Physical Aspects of Microwave and Radar Applications

Target Detection in Continuous-Wave Noise Radar in the Presence of Impulsive Noise

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In the paper a problem of target detection in continuous-wave noise radar in the presence of impulsive external noise is addressed. Noise radar uses random or pseudo-random waveform as a sounding signal. Classical correlation receiver used in noise radar is optimal for external noise with Gaussian distribution. If the external noise has distribution different than Gaussian, for example impulsive noise, the performance of the detection is degraded. In order to restore the sensitivity lost due to the impulsive noise, a robustification method is proposed. In the method, a nonlinear function is applied to the signal in order to remove the outliers. The method is verified on real-life signals.

PACS: 84.40.Xb

1. Introduction

In the paper the problem of target detection in radar is addressed. Radar (radio detection and ranging) is a device, which uses electromagnetic waves to detect and localize targets [1, 2]. The most popular radars nowadays are pulsed radars, which transmit energy for a short period of time, and then switch to the receive mode [1]. In this case one antenna can be used for transmitting and receiving. There are also radars which transmit electromagnetic wave continuously. An advantage of continuous-wave (CW) radar is that it can achieve the same detection range as a pulsed radar with much lower peak power. This is very advantageous from the point of view of low probability of intercept (LPI) capability of a radar. Usually, CW radars use two separate antennas, one transmitting and one receiving. A diagram of a CW radar is shown in Fig. 1. The radar illuminates the scene with the transmit antenna. In the scene there are both stationary and moving targets. In the paper we focus on the detection of moving targets. The reflections from stationary targets are generally unwanted, and they are called clutter. Clutter can severely degrade the radar performance. Additionally, the reflections from moving targets have to compete with the noise received by the radar.

The most popular CW radars are frequency modulated continuous wave (FMCW) radars, where the frequency of the transmitted signal is modulated by a periodic sawtooth wave. Despite low power emitted by FMCW radar, a specific periodic modulation can be relatively easily detected by the enemy, which will reveal the presence of a radar. One of the possibilities of improving LPI properties of a radar is to use noise or pseudo-noise waveform instead of deterministic and periodic waveform [3]. In this way, the signal transmitted by the radar is more difficult to distinguish from the external noise.

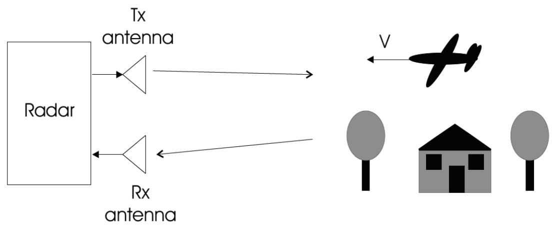

Fig. 1. Diagram of a continuous-wave radar for detection of moving targets.

The paper deals with a problem of target detection in continuous-wave noise radar in the presence of impulsive external noise. Typically the detection in noise radar is performed based on a correlation receiver [3–5]. The received signal is correlated with a copy of the transmitted signal. Under the assumption of Gaussian distribution of the external noise, this solution is optimal. This assumption is motivated by the fact that if a large number of independent random phenomena contribute to the interference, its distribution will tend to the Gaussian distribution. This is indeed a situation often encountered in practice. However, the assumption on the normal distribution of the signal disturbance is not always true. The main reason for this is that the external noise may arise from man-made electromagnetic interference with highly impulsive nature. The sources of this interference include unintentional emitters, such as computers, electric motors, as well as telecommunication systems, such as cell phones, wireless networks, etc. In the case of impulsive noise disturbance, the correlation receiver is no longer optimal. In the considered case of continuous-wave radar the impulsive external noise causes the raise of the cor-

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relation noise floor. This may significantly impair the detection capabilities of the radar.

In this paper we show the results of measurements of real-life scenario where impulsive noise was present. A method for robustification of the detector is presented. The method consist in introducing a nonlinear transformation of the received signal. The paper is an extension of work presented in [6].

2. Noise radar principles

In the paper we deal with continuous-wave narrow-band noise radar for detection of moving targets. This kind of radar operates in a similar way as a traditional radar, however, instead of a deterministic signal, a noise waveform is transmitted. The noise waveform can be generated by a noisy electronic component (e.g. diode), or a pseudo-random waveform can be generated digitally. On the receive, the reflected signal is compared with the transmitted one by means of correlation. Because the transmitted signal is random in nature, it has to be stored in order to calculate the correlation. For this reason the radar has to be equipped with two receiving channels: one for the reference and one for the echo signal. A block diagram of a noise radar is shown in Fig. 2.

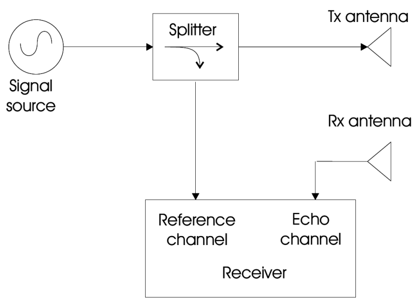

Fig. 2. Block diagram of a noise radar.

The transmitted signal can be described in the following way:

$$x_t^{\mathrm{RF}}(t) = \Re\{x_t(t)\exp(\mathrm{j}2\pi f_{\mathrm{c}}t)\}, \tag{2.1}$$

where $x_t^{\mathrm{RF}}(t)$ is the transmitted signal at the radio frequency (RF), $x_t(t)$ is the complex baseband noise or pseudo-noise waveform, and f_{c} is the carrier frequency, and $\Re\{\cdot\}$ denotes the real part. Usually, the bandwidth of the complex envelope $x_t(t)$ is much lower than the carrier frequency f_{c}, therefore, narrowband signal approximation can be used.

Assuming that the motion of an object can be described by a first order equation in the form

$$r(t) = R + Vt\,, \tag{2.2}$$

the signal reflected from a target can be expressed as

$$x_r^{\mathrm{RF}}(t) = A^{\mathrm{RF}} x_t^{\mathrm{RF}}\left(t - \frac{2r(t)}{c}\right) = \Re\left\{x_t\left(t - \frac{2r(t)}{c}\right)\exp\left(\mathrm{j}2\pi f_{\mathrm{c}}\left(t - \frac{2r(t)}{c}\right)\right)\right\}, \tag{2.3}$$

where A^{RF} is the amplitude of the echo, and c is the speed of light. On the receive, the RF signal is demodulated to the baseband. The RF signal is composed of two parts: complex envelope and carrier frequency. Due to different properties of those two parts, the time-variable delay $r(t)$ has different influence on them. Because the complex envelope $x_t(t)$ is narrowband, the velocity component Vt of the $r(t)$ has negligible effect on the change of time scale. Only the constant component R influences the delay of the envelope $x_t(t)$. On the other hand, the velocity component Vt changes the time scale of the carrier waveform, which is observed as a frequency shift of the envelope $x_t(t)$ in the baseband. The constant delay caused by R influences the phase of the complex amplitude of the target echo: $A = A^{\mathrm{RF}}\exp(\mathrm{j}4\pi f_{\mathrm{c}}R/c)$.

Taking into account the above considerations, the signal reflected from a k-th moving scatterer can be modeled in the baseband as

$$x_{rk}(t) = A_k x_t\left(t - \frac{2R_k}{c}\right)\exp\left(\mathrm{j}\frac{4\pi}{\lambda}V_k t\right), \tag{2.4}$$

where A_k is the complex amplitude of the k-th target, R_k is the range to the k-th target, V_k is the k-th target radial velocity, and $\lambda = c/f_{\mathrm{c}}$ is the wavelength. The signal received by the radar is the sum of the signals reflected from the individual scatterers and the received noise $w(t)$:

$$x_r(t) = \sum_{k=0}^{K-1} x_{rk}(t) + w(t)\,. \tag{2.5}$$

Using this model, the reflections from stationary targets and the leakage from the transmit to receive antenna can also be modeled by setting V_k to 0.

Since only the moving targets are of interest, the target echoes with zero Doppler shift ($V_k = 0$) should be removed from the received signal. This is necessary because the correlation sidelobes corresponding to those stationary targets can mask useful moving target echoes. In order to remove the stationary target echoes, an adaptive filter can be applied [7–9]. The adaptive filter can be realized in various ways, however, the most practical one is a lattice filter. A block diagram of the lattice filter is shown in Fig. 3 [10] ($x_t(n)$ and $x_r(n)$ are the sampled versions of the analog signals $x_t(t)$ and $x_r(t)$, respectively). The filter consists of two parts: lattice predictor and tapped-delay line. The lattice predictor decomposes the input signal $x_t(n)$ into set of orthogonal signals. At each stage of the predictor, backward prediction error $b_i(n)$ signal is calculated, which has a property, that it is orthogonal to the backward prediction errors from different stages, that is

$$\langle b_i(n), b_j(n)\rangle = 0 \quad \text{for} \quad i \neq j\,. \tag{2.6}$$

Thanks to this property the components of the transmitted signal $x_t(n)$ which correlate with the echo signal $x_r(n)$ are removed independently of each delay. Because the correlation of noise waveform is sensitive to the Doppler shift, only the components of echoes with no frequency shift will be removed from the echo signal $x_r(n)$. In this way, the leakage between the transmit and receive antennas, as well as reflections from stationary targets will be suppressed, and the output signal will contain only the moving target echoes and the external noise.

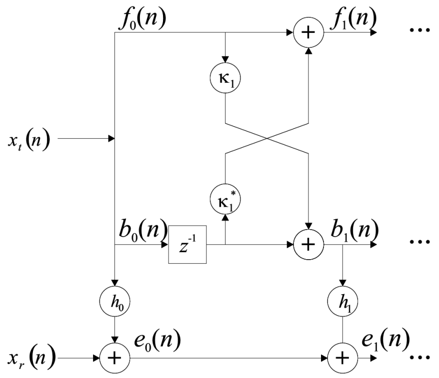

Fig. 3. Block diagram of a lattice filter.

After the clutter removal procedure, the classical correlator receiver realized according to the following equation is applied:

$$\psi(R,V) = \int_{-T_{\text{int}}/2}^{T_{\text{int}}/2} x_r'(t) x_t^* \left(t - \frac{2R}{c}\right) \times \exp\left(\mathrm{j}\frac{4\pi}{\lambda} V t\right) \mathrm{d}t\,, \tag{2.7}$$

where $x_r'(t)$ is the received signal after clutter removal, and T_{int} is the integration time. If the values of R and V for which the correlation is calculated correspond to the appropriate values in the received signal $x_r'(t)$, a correlation peak appears. The correlation (2.7) is often referred to as crossambiguity function. In practical applications the above equation is realized as an appropriate sum of discrete signals. Signal reception based on correlation, or equivalently on matched filtering, is a classical approach used in communications, radar, sonar, seismology, etc. Under the assumption of Gaussian distribution of the interference $w(t)$, this is the optimal solution of the detection problem. However, if the interference has different than Gaussian distribution, the performance of the correlator is degraded.

The target detection is performed by comparing the absolute value of the crossambiguity function $|\psi(R,V)|$ with a threshold. Usually, a constant false alarm rate (CFAR) algorithm is used for this purpose [11]. In the simplest form of CFAR, a mean power level of the noise signal is estimated by averaging signal from adjacent resolution cells. This is called cell-averaging CFAR (CA-CFAR). Next, the value from cell under test (CUT) is compared with a threshold calculated with respect to the estimated noise power. If the value of CUT exceeds the threshold, a detection is declared. The detections are then further processed by the tracking algorithm.

3. Impulsive noise

Usually, in radar systems it is assumed that the noise component $w(t)$ originates from the thermal noise of the receiver. The power of this noise can be calculated from a well known formula [1]:

$$P_w = kT_0 B_r\,, \tag{3.1}$$

where k is the Boltzmann constant, T_0 is the noise temperature of the receiver and B_r is the receiver bandwidth. The thermal noise can be very well modeled with Gaussian distribution of the form

$$\text{pdf} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right). \tag{3.2}$$

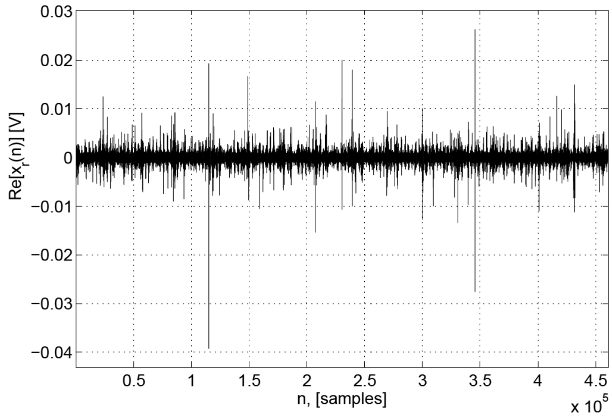

Fig. 4. Real part of the received signal.

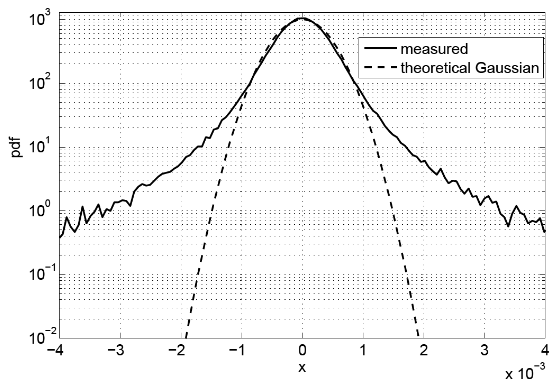

Fig. 5. Measured and theoretical (Gaussian) probability density function of the real part of the signal.

In reality, however, the assumption that the noise in the received signal originates only from the thermal noise

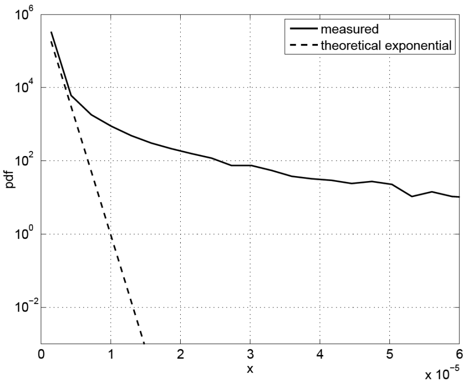

Fig. 6. Measured and theoretical (exponential) probability density function of the squared magnitude of the signal.

of the receiver, and therefore is Gaussian, may not be valid. The electromagnetic spectrum is increasingly more occupied. This results from introduction of new communication standards: wireless computer networks, cellular telephony, digital television, etc. However, apart from intentional transmitters, there are also unintentional sources of electromagnetic radiation, such as electric motors, computers, etc. Those facts suggest that the noise received by a radar system may be dominated not by the thermal noise of the receiver, but by the external noise. This noise may have distribution different than Gaussian, with heavy tails. This conjecture about impulsive nature of the external noise was confirmed with the experiments carried out by the authors. The experiments were performed by recording a real-life signal from the S band, in the vicinity of 2.4 GHz ISM (industrial, scientific and medical) band. Figure 4 shows the real part of received signal $x_r(t)$ after the application of the clutter removal procedure. The signal after clutter canceling contains the echoes from the moving targets and the received noise. The power level of the target echoes is tens of dB below the noise level, therefore, the signal is dominated by the received noise $w(t)$. As it can be seen the noise is highly impulsive and contains many outliers.

This impression is confirmed by observation of the probability density function (pdf) of the real part of the signal. Figure 5 shows the pdf of the received signal and the pdf corresponding to the theoretical Gaussian distribution of the thermal noise (3.2). The pdf of the recorded signal has much heavier tails than the theoretical normal distribution predicts. Similar results are obtained with the squared amplitude of the signal shown in Fig. 6. In theory, when the real and imaginary parts of the received signal are Gaussian, the squared amplitude should have scaled χ^2 distribution with two degrees of freedom, which is equivalent to the exponential distribution. However, as Fig. 6 shows, the measured pdf has much heavier tail.

Since the external noise is not Gaussian, the correlator realized according to (2.7) is no longer the optimal solution. It can be shown that the impulsive noise does not change significantly the pdf of the absolute value of the crossambiguity function $|\psi(R,V)|$, however, it increases the level of the noise floor.

4. Robust detection

A simple heuristic solution of the problem of impulsive noise is to apply a nonlinear transformation of the signal in order to remove the outliers — the samples of the signal significantly exceeding the values predicted by the normal distribution [12, 13, 6]. The received signal after the application of the clutter cancellation method is processed using the nonlinear transform in the following way:

$$x''_r(t) = f\left(|x'_r(t)|\right) \exp\left(\mathrm{j} \arg\left(x'_r(t)\right)\right), \tag{4.1}$$

that is, the absolute value of the signal is transformed nonlinearly, while the angle is left unchanged.

In Ref. [14] authors have investigated two nonlinear functions $f()$. Both those functions have a quasi-linear region for small values of the argument. If the value of the signal exceeds a certain threshold, the value is saturated (in one of the functions) or set to zero (in the other function). In Ref. [13] authors performed a more detailed analysis and tested other nonlinear functions. It was shown that a function in the following form:

$$f(x) = x \exp\left(-\frac{x^2}{\alpha}\right) \tag{4.2}$$

is characterized by good properties — it provides satisfactory results for a wide range of the parameters of the external noise.

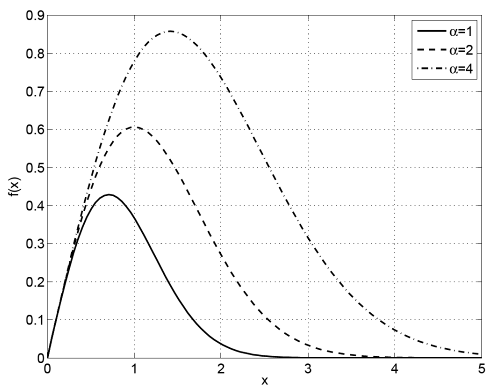

Fig. 7. Robustification functions.

In Fig. 7 an example of the robustification function (4.2) for different values of the scale parameter α are shown. It can be seen that higher values of α correspond to a larger range of values for which the function can be considered linear. Therefore, higher values of α means less influence on the absolute value of the signal.

The robustification function has to be appropriately scaled with respect to the received signal amplitude. One can achieve this by scaling the signal itself. In Ref. [13] we showed that a normalization parameter based on the median of the absolute value of the signal provides good results for a wide range of parameters of impulsive noise

$$C = \mathrm{med}\left(|x_r(t)|\right). \tag{4.3}$$

The robust detection procedure consists, therefore, of the following steps:

- application of the clutter canceller realized as a lattice filter,
- signal scaling using the normalization factor (4.3),
- signal transformation using nonlinear function (4.1),
- calculation of the crossambiguity function (2.7).

5. Numerical results

In order to assess the effects of using the nonlinear transformation on the signal an experiment was conducted. The real-life signal was used in the experiment. In order to obtain a reference level, a target echo was simulated. Next the signal-to-noise (SNR) ratio was calculated for different values of the scaling parameter α. The SNR was measured as a ratio of the peak corre-

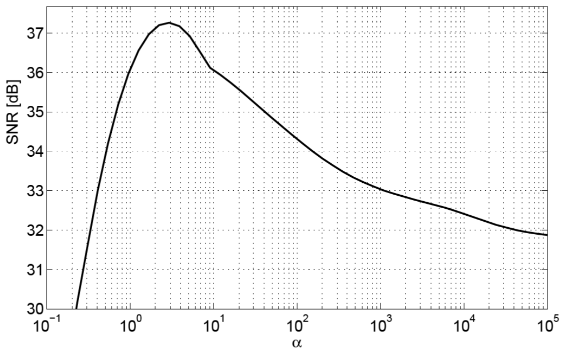

Fig. 8. Signal-to-noise ratio versus the parameter of the robustification function.

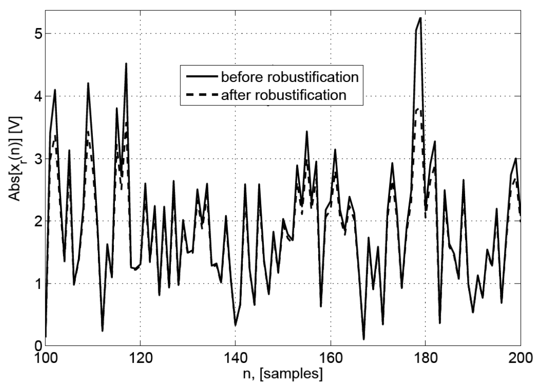

Fig. 9. Signal absolute value before and after application of the robustification function.

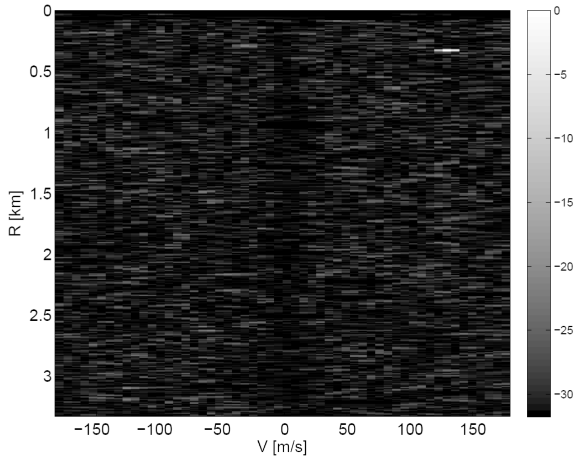

Fig. 10. Correlation function calculated for the received signal with impulsive noise.

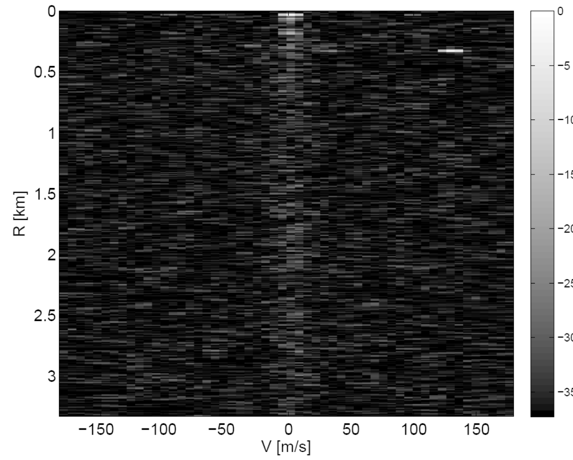

Fig. 11. Correlation function calculated for the received signal after the robustification procedure.

sponding to the simulated target echo to the mean noise floor level. The obtained results are shown in Fig. 8. It can be seen that for small values of α the SNR is also low. This corresponds to a situation when the signal absolute value is significantly reduced. On the other hand, the high values of α correspond to little influence of the nonlinear function on the signal absolute value. In can be seen that the level of SNR tends asymptotically to a certain value corresponding to the lack of robustification. One can see that there is a certain value of α resulting in the highest SNR. The maximum SNR value (corresponding to $\alpha \approx 3$) is approximately 5 dB higher than in the case when the robustification is not used.

The effect of using the nonlinear transformation on the received signal is shown in Fig. 9. The solid line is the absolute value of the received signal, where some outliers are visible. The dashed line is the absolute value of the signal after application of the nonlinear function (4.2).

It can be seen that the high values are limited, therefore the outliers are removed from the signal.

Figures 10 and 11 show the absolute values of the correlation functions $|\psi(R,V)|$ calculated for the received signal $x'_r(t)$ and the robustified signal $x''_r(t)$, respectively. The simulated target echo at $R = 200$ m and $V = 40$ m/s is visible. The minimum value on the plots corresponds to the mean noise floor level. It can be seen that the noise floor level before the robustification was approximately -31 dB, and after the robustification -36 dB.

6. Conclusions

In the paper a method for robustification of the detection in noise radar has been shown. The method was previously proposed by the authors based on computer simulations. In this paper it was shown that the method works well on real-life signals. The robustification algorithm consists in appropriate normalization of the signal and application of a nonlinear function to the signal absolute value. In the presented case a 5 dB increase in the signal-to-noise ratio could be observed after application of the proposed method.

Acknowledgments

This work has been supported by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Programme.

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