Ultra-Wideband
Impulse Radar –
An Overview of the Principles

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ABSTRACT

Over the past decade, extensive research work has been carried out to develop the ultra-wideband (UWB) technology for radar applications, and to resolve the practical challenges in implementing an efficient UWB radar system. In this paper, we present an overview of the basic principles of UWB impulse radar. The focus will be on the principles of UWB signal generation, impulse radiation, waveform design, pulse compression, range-velocity resolution (ambiguity function), array beamforming, and radar-target signature.

INTRODUCTION

The rapid advances of solid-state electronic and optoelectronic devices have made it possible to develop ultra-wideband (UWB) radar and radio transmission technology, with certain potential advantages over conventional technology [1]. A UWB radar is one having a very large relative bandwidth,

\[ \eta = \frac{\Delta f}{f_c}, \quad 0 \leq \eta \leq 1 \]  

(1)

where \( \Delta f \) is the absolute bandwidth and \( f_c \) the carrier (or center) frequency. For carrier-free nonsinusoidal signals, the relative bandwidth is defined as follows [2].

\[ \eta = \frac{f_H - f_L}{f_H + f_L}, \quad 0 \leq \eta \leq 1 \]  

(2)

In Eq. (2), \( f_H \) and \( f_L \) are the highest and the lowest frequency of interest.

The conventional technology of radar and radio communications is developed based on the phenomenon of resonance and a small relative bandwidth in the range 0.01 plain 0.01 \( \leq \eta < 0.25 \); i.e., the absolute bandwidth is at most 25% of the center frequency. A UWB radar is characterized by 0.25 \( < \eta \leq 1 \). Radar applications where UWB technology can provide potential advantages over conventional technology arc as follows:

- Line of sight, high resolution, all weather radar;
- Into-the-ground, and possibly deep into seawater, probing radar [3];
- Enhanced clutter-suppression capability for detection of low flying targets, e.g., low altitude, sea-skimming antiship missiles [4];
- Counter stealth radar detection capability;
- Terrain profiling (imaging), and detection of tactical (moving) targets under foliage or tree canopy;
- Array beamforming for ultra high resolution; and
- Spread-spectrum techniques for low probability of intercept and anti-jamming.

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for power and energy levels above that produced by an individual power source of the types mentioned above. It is possible to achieve the necessary total power or energy by combining a large number of sources in an efficient array configuration.

The radiation of carrier-free nonsinusoidal electromagnetic signals can be achieved by implementing the radiation principle of a Hertzian electric dipole [5]: The electric and magnetic field strengths, E and H, radiated to the far field by a Hertzian electric dipole are directly proportional to the time derivative of the dipole excitation current i(t),

\[ (E, H)_{\text{far field}} \propto \frac{di(t)}{dt} \]  

Based on the above principle, a large-current radiator for nonsinusoidal signals was designed and implemented at Kuwait University in the mid-1980’s [6]. The driving circuit for the antenna was a single-stage amplifier with solid state microwave power transistor of 1 W output power and 1-2.3 GHz operating frequency range. The receiver was a closed-loop sensor coupled to a balanced-input amplifier that fed into a storage digital oscilloscope of 1 GHz bandwidth. A pulse generator with 100 Hz 1 GHz repetition rate and 300-ps transition time was used to drive the power source.

The voltage transient generated by the source to drive a current through the large-current radiator is shown in Figure 1A. The nonsinusoidal electro-magnetic signal radiated by the large-current radiator and received by the closed-loop sensor is shown in Figure 1B. The UWB signal in Figure 1B includes a positive mainlobe and two small negative sidelobes. The sidelobes are generated due to nonlinearity and high pass behavior of the antenna. A finite portion of low-frequency components of the UWB pulse is suppressed by the antenna system during the excitation and radiation period.

WAVEFORM DESIGN AND PULSE COMPRESSION

For the analytical study and performance evaluation of UWB impulse radar, a Gaussian waveform can be adopted to approximate and represent nonsinusoidal signals having the features shown in Figure 1B. A Gaussian time variation can be expressed as follows:

\[ \Omega(t) = A \exp[-4\pi(t/\Delta T)^2] \]  

where A is the peak amplitude, \( \Delta T \) is the effective duration; \( \Delta T = 1/\Delta F \) is the antenna bandwidth. The Gaussian waveform \( \Omega(t) \) is unique in the sense that its autocorrelation function as well as Fourier transform are both of Gaussian shape [7].

In practice, target detection and resolution capabilities of radar are restricted by the available energy

Fig. 1A. A Voltage Transient Generated by the Source to Drive a Current Through the Surface of the Radiator; Fig. 1B. The Radiated and Received UWB Signal
and bandwidth, respectively. For UWB radar, the use of long coded waveforms and pseudo-random noise (PN) sequences, that are composed of a large number of carrier-free pulses having large peak power, can provide sufficient energy (average power) for reliable detection. Furthermore, the ultra resolution (in range) of an impulse can be accomplished by pulse compression techniques.

Carrier-free coded waveforms and PN sequences can be represented by a train of properly weighted and shifted Gaussian pulses, and at the same time attain the properties of their autocorrelation function. A binary code or a PN-sequence that is usually represented by N digits +1’s and −1’s can analytically be expressed in terms of Gaussian pulses as follows [7].

$$s(t) = \sum_{n=0}^{N-1} a_n \Omega(t - nT_D)$$

$$= A \sum_{n=0}^{N-1} a_n \exp\{-4\pi[(t/\Delta T) - nD]^2\} \tag{5}$$

where the parameter $D$ is referred to as duty cycle,

$$D = T_D/\Delta T = T_D \Delta f, \quad D \geq 1 \tag{6}$$

A technique referred to as synchronous sequential switching (SSS) [7] can be implemented to realize Eq. (5).

A pulse compression radar receiver is a physical realization of a “matched filter” whose impulse response is a time inverted replica of the radar waveform. A correlator receiver is the same as matched filter in the sense that both result in pulse compression as well as noise suppression. In principle, for a radar signal $s(t)$, the response of a matched filter with impulse response $h(t) = s(−t)$ is the autocorrelation function $R_{ss}(t)$ of the signal $s(t)$ [7],

$$R_{ss}(τ) = \int_{−\infty}^{+\infty} s(t)s(t + τ) \, dt$$

$$= A^2\Delta T \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} a_n a_m \exp\{-2\pi[(τ/\Delta T) - (m - n)D]^2\} \tag{7}$$

The matched-filter response $R_{ss}(τ)$ is of practical significance for waveform design and performance evaluation of UWB radar. The waveform $R_{ss}(τ)$ is a function of the following design parameters:

- Signal energy $A_2\Delta T$.
- Nominal bandwidth $\Delta f = 1/\Delta T$.
- Duty cycle $D$, that governs range ambiguity.
- Code length $N$, which limits total energy.
- Code characters $a_n$’s that define the type of coding.

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Fig. 2A. 13-Digit Barker Code According to the Signal Representation Given in Eq. [5] with $D=1$;

2B. Normalized Autocorrelation Function $R_{ss}(τ)/R_{ss}(0)$ according to Eq. [7] with $D=1$;

2C. $R_{ss}(τ)/R_{ss}(0)$ with $D=10$
A 13-digit Barker code and its autocorrelation function calculated in accordance to the signal representations given in Eqs. (5) and (7), respectively, with D = 1 and 10, are shown in Figures 2A, B, and C. Note that an increase in the value of duty cycle D causes widening of the spacing between adjacent pulses as illustrated in the plot of Figure 2C, on previous page.

GENERALIZED AMBIGUITY FUNCTION

The ambiguity function was introduced by Woodward in 1953. This function allows one to investigate the resolution and clutter-suppression characteristics, in range-velocity domain, of various radar signals. For nonsinusoidal waveforms, the Doppler frequency shift known for the extended periodic sinusoidal waves can be represented in terms of the change in PRI $T_D$ or duty cycle D of radar signal due to target velocity. Based on the signal representation in Eq. (5), a generalized ambiguity function $|\chi(\tau, \nu)|$ for carrier-free impulse radar was derived [8],

$$|\chi(\tau, \nu)| = \frac{A^2 \Delta T}{\sqrt{8}} \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} a_n a_m Q(\tau, \nu)$$

where

$$Q(\tau, \nu) = \exp \{-2\pi[\tau + n(D + \nu) - m(D + \theta)]^2\}$$

In Eqs. (8) and (9), the variables $\tau$ and $\nu$ are normalized range and normalized velocity, respectively. The parameter $\theta$ is referred to as matched filter velocity constant, and is usually set equal to $\nu$.

The generalized ambiguity function $|\chi(\tau, \nu)|$ is a two dimensional autocorrelation function with the characteristic

$$|\chi(\tau, \nu)| \leq |\chi(0,0)| = \frac{N A^2 \Delta T}{\sqrt{8}}$$

where $\xi$ is signal energy

Other characteristics of $|\chi(\tau, \nu)|$ are given in [8]. The generalized ambiguity function for a PN-sequence of N = 100 positive and negative Gaussian pulses is shown in Figure 3 for a pulse-compression ratio ($\xi = ND = 10^5$). According to Figure 3, the “spike” over the range velocity domain is a close representation of the thumbtack ambiguity function.

ARRAY BEAMFORMING

Advanced radar employs an active or passive array beamforming system to achieve the necessary total power, high resolution directivity (beam) pattern, electronic beam steering, and interference rejection through sidelobe nulling. The conventional method of beamforming based on periodic sinusoidal waves results in a beam pattern, or array factor $F(\phi)$, of the form:

$$F(\phi) = \frac{\sin(L\pi\phi/\lambda)}{(L\pi\phi/\lambda)} = \frac{\sin(Lc\pi\phi/f)}{(Lc\pi\phi/f)}$$

where $\lambda$ is wavelength, $f$ frequency, c speed of light, and $\phi$ angle of incidence, or radiation angle. The array factor in Eq. (11) results in classical equation for resolution angle

$$\varepsilon = \frac{k\lambda}{L} = \frac{k c}{L \Delta f}$$

where $k$ is a constant whose value is usually set equal to one.

Array beamforming based on nonsinusoidal Gaussian pulses of the form given by Eq. (4) yields the array factor [9],

$$A(\phi) = \frac{erf[(\sqrt{\pi}L \Delta f \phi)/2c]}{(\sqrt{\pi}L \Delta f \phi)/2c}$$

where $erf[\cdot]$ is the known error function. The resolution angle from the array factor $A(\phi)$ is given by

$$\varepsilon = \frac{KC}{\Delta f L} = \frac{K \Delta T c}{L}$$

where $K$ is a constant usually set equal to one. It is important to mention that the waveform representation given in Eq. (7) also results in the array factor $A(\phi)$ and the resolution angle given in Eq. (14). Plots of the array factors $F(\phi)$ and $A(\phi)$ are shown in Figure 4, on next page. According to Figure 4, the function $F(\phi)$ includes distinguishable sidelobes, whereas $A(\phi)$ is a monotonically decreasing function of angle $\phi$.

The resolution angle for nonsinusoidal signals in Eq. (14) is a function of array size $L$ and bandwidth $\Delta f$. An increase in bandwidth $\Delta f$ results in simultaneous
According to Eq. (15), each one of the target scattering centers, located at range \( r_i \) from radar, is characterized by a Gaussian impulse response of amplitude \( E_i \), Gaussian spread parameter \( a_i = 2\sqrt{\pi/\Delta T_i} \) (s^{-1}), duration \( \Delta T_i \), and relative time shift, \( t_i = 2r_i/c \). Based on Eq. (15), the response of a complex target to a Gaussian pulse \( \Omega(t) \) is given by [10]:

\[
s(t) = \Omega(t) * h_s(t)
= \sum_{i=0}^{N-1} A_i \exp[-b_i(t)] \text{erfc}[-\eta_i(t)/\alpha_i] \tag{16}
\]

where \( \text{erfc} \) is the complementary error function and:

\[
\alpha_i = (\alpha^2 + \alpha_i^2)^{1/2} = 2\sqrt{\pi} \left[ 1 + \left( \frac{\Delta T_i}{\Delta T} \right)^2 \right]^{1/2} \tag{17}
\]

\[
\eta_i(t) = a^2 t_m + a_i^2 (t - t_i), \quad t_m > \Delta T/2 \tag{18}
\]

\[
b_i(t) = [a a_i (t_m + t_i - t)/\alpha_i]^2 \tag{19}
\]

\[
A_i = \sqrt{\pi} AE_i/2\alpha_i \tag{20}
\]

The waveform \( s(t) \) can be regarded as target image, or range profile. Due to the super resolution of UWB signals, target range profile is sensitive to the change in aspect angle. This limitation requires extensive computational power when the impulse response concept described above is applied to the field of non-cooperative target recognition [10]. One can compute a bank or library of images using Eq. (16), for different types of targets and use it for target recognition based on computer correlation processing.

**CONCLUSION**

Basic and applied research work in the field of UWB technology have demonstrated that such technology has potential advantages for radar applications. The super-resolution capability of UWB signals is very attractive and worthy of the research efforts and financial investments in developing UWB technology.

**REFERENCES**


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**Obituary**

**David H. Mooney, Jr. – Pulse Doppler Radar Developer**

AESS member David H. Mooney, Jr., a Fellow of the IEEE and the 1984 IEEE Pioneer Award winner, died in Catonsville, Maryland, at the age of 71 on March 11, 1998.

His pioneering work in the 1950’s and 1960’s led to the development of the world’s first pulse doppler radar. He developed many radar systems, including those used in the BOMARC long-range interceptor missile, the AWACS E-3A surveillance aircraft, the B1 bomber, and the F-16 jet fighter.

After serving in the US Navy from 1945 to 1946, Mooney received his electrical engineering degrees – his bachelor’s from the University of South Dakota and his master’s from the University of Pittsburgh. He was a registered engineer in Maryland and held 18 patents. He was an author of one of the chapters in Merrill I. Skolnik’s “The Radar Handbook,” as well as articles in other publications.

His career at Westinghouse Electric Corporation began in 1948 in the Special Products Division, Pittsburgh, where he worked on analog computers. From 1953 to 1987, he worked on advanced airborne radars at the Westinghouse Defense and Space Center, Baltimore. He was awarded Westinghouse’s highest employee honor, the Order of Merit in 1985. He retired in 1987 and served as a consulting engineer.

To quote his daughter, Jan Mooney: “He was able to explain radar in a way that anyone could understand, and would spend extra time to explain if necessary. Also, I heard comments that he was always right, so many coworkers went to him for advice on various projects. Dad was very modest; I never knew about his work until his retirement party!”