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Strategies for FMCW radars

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Abstract—In this paper, we present a comparison of two strategies for FMCW radars. The potential presence of multiple targets implies using specific waveforms for beat frequencies association. Here, we compare performance of two such waveforms in terms of targets distance and velocity estimation. Our comparison, based on theoretical bounds derivation is validated by Monte Carlo simulations. In particular we show that Barankin variance bounds yields conclusions that are in good agreement with results of simulation experiments.

Index Terms—radar waveform; FMCW; parameter estimation; variance bounds; Barankin bound; Automatic Cruise Control (ACC).

I. INTRODUCTION

Often, in radar processing and in particular for car Automatic Cruise Control (ACC) radars, one faces both problems of detecting multiple vehicles and estimating their position and velocity. In this paper, we present two strategies for multiple vehicles detection with FMCW (Frequency Modulated Continuous Wave) radars. FMCW radar have several advantages: they are quite inexpensive and easy to operate (they can be made quite small and are robust). In addition, they can generate wideband waveforms quite easily which is an advantage for full employment of ACC radars 3GHz bandwidth.

For such radars, after demodulation of the signal reflected by the target with the emitted chirp (frequency ramp) waveform, each target outputs a beat sine waveform. The beat frequency is a linear combination of propagation delay and Doppler frequency. In particular, the beat frequency delay term is proportional to chirp slope. Thus, for velocity and position estimation several chirps are emitted. In FMCW techniques, distinct slopes are used to enable parameter estimation. Unfortunately, when several targets are present, often beat frequency values of these targets are not ordered in the same way for chirps with distinct slopes.

As explained in [1], it is clear however that using chirps with slightly differing slopes preserves targets beats frequencies ordering in most cases. However, we checked that one main drawback of this method is a high variance of estimated target velocities. This

suggests using additional chirps with significantly distinct slopes; Thus, whence rough estimation of targets parameters is achieved thanks to chirps with close slopes, good parameter estimation can be achieved from beat frequencies observed on chirps with significantly distinct slopes.

Since making low cost waveform generators producing wideband chirps with slightly different slopes may not be very easy, we also consider an alternative kind of FMCW waveform that overcomes this problem. It involves transmission of a pure sinusoid. Both waveforms presented here will be referred to as dual FMCW and Three-segments FMCW respectively.

In order to supply comparison between both waveforms, we study the variance performance for estimated position and velocity parameters of a target. We detail proposed strategies for parameters estimation and consider the corresponding variances. In order to characterize a waveform performance regardless to the specific signal processing technique employed in the radar, we calculated variance performance lower bounds. Since the celebrated Cramer-Rao bound [2] is much too optimistic at low Signal to Noise Ratios (SNR), we calculated Barankin bounds [3], [4] that are more realistic. We have shown quite good agreement of these performance bounds with Monte Carlo simulations carried out from a realistic FMCW radar simulation [5].

II. WAVEFORMS AND PARAMETER ESTIMATORS

A. Dual FMCW

Reference [1] considers a waveform consisting in 2 (or more) successive down ramps with slightly different slopes. The interest of this waveform is that the order in which targets beat frequencies are arranged on the first ramp is identical to the order in which targets beat frequencies are arranged on the second ramp. Thus the association between the beat frequencies on the first ramp with those on the second ramp is facilitated and the ambiguity of the simple FMCW is considerably alleviated. Nevertheless, this simple method of association is clearly problematic since very small slope difference results in little diversity among observed

chirps. As a consequence, bad velocity estimates are observed [1]. However, the simplified association between beat frequencies is interesting and is worse being retained for designing more advanced waveform. here, we propose a modulation format that consists in two successive FMCW waveforms with slightly different slopes on the first triangle as compared to the second triangle. The order of targets beat frequencies is thus maintained between two successive rising ramps as well as between the two down ramps. Then the association of targets is kept simple and the distance velocity ambiguity is alleviated, while the variance of velocity estimation is kept small thanks to important slope difference between up and down ramps.

The proposed dual FMCW waveform frequency versus time is plotted in Fig. 1. Main parameters are

- The carrier frequency (f_0)
- Modulation bandwidth (B)
- The total duration of the modulation (T) and
- The duration of first triangle (θ)

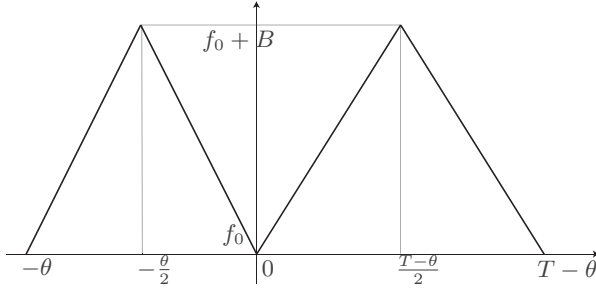


Fig. 1. Dual FMCW waveform.

After thresholding, the periodograms [2] of demodulated signals for each frequency ramp, beat frequencies of targets are detected. f_i^{upk} and $f_i^{do_k}$ denote the i^{th} detected frequency on the k^{th} ($k = 1, 2$) up ramp and down ramp respectively. In first step, since targets ordering is ensured only between both up ramps and between both down ramps, we calculate the range and velocity using separately up and down ramp pairs respectively. Thus, for up ramps we get

$$\begin{cases} d_i^{up} = (f_i^{up2} - f_i^{up1}) \frac{c\theta(T-\theta)}{4B(T-2\theta)} \\ v_i^{up} = \frac{\lambda}{2} \frac{(T-\theta)f_i^{up2} - \theta f_i^{up1}}{T-2\theta} \end{cases} \quad (1)$$

Estimators d_{do}^i and v_{do}^i are calculated in the same way from down ramps.

Based on these initial estimates, we can associate distance-speed pairs estimated on up and down ramps respectively. So, for a given target, we now know its beat frequency on the four ramps. Then we can calculate an estimate of speed and distance for each target that accounts for its beat frequencies for the 4 chirps. More precisely, from the following estimates

supplied by both FMCW sub-waveforms,

$$\begin{cases} d_i^1 = (f_i^{do1} - f_i^{up1}) \frac{c\theta}{8B} \\ v_i^1 = (f_i^{up1} + f_i^{do1}) \frac{\lambda}{4} \end{cases} \quad (2)$$

and

$$\begin{cases} d_i^2 = (f_i^{do2} - f_i^{up2}) \frac{c(T-\theta)}{8B} \\ v_i^2 = (f_i^{up2} + f_i^{do2}) \frac{\lambda}{4} \end{cases} \quad (3)$$

we get the following final estimates:

$$\begin{cases} d_i = (d_i^1 + d_i^2)/2 \\ v_i = (v_i^1 + v_i^2)/2. \end{cases} \quad (4)$$

B. Three-segments FMCW

Another variant of the FMCW waveform was presented in ref. [1], [6] and [7]. In this modulation format, a pure sinusoid is emitted and the rest of the waveform is made of classical FMCW waveform with an up and a down ramp. The frequencies of sine waves echoed during the fixed frequency emission depend only on the Doppler frequencies of targets and not on their distance. These Doppler frequency provide us with the information of the targets relative velocity and can then be used to correctly associate the beat frequencies in the up and down ramps. This waveform will be referred to as FMCW with pure sinusoid.

The frequency versus time plot of the FMCW with pure waveform is given in (2). Here, f_0 , B and T have the same value as before and $\theta = T/3$. For this waveform, target association is quite simple: the pure sinusoid part supplies Doppler frequencies. Good association of targets Doppler frequencies with up and down chirps beat frequencies is achieved by comparing corresponding delays for up and down ramps. These delays are proportional to $f_{pure} - f_{up}$ and $f_{do} - f_{pure}$ respectively:

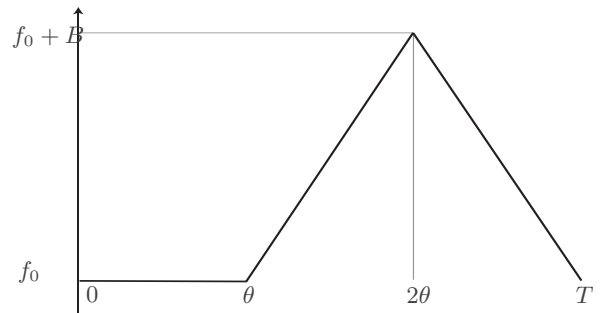


Fig. 2. Three-segments FMCW waveform

$$d_i^{up} = (f_i^{pure} - f_i^{up}) \frac{c\theta}{2B} \quad (5)$$

and d_{do}^i is calculated in the same way. After beat frequencies association, final estimates are given by

$$\begin{cases} d_i = (f_i^{down} - f_i^{up}) \frac{c\theta}{4B} \\ v_i = (f_i^{up} + f_i^{down}) \frac{\lambda}{4} \end{cases} \quad (6)$$

Let us remark that the pure frequency is not accounted for in the calculation of final estimates. This will be justified in the next section.

III. PERFORMANCE ANALYSIS

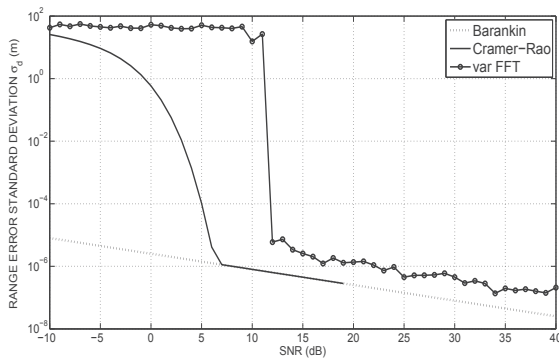


Fig. 3. Lower bounds and estimator performance for target range with dual FMCW ($d = 50m, v = 80Km/h$).

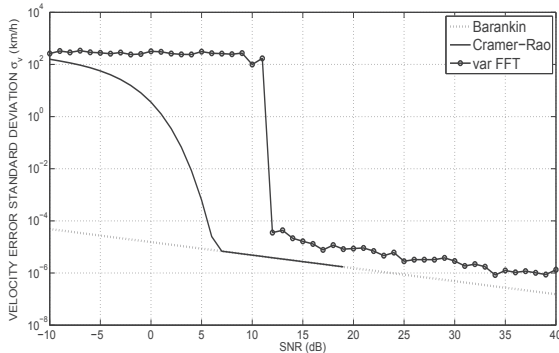


Fig. 4. Lower bounds and estimator performance for velocity with dual FMCW ($d = 50m, v = 80Km/h$).

As seen before, the distance and the velocity are obtained by a linear combination of beat frequencies. For each ramp, the beat frequencies are calculated by detection of the maxima of the periodogram. This is a standard way to estimate frequencies when large data samples are available. Here about 2000 samples are available for each ramp (and T is about 5ms). Then, the maximum of the periodogram is a good approximation of the maximum likelihood estimator [2], that tends to the Cramer-Rao bound as the SNR increases.

Fig. 8 shows the performance of the estimation of the frequency of a sinusoid wave as a function of the SNR. We can see that at low SNR the Barankin bound is far above the Cramer-Rao bound while it

reaches it for SNRs greater than about 5dB. Below this threshold level, variance becomes so high that it can be considered that the beat frequencies are not detected in general and the maximum of the periodogram corresponds to a false alarm. The variance supplied by Monte Carlo simulations and estimates of the beat frequencies supplied by the maximum of the periodogram shows the same property. However, for this estimator, the threshold is shifted around 12dB. Let us note that the maximum of the periodogram is searched for continuously varying frequencies and not only at FFT frequencies to avoid estimation bias that would be caused by frequency domain discretization. More sophisticated frequency estimators could be considered to decrease this threshold SNR, at the expense of higher processing complexity.

The range and velocity of the vehicle are obtained by a linear combination of up and down beat frequencies. This enables the calculation of their theoretical variance from those of the beat frequencies. We display standard deviation error curves versus signal to noise ratio (SNR) for a car distant of 50m from the radar and with a relative frequency of 80km/h. Fig. 3 and 4 show the standard deviation of the range error and speed error for the dual FMCW. Since velocity and distance are calculated as linear transforms of the beat frequencies, we get quite the same threshold SNRs for Barankin bounds and for the practical estimators for both distance and velocity.

Fig. 5 and 6 give respectively the range and velocity standard error deviation using the Three-segments FMCW. Here again, the threshold SNRs have the same value. We can check that theoretical bounds are lower for the dual FMCW than for the FMCW with pure sinusoid. This can be justified by the fact that the pure frequency estimate is not accounted for parameter estimation making thus part of the transmitted energy useless for estimation (the pure sinusoid is only intended for beat frequencies association with targets), resulting thus in worse performance for the FMCW with pure sinusoid waveform. The slightly better performance of the dual FMCW is confirmed by Monte Carlo simulations carried out on a realistic FMCW radar simulation program written with MATLAB simulation language.

Let us now briefly justify why one should not use the pure sinusoid frequency. On Fig. 7, we have plotted the noise level at the output of the radar RF receiver simulator. Clearly, the noise is colored, due in particular to the noise brought by the oscillator and by the mixers. As usual, it is higher at low frequencies. We have plotted on Fig. 7 the values of pure sinusoid, up and down beat frequencies. One can check that the beat frequency of the pure sinusoid part of the waveform is much lower in general than those of up and down ramps, resulting in a lower SNR and thus in

significantly higher variance of the estimator. This is illustrated in Figures 7 and 8.

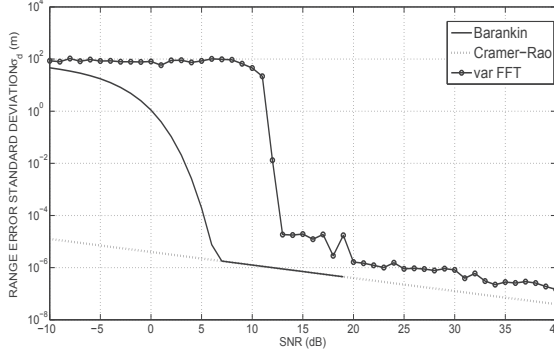


Fig. 5. Lower bounds and estimator performance of range with Three-segments FMCW ($d = 50m, v = 80Km/h$).

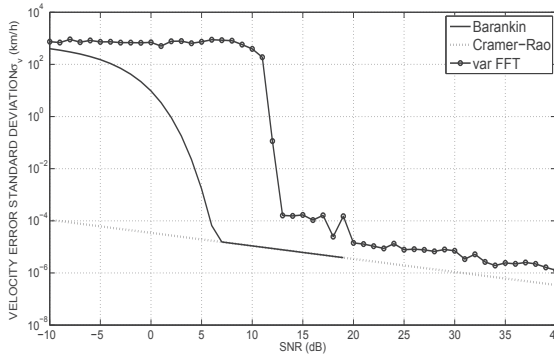


Fig. 6. Lower bounds and estimator performance of velocity with Three-segments FMCW ($d = 50m, v = 80Km/h$).

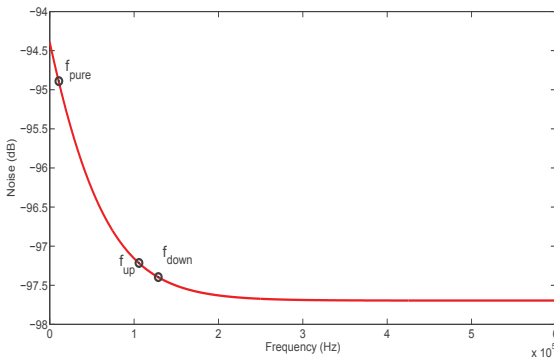


Fig. 7. Noise spectrum and beat frequencies for the FMCW with pure sinusoid waveform ($d = 50m, v = 80Km/h$).

IV. CONCLUSION

In this paper, we have presented a comparison of two strategies for FMCW radars in the presence of multiple targets. We derived Cramer rao and Barankin

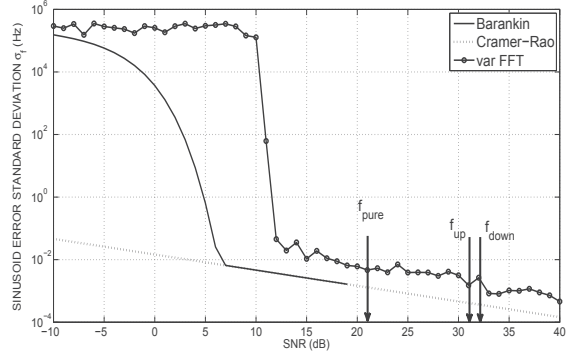


Fig. 8. Frequency variance and bounds. Comparison of beats for a car ($d = 50m, v = 80Km/h$).

lower bounds for the variance of speed and range estimators. Barankin bounds show a threshold SNR for estimators. The same threshold effect is observed on Monte Carlo simulations, but with an offset of about 7dB. This threshold clearly indicates detection capability for the waveforms. Finally, for both waveforms a 15dB detection threshold appears to be a good choice. This choice is confirmed by real life radar experiments.

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