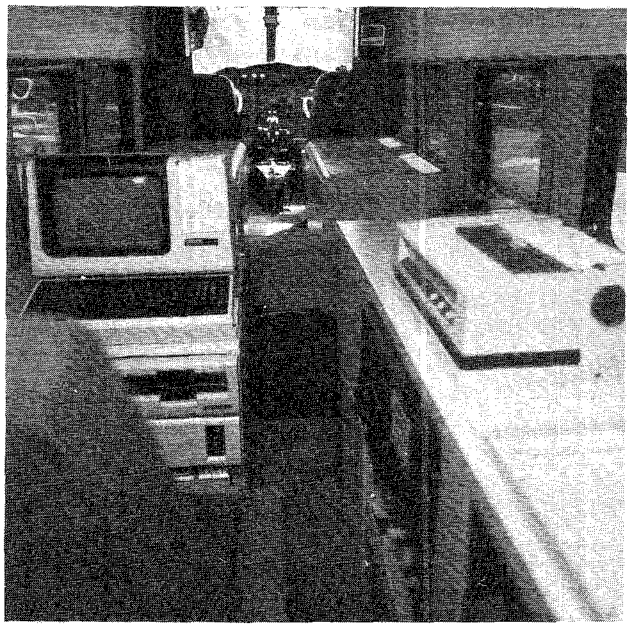
The potential applications for impulse radar include those shown in Table 1, which also shows their status at the time of writing. The foliage penetration (FOLPEN) capability derives from a combination of long wavelength and wide bandwidth. The long wavelength gives the penetration ability by decreasing the backscatter coefficient from the trees, and the wide bandwidth preserves the high resolution that would otherwise be lost by going to low frequencies. Similarly, ground penetration radars take advantage of the lower absorption at low frequencies from soils and strives to maintain resolution by the use of large percentage bandwidth. In ground-penetrating radar (GPR) design, it is common practice to use 100% bandwidth (by the definition used above), for example, 50 to 150 MHz. The transmitted waveform is often close to a single cycle of the center frequency and is commonly derived from a single switched impulse.

Table 1

POTENTIAL AREAS OF APPLICATION SUGGESTED FOR UWB RADARS

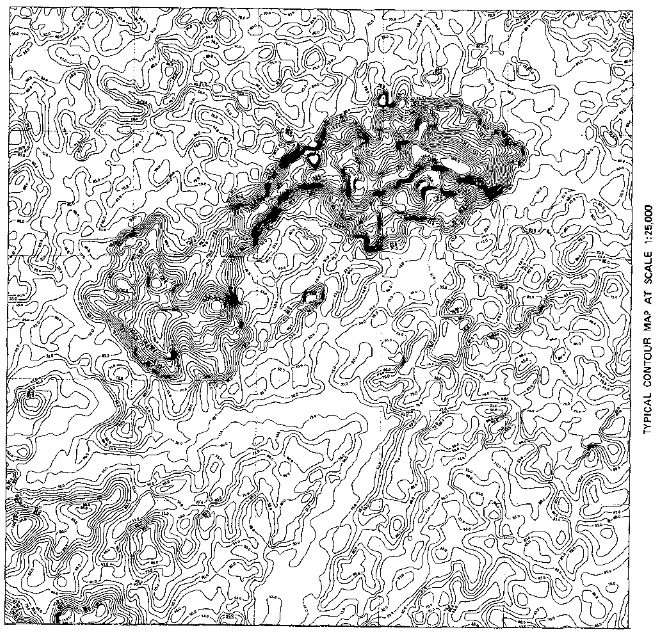
Application	Status
Foliage penetration	Demonstrated at near vertical incidence, oblique incidence currently under investigation
Target identification	Work currently in progress, not a proven application as yet.
Ground penetration	Demonstrated for a wide variety of target and soil types.
Counter low observable	Not demonstrated yet.
Nonlinear effects	Some demonstrated effects due to high-field strengths. Limited range capability.

The applications for radars with ground or foliage penetration ability are numerous, and include military uses such as detection of bunkers and mines, and location of targets under foliage. In the civilian sector GPRs have been used for toxic waste location, detection of utility lines, archeological surveys, and precision terrain mapping in the presence of forest cover. Figure 3, for example shows an impulse radar on board a light twin aircraft for making terrain profiles through tropical forest. Figure 4 shows an example of the resulting elevation models, with a contour interval of 5 m. This radar was used to acquire line profile data over 14,000 km of tropical forest, and did not experience any conditions where it failed to penetrate the foliage completely. Details of this work were reported earlier (2).



30791-3a

FIGURE 3 AN IMPULSE RADAR SYSTEM FOR FOLIAGE PENETRATION FLOWN FROM 1982 - 1986 IN INDONESIA



30791-3

FIGURE 4 TERRAIN MODEL MADE FROM DATA TAKEN THROUGH TROPICAL FOREST WITH AN IMPULSE RADAR

In target identification, the wide bandwidth is used to excite multiple resonances in the targets, and these are analyzed to give a specific signature for each target. Although work is believed to be progressing in the classified arena, it is not yet commonly accepted that this benefit can be derived from UWB techniques in general and impulse techniques in particular. Even less accepted at present is the performance of UWB radars into defeating stealth techniques, although the wide bandwidth, together with a judicious choice of center frequency can be expected to make RCS reduction by either LO coatings or shaping more difficult to implement.

The high peak powers associated with impulse radar have led to suggestions of applications involving non-linear effects. Some of these have in fact been demonstrated using conventional waveforms (e.g., the METTRA radar, which is now a decade old) (3), but in general the necessity for high field strength at useful ranges dictates the use of extraordinarily energetic sources as yet not available to radar designers.

Table 2 shows three UWB radar systems, two of which are currently in operation and one (the sea-clutter radar) due to go on-line in April 1991. The sea-clutter radar is designed to measure ocean backscatter and target RCS in the region from 200 to 1000 MHz. The Impulse-SAR is a FOLPEN synthetic aperture radar operating with 200-MHz bandwidth in the VHF/UHF region. The aircraft ID radar is a short-range unit designed to capture resonance frequency phenomena from airborne targets.

Table 2
THREE UWB RADARS AT SRI

	Sea-Clutter Radar	Impulse-SAR	Aircraft ID Radar
Impulse (monopolar)	200 kV	2 kV	200 V
Source	Spark (Physics International)	Transistors	Transistors
Bandwidth	800 MHz	200 MHz (Ch. 1) 300 MHz (Ch. 2)	1000 MHz
Center Frequency	600 MHz	200 MHz	700 MHz (Ch. 1) 1500 MHz (Ch. 2)
Antenna	30-ft Dish	Dipole array	Horn
Usable Range	20 km	2 km	200 m
PRF	100 Hz	200 Hz	2000 Hz

When using these numbers in the Radar Equation, the usable ranges quoted here seem too conservative. The reasons for this are manyfold. For example the conversion of the unipolar impulse to a radiated wave is not usually an efficient process, particularly if one uses resistive loading to improve the antenna's impulse response. The translation from impulse amplitude to actual peak transmitted power is complex, depending on the antenna characteristics over the bandpass in question, but the best that can be expected is that the monopolar impulse will be turned into a bipolar monocycle at half the amplitude. In addition, all of the radars shown occupy a region of the spectrum which contains significant excess noise from man-made sources, as was shown in Figure 2. Both these effects reduce the range capability of the radar significantly to the figures shown.

An example of the data from the aircraft radar is shown in Figure 5, which gives the time-domain response of a Cessna 182 in the spectral region from 1000 to 2000 MHz. This is a single snapshot of the signature, and does not show the dynamics of the response as the aircraft flies through the beam. The dynamic variations of the signature with aspect angle reveals much information about the dimensions of the aircraft's exterior components. Observations have also been made at lower frequencies of both composite and metallic airborne targets; it has been noted that the fundamental resonances of these targets are not entirely aspect free as has been suggested, particularly in terms of the efficiency with which the resonances are excited.

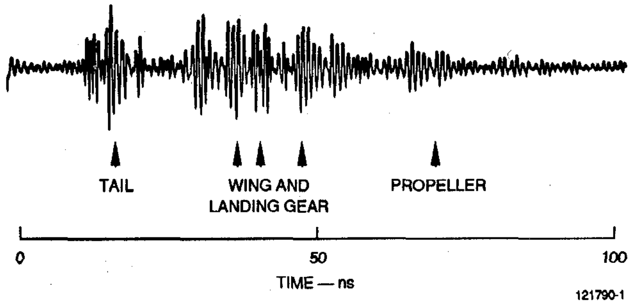


FIGURE 5 IMPULSE RADAR SIGNATURE OF A CESSNA 182 (1000 - 2000 MHz)

In the case of the SAR shown in Table 2, data has been obtained at modest altitudes using a transistor source providing highly coherent pulses with a spectrum centered in the VHF. Figure 6 shows the two-dimensional impulse response of two retroreflectors spaced 2 m apart, using the this radar. Figure 7 shows a typical scene from the SAR, with the photographic image for comparison. The resolution in azimuth and range is approximately 1 m, and the operational altitude is 2000 ft. The performance of this particular radar is at present limited by the lack of output power, together with the high levels of excess (man-made) noise in the VHF, resulting in SNR ratio for ranges greater than 1 km.

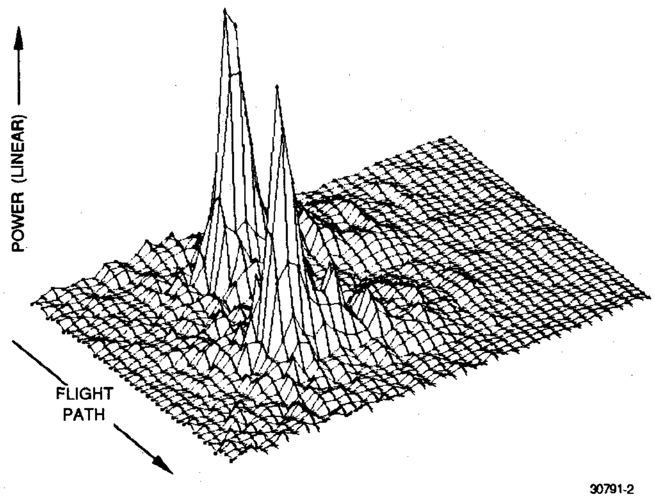


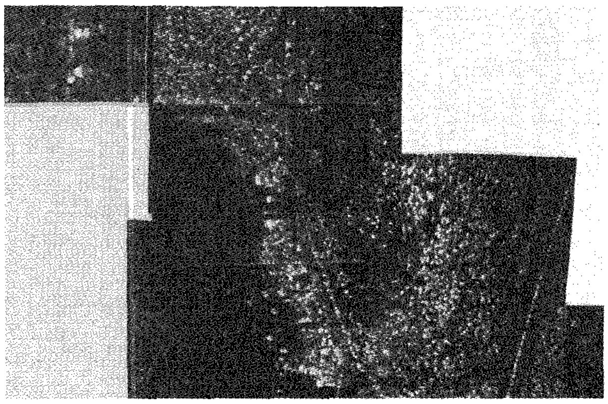
FIGURE 6 TWO DIMENSIONAL IMPULSE RESPONSE OF RETRO-REFLECTORS SPACED 2 METERS APART

The use of a suitably long-lived, highly coherent OASS device would enable such an impulse SAR to operate at substantially higher altitudes and to gather data from larger areas, thus making the radar more economical to operate.

Despite the limitations on output power, impulse radars are attractive because of the extreme simplicity and economy of the transmitter section. For example, the SAR shown was designed and assembled from the component level and flown within 90 days.

OPTICAL SWITCHES FOR RADAR USE

It has been shown that output power is one limiting factor in impulse radars. OASS devices offer one possibility for improving the situation, although parameters other than just power are also important. For many radar applications, the pulse-to-pulse coherence is vital. One such application is the UWB-SAR shown earlier, where between 500 and 1500 pulses must be coherently integrated. Other applications are those in which a burst of impulses are radiated instead of the single pulse used in the examples shown here. In applications such as the SAR, the integration gain only happens if the



(a) IMPULSE SAR IMAGE OF A COASTAL AREA, SHOWING FENCES, ROADS THROUGH THE TREES, AND INDIVIDUAL TREE ECHOES

(b) PHOTOGRAPH OF THE SAME AREA

30791-0

FIGURE 7 UWB-SAR AND PHOTOGRAPHIC IMAGES OF A COASTAL SCENE

phase of the pulses and their associated trigger jitter is stable. At 1000 MHz for example, stability to 1/10 of a wavelength implies trigger jitter less than 100 ps. In the case where active antenna arrays are used, as in the UWB-SAR in Table 2, trigger jitter can cause undesirable sidelobes, beam squinting, and waveform distortion. Recent specifications outlined in a procurement from Kirtland AFB required 25-ps jitter to produce wavetrains from a frozen-wave-switch geometry at 1000 MHz. The repetition rate for a radar-oriented OASS device needs to be at least in the hundreds of Hertz. The radars shown in this paper all operate with a PRF of 100 to 200 Hz.

This brings up the primary area of concern for OASS sources: their reliability. If a switch is good for 10^8 shots, and it is put to use in a radar operating with a PRF of 200 Hz, then the lifetime is exhausted in 58 days. The mode in which these switches are used (linear, avalanche, or "lock-on") is of importance in this respect. In general, avalanche OASS devices are believed to have less potential than either linear or lock-on mode devices in terms of their lifetimes. However, with the absence of the avalanche process to give switching gain, the power and physical size of the laser pump must be increased, and its reliability becomes a concern. One promising possibility is the use of solid-state diode laser arrays pumping a silicon switch in the linear mode. These switches have yet to reach demonstrated performance at the lifetimes and repetition rates required, but of the various options available in OASS technology, they appear to be the most likely to be the first into operational radar systems.

CONCLUSIONS

The significant recent progress presented herein supports and encourages continued exploration into the uses of UWB radars in general and impulse radars in particular. It is recognized that many of the applications demonstrated by data in this paper are not peculiar to impulse excitation, but could be duplicated by other wideband waveforms. However, the lack of complexity in impulse radar designs and the complete time registration of all the spectral components are unique to this family. The current limitation on performance is primarily in the impulse source, although it is clear that other obstacles to continued increases in operating range would soon emerge. The evolution of the optically activated switch appears to be a near-future solution to the impulse power problem; with improvements in lifetime, repetition rate, and output power, we can expect to see OASS-powered radars in regular operation in the next two-three years.

References

(1) *Abstracts of Papers Presented at the First Los Alamos Symposium on Ultra-Wideband Radar, March 5–8, 1990,* Compiled by Bruce W. Noel, Ph.D., Los Alamos National Laboratory, Los Alamos, New Mexico.

(2) Vickers, Roger S., Raymond T. Lowry, and Arlen D. Schmidt, "A VHF Radar To Make Terrain Elevation Models Through Tropical Jungle," *Proc. 1988 IEEE National Radar Conf.*

(3) Eisenberger, A.J., J.A. Graff, and G.F. Origlio, "New Radar Detection Systems for Metal Military Targets," *JDRB*, p. 288 (Summer 1974).