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# Performance Prediction of Wideband Unambiguous Target Detection in Diffuse Ground Clutter

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*Abstract*—**In this paper the influence of clutter power spectrum on unambiguous radar target detection with single low pulse repetition frequency wideband waveform is analyzed. Impact of both stationary and diffuse clutter components for different signal bandwidths and coherent processing intervals (CPI) is studied. Exponential model of the ground clutter power spectrum for the diffuse component is used. For the first time, radar detection performance for wideband signals at ambiguous to clutter velocities is predicted as function of bandwidth and CPI.**

## I. INTRODUCTION

Recently wideband radars attracted significant attention due to their advantages for target detection and classification. Due to high range resolution, such wideband radars faces migration phenomenon of moving targets, which can be exploited in order to resolve velocity ambiguities in low pulse repetition frequency (PRF) mode. It has been shown that targets amplitudes can be estimated unambiguously using high resolution spectrum estimation techniques, capable to deal with non-uniformly sampled data. Among them, the most promising results are obtained with the sparsity-driven Bayesian approach [1] and non-parametric Iterative Adaptive Approach (IAA) [2]. Although these techniques provide accurate estimation of targets amplitudes, they both suffer from the impact of clutter, which is typically not sparse. In order to deal with ground clutter, the Bayesian approach has been extended to handle autoregressive noise [3], and IAA has to be followed by some detector to remove the residuals of clutter. Anyway, in presence of clutter both approaches suffer from signal to noise ratio loss around the ambiguous to clutter velocities, as it is shown in different scenarios [3], [2]. Despite the research mentioned above, the generic study about the influence of ground clutter on wideband radar performance around ambiguous velocities is still missing.

In order to predict the ability to suppress the ambiguous responses of ground clutter, the model of clutter should be defined. In this paper we use the clutter model of Billingsley [4], which has been verified in many data sets [5], [6] and phenomenologically explained in [7]. Power spectrum of clutter is assumed to be a superposition of stationary and diffuse components. In order to obtain a deep understanding on the effects of each component on the ambiguous clutter responses, their influence is first analyzed separately and then the joint effect is studied.

This paper is organized as follows: in Section II the models of clutter and a point moving target observed by wideband radar are given. In Section III the analysis of clutter impact on detection at the ambiguous velocities is presented. The conclusions are given in Section IV.

## II. CLUTTER AND TARGET MODELS

As it has been shown in [8], [1], a point target signature with initial time delay $\tau_0 = 2R_0/c$ depending on the initial target range ($R_0$) and constant velocity ($v_0$) is modeled in fast-frequency / slow-time domain as following:

$$\mathbf{T}^{ft}_{k,m} = \exp\left(j2\pi\left(-\frac{\tau_0 B}{K}k + \frac{2v_0 f_c T_r}{c}\left(1+\frac{B}{K f_c}k\right)m\right)\right) \tag{1}$$

where $m = 0...M-1$ is the pulse (sweep) number, $k = 0...K-1$ is the fast-frequency index, $T_r$ is the pulse repetition interval (PRI), $f_c$ is the carrier frequency and $B$ is the waveform bandwidth (BW), so the signal occupies frequencies from $f_c$ to $f_c + B$. The last term in (1) is specific for the wideband waveform, it models range migration of moving target and depends only on its radial velocity $v_0$ unambiguously, contrary to Doppler frequency measurement.

Making one step back in the derivation of (1) in [8], a moving target signature can be expressed in slow-time/fast-time domain:

$$\begin{aligned}\mathbf{T}^{tt}_{l,m} = \exp\left(j2\pi\frac{2v_0 f_c T_r}{c}m\right)\\ \operatorname{sinc}\left(\pi\left(l-\left(l_0-\frac{v_0 T_r}{\delta_R}m\right)\right)\right),\end{aligned} \tag{2}$$

where $L = K$, $l = 0..L-1$ is fast time index, $l_0$ is the initial range cell of the target and $\delta_R$ is the radar range resolution.

The following assumptions on clutter are made in this study:

- Clutter can be modeled in each range cell separately, since it does not migrate - the assumption is done to distinguish between clutter and targets [9]. Therefore, the migration term in target model (1), (2) is negligible for clutter scatterers and can be ignored;
- In each range cell clutter is an independent realization of stationary multivariate Gaussian random process with zero mean and covariance matrix (CM) $\mathbf{M}$.

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The power spectral density of clutter in each range is assumed to have normalized power spectral density (PSD) including stationary (dc) and diffuse terms [4], [5]:

$$P_{cl}(f) = \frac{r}{r+1}\delta(f) + \frac{1}{r+1}P_{ac}(f), \tag{3}$$

where $f$ if the Doppler frequency in Hz $-F_r/2 < f < F_r/2$, $F_r = 1/T_r$ (in this paper we assume the Doppler frequency corresponding to the lower frequency of the band $f_c$), $\delta(f)$ is the delta function and $r$ is the ratio between powers of stationary and diffuse components of the clutter. The normalization is applied such that: $\int_{-\infty}^{\infty} P_{cl}(f)df = 1$. Then the normalized clutter correlation function has the form [10]:

$$r_{cl}(\tau) = \frac{r}{1+r} + \frac{1}{1+r}\frac{(\beta\lambda_c)^2}{(\beta\lambda_c)^2 + (4\pi\tau)^2}, \tag{4}$$

where $\tau$ is the time argument.

As discussed in the previous work on the topic, unambiguous estimation of range-velocity map can be obtained by coherent summation of target amplitude in several range cells. Then clutter filter should be applied on the low range resolution segment (LRRS) containing a few range cells such that the condition on maximal target velocity ($V_{max}$) holds:

$$L \geq [V_{max}MT_r/\delta_R] + \Delta_E. \tag{5}$$

where $\Delta_E = 1$ is the extent of a point target and $[\cdot]$ is the rounding operation. Therefore, the clutter covariance matrix should be estimated for the whole LRRS opposite to a range cell in the narrow-band case. If aforementioned assumptions on clutter are held and its power spectrum is known, the $KM \times KM$ clutter CM of a LRRS is given as a Kronecker product of identity matrix of size $K$ ($\mathbf{I_K}$) and $M \times M$ clutter CM in slow-time $\mathbf{M}$ with the elements $\mathbf{M}_{i,n} = r_{cl}\left((i-n)T_r\right)$:

$$\mathbf{R_C} = \mathbf{I_K} \otimes \mathbf{M}. \tag{6}$$

In practice, slow-time CM $\mathbf{M}$ should be estimated from the reference range cells similar to what is done in the narrow-band case.

## III. ANALYSIS OF CLUTTER IMPACT ON DETECTION AT AMBIGUOUS VELOCITIES

As mentioned before, the coherent and diffuse clutter components are expected to have different impact on the ability to detect targets at ambiguous to clutter velocities (”blind” in narrow-band case). The influence can be described in terms of signal-to-interference-plus-noise ratio (SINR) loss factor, comparing the interference-limited performance to the noise-limited performance [11]:

$$L(v) = \frac{\mathbf{w}_k^H(v)\mathbf{R_S}(v)\mathbf{w}_k(v)}{\mathbf{w}_k^H(v)\mathbf{R_C}\mathbf{w}_k(v)}\frac{\sigma_n^2}{M}, \tag{7}$$

where $\mathbf{R_S}(v) = \mathbf{a}(v)\mathbf{a}^H(v)$ is the covariance matrix of the signal given by the steering vector $\mathbf{a}(v)$, obtained by raw vectorization of transposed target signature in slow-time/fast-time (2), i.e. $\mathbf{a}(v) = vec((\mathbf{T}_{l,m}^{tt}(v))^T)$; $\mathbf{w}_k(v) = \mathbf{R_C}^{-1}\mathbf{a}(v)$ and $\sigma_n^2 = 1$ is the white noise power, added to the diagonal elements of $\mathbf{R_C}$ in (6). Note that in Gaussian clutter the loss factor does not depend on the range position of a target, thus range index is skipped in the notations. For all the simulations herein, the following radar parameters are fixed: $f_c = 10$ GHz, $T_r = 1$ ms, $V_a = 15$ m/s. An example of SINR loss vs velocity in the case of wideband and narrowband waveforms is shown in Fig. 1. The axis represents the absolute value of velocity due to mirrow symmetry of the spectrum around zero.

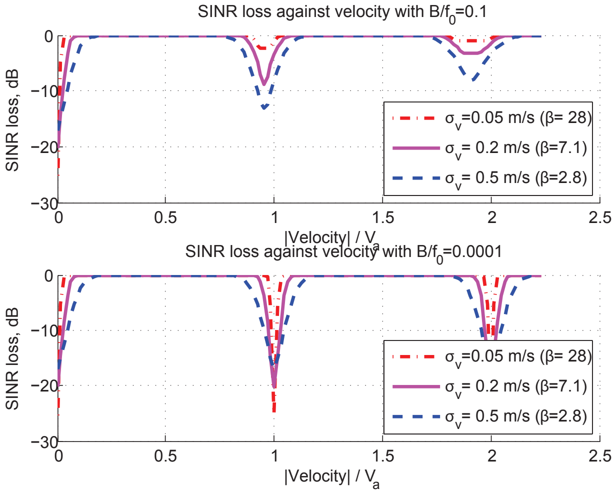

Fig. 1: SINR loss against velocity in diffuse clutter for $M = 32$ pulses: (top) - Wideband signal, (bottom) - Narrowband signal

### A. *Impact of the stationary clutter component*

Typically dc component of clutter is placed in the maximum of the clutter spectrum and defines the depth of the notch at blind velocities. This strong component models the reflection from non-moving objects and its power is concentrated at zero velocity. Due to the fact that target signatures separated by one velocity ambiguity are highly correlated, the dc clutter component can cause SINR loss at the ambiguous velocities. DC clutter component can be considered as a set of point scatterers, for which the ambiguous sidelobes level depend on the time-BW product. This comparison is proved by simulations in Fig. 2, where different combinations of CPI and BW converges to similar small loss, given time-BW product fixed. The maximum loss at the first ambiguous velocity due to coherent clutter component as a function of the CPI is shown in Fig. 2. These results show that any variation of time-BW product such that the migration effect exists ($\mu_a = V_aMT_r/\delta_R = MB/f_c > 1$) results just in a few dBs loss due to coherent component, almost independenty on its power. The chosen migration per velocity ambiguity $\mu_a$ is used for comparison in a few papers on the topic (e.g. [3]) as a significant value to resolve velocity ambiguity of targets.

On the other hand, in the narrow-band cases shown in Fig. 1 the loss at ambiguous velocity is equal to the clutter power around zero, which generates the ”blind speeds” effect. Hence Fig. 1 consider diffuse clutter component, the effect for coherent component in NB case is similar.

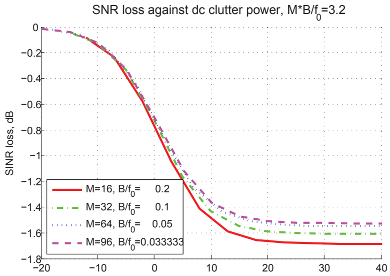

Fig. 2: Maximum SINR loss at $V_a$ against dc clutter power for a fixed migration factor

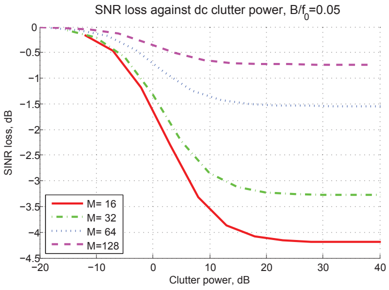

Fig. 3: Maximum SINR loss at $V_a$ against dc clutter power for different values of $M$

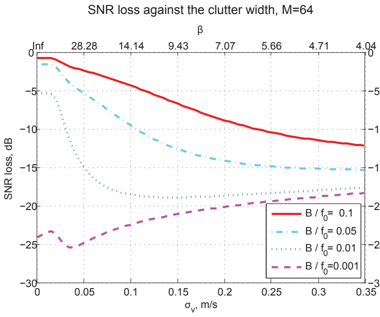

Fig. 4: Maximum SINR loss at $V_a$ against clutter spectral width for different relative bandwidth

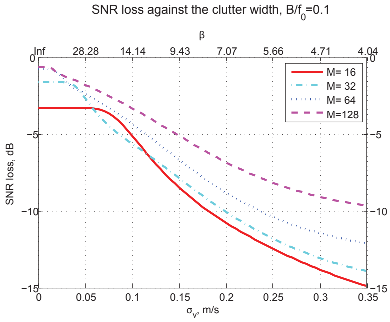

Fig. 5: Maximum SINR loss at $V_a$ against clutter spectral width for different number of pulses in CPI

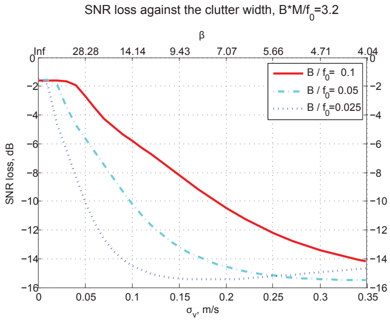

Fig. 6: Maximum SINR loss at $V_a$ against clutter spectral width for a fixed time-bandwidth product

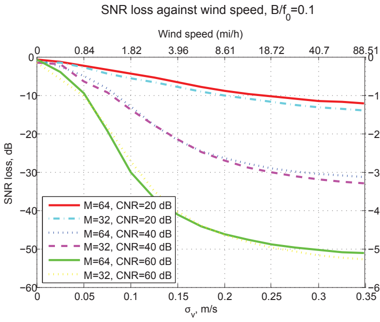

Fig. 7: Maximum SINR loss at $V_a$ against clutter spectral width for different number of pulses in CPI

### B. Impact of diffuse clutter component

Diffuse clutter component models the movement of vegetation and typically has less power, than the coherent component, but significant spectral width. Opposite to the dc component, it can not be represented as a point target, but it can be modeled as a white Gaussian noise with defined correlation function (4). SINR against velocity for the diffuse only clutter with clutter-to-noise ratio (CNR) 20 dB is shown in Fig. 1 considering the wideband and narrow-band waveforms. As expected, in the narrow-band case, deep notches of the clutter filter are repeated from one ambiguous velocity to another. On the other hand, for the wideband waveform the effect of clutter diminishes as the ambiguity number increases, or in other words, as the migration effect grows. Secondly, as the clutter width grows, the maximum loss reduces in the narrow-band case: given clutter power fixed, the wider the spectrum is, the smaller its the peak power is, and therefore, the lower the maximum loss is. In the wideband case the effect is opposite: the larger the clutter width, the more clutter differs from the point scatterer, the worse it can suppressed by the migration effect.

Taking into account the aforementioned phenomenon, the influence of diffuse clutter width on the maximum SINR loss in the first ambiguous sidelobe of clutter is analyzed below (CNR $= 20$ dB). The results for different $B/f_c$ and $M = 64$ are shown in Fig. 4 (along horizontal axes $\beta$ and $\sigma_v = 2^{0.5}/\beta$, defined as the standard deviation of clutter distribution against velocity). As expected, in the wideband cases ($B/f_c$ = 5% or 10%), the SINR loss became more critical as the clutter width increases. The examples with the narrow-band signals ($B/f_c$ = 1% or 0.1%), show the combination of both effects: for narrow width of clutter spectrum, the ambiguous residuals are partly suppressed by migration (less than one range cell per ambiguity in this case), while for significant clutter width, the decrease of clutter peak power due to its widening is visible.

Similarly, Fig. 5 presents analysis of the number of pulses in CPI on the maximum SINR loss at ambiguous velocity. A comparison with the previous results shows that doubling of the CPI provides only 1-2 dBs gain, while doubling the BW brings around 5 dBs improvement for most values of $\sigma_v$ in the wideband case.

The joint effect for fixed time-BW product, shown in Fig. 6, proves that it is preferable to use larger BW, given time-BW product and PRF fixed. This effect can be explained as following: the first ambiguous sidelobe of a target is extended in range over $\mu_a = V_a M T_r/\delta_R$ range cells and in velocity from $V_a^{min} = c/(2(f_c + B)T_r)$ to $V_a^{max} = c/(2 f_c T_r)$. Therefore, the increase of the BW enlarge the spread of a target signature both in velocity and in range, while the increase of CPI spreads the target signature only over range. In fact, it occupies the same number of velocity cells, while the velocity

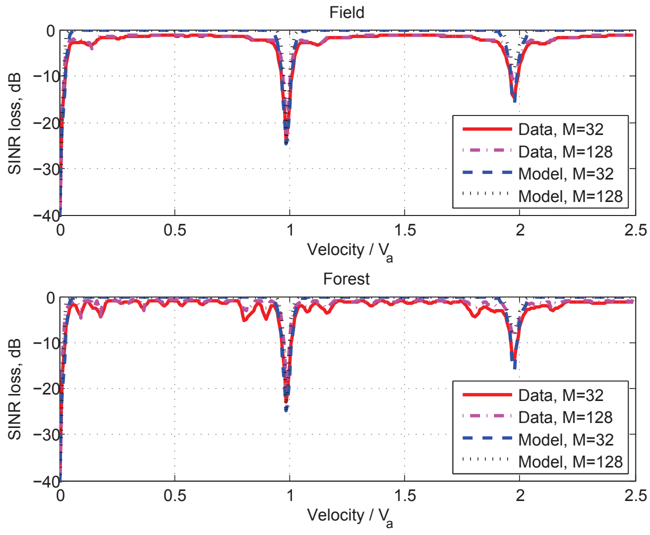

Fig. 8: SINR loss of PARSAX data: (top) - Field clutter, (bottom) - Forest clutter

resolution changes. The ICM model of clutter implies the clutter to have similar power along range and exponentially decreasing power along velocity, which results in better clutter suppression for signal with wider BW than for signal with longer CPI. In practice, signal-to-clutter ration is also increases as the range resolution improves, at least until the target can be assumed a point scatterer.

### C. Performance prediction in presence of both components

In order to study the joint effect of stationary and diffuse components of clutter, the relationship between them should be defined. In this paper we use empirically derived analytical expressions (see [5] and references therein) for the exponential shape parameter $\beta$:

$$\beta^{-1} = [\lg(w) - \lg(2/3^{1.5})] \cdot (20 \lg 3)^{-1} \tag{8}$$

and ratio of dc component power to diffuse clutter power:

$$\lg(r) = -15.5 \lg(w) - 12.1 \lg(f_c/10^6) + 63.2, \tag{9}$$

where $w$ is wind speed in mi/h. Using these relationships, SINR loss at ambiguous velocity depends on the radar parameters and clutter power. Assuming a wideband waveform is used, SINR loss as a function of CNR, $M$ and wind speed is shown in Fig. 7. Note that for CNR= 20 dB the curve is similar to the one shown in Fig. 4. Therefore, we can conclude that in presence of both diffuse and stationary (dc) clutter component, SINR loss at ambiguous velocity depends on the parameters of diffuse clutter component only.

### D. Validation on real data

In order to justify the study presented above, we analyze two data records made on 25.11.2015 with PARSAX radar. The parameters of the radar are $f_c = 3.265$ GHz, $B = 100$ MHz, $V_a = 45$ m/s, $T_r = 1$ ms. The footprint of the radar beam covers the reflection from a field and a forest accordingly. The data is averaged over 20480 PRIs and 200 range cells including homogeneous clutter. The data PSD around zero velocity is best fitted with the model using $w \approx 3$ mi/h. The power of DC component is estimated from $v = 0$ and used to define the power of AC component via (9). The comparison of real SINR loss obtained using sample CM and the one obtained using the defined model with estimated parameters is shown in Fig. 8. For both scenarios the model shows a good fit to the data for all velocities of interest. The difference between SINR loss using simulated clutter and estimated from the record does not exceed 5 dB and shows a good fit around $V_a$.

## IV. CONCLUSIONS

Coherent and diffuse components of ground clutter have different impact in the ability of wideband radar to remove ambiguous clutter. Coherent component can be suppressed very efficiently independently on its power with moderate migration. Diffuse clutter component causes significant loss at ambiguous to clutter velocities. The ability to suppress it depends mostly on the bandwidth used, opposite to the time-bandwidth product in coherent clutter case. Diffuse component of the ground clutter is simulated using the Exponential model resulting in a good agreement between predicted SINR loss and the measured one. We showed that in presence of both diffuse and stationary (dc) clutter component, SINR loss at ambiguous to clutter velocities depends on the parameters of diffuse clutter component only.

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