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VHF Radar Target Detection in the Presence of Clutter*

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Abstract: *Clutter is the term used to describe unwanted returns (echoes or reflections) in the radar signal. These clutter signals are often as strong as or stronger than the signals returned from the desired target. Doppler frequency forms the basis of target-detection/clutter suppression techniques discussed in this work. Three variants of modern complex algorithm for Very High Frequency (VHF) radar target detection in the clutter environment (ground and/or weather returns) are presented. The problem of clutter and target doppler ambiguity is alleviated by distinctly applying two periodic waveforms. The algorithm performances are investigated by means of Monte Carlo simulation analysis. The results indicate that the designed algorithm with aperiodic waveform is very effective even for relative short data records.*

Keywords: *radar signal processing, adaptive filtering, adaptive detection.*

Introduction

Radars have been used for decades to detect targets for traffic control, air defense, weather prediction, etc. For a particular application there is no perfect solution. The design of radar systems is a constant trade-off as increasing the goodness of one parameter always causes degradation of another parameter. It is well known that L-, S- and X-band radars are more precise in target parameter measurements and give less sensitivity for propagation effects than the lower Very High Frequency (VHF) band radars. On the other hand, the use of metric band significantly improves detection possibilities of the radar against stealth and other type of targets having small Radar Cross-Section (RCS). In addition, VHF radars are less sensitive to clutter, such as unwanted ground and weather returns. The netcentric approach augmented L- or S-band radars by VHF radars, is one of the best solutions that can solve the detection

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and measurement problems efficiently [1]. In this approach the primary function of the L- or S-band radars is to pick up the targets already detected by VHF radar and initiate a track on it. This paper deals with the design of effective detection algorithm for coherent surveillance VHF radar.

The most common technique used to detect the presence of a target, ignoring the presence of clutter, is based on the radial velocity difference between these types of scatters. This difference leads to frequency difference of received pulses, called doppler frequency. One of the major problems in using doppler detectors is the radial velocity v_r ambiguity. Specifically a doppler equal to f_d cannot be distinguished from one equal to f_d plus m multiplied by Pulse Repetition Frequency (PRF), for any integer value of m. Because of the relation between $v_{r\,\max}$, carrier frequency f_0 and PRF, the unambiguity domain [0, $v_{r\,\max}$] remains constant for fixed f_0 and PRF. Different methods using carrier frequency or PRF variation have been proposed to solve the problem ([2-5]). But the application of a concrete solution is often not technologically affordable.

In this work the problem of clutter and target doppler ambiguity in a VHF radar detector is alleviated by distinctly applying two periodic waveforms. The pulse train consists of:

Variant 1 – two subtrains with equal carrier frequencies and different PRF_s ($f_{01} = f_{02}$, $\mathrm{PRF}_1 \neq \mathrm{PRF}_2$);

Variant 2 – two subtrains with different carrier frequencies and different PRF_s, but constant product of these frequencies ($f_{01}\times\mathrm{PRF}_1 = f_{02}\times\mathrm{PRF}_2$);

Variant 3 – pulses with equal carrier frequencies and inverse of PRF, called Pulse Repetition Interval (PRI), alternating between two values, i.e. stagger coded waveform (PRI = $T \pm \Delta T$).

On the basis of these waveforms, three variants of modern complex algorithm for target detection in the clutter environment (ground and/or weather returns) are presented.

The algorithm performances are investigated by means of Monte Carlo simulation analysis. The results indicate that the designed algorithm with aperiodic waveform is very effective even for relative short data records.

Three variants of target detection algorithm

The use of a concrete waveform variant specifies a detection process. Nevertheless each variant of the detection algorithm includes a cascade of filters as follows:

1) Canceller for the clutter suppression and whitening;

2) Matched filters for the modified (by the whitening operation) useful signals;

3) Weighting window for the sidelobe responses reduction (followed by *noncoherent integrator* for *Variant 2*);

4) Threshold processor for the target-present or absent decision.

The classical delay-line *canceller* [6] is realized to suppress and decorrelate **immovable** ground returns. The technique for **moving** clutter adaptive cancellation commonly in use today is based on linear prediction of AutoRegressive (AR) model signals [3]. In this work multisegment Burg's algorithm [7] is used to estimate AR coefficients for moving clutter. The clutter references are taken from each sweep in range rings adjacent to the ring of interest. The expectations in Burg's harmonic-mean formula are replaced by numerator and denominator approximations using one and the same exponential weighting factor [8]. In this way the canceller coefficients are updated without recalculating the total expectation sums.

After the cancellation the clutter residues are supposed as white noise. Due to the easy hardware implementation the *matched filtering* of the signal in noise is configured using a Fast Fourier Transform (FFT) as a doppler filter bank. The outputs of the FFT processor are combined in *weighted* triples to reduce the sidelobe responses. Specifically, the output of each filter is combined with the pair of adjacent filters by using weights of relative values of –0.23, 0.54 and –0.23 (Hamming windowing in the frequency domain). If the transmitted waveform is as described in *Variant 2*, the frequency magnitudes of both subtrains are summed respectively (*noncoherent integration*).

A target present or absent decision is made for each range cell by adaptive *thresholding*, incorporating Constant False Alarm Rate (CFAR) technique. As the shape of the CFAR input can be approximated by a Gaussian function of doppler frequency [7], cell-averaging CFAR (normalizer) [6] is used in this work. For many radar applications, each doppler channel magnitude is passed through a CFAR circuit. For the considered radar application, the target doppler in not required and the CFAR implementation is simplified. This is done by selecting the maximum magnitude and comparing it to the adaptive threshold. This threshold equals the total sum of the reference range cells magnitudes multiplied by a constant which depends on the designed false-alarm probability and the number of reference cells.

As mentioned above, three variants of complex detection algorithm are investigated. These variants are closely related to *Variant 1-3* waveforms as follow:

1) The pulse train is formed as in *Variant 1,* so that the subtrain returns from moving object have spectral peaks in different doppler channels (see Fig. 1). The subtrains' PRFs are chosen according to the required unambiguous maximum detection range and maximum radial velocity of the detected targets. Both subtrains are separately processed. A target present decision is made, if for a given range discrete the threshold value is exceeded at least in one channel. In this way the clutter and target doppler ambiguity is alleviated, but false-alarm requirements force up the threshold values.

2) The pulse train is formed as in *Variant 2*. That means the first subtrain target returns have spectral peak in the channel with number equal to the number of second subtrain target peak, because $f_{01}\times PRF_1 = f_{02}\times PRF_2$ (see Fig. 2). The subtrains' PRFs are chosen according to required unambiguous maximum detection range. Both subtrains are separately processed from the clutter canceling to the Hamming windowing inclusive. Then, in each resolution cell, the pair magnitudes of subtrains doppler channels are summed. Detection decision is made after CFAR processing. The detection in

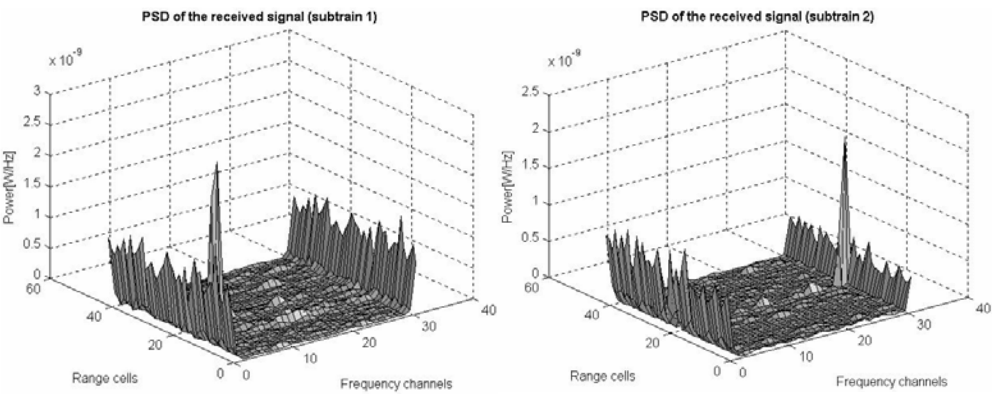

Fig. 1. *Variant 1* – power spectral densities of the subtrain's returns

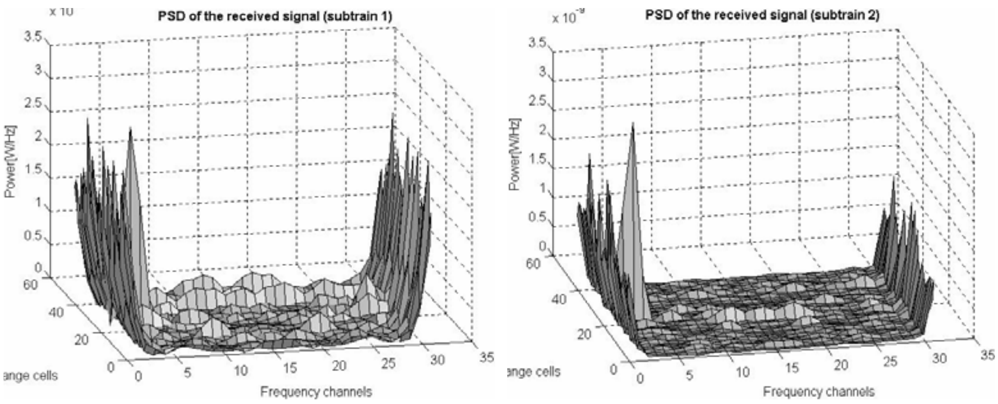

Fig. 2. *Variant 2* – power spectral densities of the subtrain's returns

clutter doppler channel is accomplished with probability level of false alarm a way above the fixed one for other channels. Thus the blind velocity problem is alleviated.

3) The pulse train is formed as in *Variant 3*. The PRI parameters T and ΔT are chosen according to the required unambiguous maximum detection range and maximum radial velocity of the detected targets [2]. The train returns from target of interest have two spectral peaks [5]. They are located in doppler channels with frequencies multiple of $1/(2T)$ and $1/T$ (see Fig. 3), whereas the slowly moving scatter returns have one sharp spectral peak which repetition period equals $1/T$. This fact is used to discriminate – and to cancel the clutter. The received pulse train is processed by the above described cascade of four filters. It must be noted that the FFT, i.e. the coherent integration, is accomplished over whole train signal, which is more then two times longer, then that in *Variants 1-2*.

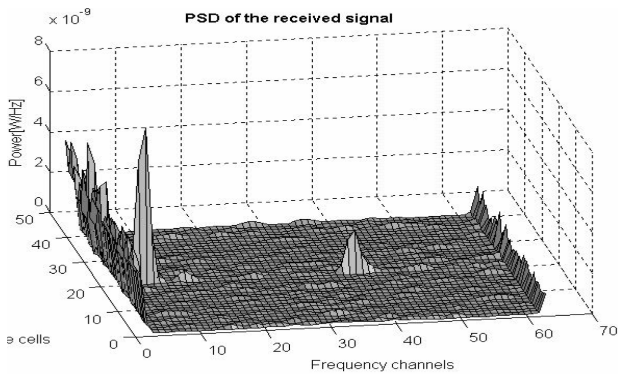

Fig. 3. *Variant 3* – power spectral density of the train's returns

Simulation analysis

Probability characteristics of the designed algorithms in condition of intensive ground and/or weather clutter are investigated. The complexity of the system under consideration (radar, target, clutter and detection algorithms) suggested utilization of a simulation approach to evaluate the detection process. This approach requires realization of adequate models for simulation of target and clutter returns. The simulation scenario consists of distributed ground and/or weather clutter, white Gaussian noise, and point target echo. The clutter is synthesized under the assumptions of lognormal (for ground return) and Rayleigh (for weather return) amplitude models [6]. As a basis two-dimensional Gaussian field is first realized. The target amplitude is modeled assuming case of highly fluctuating target. The return amplitudes are modulated in order to simulate the cosine-squared antenna beam pattern. The noise is white Gaussian. The signals are sampled in range by M resolution cells. The samples from each range resolution cell are modeled as a train of K pulses. The range-azimuth spaces so obtained are arranged in three $M \times K$ matrices in compliance with each investigated waveform variant. This process is repeated numerous times to yield independent realization for given radar, target, clutter and detection algorithm. Then the detectors performances are analyzed in terms of probability of false alarm (P_{fa}) and probability of detection (P_{d}).

The simulated radar parameters are:

- pulse length – 6.7 μs;
- antenna beamwidth – 8°;
- antenna rotation rate – 6 rev/min;
- carrier frequency – 160 MHz for *Variants 1* and *3,*
  166.96 MHz and 153.60 MHz for *Variant 2*;
- pulse repetition frequency – 300 Hz and 214.3 Hz for *Variants 1* and *3*,
  260.9 Hz and 240 Hz for *Variant 2*.

These parameters yield an unambiguous range of approximately 400 km and detection of targets with maximum radial velocity of no less then 1200 m/s.

Figs. 1-3 depict the received signals Power Spectral Densities (PSDs) for the transmitted waveforms considered in this work, M = 42 and K = 60. The target echo is placed in range cell number 21. The clutter (weather returns) radial velocity is 5 m/s, and the target radial velocity is 1200 m/s.

Figs. 4-6 illustrate the probabilities of detection for three algorithm variants in the cases of **unmoving** clutter and different (critical for detector performances) target radial velocities. Monte Carlo simulation of 200 runs is executed for Clutter-to-Noise-Ratio CNR = 70 dB and each given value of the Signal-to-Noise-Ratio SNR = 55÷75 dB. The signal processing parameters are:

- three-pulse delay-line canceller;
- 32-point FFT for *Variants 1* and *2*,
  64-point FFT for *Variant 3*;
- probability of false alarm is $P_{\mathrm{fa}} = 10^{-6}$;

it must be noted that: i) the probability of false alarm for each doppler channel is $P^{1}_{\mathrm{fa}} = 10^{-6.3}$ for *Variant 1*, as $P_{\mathrm{fa}} = 10^{-6} = 2P^{1}_{\mathrm{fa}}(1 - P^{1}_{\mathrm{fa}}) + (P^{1}_{\mathrm{fa}})^2$; ii) the probability of false alarm for zero doppler channel is $P_{\mathrm{fa}} = 10^{-3}$ for *Variant 2;*

- 8 reference cells (surrounding each test cell) formed the adaptive thresholds;

The accomplished analysis shows for the so chosen radar parameters and signal processing technique, the target detection is effective even in the case of powerful clutter environment.

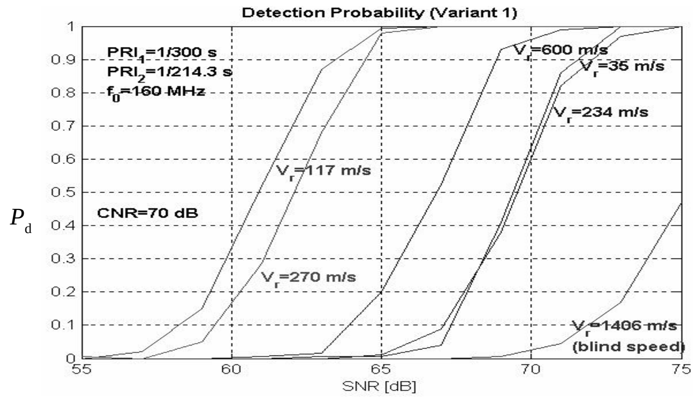

Fig. 4. *Variant 1* – detection probabilities in the case of unmoving clutter

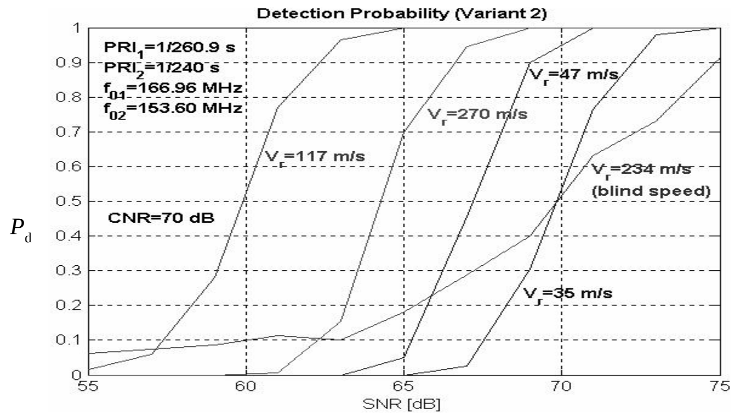

Fig. 5. *Variant 2* – detection probabilities in the case of unmoving clutter

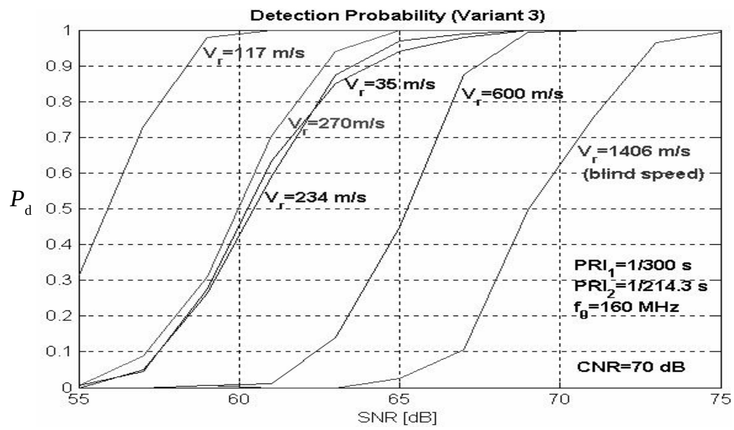

Fig. 6. *Variant 3* – detection probabilities in the case of unmoving clutter

Figs. 7-9 illustrate the probabilities of detection for three algorithm variants in the cases of **moving** clutter with radial velocity V_{meteo} = 15 m/s. The clutter suppression algorithm realizes three-pulse canceller (AR model of order p = 2) using two-segment Burg formula and weighting factor μ = 0.8. The simulated radar parameters and the signal processing parameters are as the above described, but the canceller is adaptive. The Monte Carlo analysis is accomplished in much the same manner as in the case of unmoving clutter. The results are analogous to the previous ones and show high quality of adaptive canceller performance.

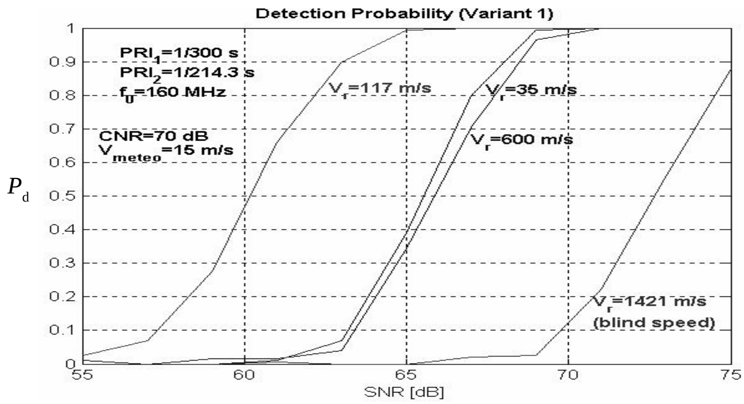

Fig. 7. *Variant 1* – detection probabilities in the case of moving clutter

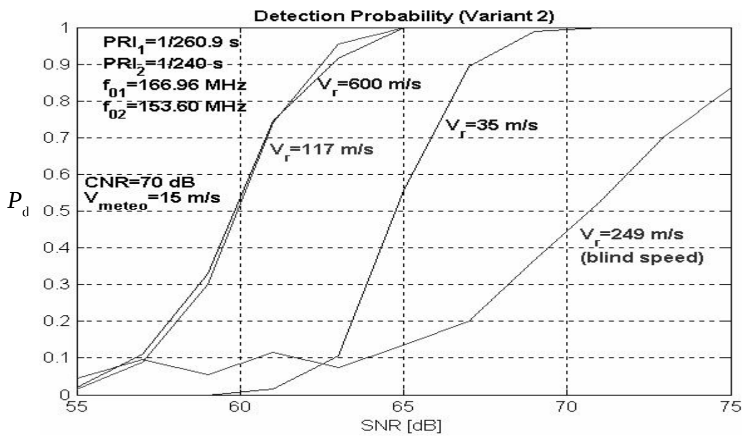

Fig. 8. *Variant 2* – detection probabilities in the case of moving clutter

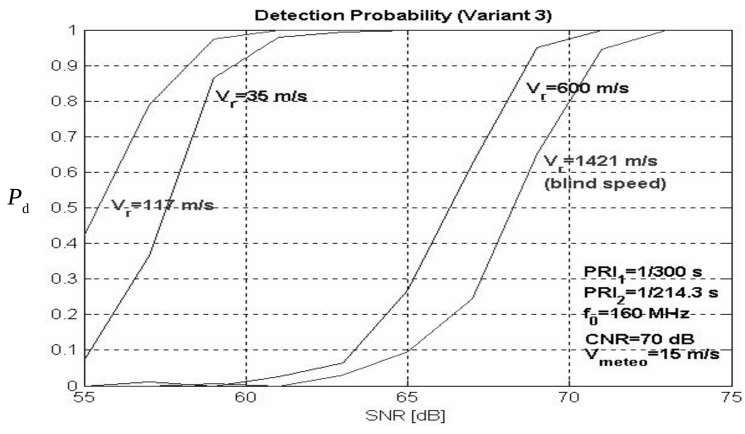

Fig. 9. *Variant 3* – detection probabilities in the case of moving clutter

Conclusions

The main radar problem is to detect the presence of target-signal in clutter signal. The doppler frequency forms the basis of target-detection/clutter suppression techniques discussed in this work. For the considered VHF radar, the target doppler ambiguity is not of concern, being the doppler shift used only to discriminate and to cancel the clutter. The problem of target and clutter doppler ambiguity is alleviated using two periodic waveforms. In compliance with each waveform, three variants of detection algorithm are presented and their probability characteristics are investigated. The accomplished analysis shows:

- The noncoherent integration in *Variant 2* increases probability of detection slightly compared with that for *Variant 1*. The clutter residuals become whiter and the mean number of false alarm slightly decreases. The required carrier frequency variation and unsatisfactory solution of target and clutter ambiguity problem make *Variant 2* less preferable.
- *Variant 1* produces detection characteristics of good quality. It gives an acceptable solution to the clutter and target ambiguity problem. However its implementation is complicated when the antenna is rotating. The main problem is that the beginning and end of the reflective point hits are unknown.
- *Variant 3* produces detection characteristics of high quality. This is as a result of the chosen aperiodic waveform and FFT integration, accomplished over a twice longer sample. This variant is also a good solution to the clutter and target ambiguity problem. Its computational complexity exceeds the *Variant 1* complexity by 20%.

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