Radio Physics and Radio Astronomy, 2002, v. 7, No. 4, pp. 339-344

# MAIN CAPABILITIES AND FEATURES OF ULTRA WIDEBAND (UWB) RADARS

I.J. Immoreev, Senior Member IEEE

*Moscow Aviation Institute*
*Gospitalny val, Home 5, block 18, apt 314. 105094, Moscow, Russia*
*E-mail: immoreev@aha.ru*

This review paper discusses the differences between ultra wideband (UWB) radars and the conventional narrow-band radars. The features are shown of the generation, radiation and processing of UWB radar signals evoked by the change of the signal waveform in the process of location, by appearance of the mutual dependence between the signal waveform and antenna directivity, and other. The possibility for the reception of the target radioimage is shown.

## 1. Introduction

The vast majority of modern radio systems has a narrow frequency range and as the carrying waveform uses harmonic (sinusoidal) or similar quasiharmonic signals to transmit formation. The reason is very simple – sinusoidal oscillations are generated by the RLC oscillating contour itself – the simplest electrical oscillatory system. And the resonance properties of this system allow to select the necessary signals by their frequencies. That’s why the frequency range of most radio engineering systems is many times less than the carrying frequency they employ. Both the theory and practice of the modern radio systems allow for this distinctive feature.

At the same time the narrow frequency range of the signal restricts the informational capacity of radio systems. That’s why it is necessary to expand the frequency range in order to increase the informational capacity. The only alternative is to increase the transmission time.

This problem is especially urgent for radars, where the detection time is always strictly limited. The common radars with the frequency range not exceeding 10% of the carrying frequency have practically exhausted their informational potentialities. That’s why the further development of radars lies in the employment of signals with frequency range up to 1 GHz (the duration of the radiated pulses around 1 ns). The informational content in the UWB location increases owing to the range reduction of the pulse volume of radar. Thus, when the length of a sounding pulse changes from 1 μs to 1 ns the depth of the pulse volume reduces from 300 m to 30 cm. It could be said that the instrument, which investigates the space, becomes more fine and sensitive. It allows to obtain the radioimage of the targets.

## 2. The Main Capabilities of UWB Radars

The reduction of the signal length in the UWB radar enables to:

1. Improve the measurement accuracy of the detected target range. This results in the improvement of the radar resolution for all coordinates since the resolution of targets by one coordinate does not require their resolution by other coordinates.
2. Identification of target class and type because the received signal carries the information not only about the target as a whole, but also about its separate elements.
3. Reduces the radar effects of passive interference from rain, mist, aerosols, metalized strips, etc. This is because the scattering cross-section of interference source within a small pulse volume is reduced relative to the target scattering cross-section.
4. Improved stability observing targets at low elevation angles at the expense of eliminating the interference gaps in the antenna pattern. This is because the main signal and any ground return signal arrive at the antenna at different times, which thus enables their selection.
5. Increase the probability of target detection and improved stability observing a target at the expense of elimination of the lobe structure of the secondary-radiation pattern of irradiated targets since oscillations reflected from the individual parts of the target do not interfere and cancel, which provides a more uniform radar cross section.
6. A narrow antenna pattern by changing the radiated signal characteristics.

7. Improvement of the radar's immunity to external narrowband electromagnetic radiation effects and noise.
8. Decrease the radar "dead zone."
9. Increase the radar's secretiveness by a signal, which will be hard to detect.

These above-listed advantages are potentially attainable. Their realization requires a theoretical base allowing the calculation of the characteristics of UWB radars. This base is also necessary for the development of appropriate equipment. However, a satisfactory and systematized theory of ultra-wideband radars has yet to be developed. The reason has to do with the significant distinctions of the process of ultra wideband observations from the similar process when common narrow-band signals are used. Let us consider these distinctions.

## 3. The Main Features of UWB Radars

### *3.1. Changes of the Signal Waveform in the Process of Detection and Ranging*

Narrow-band – sinusoidal and quasi-sinusoidal – signals have the unique property. In the course of widespread signal conversions, such as addition, subtraction, differentiation and integration, the shape (waveform) of sinusoidal and quasi-sinusoidal signals remains unchanged; the signals have a shape identical to that of the original function and may differ only in their amplitude and time shift. Hereinafter, shape is understood as the law of change of a signal in time. On the contrary, the ultra wideband signal, at the specified (and other) transformations, changes not only parameters, but also shape.

Let us assume that UWB signal $S_1$ (Fig. 1) is generated and transmitted to the antenna in a form of a current pulse. Pulse duration in the space $c\tau$ ($c$ is velocity of light, $\tau$ is pulse duration in time domain) is lesser than the linear size of the radiator $L$.

The first change of the UWB signal shape ($S_2$ in Fig. 1) occurs during the pulse radiation since the intensity of radiated electromagnetic field varies proportionally with the derivative (first or higher) of the antenna current.

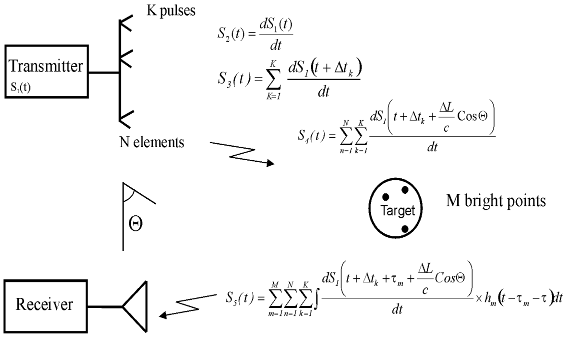

**Fig. 1.**

The second change of the shape occurs when the antenna is excited in one point and the current pulses move along the radiator. In this case the elements of the antenna which have length $\Delta L = c\tau$ radiate pulses of electromagnetic wave serially. As a result, the single pulse transforms into a sequence of $K$ pulses divided by time intervals $\Delta t$ ($S_3$ in Fig. 1). Visible radiator length varies against variations of the angle $\Theta$ between the normal to the antenna array and the direction towards the point of receiving. Thus, the inter-pulse intervals vary with this angle as follows: $\Delta t \sin\Theta$.

The third change of the shape occurs due to the delay of fields, radiated by $N$ elements of the antenna, in space. The pulse radiated by one antenna element at the angle $\Theta$ is delayed by the time $(d/c)\cos\Theta$ compared to the pulse radiated by the adjacent antenna element. The combined pulse will have various shapes and durations at different angles $\Theta$ in the far field ($S_4$ in Fig. 1).

This UWB signal is scattered by the target. Thus its shape changes for the 4th time ($S_5$ in Fig. 1).

The target consists of $M$ local scattering elements ("bright points") located along the line $L_t$. For UWB signal $c\tau \ll L_t$. Such UWB signal reflects from discrete target elements and forms pulse sequence. The number of pulses, time delay $\tau_m$, and intensity depend on the target shape and the target element pulse response $h_m$ This pulse sequence is named "target image". The whole image presents the time distribution of the scattered energy and is formed during time interval $t_0 = 2L_t / c$.

Thus, target RCS becomes at a time-dependent magnitude (the concept of instantaneous RSC was introduced). The image changes with viewing angle variations. In this case the target secondary pattern is nonstationary and variable. The scattered signals do not interfere and form no secondary pattern "nulls". This promotes the steady target viewing. Some target elements may have the frequency bandwidth out of the UWB signal spectrum. Such elements are frequency filters and change the shape furthermore.

The 5th change of the shape occurs at the reception. The reason for this is the same as for the radiation, that is the time shift between the current pulses induced by the electromagnetic field in the antenna elements located at various distances to the target.

The 6th change occurs during the signal propagation through the atmosphere because of different signal attenuation in various frequency bands.

The real example of a UWB signal reflected from a target is given in Fig. 2.

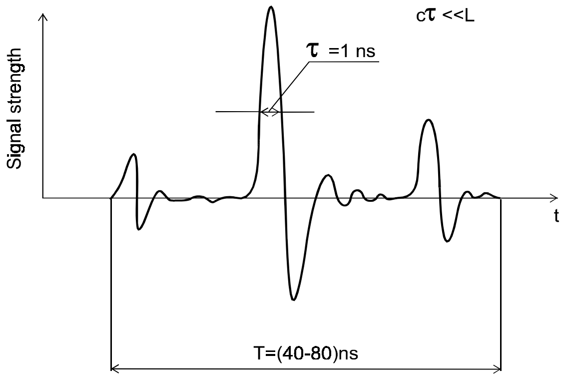

**Fig. 2.**

### 3.2. The Dependence of the Antenna Pattern on the Signal Length and Waveform

When the condition $L\cos\Theta > c\tau$ is satisfied, the signal waveform begins to vary depending on the direction of radiation (reception), i.e. on the space coordinates. In this case an unambiguous correspondence between the signal amplitude and its power inherent in the narrow-band oscillations is not available. This circumstance hinders the construction of any conventional antenna pattern based on the field. Therefore, the antenna pattern construction based on the energy is accepted for the UWB signals (Fig. 3). These antenna patterns have fundamental distinctions from the similar antenna patterns of antennas emitting harmonic and quasi-harmonic signals. They do not feature a lobe nature.

The other difference is that variations of the ratio between $c\tau$ and the radiator spacing $d$ of an antenna array can change the width of the main lobe of the antenna pattern of the array. With the decrease of $\tau$ or the increase of $d$, the antenna pattern width decrease for both the UWB signal and the narrow-band one.

However, in contrast to the latter, the UWB pattern structure does not become multi-lobe, owing to the absence of the interference of the oscillations of individual radiators. Theoretically, this method can be used to make the antenna pattern of an antenna emitting the UWB signal as narrow as is desired.

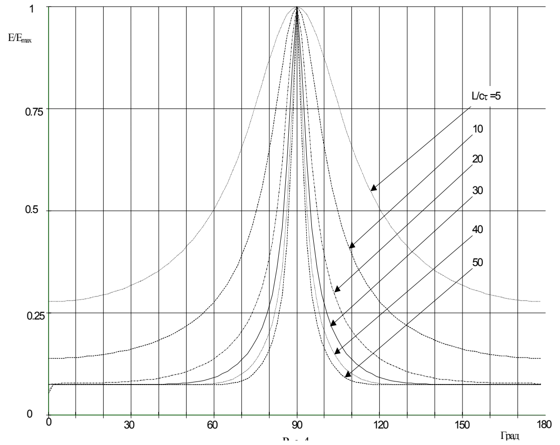

**Fig. 3.**

Thus, the antenna pattern for the UWB signal depends not only on angular coordinates, but also on the time-dependent waveform which is designated as $S$. Therefore the expressions for the UWB signal antenna pattern will take the form: $P(\Theta,\varphi,S,t)$ and $W(\Theta,\varphi,S,t)$. Since the antenna pattern of any antenna radiating or receiving the UWB signal becomes dependent on the signal waveform and duration, it is obvious that the directivity factor $G(\Theta,\varphi,S,t)$, the gain factor $K(\Theta,\varphi,S,t)$ of the antenna and its effective cross-section $A(\Theta,\varphi,S,t)$ become also dependent on the signal parameters.

## 4. Moving Target Selection in the UWB Radar

One more distinction of the UWB radar from a narrow-band one emerges when operating under passive jamming conditions.

A small pulse volume permits moving targets to be separated without using the Doppler effect. If over the repetition period $T$ a target travels a distance exceeding a range element (30 cm at $\tau = 1$ ns), then when interleaved periodic subtraction is applied the signal of this target will be separated and the signals of stationary or low-mobility targets will be suppressed. The following condition has to be met in order to operate such IPC system:

$$c\tau < 2V_R T \,,$$

where $V_R$ – the radial velocity of a target. This system of selection lacks “blind” velocities and does not impose special requirements on the coherence of radiated signals. The target velocity is always unambiguously measured. The target radial velocity $V_R$ can be determined in the selection system by the variation of the range to target. The minimal determined velocity of a target is equal to:

$$V_{R\min} = c\tau / 2T \,.$$

Over the pulse repetition period, however, the quantity of interferences entering into and leaving a small pulse volume may become comparable with the quantity of interferences residing in this pulse volume. This may lead to a significant decorrelation of interferences and the decrease in the efficiency of the alternate-period compensation equipment. Thus, two contradicting tendencies emerge with the decrease of the pulse length and the reduction of the radar pulse

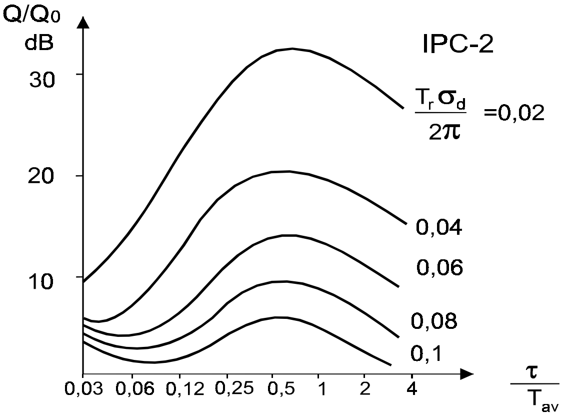

**Fig. 4.**

volume. Namely, the reduction of interference power and the increase in their interperiod decorrelation. Fig. 4 shows the signal-to-interference ratio $Q/Q_0$ dependence on the pulse length $\tau$. This Figure has the following notations:

$\omega_d$ – Doppler frequency of interference;

$Q$ – signal-to-interference ratio at the alternate-period compensation output;

$Q_0$ – signal-to-interference ratio at $\tau = 1$ and $\omega_d / T = 0.1$.

The parameter of the family of curves is the ratio of the average Doppler frequency to the pulse repetition frequency $\omega_d / T$. The plots show that as the pulse length decreases, the signal-to-interference ratio is initially increasing owing to the pulse volume reduction, and then it drops down due to the increase in the interperiod decorrelation of noise. For very small pulse lengths, the alternate-period compensation system ceases to work completely and the increase in the signal-to-interference ratio is accounted for by reducing the amount of interference within the pulse volume.

For the more efficient double alternate-period compensation of interference, the mentioned regularities are evident more clearly owing to a higher sensitivity of this alternate-period interference compensation to the correlation properties of interference. Thus, the use of the moving target indication is advisable for sufficiently narrow-band interferences (e.g. local things) and a sufficiently high repetition frequency, which is used in short-range radars.

## 5. Detection of Target in the UWB Radar

During the process of target location UWB signal changes its shape many times including the cases of signal scattering from target bright points. As a result a returned signal is transformed into the sequence of pulses with random parameters. Such signal is often named "target image", because it carries knowledge of not only target presence and target coordinates, but also target structure. Proper image processing makes possible to recognize a target and to form a radioimage of it. At the initial stage of location, before target recognition, it is necessary to detect target. It is not advisable to use for the UWB signal detection the traditional methods, such as optimum signal processing by matched filtering or correlation with the reference signal, as the structure of UWB returned signal is fully unknown.

In principle, the detection of an unknown multi-unit target can be realized. If the number of independent resolution intervals, $P$, arranged along a target is higher than the number of intervals, $Q$, including brilliant points, then all combinations of $P$ intervals taking $Q$ brilliant points at a time need be taken into account for obtaining optimal detector. However, the realization of this algorithm requires a very large number of processing channels.

Methods for quasi-optimum processing of such signals are well known. But all quasi-optimum detectors suffer from significant losses compared to optimum detector. So it is very important to develop an optimum detector for UWB signals scattered by a complex target.

The repetition period $T$ is the only known parameter of such signals. This parameter may be used for development of the optimal detector for UWB signals. It uses, as the reference signal, the signal received in the adjacent repetition period and delayed for time interval $T$. So the received signal is not compared to the reference signal as in a traditional correlator but to the identical echo signal. In this case the background noise in two adjacent repetition periods are noncorrelated. Thus the signal shape becomes the parameter that determines the efficiency of such correlation detector (Fig. 5). This signal processing is named the interleaved periodic correlation processing (IPCP).

The scheme in Fig. 5 has three dissimilarities from the conventional correlator:

a) the received signal is compared not with the radiated one, but with the signal scattered by a target;

b) noises are fed to both correlator inputs; at the correlator outlet we have the distribution function for the product of normally distributed noises;

c) the integration period $T_i$ is determined not by the

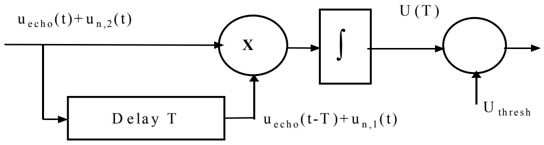

**Fig. 5.**

radiated signal duration, but by the observation interval, that is, by the scattered signal duration (if a target physical length is $L_t$, the integration time is equal to $T_i = (2L_t / c) - \tau$, where $\tau$ is the duration of a radiated signal).

As it is rather difficult to have analytical expressions for the distribution functions of the normally distributed noises product at the IPCP outlet, we use mathematical modeling to plot the detection characteristics.

Fig. 6(a) and 6(b) show the detection characteristics of IPCP for a signal scattered by a stationary target for two values of false alarm rate $10^{-2}$ and $10^{-4}$ ($D$ – probability of detection, $q$ – ratio signal-noise).

These Figures also show the detection characteristics of a conventional correlator for fully known signal. In order to make the comparison valid, the duration of the received signal is taken equal to the duration a radiated signal (one point target).

The analysis of results shows the following.

The IPCP detection characteristics approach the conventional correlator detection characteristics for high false alarm rates ($10^{-2}$). The difference between positions of these characteristic increases with reducing the false alarm rates ($10^{-4}$). This can be explained by the long duration of the "tails" of the distribution function for the product of normally distributed noises. In IPCP the given level of false alarm rate can be maintained by setting up the threshold level higher than in the conventional correlator. At the same time the detection characteristics of IPCP are much better than those of the energy detector.

Fig. 7 shows the dependence of the detection characteristics on the integration time $T_i$ (determined by target's length). The false alarm rate $10^{-4}$ and the integration time $T_i$ equal to $2\tau$, $10\tau$, and $20\tau$ were taken for the modeling. This Figure also shows the detection characteristic for a conventional correlator. It is seen from the picture that with increasing the target length, the IPCP detection characteristic for a stationary target approaches more and more the conventional correlator characteristic when it detects the fully known signal.

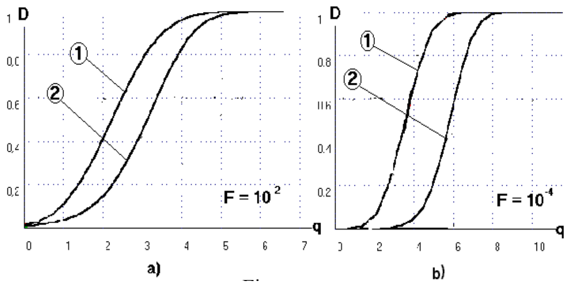

**Fig. 6.**
*1. Traditional correlator for fully known signal;*
*2. IPCP for stationary target*

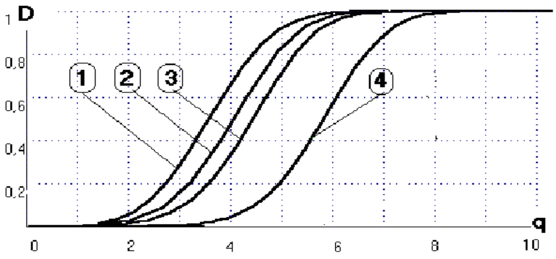

**Fig. 7.**
1. *Traditional correlator for fully known signal for $T_i = 2\tau$;*
2. *IPCP for a stationary target for $T_i = 20\tau$;*
3. *IPCP for a stationary target for $T_i = 10\tau$;*
4. *IPCP for a stationary target for $T_i = 2\tau$*

The reason for this is that the distribution function for the normally distributed noises product approaches the normal distribution, while integrating the noise samples.

## 6. Detection of the Moving Target

Above, we have considered the detection characteristics for a stationary target. If a target is moving, then emerges the problem concerning the target's passing from one resolution cell to another during the pulse repetition period. We can solve this problem by using a multi-channel scheme, similar to Doppler filtration system, which provides the optimal detection of moving targets. The similar multi-channel scheme can be used for the selection of optimal integration time T while detecting targets with various physical lengths L. The losses resulted from the multi-channel configuration of the scheme can be calculated using the conventional methods that are valid for the similar multi-channel digital Doppler systems.

## References

1. I. Immoreev. Use of Ultra-Wideband Location in Air Defence. Questions of Special Radio Electronics. Radiolocation Engineering Series. Issue 22. 1991, pp. 76-83.
2. I. Immoreev. Ultrawideband (UWB) Radar Observation: Signal Generation, Radiation and Processing. European Conference on Synthetic Aperture Radar (EUSAR'96). Konigswinter, Germany. 1996.
3. I. Immoreev. Ultrawideband Location: Main Features and Differences from Common Radiolocation. Electromagnetic Waves and Electronic Systems. V.2, № 1, 1997, pp. 81-88.
4. I. Immoreev. Signal Processing in Ultra Wide Band (UWB) Radars. Fifth International Conference on Radar Systems (RADAR'99). France, Brest, 1999.
5. I. Immoreev, J.D. Taylor. Selective Target Detecting

Short Pulse Ultra- wideband Radar System. Euro Electromagnetics (EUROEM 2000), Scotland, Edinburgh, 2000.

6. I. Immoreev. “Main Features Ultra-Wideband (UWB) Radars and Differences from Common Narrowband Radars” in book «Ultrawideband Radar Technology», Edited by James D. Taylor, CRC Press, Boca Raton, London, New Work, Washington, 2000.
7. I. Immoreev. “Features of Signals Detecting in the UWB Radars” in book «Ultrawideband Radar Technology», Edited by James D. Taylor, CRC Press, Boca Raton, London, New Work, Washington, 2000.
8. I. Immoreev, Wu Shunjun. “Use Ultra Wideband Radar Systems for Increase Information About Target,” 2001 CIE International Conference on Radar, RADAR 2001, Beijing, China, October 15-18, 2001.

## ОСНОВНЫЕ ВОЗМОЖНОСТИ И ХАРАКТЕРИСТИКИ СВЕРХШИРОКОПОЛОСНЫХ РАДАРОВ

*И.Я. Иммореев*

В этой обзорной статье обсуждаются различия между сверхширокополосными радарами и обычными узкополосными. Приведены особенности генерирования, излучения и обработки сверхширокополосных радарных сигналов, связанные с изменением формы сигнала в процессе локации, в виде взаимозависимостей между формой сигнала и направленностью антенны и другими параметрами. Показаны возможности получения радиоизображения объекта.

## ОСНОВНІ МОЖЛИВОСТІ ТА ХАРАКТЕРИСТИКИ НАДШИРОКОСМУГОВИХ РАДАРІВ

*І.Я. Імморєєв*

У даній оглядовій статті обговорено відмінності між надширокосмуговими радарами та звичайними вузькосмуговими. Наведено особливості генерування, випромінювання та обробки надширокосмугових радарних сигналів, пов’язані зі зміною форми сигналу в процесі локації, у вигляді взаємозалежностей між формою сигналу та спрямованістю антени та іншими параметрами. Продемонстровано можливості отримання радіозображення об’єкту.