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Nonlinear processing for enhanced delay-Doppler resolution of multiple targets based on an improved radar waveform☆

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ABSTRACT

In this paper, an improved radar waveform scheme is put forward and a family of nonlinear processing methods is applied for enhanced delay-Doppler resolution in multiple targets scene. A double V-chirp waveform is first proposed to overcome the disadvantages of traditional V-chirp waveform used in the delay-Doppler resolution and detection. Then, a combined operation based on a family of nonlinear processing methods is employed to further enhance the delay-Doppler resolution. Next, a paraboloid function is given as a filter in order to raise the power of the non-center targets presented in the delay-Doppler maps while keeping the delay-Doppler resolution. Finally, numerical simulations in the paper prove the performance improvement of proposed waveform and methods. Besides, discussions about the most suitable chirps' number for the waveform, the influence of targets position and chirp rates chosen, and the design trade-off of double V-chirp waveform in hardware transmitting and detection performance loss are also illustrated in this section, which make the model adaptive to more complex situations.

1. Introduction

The design and processing of radar signals for high delay-Doppler resolution has long been a problem of great interest [1–7], since it reflects the ability of radar system to separate spatially close targets and targets with similar radial velocities. The ambiguity function (AF) of transmitted signal is always used to characterize the delay-Doppler resolution of matched-filter radar in the delay-Doppler maps, which is considered as a standard tool to evaluate the radar resolution [8–12]. However, the delay-Doppler maps may appear significantly different compare to what would be expected by looking at the signal's AF if the process is based on received signal and other than matched-filter is used. It is potential to get the delay and Doppler information of target through the AF of received signal, which could achieve moving target detection when the direct of arrival (DOA) or the direction angle of radar is known beforehand. Besides, the processing other than traditional matched-filter do have the ability to enhance the delay-Doppler resolution [13–15].

Previous works have discussed a kind of biologically inspired waveform, the V-chirp waveform, for the enhancement of delay-Doppler resolution through a family of nonlinear processing algorithms in the delay-Doppler maps [4,16,17]. Those techniques are indeed useful in single target situation. But in multiple targets scenario, the problems caused by those techniques are still worth researching. The presence of multiple targets in the delay-Doppler maps will significantly degrade the system performance and give rise to false targets and ghosts. This is because in multiple targets scenario, the processing algorithms on the received V-chirp waveform will provide cross terms in the delay-Doppler maps, which cause the appearance of false targets and ghosts. Furthermore, since the AFs of chirps are matched by their transmitted signals, the echo waves that have a time delay and Doppler shift decrease the power of AFs due to the mismatch. The result of this situation is the powers of targets that are too far from the center of delay-Doppler maps are too low and those targets may be submerged in the sidelobes and noise, which makes them hardly to be recognized.

Based on the previous research, an improved radar waveform scheme is presented for pulse-echo nonlinear processing to suppress the false targets and further enhance the delay-Doppler resolution of multiple targets scene in this work. The paper is organized as follows. In Section 2, an improved waveform named here as "double V-chirp" waveform, is proposed based on the current V-chirp waveform. In Section 3, a combined operation

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based on a family of point-wise nonlinear processing methods is applied to the delay-Doppler maps for further enhancement of resolution performance. In Section 4, a paraboloid function is given as a filter to the delay-Doppler maps, in order to raise the power of the non-center targets presented in the maps while keeping the delay-Doppler resolution. In Section 5, numerical simulations are given to prove the performance improvement of proposed waveform and methods. Discussions about the most suitable chirps' number for the waveform, the influence of targets position and chirp rates chosen, and the design trade-off of double V-chirp waveform in hardware transmitting and detection performance loss are also illustrated in this section. Conclusions and a few possible extension of the future work are given in Section 6.

2. Waveform improving and modeling

In this section, an improved waveform scheme is put forward based on the current V-chirp waveform.

The V-chirp waveform is biologically inspired from the processing of echolocating bat [18,19], while it substitutes the waveform of constant frequency-downchirp to the upchirp-downchirp combined, in order to obtain better time-bandwidth products through two segments [16]. To solve the problems mentioned in the introduction, some unique characters are needed to provide for real targets and increase their amplitude or power difference compare to false targets. An effective way is to add the number of chirps, but too many chirps will seriously increase the burden of hardware. Here an improved waveform scheme with 4 chirps named as "double V-chirp" waveform is proposed, as is shown in Fig. 1. A detail deduction for why the number of chirps is chosen 4 here is given in Section 5, which shows that 4 chirps can adapt most situations of multiple targets.

The transmitted waveform of double V-chirp $s(t)$ can be given as

$$s(t) = s_1(t) + s_2(t + T_r) + s_3(t) + s_4(t + T_r) \tag{1}$$

$$s_1(t) = \exp(j\pi k_1 t^2)\cdot 1_{[-T,0]}(t) \tag{2}$$

$$s_2(t) = \exp(j\pi k_2 (t - T)^2)\cdot 1_{[0,T]}(t) \tag{3}$$

$$s_3(t) = \exp(j\pi k_3 t^2)\cdot 1_{[-T,0]}(t) \tag{4}$$

$$s_4(t) = \exp(j\pi k_4 (t - T)^2)\cdot 1_{[0,T]}(t) \tag{5}$$

where chirp rates $k_1, k_3 > 0$, $k_2, k_4 < 0$, $k_1 \neq k_2 \neq k_3 \neq k_4$, the upchirps and downchirps have the start time interval of T_r with both duration T. To obtain the double V-chirp signal shown in Fig. 1, $T_r = T$ is set throughout the remainder of the paper. Actually the chirp rates are not limited to $k_1 = -k_2$ and $k_3 = -k_4$ as a rigorous double V-chirp waveform, and a further discussion is given in Section 5 for the chosen of chirp rate to hold on the resolution as possible. Then, the echo wave of double V-chirp signal is demonstrated as

$$\begin{aligned} r(t) &= r_1(t) + r_2(t + T_r) + r_3(t) + r_4(t + T_r) \\ &= [s_1(t-\tau) + s_2(t-\tau+T_r) + s_3(t-\tau) + s_4(t-\tau+T_r)] \\ &\quad \cdot\exp(j2\pi F_D t) \end{aligned} \tag{6}$$

where $r_1(t)$~$r_4(t)$ represent the echo wave of $s_1(t)$~$s_4(t)$, τ and F_D represent the delay and Doppler of the target, respectively.

The delay-Doppler map of a signal is always characterized by its transmitted AF, as is defined in (7) [20].

$$A(t, F_D) = \int_{-\infty}^{+\infty} x(s)\exp(j2\pi F_D s)x^*(s - t)\mathrm{d}s \tag{7}$$

On the other hand, when the $x(s)$ is replaced with $r(s)$, the $A(t, F_D)$ represents a delay-Doppler map that could reflect the delay and Doppler information of target by processing the echo wave of waveform.

It is obvious that the proposed double V-chirp waveform has better waveform diversity than traditional V-chirp waveform. By calculating the delay-Doppler map of double V-chirp echo wave it could be found that the real targets in the delay-Doppler map are crossed by four chirp ridges, while the false targets are only crossed by two in most situations (this can be easily seen in the following simulation of Fig. 3(c)). This unique character can significantly increase the power difference between the real targets and false targets, which is effective for the false targets suppression.

3. Point-wise nonlinear processing

In this section, a combined operation based on a family of point-wise nonlinear processing methods is applied to the delay-Doppler maps of double V-chirp waveform to further enhance the delay-Doppler resolution.

First we refer to the concept of cross AF of two waveforms $x_m(s)$ and $x_n(s)$ as [21,22]

$$A_{mn}(t, F_D) = \int_{-\infty}^{+\infty} x_m(s)\exp(j2\pi F_D s)x_n^*(s - t)\mathrm{d}s \tag{8}$$

In this paper if $m = n$, the cross AF becomes the AF of a certain chirp segment. When calculating the delay-Doppler map of double V-chirp waveform echo wave, the echo wave should be matched with each chirp segment of double V-chirp waveform, which could be characterized by 16 cross AFs given in (9)

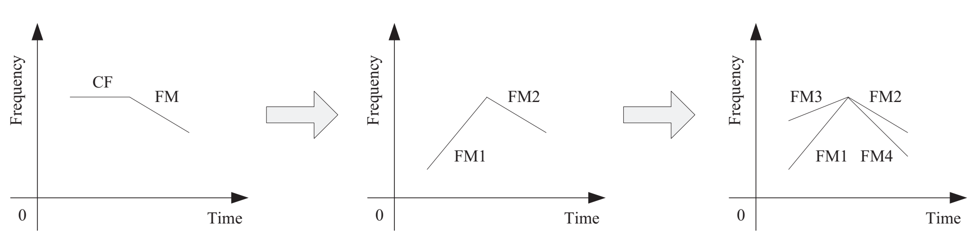

Fig. 1. Schematic figure of the improvement of waveform.