CLUTTER SUPPRESSION FOR MOVING TARGETS DETECTION WITH WIDEBAND RADAR

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ABSTRACT

Wideband (high range resolution) radars have been proposed [7] as high performance systems for detection of small targets in adverse environments, due to their small resolution cells and non-ambiguity in range and velocity (velocity ambiguity removed by the measurement of the range migration of the target during the pulse train duration). However, the issue of cancelling clutter while still coherently summing the echoes received from the moving – and migrating in range – targets has not yet been properly demonstrated.

In this paper, a basic procedure for such extraction of targets from clutter is proposed, and demonstrated on real signals, thus opening the way to the development of high range resolution radars for long-range surveillance.

Key words: Wideband, migration, non-stationary, clutter, detection, radar, ambiguity

1. INTRODUCTION

Radar detection of moving targets in presence of clutter echoes (ground, maritime, or atmospheric) is classically performed by velocity (Doppler) analysis, and limited by the properties of the well-known time-frequency (or delay-Doppler) ambiguity function. More precisely, for periodic narrowband waveforms – which are often adopted, primarily for their good performance in clutter rejection – moving targets detection has the following limitations:

- Velocity resolution is limited, inversely proportional to the time duration of the coherent waveform;
- Clutter rejection (or signal to clutter improvement) is limited by the weighting or filtering applied for spectral analysis;
- Blind speeds and velocity ambiguity occur, due to the fact that Doppler is measured as a phase shift from pulse to pulse, modulo 2π. In order to remove the ambiguities, successive pulse trains of periodic waveforms (with different periods) are generally sent, with the consequence of shorter coherent duration for each train – and thus poorer velocity resolution.

Non-periodic waveforms have been advocated for mitigating the last limitation [1], but their poor performances against strong clutter echoes at long ranges (e.g., mountains) has, until now, prevented their application to long-range surveillance radars.

Another approach consists in using high range resolution waveforms with low pulse repetition frequency (PRF), so that velocity is measured not only by phase shift from pulse to pulse, but also through the variation of range during the burst (“range migration”): an appropriate coherent summation of the received echoes then allows non-ambiguous measurement of target range and velocity with only one burst of coherent pulses [2]. However, the ambiguity functions of such wideband waveforms still have high sidelobes, unsuitable for clutter rejection.

In this paper, such a wideband waveform and a new signal processing scheme which alleviates the three limitations – resolution, rejection, and ambiguities – will be presented, illustrated with simulations, and with experimental results obtained with the radar demonstrator PARSAX [5].

The main characteristics of coherent signal processing for such a wideband radar will first be explained (Section 2), and illustrated with the analysis of a typical ambiguity function. The limitations of such processing in presence of clutter will then be discussed, and an appropriate clutter cancellation technique, based on stationarity analysis, will be presented (Section 3). Simulation and experimental results will finally be shown (Section 4), before concluding on future perspectives in Section 5.

2. WIDEBAND MOVING TARGET DETECTION

An essential limitation for standard radars comes from periodic radar range-Doppler ambiguity relation, which states

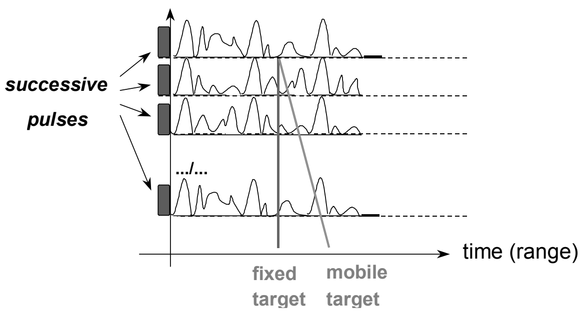
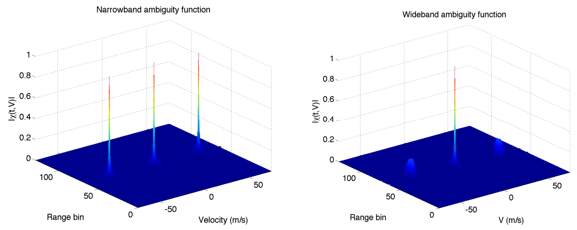


Figure 1. Range walk phenomenon for wideband radars



(a) (b)

Figure 2. Ambiguity functions:
(a) narrowband, $\Delta F/F_0 = 1/10000$; (b) wideband, $\Delta F/F_0 = 1/10$

that the ambiguous velocity V_a and the ambiguous range D_a are related by: $D_a \times V_a = \lambda_0 \times c / 4$ where λ_0 is the wavelength and c is the speed of light. This relation means that many ambiguities, either in range or velocity (or both), have to be dealt with, which in turn implies the transmission of successive pulse trains with different repetition frequencies, requiring more time to be spent on target for ambiguity and blind speeds removal. In case of a fixed given update rate, shorter pulse trains, providing lower velocity resolution.

An alternative solution is obtained by increasing the range resolution (or the instantaneous bandwidth), so that the moving target range variation (range migration) during the pulse train becomes non-negligible compared with the range resolution, which is equivalent to stating that the apparent Doppler frequency is varying across the whole bandwidth (compared with the Doppler resolution), and can not be considered as a mere frequency shift any more. Such radars may use bursts with low PRF (no range ambiguities) wideband pulses, such that the range migration phenomenon during the whole burst is significant enough to remove the velocity ambiguity. It then becomes possible to detect the target and measure range and velocity with only one coherent pulse train. Range walk phenomenon is illustrated in Figure 1.

The condition is written, if P is the number of pulses in the pulse train, $T_r=1/F_r$ the repetition period, V_a the standard ambiguous velocity [$V_a = \lambda_0/(2T_r)$], ΔF the instantaneous bandwidth, and δR the range resolution [$\delta R = c/(2\Delta F)$]:

$$P V_a T_r \gg \delta R \quad \Leftrightarrow \quad \frac{\lambda_0}{2} P \gg \delta R \quad \Leftrightarrow \quad P \gg \frac{F_0}{\Delta F}$$

where $F_0=c/\lambda_0$ is the central carrier frequency. For example, a burst of 60 pulses at 1 kHz repetition frequency with 300 MHz bandwidth would be a possible candidate for non-ambiguous MTI detection with 3 GHz carrier frequency.

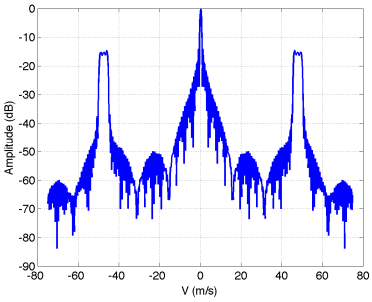


Figure 3. Wideband ambiguity function with $\Delta F/F_0 = 1/10$: cut along the line of migration

The coherent signal processing of such radars (whose range resolution is in the order of several wavelengths, typically $\delta R \approx 10\ \lambda_0$) involves, for each velocity hypothesis, a coherent summation of the received echoes (Fourier transform), after rangewalk compensation (Figure 2).

If $x_{p,t}$ is the signal received from the p^{th} pulse, at t^{th} time sample, the quantity to be compared to the threshold, for hypothesis $t\delta R$ in range and V in velocity, is:

$$T_{t,V} = \sum_{p=0}^{P-1} x_{p,\Gamma\left[t - p\frac{VT_r}{\delta R}\right]} e^{-2\pi j p \frac{F_0}{F_r}\frac{2V}{c}} \tag{1}$$

with $\Gamma(u)$ the nearest integer from u.

This processing leads to an ambiguity function denoted by $\chi(t,V)$ (Figure 2) which drastically decreases the periodic ambiguities in Doppler. More precisely, the relative level of the first remaining ambiguity is equal to the fraction of the pulse train during which no migration occurs for a target at V_a. Typically, if the migration at V_a is m range cells, then the relative level (energy) of this first ambiguity is $(1/m)^2$. With the example given above (F_r =1kHz , λ_0=0.1m, ΔF = 300 MHz), we obtain V_a = 50m/s, δR= 0.5m. The total migration at V_a is 50 x 60 10^{-3}=3m, or 6 range cells, so the first sidelobes of the ambiguity function are 16 dB under the maximum. This can be clearly seen in Figure 3.

This level of ambiguous sidelobe might not be a serious problem for the targets, but it is a very severe one for clutter, since clutter scatterers radar cross-section (RCS) can be much higher than target scattering centers RCS: clutter sidelobes might then often mask target echoes.

For this reason, a stationarity analysis will be described in the next Section, for increased clutter rejection with wideband radars.

3. CLUTTER REJECTION BY STATIONARITY ANALYSIS: MIGRATING TARGET INDICATOR

The proposed procedure derives from the observation that, in situations of interest, the velocities of clutter echoes are much lower than the ambiguous velocity, so that there is no migration effect on clutter echoes. The problem of cancelling clutter echoes therefore is tantamount to cancelling non-migrating echoes. We will see that this can be done through comparison of successive (overlapping) coherent processing similar to Eq (1).

More precisely, the matched filter described by (1) for wideband signals simply consists in a coherent summation of the received samples, for each possible velocity V and delay t $(t=2R/c)$ of the target. The literal expression of the output is written [4]:

$$T(t,V) = \sum_{\substack{f=0,\dots,N-1 \\ p=0,\dots,P-1}} y_{f,p} \exp\left(2\pi j \frac{f\,t}{N}\right) \tag{2}$$
$$\times \exp\left(-2\pi j\, p \frac{2V}{\lambda_0} T_r\right) \exp\left(-2\pi j\, pf \frac{\delta F}{F_0} \frac{2V}{\lambda_0} T_r\right).$$

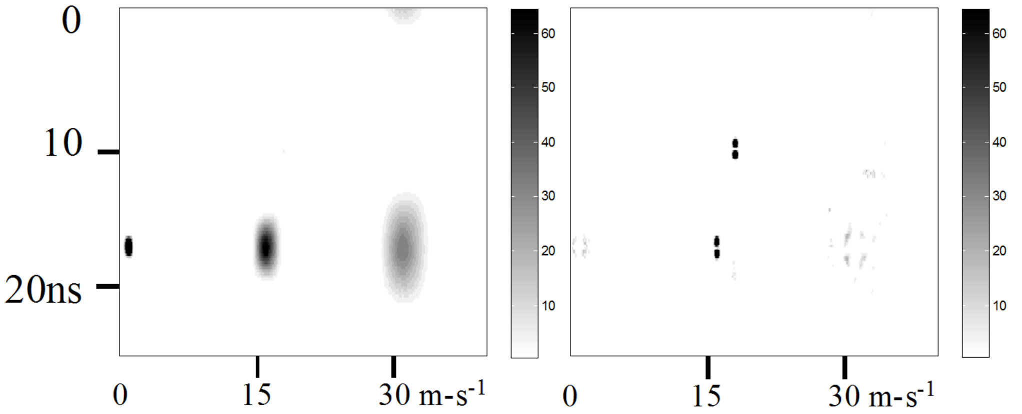


Figure 4. MiTI, Migrating Target Indicator. Left: standard processing; Right: Migrating Target Indicator

In this expression, $y_{f,p}$ is the received signal as a function of frequency (sub-band) f and pulse number p, N is the number of frequencies (sub-bands), $\delta F=\Delta F/N$ is the frequency step (sub-band width). The coupling between velocity and range, introduced by the migration effect (or, equivalently, by the fact that the Doppler shift is varying with frequency) is taken into account by the last term in this expression.

The performances of such wideband radars for moving targets extraction from clutter can then be improved by subtracting "non-migrating" echoes, to keep only migrating targets: MiTI, Migrating Target Indicator [4], is a simple version of such a technique, illustrated in Figure 4, for a radar at F_0=10 GHz, F_r=1 kHz and a train of P=60 pulses, each with 250 MHz bandwidth. The principle consists in calculating a first image (Delay-Doppler), e.g., from the pulse train 1 to 57, then a second image, e.g., from the pulse train 3 to 60, and finally subtracting non-coherently the amplitudes of these two images. This subtraction cancels stationary (non-migrating) targets, and migrating targets are then obtained as doublets (initial range – final range).

The literal expression of such "Migration Target Indication", which subtracts two images obtained by overlapping bursts: pulses 0 to P - P_0 - 1, and pulses P_0 to P - 1, is written:

$$
\begin{aligned}
T(t,V) = \; & Abs\left\{ \sum_{\substack{f=0,\dots,N-1\\ p=0,\dots,P-P_0-1}} \left[y_{f,p}\right] \exp\left(2\pi j\,\frac{f\,t}{N}\right) \exp\left(-2\pi j\; p\,\frac{2V}{\lambda_0}T_r\right) \exp\left(-2\pi j\; pf\,\frac{\delta F}{F_0}\,\frac{2V}{\lambda_0}T_r\right)\right\} \\
& - Abs\left\{ \sum_{\substack{f=0,\dots,N-1\\ p=0,\dots,P-P_0-1}} \left[y_{f,p+P_0}\right] \exp\left(2\pi j\,\frac{f\,t}{N}\right) \exp\left(-2\pi j\; p\,\frac{2V}{\lambda_0}T_r\right) \exp\left(-2\pi j\; pf\,\frac{\delta F}{F_0}\,\frac{2V}{\lambda_0}T_r\right)\right\}
\end{aligned}
\tag{3}
$$

In the example of Figure 4, the clutter is made of 2 slowly moving echoes (1 m/s and 0,5 m/s)[1], with a delay of 17 ns (arbitrary origin), and two targets are inserted, 23 dB below clutter level, one at the same range as clutter (delay of 17 ns) and with velocity 16 m/s (slightly above the first ambiguous velocity of 15 m/s), the other exo-clutter at delay 10 ns and velocity 18 m/s.

On the left-hand side of Figure 4, where the matched filter output is depicted, only clutter echoes are visible, with residual ambiguous sidelobes around 16 m/s and 31 m/s, due to the repetition frequency at 1 kHz (i.e., ambiguous velocity V_a =15 m/s). On the right, after subtraction of overlapping pulse trains (3), these clutter residues are cancelled, leaving the two doublets corresponding to the two targets (note that each figure is normalized by its maximum value).

This simple example clearly illustrates the improvements that can be obtained in clutter rejection with wideband radars, using stationarity analysis. More sophisticated techniques can be designed on this principle, for instance by combining more than two sub-trains.

Most importantly, such techniques open the way to radar detection schemes where only one coherent pulse train is used for target extraction from clutter, thus alleviating the standard limitations of narrow-band radars, as stated in the Introduction. The critical issue remaining to be checked is the performance of such stationarity analysis on real clutter, with its own characteristics of amplitude and phase fluctuations. This is the object of the next Section.

4. EXPERIMENTATION WITH PARSAX

In this Section, the results obtained after stationarity analysis ("migration indication") with real clutter data collected by PARSAX will be briefly described (the detailed experiment, together with formal demonstration of the coherent integration signal processing, are presented in [6]). PARSAX is a programmable radar, used here in a linear frequency modulation (FMCW) mode. The characteristics of the radar are described in [5], and the parameters used in this experiment are:

Carrier frequency: F_0:=3.315 GHz;
Bandwidth: ΔF= 100 MHz;
Range resolution: δR = 1.5 m;
Repetition period: T_r= 1 ms;
Ambiguous velocity: V_a = ± 22.6 m.s^{-1}.

The PARSAX radar system is situated on the rooftop of the EEMCS building at TU-Delft, at a height of about 100m. Transmitter and receiver antennas are two parabolic reflectors that are isolated from one another and can be considered as co-located. For the experiment, the radar mainlobe has

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[1] It is important to take into account the situations where several clutter scatterers, with slightly different velocities, are present in the same range-velocity cell, since the stationarity of the resulting signal, from the first sub-train to the second, is not perfect in this case.

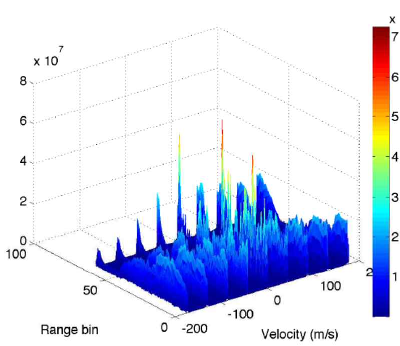

Figure 5. PARSAX signals, with coherent integration: no target visible in presence of clutter ambiguities

been pointed towards the Rotterdam/Den Haag freeway during a heavy traffic time. Hence, mainlobe ranges are spanning around 1.8km.

We used data with P=128 “pulses” (chirps, in this case) and N=64 range bins. After inverse Fourier transform, the data set in the slow frequency/fast frequency domain is made up of 128 pulses and 64 sub-bands. For each processing, zero-padding was also performed, providing 512 Doppler frequencies (per velocity ambiguity) and 256 range frequencies. Note that the migration effect, at velocity V_a, is only about 3.5 range cells.

For validation, a synthetic target has been inserted in the clutter data, with velocity $V = -2V_a = -90.5$ m.s^{-1}, with an RCS 15dB under clutter level. Typical results, presented on Figure 5 and Figure 6, show that the Migrating Target Indication indeed enhances the visibility of the moving target, which becomes clearly visible after processing (notice the vertical scale difference between the two Figures).

Figure 7 shows a cut along range, at the exact target velocity, where the “doublet”, corresponding to the result of the subtraction of overlapping pulse trains, is clearly evidenced. Note that we have plotted in Figure 5, Figure 6 and Figure 7 the absolute value of (3).

This experiment validates the principle of stationarity analysis for clutter cancellation on wideband radars, and opens the way to more elaborate stationarity analysis, e.g., using higher order adaptive filters.

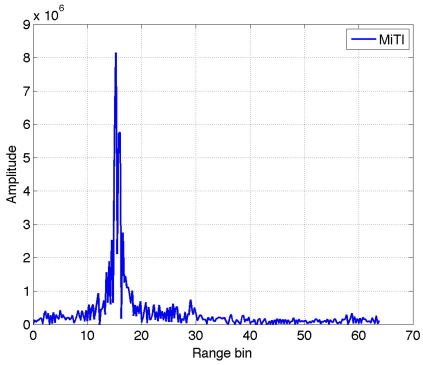

Figure 7. PARSAX signals, with Migrating Target Indication Cut along range, at the target velocity, showing the “doublet” due to subtraction of overlapping pulse trains

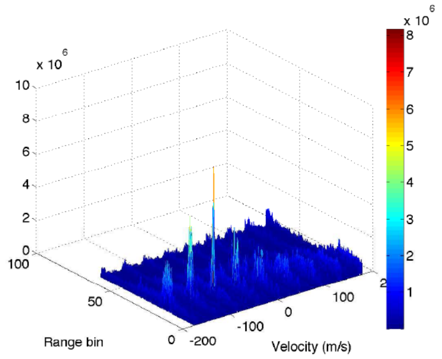

Figure 6. PARSAX signals, with Migrating Target Indication (notice the change in vertical scale): the target and its own sidelobes are clearly visible

5. CONCLUSION

In this paper, the feasibility of clutter cancellation by stationarity analysis (Migrating Target Indication) has been examined and demonstrated in simulations and with experimental signals for the first time. This experiment is an important step towards wideband radars high performance development, as proposed in [6], [7], since it validates the principle of stationarity analysis for clutter cancellation on wideband radars, and opens the way to more elaborate stationarity analysis, using higher order adaptive filters.

6. ACKNOWLEDGEMENTS

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