LOCATING THE BURIED OBJECT USING UWB SYSTEM WITH HILBERT TRANSFORM AND THE LEAST SQUARE CURVE FITTING ALGORITHM

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ABSTRACT

This paper proposes a new method to improve the accuracy of locating buried object using Hilbert transform combined with the least square curve fitting algorithm (LSCF) in impulse radio ultra wide-band (IR-UWB) system. In buried object locating methods, the UWB pulse is considered as an ideal candidate in a short-range with high spatial resolution. Howerver, the power of UWB signals rapidly reduce while traveling in propagation medium, hence detecting reflected UWB pulses are difficult. The Hilbert transform is applied to the correlation function to enhance the detection of reflected UWB pulses, and to increase the accuracy in determining the propagation time and to locate the buried object more accurate when combined with the LSCF method. The analytical expression is validated by Matlab simulation and the locating errors used to assess the performance of systems. The numerical results indicate that the proposed method has higher accuracy than the conventional ones.

ĐỊNH VỊ ĐỐI TƯỢNG BỊ CHÔN VÙI SỬ DỤNG HỆ THỐNG UWB VỚI BIẾN ĐỔI HILBERT VÀ THUẬT TOÁN PHÙ HỢP ĐƯỜNG CONG BÌNH PHƯƠNG NHỎ NHẤT

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TỪ KHÓA

Công nghệ UWB
Biến đổi Hilbert
Đối tượng bị chôn vùi
Thuật toán phù hợp đường cong
Xung Gauss

TÓM TẮT

Bài báo đề xuất một phương pháp mới để cải thiện độ chính xác của việc định vị đối tượng bị chôn vùi bằng cách sử dụng phép biến đổi Hilbert kết hợp với thuật toán phù hợp đường cong bình phương nhỏ nhất (LSCF) trong hệ thống băng thông siêu rộng xung vô tuyến (IR-UWB). Trong các phương pháp định vị đối tượng bị chôn vùi, xung UWB được coi là một ứng cử viên lý tưởng trong phạm vi ngắn với độ phân giải không gian cao. Tuy nhiên, công suất của tín hiệu UWB bị suy giảm nhanh chóng khi thu phát trong môi trường lan truyền, do đó việc phát hiện các xung UWB phản xạ về là rất khó khăn. Biến đổi Hilbert được áp dụng cho hàm tương quan nhằm nâng cao khả năng phát hiện xung UWB phản xạ, tăng độ chính xác trong việc xác định thời gian lan truyền và việc định vị đối tượng bị chôn vùi chính xác hơn khi kết hợp với phương pháp LSCF. Biểu thức phân tích được xác thực bằng mô phỏng Matlab và sai số định vị được sử dụng để đánh giá hiệu quả thực hiện của hệ thống. Các kết quả tính toán chỉ ra rằng phương pháp được đề xuất có độ chính xác cao hơn so với các phương pháp thông thường.

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1. Introduction

Buried object locating systems in the underground or in structures using nondestructive technique (NDT) play an important role in modern life especially in rescue, and testing the imperfection of material structures. There is a variety of techniques which have been developed for detecting and locating the buried object by NDT such as ground penetrating radar (GPR) [1], acoustic transmission [2], microwave SAR imaging [3], ground penetrating synthetic aperture radar (GPSAR) [4],... Among these techniques, the data processing methods in the GPR system are more widely used due to its advantages of fast, convenient data collection, high image resolution, and nondestructive testing capabilities.

The GPR system transmits pulses of electromagnetic waves at difference frequencies depending on the type of application. At the boundaries between layers of the medium or between the buried objects and medium, there will be reflected waves back to the receiving antenna due to the difference in dielectric properties. Traditional systems use a narrow band signal to modulate a sinusoidal carrier signal and the resulting radargram is an image (B-scan image) that shows the difference regions of heterogeneity in the survey medium. The hyperbolic feature in B-Scan images of GPR is the most common shape found to detect distinct objects in the survey medium. In the literature, there are many studies which have been conducted to analyze the shape of hyperbolic for detecting and locating the buried objects such as Hough transform [5], neural network [6], [7], template matching [8]. The size of buried objects can be predicted by CNN model [6], [9]. For improving the detection of deep targets, the multiresolution time-frequency analysis technique by the log-Gabor filters [10] is proposed.

These above techniques can detect various types of metallic and plastic buried objects and the size of them but greatly affected by environmental characteristics, noise and cannot determine the wave speed as well as the dielectric constant of the medium. Besides, the methods based on neural network require storing a lot of annotated data, and they rely on pre-trained models. Furthermore, in the GPR systems, the penetration and resolution of the system depend mainly on the signal bandwidth. The narrow bandwidth makes the information capacity of the radio system limited and have practically exhausted the information opportunities in range resolution and target characteristics. To solve this problem, a new penetrating radar system was developed to transmit radio impulse with ultra-wide bandwidth (GPR-UWB). For practical purposes, the UWB radar means radio detection and ranging systems which use signal bandwidths greater than 500 MHz to measure distances with spatial resolutions Δr < 30 cm [11]. Combining the ability of range determination with a fine resolution and the material's penetrating ability of electromagnetic waves can provide a wide range of remote sensing capabilities.

In general, the location of the buried object is determined based on the parameters of the reflected pulse such as received signal strength index, time of arrival (TOA) in which the TOA parameter is commonly preferred for UWB positioning systems [12]. However, the based-TOA technique depends strongly on the method for determining the delay time of the reflected pulse corresponding to the peak of the correlation function. Hence, the error of the estimated TOA depends on the transceiver synchronization and the determining correlation peak. In order to increase the accuracy in determining the propagation time of UWB pulse and locating the buried object of GPR UWB system, in the paper, a method of applying Hilbert transform combined with LSCF is proposed. The proposed method is applied to locate a single buried object in both homogeneous and heterogeneous medium with the high accuracy.

The rest of the paper is organized as follows. Section 2 describes the system model and methodology for the proposed method. In Section 3, we present the simulation results to evaluate the proposed method performance in comparison with previous method using Matlab software. In Section 4, we draw conclusions and outline areas for future work.

2. Research methodology

2.1. System model

A system using UWB technology for detecting and locating the buried object is illustrated in Figure 1. This paper specifically examines a transmission medium consisting of two layers with relative permittivities (dielectric constants) denoted as ε_1 and ε_2, respectively. The transmitted UWB pulses denoted as $s(t)$ are generated at the transmitter, then go through to the survey medium and reflected back from the buried object, the boundary between the layers. The reflected pulses denoted as $r(t)$ contain information about the location of the buried object which is defined in two-dimensional space including the horizontal parameter of X_{ob} (the direction moving of the GPR UWB device) and the burial depth of d_{ob}. In this paper, we focus on the Signal Processing block based on the proposed method to determine the wave propagation time and the object's location using Hilbert transform combined with CFM.

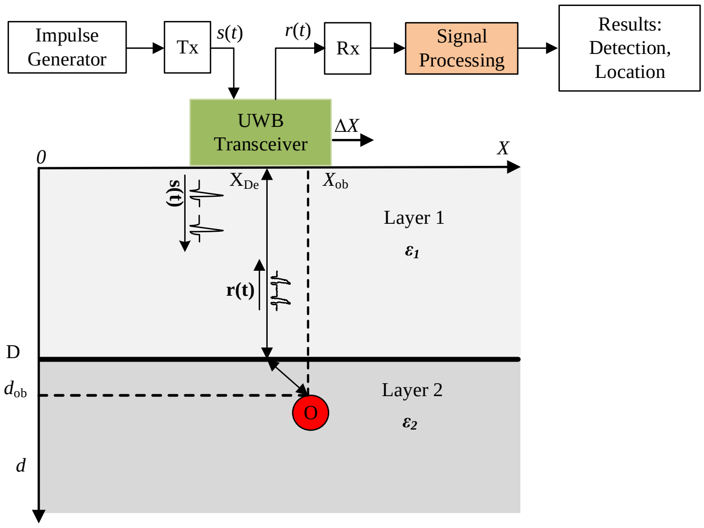

Figure 1. *The UWB system model used detecting and locating buried objects*

In the system model shown in Figure 1, the impulse radio UWB (IR-UWB) is used as transmitted pulse. A IR-UWB pulse takes the form [17]:

$$s(t) = \sqrt{P}\sum_{i=0}^{N_p} g(t - iT_r), \tag{1}$$

where t is time, P is the transmit power, N_p is the number of transmitted pulses, $g(t)$ is the derivatives of the basic Gaussian pulse with pulse width of T_p and the repetitive period of T_r. The derivative of n^{th} order of the basic Gaussian is:

$$g_n(t) = E_n \frac{d^n}{dt^n} e^{\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right]}, \tag{2}$$

where τ_p is a time normalization factor and E_n is normalized energy of $g_n(t)$. The reflected pulse $r(t)$ has the form:

$$r(t) = A_1 A_{12} s(t - \tau_1) + A_2(1 - A_{12}) s(t - \tau_{ob}) + n(t), \tag{3}$$

where A_1, A_2 are the attenuation factors of the medium with layer 1 and 2 respectively; A_{12} is the reflection factor from the boundary between two layers; $n(t)$ is additive white Gaussian noise;

and τ_1, τ_{ob} are the propagation time from the transceiver to the boundary and the buried object respectively.

In conventional UWB receivers, the propagation time is determined by calculating the peak of the correlation function (CF) in Equation (4):

$$R(\tau) = \int_{-\infty}^{+\infty} r(t)\omega(t-\tau)dt \quad (4)$$

ω(t) is the template pulse generated at the receiver, usually use g(t) pulse.

Determining the peak of the CF correctly depends on choosing the quantization step to take the value of CF. In this work, in a simpler approach, we propose to use the Hilbert transform applied to the CF for determination the propagation time. The Hilbert transform [13] of the correlation function (HTCF) is determined:

$$\hat{R}(t) = HT\{R(t)\} = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{R(u)}{(t-u)} du\ . \quad (5)$$

Figure 2 presents the shapes of the autocorrelation function of a UWB pulse using a 2nd order Gaussian pulse normally and when applying the Hilbert transform.

As depicted in Figure 2, the propagation time (delay time) can be determined by identifying the argument value that results in the Hilbert transform of the correlation function reaching zero:

$$\tau = \text{Arg}\left\{\hat{R}(t) = 0\right\}. \quad (6)$$

The propagation velocity through layers of medium is [14]:

$$V_i = \frac{c}{\sqrt{\varepsilon_i}};\ \ i = 1,2\ , \quad (7)$$

where ε_i is the relative permitivity of the i^{th} layer and $c = 3\times10^8$ *m/s* is the velocity of light in the vacuum medium. The distance from the transceiver and the buried object is determined based on propagation time and velocity as follows:

$$l = \frac{1}{2}V_1\tau_1 + \frac{1}{2}V_2\tau_2\ , \quad (8)$$

where τ_1 and$_2$ represent the propagation time of UWB pulses through the first and second layers, respectively.

2.2. Locating method

In Figure 1, to determine the location of buried objects '**O**', the tranceiver is moved horizontally and emits a chain of UWB pulses after every movement step of ΔX, the pulses are transmitted along the d direction. The system parameters of ε_1, X_{ob}, D, ε_2, d_{ob} are estimated based on the propagation time values τ_1, τ_2 and coordinates in the direction X (X_{De}) of the transceiver. The relationship between those parameters are expressed in the following equations:

$$\tau_1 = 2\frac{D\sqrt{\varepsilon_1}}{c}\ , \quad (9)$$

$$\tau_{obi} = \tau_1 + 2\frac{\sqrt{\varepsilon_2\left((d_{ob} - D)^2 + \left(X_{ob} - X_{De_i}\right)^2\right)}}{c}\ . \quad (10)$$

In the case of the buried object '**O**' is in the first layer of medium, we have the following relationship:

$$\tau_{obi} = 2\frac{\sqrt{\varepsilon_1\left(d_{ob}^{\ 2} + \left(X_{De_i} - X_{ob}\right)^2\right)}}{c}\ , \quad (11)$$

where $X_{Dei}= i\Delta X$ is the position of device at the i^{th} moving times, τ_1, τ_{obi} are the propagation time from the device to the boundary between the two layers and to the buried object, respectively. In this paper, we propose a method of determining these times and the unknown parameters using the Hilbert transform combined with LSCF [14]. Accordingly, τ_1, τ_{obi} are determined by Equation (6) and ε_1, X_{ob}, D, ε_2, d_{ob} are calculated using LSCF which makes the deviation function in Equations (12) reach the minimum value:

$$DF=\sum_{i=1}^{N}\left[\tau_{obi}-f\left(X_{Dei}\right)\right]^2=\sum_{i=1}^{N}\left[\tau_{obi}-\left(\tau_1+2\frac{\sqrt{\varepsilon_2\left(\left(d_{ob}-D\right)^2+\left(X_{ob}-X_{De_i}\right)^2\right)}}{c}\right)\right]^2, \quad (12)$$

where N is the number of movements of transceiver and DF is a function of variables ε_1, X_{ob}, D, ε_2, d_{ob}.

In addition, as seen in Figure 3, the value of τ_1 is constant when the transceiver is moved, so with the value of τ_1, the value of the remaining unknown parameters can be estimated.

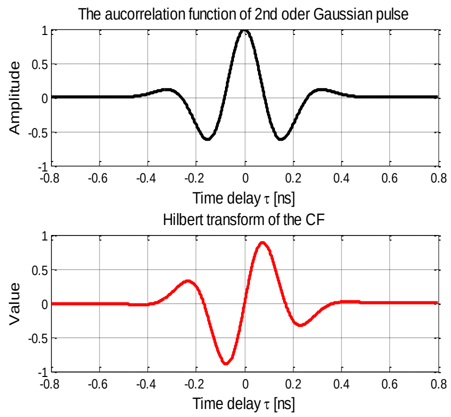

Figure 2. *The shapes of autocorrelation function and Hilbert transform*

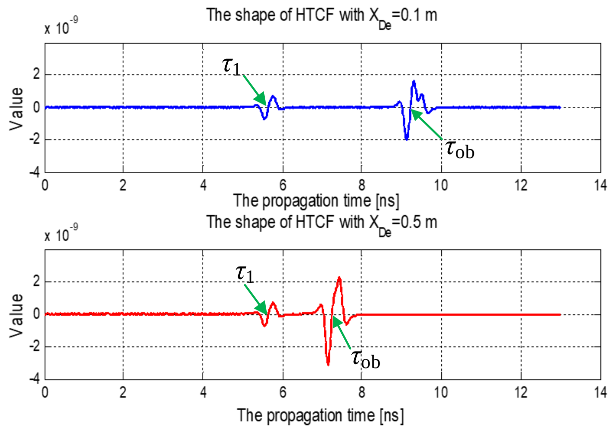

Figure 3. *The shapes of HTCF in IR-UWB system as shown in Figure 1 with different position of the transceiver (X_{De}) and the location of buried object is (X_{ob}, d_{ob})= (0.4, 0.5) m, the boundary at the depth of D=0.4 m*

Denote **Y** as a vector of unknown parameters to be determined, **Y** is represented as:

$$\mathbf{Y}=\left[D,\varepsilon_2,X_{ob},\,d_{ob}\right]. \quad (13)$$

Hence, Equation (12) can be rewritten as follows.

$$DF=\sum_{i=1}^{N}\left[\tau_{obi}-f\left(X_{De_i},\mathbf{Y}\right)\right]^2 \quad (14)$$

The value of τ_{obi} corresponding to X_{Dei} is determined using the Hilbert transform, with the values of τ_{obi}, X_{Dei}, the vector **Y** is estimated so that the value of DF in Equation (14) reaches the minimum value. In this paper, a nonlinear estimation method called least square curve fitting is proposed to be applied to estimate the unknown vector **Y**. The estimation procedure is shown in Figure 4.

The graph of τ_{ob} versus X_{De} is a curve, the **Y** vector is estimated to best fit this curve. According Figure 4, the values of the unknown parameters are estimated as follows.

Step 1-Initialization: The **Y** vector is initialized with any value (usually in the range of (0÷1)) as well as the values of λ (the damping factor is adjusted at each iteration), $\boldsymbol{\theta}$ (the updated step vector), and the number of iterations of K, the initial value of the deviation function is also calculated in this step.

Step 2 - Update values of variables: The **Y** vector is updated by the newone (**Y**+ **θ**) and the deviation function is calculated by the Equation (12). The deviation function reaches its minimum value at zero gradient with respect to **θ** vector, hence **θ** vector can be determined satisfying:

$$\left[\mathbf{J}^T\mathbf{J}+\lambda\,\mathrm{diag}\left(\mathbf{J}^T\mathbf{J}\right)\right]\theta=\mathbf{J}^T\left[\tau-\mathbf{f}\left(\mathbf{Y}\right)\right]. \tag{15}$$

Therefore, **θ** vector is computed as follows.

$$\theta=\left[\mathbf{J}^T\mathbf{J}+\lambda\,\mathrm{diag}\left(\mathbf{J}^T\mathbf{J}\right)\right]^{-1}\mathbf{J}^T\left[\tau-\mathbf{f}\left(\mathbf{Y}\right)\right], \tag{16}$$

where $\mathbf{f}\left(\mathbf{Y}\right)=\left[f\left(X_{Dei},\mathbf{Y}\right)\right]$, and **J** is the partial derivative Jacobian matrix, whose i^{th} row equals:

$$J_i=\frac{\partial f\left(X_{Dei},\mathbf{Y}\right)}{\partial\mathbf{Y}}. \tag{17}$$

The damping factor λ has a non-negative value which is used to increase the convergence speed of the CF algorithm, if the value of *DF* is reduced rapidly, a smaller value of λ can be used, whereas λ can be increased.

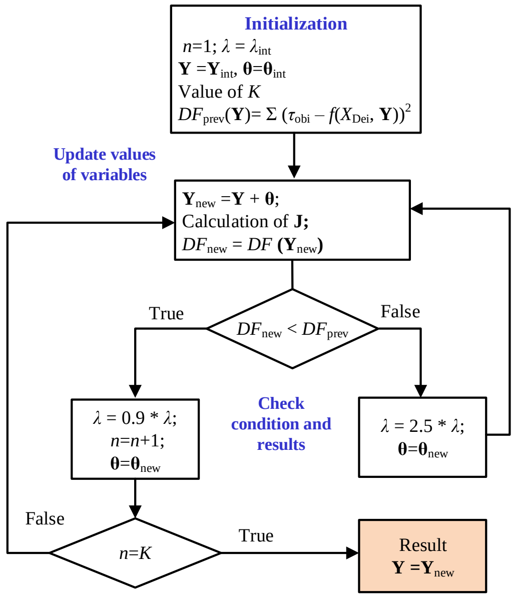

Figure 4. *The flowchart algorithm of the CF method*

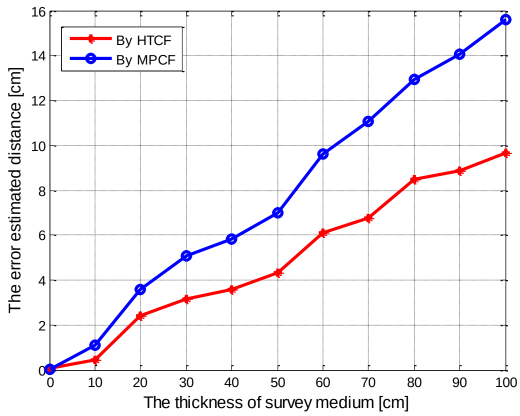

Figure 5. *The errors of estimated distance by MPCF and the proposed HTCF method*

Step 3 – Check condition and results: The updated value of *DF* is checked against the minimum value constraint. If not satisfied, the algorithm repeats steps 2 and 3, vice versa, we have the estimated values of **Y** vector which is the best fitting curve.

In the case of buried object in a homogeneous medium (only one layer), the LSCF is performed with $\boldsymbol{\tau}_{ob}$ determined by Equation (10). In case of heterogeneous medium (from 2 layers or more) LSCF performs with $\boldsymbol{\tau}_{ob}$ determined by Equation (11).

3. Simulation results and discussion

The simulations were perrformed on Matlab software, the errors of estimated values in comparison with the true values were used to evaluate the proposed and conventional methods.The UWB system employed in this research is characterized by parameters listed in Table 1, utilizing a second-order Gaussian pulse. The simulation model is illustrated in Figure 1. Firstly, the simulations were performed to determine the different thicknesses of a homogeneous medium based on the method of determining the maximum peak of the correlation function (MPCF) and the proposed method using Hilbert transform for the correlation function (HTCF).

Secondly, the LSCF is applied to locate the buried object and determine the parameters of the medium.

At the first stage, the survey medium is considered of concrete material with ε=4.5 with various thickness from 0.1 m to 1 m. We compare the exact estimation errors of the implementation of the two methods MPCF and HTCF in determining the thickness of medium by the propagation time (Figure 5). To assess the performance of those methods, the error of estimated distance is defined as:

$$\delta_D = \left| d_{est} - d \right| \ , \quad (18)$$

where d_{est} denotes the estimated distance and d is the true value. As seen in Figure 5, with the same system parameters, the HTCF give smaller errors than the MPCF, the HTCF method outperforms the conventional with average relative error in comparison to the true value is about 7.1% meanwhile with the MPCF, it is about 13.2%. This result comes from the fact that the Hilbert transform is an effective tool in detecting the reflected signals, especially pulsed signals such as IR-UWB [16], hence, the detection of received pulses is significantly enhanced compared to conventional system. Morever, the replacement of determining the delay time with the HTCF changes the search for the maximum location of the CF to the zero crossing location of the HTCF (see Figure 2). This approach is simpler and hence provides more accurate results.

Table 1. *Simulation parameters*

Parameter	Notation	Value
Impulse Width		0.7 ns
Pulse repetition cycle	T_r	0.2 ns
Time normalization factor	τ_P	0.2877 ns
Number of pulses	N_p	100
Movement step of the device	ΔX	10 cm

At the second stage, to determine the relative permitivity and location of the buried object in model system as in Figure 1, the transceiver moved from position 0 in the X axis direction at each movement step ΔX = 10 cm, transmited a sequence of Np pulses, received the reflected pulses, calculated the propagation time from interface D object '**O**' and then LSCF is used to estimate the model parameters. The results is indicated in Figure 6 and Table 2 for two above methods.

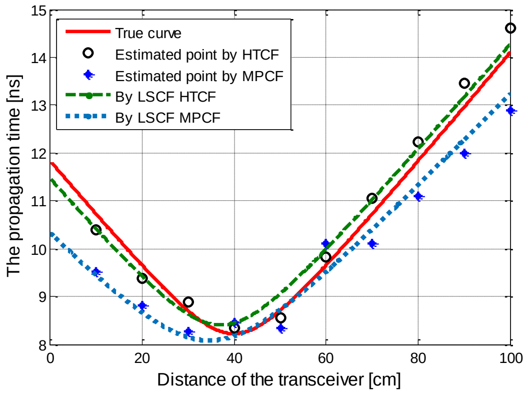

Figure 6. *The curves of propagation time according to the position of transceiver estimated by proposed method*

Table 2. *The simulation results and comparison*

Parameter/Notation	$\varepsilon_1,\varepsilon_2$	***D* [cm], (*X_{ob}*, *d_{ob}*)**
True value	4.5,3.0	50, (40, 60)
By MPCF LSCF	3.1,2.2	56.2 (34.6,70.2)
By HTCF LSCF	4.0, 2.8	53.5 (37.1, 64.9)
Error of MPCF LSCF	1.3,0.8	6.2 (5.4,10.2)
Error of HTCF LSCF	0.5,0.2	3.5 (2.9,4.9)
Error of multiresolution monogenic signal analysis method [10]	--	**5.8**
Error of wide-band chaotic [17]	--	**10**

When compared with the conventional methods, the method based on processing GPR images (multiresolution monogenic signal analysis [7] and wide-band chaotic [31]) have problems with nearby hyperbolas and background noise. Therefore, with the same survey depth D=50 cm, the estimated error of the proposed (3.5 cm) is smaller than in the previous methods (5.8 cm, 10 cm).

However, the proposed method is based on the assumption that each layer of the medium is completely homogeneous and the object's position as a point.

4. Conclusions

In this paper, we propose a method to locate buried objects in the both homogeneuos and heterogeneous environments using Hilbert transform and LSCF for IR-UWB systems. Our analysis indicates that by applying the Hilbert transform to the correlation function at the receiver of the IR system UWB, the accuracy of determining the propagation time and locating the buried object can be improved. The performance of proposed method is assessed based on locating errors with the second-oder Gaussian pulse, however it can be also applied to UWB systems with arbitrary order in locating applications. The identification of object was left in future work.

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