Frequency Band Selection of Radars for Buried Object Detection

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Abstract—Choice of the operational frequency is one of the most responsible parts of any radar design process. Parameters of radars for buried object detection (BOD) are very sensitive to both carrier frequency and ranging signal bandwidth. Such radars have a specific propagation environment with a strong frequency-dependent attenuation and, as a result, short operational range. This fact dictates some features of the radar’s parameters: wideband signal—to provide a high range resolution (fractions of a meter) and a low carrier frequency (tens or hundreds megahertz) for deeper penetration. The requirement to have a wideband ranging signal and low carrier frequency are partly in contradiction. As a result, low-frequency (LF) ultrawideband (UWB) signals are used. The major goal of this paper is to examine the influence of the frequency band choice on the radar performance and develop relevant methodologies for BOD radar design and optimization. In this article, high-efficient continuous wave (CW) signals with most advanced stepped frequency (SF) modulation are considered; however, the main conclusions can be applied to any kind of ranging signals.

Index Terms— Radar resolution, radar signal processing, stepped-frequency radar, ultrawideband signals.

I. INTRODUCTION

The major radar parameters under consideration are the range resolution (ΔR) and the maximum depth of penetration (R\text{MAX}). The attenuation of microwaves in most ground materials depends on the carrier frequency f\text{C} as an exponential function [1]

\[ L_{\text{Att}} \approx \exp(4\pi f\text{C}R/QV\text{M}) \]  

where Q is a quality factor for the given medium (at least for f \geq 10 MHz), R is the range to the target, and \( V\text{M} \) is a wave propagation velocity. Radar imaging in a highly attenuating medium requires the use of low carrier frequencies to increase penetration depth. In Fig. 1, the dependence of wave attenuation on penetration depth is represented for \( f\text{C1} = 50 \text{ MHz}, f\text{C2} = 250 \text{ MHz}, \) and for \( Q\text{1} = 2 \) (wet send), \( Q\text{2} = 20 \) (coal) [2]. This is presented for a typical velocity \( V\text{M} = 2 \cdot 10^3 \text{ m/s} \). It is clear that for the same attenuation parameter the highest penetration depth can be achieved with the lowest frequency. Thus, in wet send (\( Q\text{1} \)) for propagating range \( R = 5 \text{ m} \), the difference in attenuation of ranging signals with these two different center frequencies is about 120 dB, and in coal (\( Q\text{2} \)) for \( R = 40 \text{ m} \), the difference is about 100 dB.

![Fig. 1.](image)

In the first approximation, for the signal with near-rectangular envelope, the range resolution can be described as [3]

\[ \Delta R \approx V\text{M}/2(f\text{H} - f\text{L}) = V\text{M}/2B \]  

where \( f\text{H}, f\text{L} \) are the highest and the lowest frequencies in the ranging signal spectrum, respectively, and \( B \) is the signal bandwidth. It will be shown later that this equation can be used as a potential limit of resolution in highly attenuating medium. Requirements of low carrier frequency and high range resolution lead to ultrawideband (UWB) utilization. The bandwidth of the UWB signal can be characterized by a fractional bandwidth [4]

\[ B_F = 2(f\text{H} - f\text{L})/(f\text{H} + f\text{L}). \]  

The definition of UWB radar that has become commonly accepted is that it is a radar whose fractional bandwidth is greater than 0.25, with respect to a center frequency [5]. UWB signals with low center frequency have fractional bandwidth, that is more than one and tends to two. Radars that employ such signals are considered in this paper and defined as UWB low-frequency (LF) radars.

In any radar for buried object detection (BOD) application, the antenna is the most critical component through which signals must be both transmitted and received. Recent investigations in antenna design for BOD radars have shown that in reality fractional bandwidth of the signal is limited by capabilities of antennas and does not exceed the value of 1.4–1.8 [6]. However, this is enough for effective UWB LF radar performance.

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The ranging signal can use pulses as well as continuous wave form with inner modulation [7]. In this article, a stepped frequency (SF) modulation will be considered, but this does not limit the utilization of method developed here. The SF radar allows high-resolution and high-mean transmitter power as well as use of low-speed components [8]. It operates by transmitting and receiving a series of bursts of narrowband pulses, in which each burst consists of \(N\) pulses stepped between a start frequency \(f_L\) and a stop frequency \(f_H\) in equal, linear increments of \(\Delta f\), such that [3]

\[
f_H = f_L + (N - 1)\Delta f.
\]

To synthesize the short pulse at the receiver output an inverse fast Fourier transform (IFFT) is used. This converts the data into a time-domain pulse response equivalent. Range information is then based on the phase time-delay measurement.

In comparison with conventional radars, UWB LF radars have new features that should be investigated. Their transmitting and receiving signal spectrums are essentially different, as the propagating medium has a frequency response with the characteristic of a low-pass filter, with transfer function \(H(f) = \exp(-\alpha f)\). As a result, both major parameters of the radar \(\Delta R\) and \(R_{\text{MAX}}\) will essentially depend on carrier frequency, signal bandwidth, and parameters of the medium. So this type of radars needs an optimization of their structure and parameters.

The major goal of this paper is to investigate the LF UWB SF radar for BOD, the influence of frequency band choice on its parameters, and represent some ways to increase the radar performance. This analysis is provided by analytical investigations and a specially developed computer model of the radar.

II. Spectrum Utilization Efficiency

A. Signals with Maximal Spectrum Efficiency

For UWB signals, (1) cannot be applied directly because there is a big difference between attenuations for the different components in signal spectrum. In this case, it will be more accurate to operate with average losses over the whole signal spectrum or with attenuation at the highest frequencies. The average losses are

\[
\mathcal{L}_{\text{Att}} = \frac{1}{B} \int_{f_L}^{f_H} \mathcal{L}_{\text{Att}}(f) \, df = \frac{1}{B} \int_{Q_{\text{MIN}}}^{Q_{\text{MAX}}} \frac{Q}{4\pi R} \left[ e^{\frac{\pi f_H R}{Q_{\text{MAX}}}} - e^{\frac{\pi f_L R}{Q_{\text{MIN}}}} \right].
\]

Minimization of \(\mathcal{L}_{\text{Att}}\) in the frequency domain under the condition of constant \(B\) gives

\[
\mathcal{L}_{\text{Att}}\text{min} = \min \{ \mathcal{L}_{\text{Att}} \} \bigg|_{B=\text{const}} = \frac{1}{f_H} \frac{Q_{\text{MAX}}}{4\pi R} \left[ \exp\left(\frac{2\pi R}{Q_{\text{MAX}}}\right) - 1 \right],
\]

that is achieved when \(B_F = 2\) or \(f_L = 0\). The expression (6) means that ranging signals with \(B_F \to 2\) have minimum attenuation in the media for other similar conditions. As a result, radar, which employs such a signal, has the maximal penetrating range.

Thus, a radar for buried object detection with a fractional bandwidth \(B_F = 2\) can be described as a radar with maximal spectrum efficiency (MSE).

B. Comparative Parameters of MSE and Non-MSE Radars

Signals with \(B_F = 2\) are not achievable in practice, and the MSE radar parameters are the potential limits. So it is useful to compare the parameters of real radar with these limits [9]. Equation (6) can be rewritten for \(B_F = 2\) using (2)

\[
\mathcal{L}_{\text{Att}}\text{min} = \frac{Q}{2\pi R N} \left[ \exp\left(\frac{2\pi R N}{Q}\right) - 1 \right].
\]

where \(R_N = R/\Delta R\) is depth of penetration, normalized to the range resolution. This attenuation merely depends on \(R_N\) and the ground parameter \(Q\), which is out of the designer’s control. Dependence \(\mathcal{L}_{\text{Att}}\text{min}\) on \(R_N\) is shown in Fig. 2 (continuous line) for typical \(Q\). From Fig. 2, it is clear that \(R_N\) varies for different \(Q\) parameters. There is a tradeoff between \(\Delta R\) and \(R\) in MSE radar. For example, a signal has 120-dB attenuation in medium for \(Q = 2\) in case of \(\Delta R = 1\) m and \(R = 10\) m as well as in case of \(\Delta R = 5\) m and \(R = 50\) m (for \(B_F = 2\)).

It is important to compare MSE radars with other radars in terms of the maximal penetration depth and the equivalent energy losses. Assume now that reflected signals can be processed properly only if all frequency components of its spectrum are above the detection threshold. The highest frequency of the signal spectrum will have strongest attenuation. At the highest spectral component, these maximal losses can be expressed for the MSE systems using \(B\) against \(f_C\) in (1)

\[
\mathcal{L}_{\text{Att}}\text{min} = \exp\left(\frac{2\pi R N}{Q}\right)
\]

which is plotted in Fig. 2 by dashed lines. So, the radar should provide the given SNR for the highest components in the ranging signal spectrum. The radar equation for BOD radar [1]

\[
\left(\frac{S}{N}\right) = \frac{A \lambda^2}{R_{\text{MAX}}} \cdot e^{-\frac{4\pi R}{Q_{\text{MAX}}}} P_{\text{FR}} \cdot T_S
\]

\[
A = \frac{L \cdot G_{\text{TH}} \cdot G_{\text{REF}} \cdot \sigma}{k_B \cdot T_N \cdot (4\pi)^3}
\]
where

\( (S/N) \) \quad \text{SNR at the output of the matched receiver;}

\( P_{\text{TR}} \) \quad \text{mean transmitting power;}

\( T_s \) \quad \text{integration time;}

\( G_{\text{TR}}, G_{\text{RE}} \) \quad \text{transmitter and the receiver antenna gains, respectively;}

\( \sigma \) \quad \text{target radar cross section;}

\( p \) \quad \text{target dependent parameter (from two to four);}

\( k_B \) \quad \text{Boltzmann’s constant;}

\( T_N \) \quad \text{noise temperature;}

\( L \) \quad \text{mismatch losses.}

Now, using (9), the maximal penetrating depth \( R_{\text{MAX}} \) of any radar with \( B_F < 2 \) can be compared to the maximal penetrating depth, which potentially can be achieved via MSE radar when SNR’s are the same in both systems. Taking into account that, for the system with \( B_F < 2 \), \( \lambda = \frac{\sqrt{\gamma}}{B(2+B_F)} \), we can get

\[
\left[ \frac{1}{R_{\text{MAX}}^2} \right] \cdot e^{-4\pi B_{\text{MAX}}^2 R_{\text{MAX}}^2} = \left[ \frac{1}{R_{\text{MAX}}^2} \left( \frac{2B_F}{2+B_F} \right)^2 \right] \cdot e^{-4\pi B_{\text{MAX}}^2 R_{\text{MAX}}^2 + 2B_F R_{\text{MAX}}^2}.
\]

Dependence (11) is shown in Fig. 3.

The attenuation losses, expressed through the exponential terms in (11), are significantly predominate over others. So we get in the first approximation

\[
\frac{R_{\text{MAX}}}{R_{\text{MAX}}} = \frac{2B_F}{2+B_F} = \eta_k
\]

Dependence (12) is shown in Fig. 3.

Comparing the maximal penetrating depth of two equivalent radars, it can be seen from Fig. 3 that MSE radar with \( B_F = 2 \) (for instance \( B = 0-500 \) MHz) has the depth of penetration equal to its maximal value (\( \eta = 1 \)), while the same radar with \( B_F = 0.5 \) (\( B = 750-1250 \) MHz) has \( \eta = 0.4 \) (it means that depth of penetration of the radar is only 40% of the MSE radar). Using the \( \eta = 0.707 \) as a starting level, all systems with \( B_F > 1.1 \) can be attributed to a class of radars for BOD with high spectrum efficiency (HSE). This means that, for other equal radar parameters, the difference in maximal penetration depths for HSE and MSE radars is less than 30%.

III. MATCHED FILTERING IN HSE SYSTEMS

UWB transmitting and receiving signals have essentially different envelopes due to the nonuniform frequency-dependent attenuation (1). Therefore, UWB requires relevant matched filtering algorithms because of the distortion of the receiving signal envelope.

To have a maximum SNR, the signal should be processed in the filter matched to this signal. In the case of SF signals, the matched filter consists of two parts: filter (window) matched with the signal envelope \( U_{\text{SF}}(f) \) and IFFT processor matched to the carrier frequency (Fig. 5) [10]. When the signal has...
a constant envelope \( U_S(f) = U_S \). IFFT with a rectangular window is a quasioptimal filter. However, when \( U_S(f) \) changes essentially in the frequency, a filter (window) matched to this envelope \( U_S(f) \) should be placed before the IFFT processor. In the BOD radars, the receiving signal envelopes and surface return (clutter) are essentially different. We will have an exponential envelope and another—near symmetrical. This clutter is one of the major problems in BOD. So an utilization of the filter matched to the signal envelope will not only maximize SNR, but reduce the clutter. The SF signal at the input of the matched filter has an exponential spectrum envelope

\[
U_S(f) = U_0 \cdot \exp \left( \frac{-4\pi f R_{\text{MAX}}}{Q V_M} \right) = U_0 \cdot L_{\text{MAX}}^{-1}(f) \quad (14)
\]

or

\[
U_S(f) = \begin{cases} 
U_0 \cdot e^{-\alpha f}, & f_L < f < f_H \\
0, & \text{otherwise}
\end{cases} \quad (15)
\]

The signal at the output of the matched filter is

\[
U_{\text{OUT}}(t) = \int_{-\infty}^{\infty} U_S(f) H(f) \exp(j2\pi ft) df \quad (16)
\]

where \( H(f) \) is the frequency responses of an appropriate matched filter.

Let’s determine that \( H_r(f), H_\alpha(f) \) are frequency responses of the filters matched to the rectangular (\( \alpha = 0 \)) and the exponential envelopes (\( \alpha \neq 0 \)), respectively.

Using filter with \( H_\alpha(f) \), we maximize SNR and increase signal-to-clutter ratio (SCR) parameters because of its mismatching with clutter, which has nearly rectangular spectrum envelope \( U_C(f) \). For the conventional radar, if the signal is received on the background on a thermal noise, the SNR at the output of the filter is [11]

\[
\text{SNR}_C = \frac{P_S}{F_N} = \frac{2}{N_0} \left[ \int_{-\infty}^{\infty} U_S(f) H_r(f) \exp(j2\pi ft_0) df \right]^2. \quad (17)
\]

In case of matched filtering, the maximum SNR is

\[
\text{SNR}_{\text{OPT}} = \frac{2}{N_0} \left[ \int_{-\infty}^{\infty} U_S(f) H_\alpha(f) \exp(j2\pi ft_0) df \right]^2 = \frac{2E_S}{N_0} \quad (18)
\]

where \( N_0 \) is a spectral density of the noise, \( E_S \) is the signal energy, and \( t_0 \) is time when signal reaches its maximum.

In case of processing of the signal with an exponential envelope in conventional ground penetrating radar (GPR), the rectangular window leads to losses in SNR (\( \text{SNR}_C \)). The gain of optimal filtering utilization can be characterized by coefficient \( \rho(\alpha) \)

\[
\rho(\alpha) = \frac{\text{SNR}_C}{\text{SNR}_{\text{OPT}}} = \left[ \int_{-\infty}^{\infty} U_S(f) H_r(f) \exp(j2\pi ft_0) df \right]^2 / E_S. \quad (19)
\]

IV. RANGE RESOLUTION IN UWB RADARS

Another important characteristic of radar is range resolution. The fundamental relationship for the range resolution is associated with ranging signal bandwidth (2). In a case of SF signal utilization, equivalent time-domain and frequency-domain measurements of reflectivity are related by the Fourier transform.

A rectangular frequency spectrum of bandwidth \( B \) has \( \text{sinc}(Bt) \) envelope response in the time domain. The resolution of two such signals with equal amplitudes can be adapted from Rayleigh’s criterion for optical resolution [3] and defined when the peak of the first pulse response is directly over the first minimum of the second pulse response. This corresponds to the \(-4 \text{ dB} \) point, where both peaks are separated by \( 1/B \). In BOD radar, the receiving signal is distorted due to the ground exponential attenuation, depending on frequency, and its response is essentially wider than response of transmitted signal with rectangular shape. The degradation of the range resolution is a function of the attenuation parameter \( \alpha \) and signal bandwidth \( B \).

To examine this effect in the BOD radar at the output of the optimal receiver for signals with different bandwidth, let us at first consider SF signal with rectangular spectrum envelope defined by

\[
U(f) = \begin{cases} 
U_0, & f_L < f < f_H \\
0, & \text{otherwise}
\end{cases} \quad (22)
\]

At the output of the matched filter, the magnitude of the signal normalized to its maximal value is

\[
S_{\text{out}}(t) = S_{\text{out}}(1/2B) \left[ \frac{S_{\text{out}}(0)}{S_{\text{out}}(1/2B)} \right] \approx -4 \text{ dB}, \quad (23)
\]
Fig. 7. Comparison of the signal levels, which corresponds to the point \( t = 1/2B \), at the output of the matched filter for different signal bandwidths and for different attenuations.

Now let us consider signal with an exponential spectrum envelope \((15)\). Its normalized magnitude at the output of the filter matched with an exponential pulse is

\[
S_{\text{outy}}(t) = \frac{\alpha^2}{\alpha^2 + (2\pi t^2)^2} \frac{e^{\alpha B} + e^{-\alpha B} - 2 \cos(2\pi t B)}{e^{\alpha B} + e^{-\alpha B} - 2}. \tag{24}
\]

The level that corresponds to the \( t = 1/(2B) \) is

\[
S_{\text{outy}} \left( \frac{1}{2B} \right) = \frac{\alpha^2}{\alpha^2 + (\pi/B)^2} \left( \frac{e^{\alpha B} + 1}{e^{\alpha B} - 1} \right)^2. \tag{25}
\]

Taking into account that an expression \( \left( \frac{e^{\alpha B} + 1}{e^{\alpha B} - 1} \right)^2 \) aspires to one for \( B \) in range of our interest, we can write

\[
S_{\text{outy}} \left( \frac{1}{2B} \right) = \frac{\alpha^2}{\alpha^2 + (\pi/B)^2}. \tag{26}
\]

As it can be seen, the width of the impulse response does not depend on \( f_L \) or \( f_H \) and, consequently, on fractional bandwidth. It is a function of ground attenuation parameters and absolute signal bandwidth. Dependence \((16)\) is shown in Fig. 7 for different attenuation parameters. As it follows from the figure, range resolution decreases with attenuation rising. At the level of \(-4\) dB, where two rectangular responses \((L_{\text{Att}} = 0)\) are just at the point of being resolved, the signal with exponential pulse spectrum abruptly degrades. Thus, for usual radar parameters \( B = 300 \) MHz and \( L_{\text{Att}} = 50 \) dB, two signal peaks are separated by \( 1/B \) s at the level of about 0.8 dB, which leads to the lack of ability to resolve these signals.

Considering the \(-4\)-dB level as a threshold of resolution, it is possible to calculate the “degree” of the signal expansion in comparison with the signal that has rectangular spectrum envelope with frequency band \( B \).

From \((24)\)

\[
\left. \frac{\alpha^2}{(\alpha^2 + (2\pi t^2)^2)} \frac{e^{\alpha B} + e^{-\alpha B} - 2 \cos(2\pi t B)}{e^{\alpha B} + e^{-\alpha B} - 2} \right|_{t = 1/2B} = -3.92 \text{ dB} \tag{27}
\]

or

\[
\alpha^2(e^{\alpha B} + e^{-\alpha B} - 2 \cos(2\pi B)) \equiv 0.4(\alpha^2 + (2\pi t^2)^2)(e^{\alpha B} + e^{-\alpha B} - 2). \tag{28}
\]

The numerical solution of \((25)\) gives range resolution in time of two signals with exponential spectrum \( \Delta t_{\text{exp}} \) after matched filtering.

The effect of resolving ability degradation can be seen in Fig. 8 (continuous line) more clear, where signal range corresponding to the level \(-4\) dB at the output of IFFT processor, is demonstrated for different parameters of attenuation and signal bandwidth.

The process of the signal widening due to envelope shape distortion for the high attenuation \((L_{\text{Att}} > 50 \text{ dB})\) is quicker than the process of narrowing due to increasing of spectrum bandwidth \( B \). For example, signals with \( B = 200 \) MHz and \( B = 500 \) MHz for \( L_{\text{Att}} = 50 \) dB have practically the same range resolution, which approximately corresponds to the signal with \( B = 100 \) MHz, operating in nonattenuating medium. The effect of UWB signal widening in the frequency attenuating medium is a negative factor that can be a serious obstacle to simultaneous improvement of the radar range resolution and signal performance. Nevertheless, it is not difficult to show that the fundamental relationship for the range resolution \((2)\) can be applied for the case of UWB signal propagation in highly attenuation medium.

To correct the spectrum envelope of receiving signal, the transmitting one can be preliminarily distorted. If attenuation is known, then signal can be transmitted with energy, which has an inverse effect on the attenuation exponential dependence on frequency. This effect has been used in \([12]\) for transmitting power optimization in GPR. It can be achieved by transmitting of the signal with different frequency step duration as well as with different power for each carrier frequency.

For the sake of visuality, let us consider the case of power varying. If propagating medium has attenuation, described by \((1)\), then signal can be transmitted with different energy for each frequency in such a manner that its spectrum will have envelope

\[
U_{\text{TR}}(f) = U_0 e^{\alpha R f/Q \beta_M} = U_0 e^{\alpha f}. \tag{29}
\]

In consequence of signal propagating through the medium, which can be represented as a low-pass filter with transfer function \( P(f) = e^{-\alpha f} \), the receiving signal spectrum will
and corresponding range resolution. In this case, the dependence of the resolution on attenuation and signal bandwidth is shown in Fig. 8 by dashed lines. It has mirror symmetry with the graphs for the case when transmitting signal spectrum has a rectangular shape. So, the expression (2) is still valid for considering condition, but only for maximal propagating range \( R_{\text{MAX}} \) for the given attenuation. For other ranges of propagation, the resolution will get worse. In general, the transmitting signal can be preliminary distorted in such a way that radar will have maximal range resolution for any deviations. The case when transmitting signal has predistortion with \( \alpha \), which corresponds to the attenuation at the half of the maximal depth, is demonstrated in Fig. 9. For example, at the depth of 5 m, resolution of the signal with \( B = 300 \text{ MHz} \) will be \( t = 1.6 \cdot 10^{-9} \text{ s} \), while at the depth of 10 m, \( t = 6 \cdot 10^{-9} \text{ s} \), i.e., the radar performance degrades.

The preliminary spectrum distortion does not give the perfect improvement of the range resolution along the whole depth. It can be matched only in a relatively small area. Moreover, taking into account that \( Q \) and \( V_M \) parameters are preliminary unknown, it can be concluded that resolution maximization for the given propagating range has to be realized with the aid of adaptive algorithms, which is not the subject of this paper.

Fig. 11. Range resolution of signals, passed through the medium with different attenuation. For \( L_{\text{Att}} = 50 \text{ dB} \), nondistorted signals are shown with dashed line and signals that have been preliminary distorted are shown with a continuous line.

\[ U_{\text{REF}}(f) = P(f) \cdot U_{\text{TR}}(f) = U_0 \cdot e^{-\alpha f} \cdot e^{\alpha f} = U_0 \]  

(30)

\[ U_{\text{REF}}(f) = P(f) \cdot U_{\text{TR}}(f) = U_0 \cdot e^{-\alpha f} \cdot e^{\alpha f} = U_0 \]  

(30)

Fig. 12. Losses \( \xi(\alpha, \alpha_0) \), when filter is matched to the signals with \( \alpha_0 \) as the function of attenuation parameter \( \alpha \).

V. RESULTS OF COMPUTER SIMULATION

To confirm signal-to-clutter reduction effect of optimal matched filtering, the SF BOD radar has been simulated for \( B_F = 1.3 \). Fig. 10 demonstrates the gain in SCR (24) with optimal filtering, when \( L_{\text{Att}} = 50 \text{ dB} \). It is clear, which for \( L_{\text{Att}} = 50 \text{ dB} \) optimal filtering gives an improvement of about \( 7 \text{ dB} \) in the SCR, this almost coincides with theoretical results (Fig. 6).

The effects of resolving ability degradation and of preliminary distortion of the transmitted signal are illustrated in Fig. 11. Two reflected SF signals with \( B_F = 1.6 \), passed
through the ground with different attenuation, are represented here. As it can be seen, an insignificant increasing of the attenuation ($\Delta L_{\text{Att}} > 30$ dB) leads to the signal becoming impossible to resolve. The dashed line illustrates two signals passed through the frequency attenuating medium (ground, $L_{\text{Att}} = 50$ dB) that cannot be resolved. The continuous line demonstrates the ability to resolve the same signals but with predistortion according to the known ground attenuation.

VI. PRACTICAL ASPECTS OF THE METHOD’S APPLICATION AND EXPERIMENTAL RESULTS

A. Uncertainties of the Losses in the Ground

Optimal filtering (14), (27) as well as signal structure optimization [12] assumes that the ground losses $L_{\text{Att}}$ (8) or coefficient $\alpha$ (15) are preliminary known. However, these parameters cannot be measured or predicted exactly. The general attenuation of the signal, which can be easily estimated during radar operation, depends on two unknown parameters—radar target cross section $\sigma$ and antenna-ground coupling $L$ (9, 10). Let’s consider a situation when a filter is matched to the signal with $\alpha = \alpha_0$ and has a frequency response $H_{\alpha_0}(f)$, but the real received signal $U_{\alpha_0}(f)$ has an envelope with $\alpha \neq \alpha_0$. This situation has been analyzed in [10].

In this case output, $\text{SNR}_{\alpha}$ will be less than optimal $\text{SNR}_{\alpha_0}$ (18) but more than in case of the rectangular window utilization (17). These losses of mismatching can be expressed with coefficient $\xi(\alpha, \alpha_0)$

$$\xi(\alpha, \alpha_0) = \frac{\text{SNR}_{\alpha}}{\text{SNR}_{\alpha_0}} = \frac{\left[ \int_{-\infty}^{\infty} U_{\alpha_0}(f) H_{\alpha_0}(f) \exp(i2\pi t_0) df \right]^2}{E_S}$$

(31)

where it is assumed that all signals have the equal energy $E_S$. These losses as a function of $\alpha$ and $\alpha_0$ are shown in Fig. 12 by dashed lines. Fortunately, the function of losses $\xi(\alpha, \alpha_0)$ is smooth, which allows us to estimate that practical gain will be not more than 2–3 dB lower than the potentially achievable one. Losses in SCR (20) are analogous to $\xi(\alpha, \alpha_0)$.

The same approach can be applied in estimation of the range resolution improvement for the given depth of penetration. Suppose that signal has been predistorted with coefficient $\alpha_0$ and transmitted through the medium with attenuation $\alpha = \alpha_0$, then range resolution of this signal will have an optimum value $\Delta t_{\alpha_0}$. If the real attenuation is $\alpha \neq \alpha_0$, resolution became worse $\Delta t > \Delta t_{\alpha_0}$. For the known frequency band and penetration depth, this degradation can be determined by the next factor

$$\nu(\alpha, \alpha_0) = \frac{\Delta t_{\alpha_0}(\alpha_0)}{\Delta t(\alpha)} \text{[dB]}$$

(32)

Fig. 13 demonstrates this effect for $B = 400$ MHz and $R = 10$ m. Thus, if the real attenuation is $\alpha = 2 \cdot 10^{-8}$, and signal has been distorted with $\alpha_0 = 3 \cdot 10^{-8}$ (continuous line), range resolution degradation will be about 4 dB. In absence of the signal predistortion ($\alpha_0 = 0$), range resolution degradation will be about 10 dB.

B. Dependence of Attenuation on Frequency

The elaborated method of improvement of the BOD radar performance is based on the assumption that losses have an exponential dependence on a signal carrier frequency. Experimental data, obtained with gated, SF GPR and published in [8] have confirmed in average this assumption through the frequency band 50–350 MHz. This paper demonstrates a significant reduction of the higher frequencies strength in comparison with low frequencies because of the highly attenuating soil in the investigated area.

C. Predistortion of the Transmitting Signal

The experiments also included a procedure of transmitting signal with different energy for each frequency, described in Section IV, to improve image clarity. The image in Fig. 14, adapted from [8] was taken across a shallow culvert on the banks of the Brisbane River by the radar stepped in frequency from 50 to 350 MHz. Fig. 14(a) demonstrates the appearance...
of significant signal widening because of the severe attenuation at higher frequencies, which causes a reduction in the resolving power. Transmission of the signal with exponential spectrum considerably improves resolution [see Fig. 14(b)]. To show this effect more clearly, a synthesized pulse extracted from the radar image of Fig. 14 for range profile 100 is represented in Fig. 15. It can be seen that signal with exponential spectrum (continuous line) leads to essentially better resolution than signal with rectangular spectrum (dashed line).

VII. CONCLUSION

This paper has considered the influence of the frequency band choice on the radars for BOD and optimal filtering and developed the relevant methodologies for radar design and optimization. In particular, it was shown the following.

1) Ranging signal with fractional bandwidth $B_F = 2$ provides the maximum penetration depth for the given resolution, which corresponds to the maximal spectrum efficiency. The subclass of the radars with ranging signals that have $B_F \geq 1.1$ can also be classified as high spectrum efficiency radars as they provide not more than 30% of the penetration depth reduction under the same conditions.

2) Signal received from the underground targets has a near exponential envelope that requires a filter (window) match with this signal. This optimal filtering provide not only maximum SNR, but reduce a clutter above the ground by 10–12 dB.

3) Attempt to design radar that can overcome strong ground attenuation (more than 50–100 dB) conflicts with a problem of a signal width extension and relevant range resolution reduction. The potential boundary for the range resolution in this case depends on the signal bandwidth $B$. To maximize resolution that corresponds to this bandwidth $B$ and one particular value of depth, the transmitted signal magnitude should be predistorted. However, it is often impossible to know the medium electrical parameters in advance in practical situations. In this case, different sorts of adaptive and autofocusimg algorithms should be used to optimize the range resolution.

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