Novel technique for reducing effects of non-linear frequency sweeps in LFM ranging radars

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Abstract—**A new technique for overcoming VCO (Voltage Controlled Oscillator) non-linearity in FMCW (Frequency Modulated Continuous Wave) radar transceivers is presented. The proposed technique relies on correlating the output beat signal in the stretch processing technique with a pre-formed reference correlation signal that accounts for the VCO non-linearity. An overview of the FMCW radar is presented followed by a discussion of the VCO non-linearity problem with existing solutions. The proposed solution is demonstrated with supporting simulation results. The benefits of the proposed solution are stated with a suggestion of a possible simple realization.**

Keywords-component; FMCW; LFM; stretch processing; radar; chirp non-linearity;

I. INTRODUCTION

FMCW radars find a variety of applications due to their fine range resolutions, high SNR (and hence long range measurement capability) and practical H/W implementations [1]-[3]. Such applications include altimeters [4], [5], automotive applications [6], [7], railway hazard detection systems [8], [9] and military applications.

The base of the FMCW radar transmitter is to modulate the frequency of the transmitted sinusoid with a sweep signal (saw-tooth, triangular or sinusoid). This frequency modulation is achieved principally by applying the sweep signal to the input of a VCO. The resulting transmitted signal can utilize very large bandwidth while having relatively long sweep period which in turns results in a fine range resolution while maintaining high SNR and long range detection capability. The LFM (Linear Frequency Modulation) is most widely used, with either a sawtooth or a triangular modulating sweep signal, due to its ease of implementation and high performance, so we will concentrate mainly on LFM radars.

LFM radar signal processing in the receiver is usually accomplished in one of two ways; matched filter or stretch processing (active correlation):

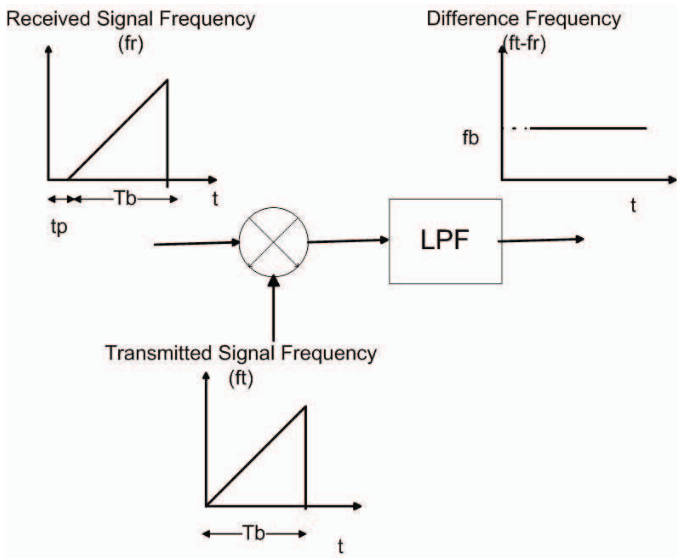

Figure 1. The basic idea of the LFM radar using stretch processing technique

A. Matched Filter

The matched filter method is the fundamental way of processing any radar waveform. It is performed by passing the received signal through an analog filter, usually Surface Acoustic Wave (SAW) filter, matched to the transmitted waveform or by applying DSP (Digital Signal Processing) techniques to the received signal to perform the matching filter processing. The matched filter receiver is much more complex than active correlation method and requires processing the received signal directly with its very wide bandwidth.

B. Stretch Processing (Active Correlation)

It is the most widely used method in LFM radars due to its ease of implementation compared to matched filter Receiver and its comparable performance (range resolution and SNR).

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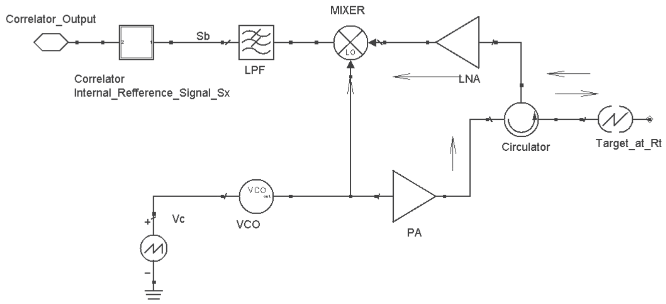

Figure 2. The basic block diagram of the LFM transceiver with the stretch processing technique

The basic idea of the active correlation receiver is illustrated in “Fig. 1”. The received signal is mixed with a replica of the transmitted signal and the resulting signal passes through a LPF (low-pass filter). The received signal (the echo signal) is a delayed version of the transmitted signal by the propagation delay “T_p”, which corresponds to twice the range between the radar and the target “R_t”. The resulting signal of the LPF is the beat signal "S_b", which is a single tone with the beat frequency between the transmitted and received signals “f_b”. This beat frequency can be calculated from the LFM signal slope as shown in “Fig. 1” and is given by:

$$fb = \frac{Tp \times B}{Tb} = \frac{\frac{2 \times R}{c} \times B}{Tb} \quad . \tag{1}$$

Where “B” is the bandwidth of the LFM signal (also called chirp signal) and “T_b” is the sweep period. Equation (1) reveals that the beat frequency “f_b” is directly proportional to the required range “R_t”, so the radar mission (which is measuring the target range in our case) is completely accomplished by determining f_b.

There are several methods of determining the resulting beat frequency (f_b). Most of these methods are performed by means of (DSP) because S_b is a low frequency signal that can be converted easily to the digital domain to make use of the advanced DSP algorithms. One of these methods is to apply the Fast Fourier Transform (FFT) algorithm to S_b and divide the spectrum to a group of frequency bins corresponding to the range bins forming the receive window (which is a composite of the detectable target ranges). By determining the frequency bin to which f_b belongs the target range bin is identified.

Another way is to correlate the resulting signal from the LPF with a set of frequencies corresponding to a set of ranges forming the receive window and by comparing the results of the different correlators we can determine the best match between f_b and the set of frequencies and hence determine the corresponding target R_t.

Although the first method is more widely mentioned in literature, we will adopt the second method because it is simpler and directly applicable to our proposed technique as will be shown in the following sections. The basic block diagram of the LFM transceiver is illustrated in "Fig. 2".

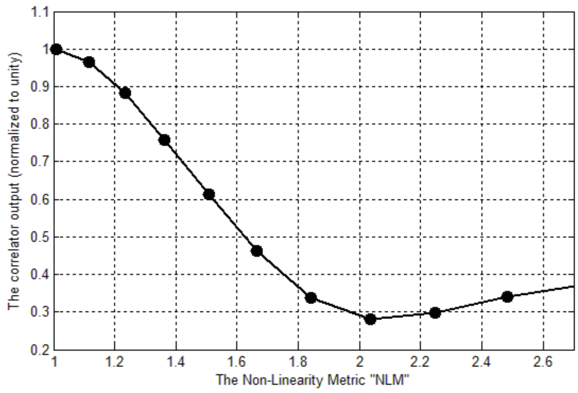

Figure 3. The correlator output, for a range corresponding to the required target range, versus different amounts of non-linearity in the VCO

The LFM radar suffers from some problems that can limit its performance if not addressed properly. One significant problem is the non-linearity of the frequency sweep. This problem will be explained in details in section II with an overview of the existing solutions, and then a new proposed solution for this problem is introduced with the advantages of the solution and an idea of a possible practical realization in section III followed by the simulation results supporting he validity of the solution, obtained using MATLAB/Simulink, illustrated in section IV. Finally, our conclusion is given in section V.

II. Frequency Sweep Non-Linearity Problem

As explained in the previous section, the target range detection in LFM radars depends mainly on having a single tone at the LPF output with frequency corresponding to R_t. This single tone results from subtracting the frequency of two chirp signals (with linear frequency versus time). The frequency linearity of the chirp signal is usually accomplished by applying a ramp signal to a VCO input. If the VCO tuning curve is not linear over the swept frequency range, which is usually the case in RF VCOs (particularly, integrated ones), the transmitted signal will exhibit a non-linear slope of frequency versus time, which in turns lead to a non-constant frequency signal at the LPF output.

VCO non-linearity is considered a serious problem in LFM radars because it potentially limits its performance [10]. To see the effect of VCO tuning curve non-linearity, we will first define a Non-Linearity Metric (NLM) that represents the amount of non-linearity in a certain tuning curve:

$$NLM = \frac{Smax}{Smin} \quad . \tag{2}$$

Where S_{max} is the maximum slope of the tuning curve, S_{min} is the minimum slope of the tuning curve. Note that in the ideal linear case: $S_{max} = S_{min}$ and NLM=1 (constant slope over the whole tuning range). Simulations of the shown system in "Fig. 2" were performed for different signals suffering from different amounts of non-linearity (different NLMs) using MATLAB/Simulink as follows: A set of non-linear curves were generated to be used as the control signals for an ideal linear VCO. For each curve, the NLM is calculated and the simulation is run to obtain the correlation output normalized to unity (for the same target range "R_t"). A plot of the normalized correlation output versus NLM is shown in “Fig. 3”. The simulation was run assuming that the generated chirp signal has a center frequency of 2.4 GH, a bandwidth of 150 MHz and a sweep rate of 100 KHz (T_b=10 us). Also the required target range "R_t" was assumed to be 10 m so, the reference correlation signal is a single tone with a frequency of 1 MHz (obtained by substituting in (1)) and the actual simulated range (R_x) was also 10 m. The resulting curve indicates clearly how performance is degraded by increasing the amount of non-linearity produced by the VCO; as the NLM increases, the resulting frequency of the beat signal deviates from that of the reference correlation single tone used in the correlator, which in turns degrades the correlation output. Note that a correlation output of “1” corresponds to a perfect matching between both signals.

Several solutions have been proposed in literature for this problem. These solutions include pre-distorting the control signal at the VCO input in a way that produces a linearly swept frequency at the VCO output [9]. Usually, the pre-distorted curve is obtained by measuring the VCO tuning curve after fabrication. Although fairly simple, this solution does not account for process, supply, temperature (PVT) variations and time variations (aging factor). The second solution uses the same idea but it utilizes a feedback loop that takes measurements from the VCO output and produces an error signal that is converted to a correcting signal to the pre-distortion curve to ensure the linearity of the swept frequency versus time [11]. This is considered a real-time solution that can account for PVT and time variations but it requires much more hardware components or complex signal processing techniques. Another similar solution is to lock the VCO to a linear chirp reference signal using a Phase Locked Loop (PLL) [12]. The PLL needs to have a very wide bandwidth which increases its noise contribution leading to performance degradation. Some systems concentrate on designing an extremely linear VCO [13], but implementation of such a VCO is limited by practical considerations especially for monolithic implementations. Also, many LFM radars generate the chirp signal digitally using a Direct Digital Synthesizer (DDS) and then the DDS signal is up-converted to the required carrier frequency [14]. This gives a very linear and accurate swept frequency versus time curve, but the problem of the DDS is its large spurious emission due to quantization errors and its relatively limited bandwidth. In the following section a new proposed technique for overcoming VCO non-linearity problem is presented.

III. CORRELATING WITH A SIMILARLY PRE-FORMED SIGNAL

All the above-mentioned solutions for the non-linearity problem concentrate on how to produce a linearly-swept frequency with time. On the other hand, the proposed solution is based on the fact that the degradation in the correlation output results from the deviation of the beat signal S_b (in case of a non-linear transmitted chirp) from the reference correlation signal S_x. First, we produce a pre-formed signal (S_{xpre}) that matches the beat signal S_b (contains the same amount of deviation from the expected single tone) when the target is at a distance corresponding to the required target range (R_t). Then, we use this signal as the reference signal (S_x) to be correlated with S_b. The response of the correlator should be very close to that of the correlator when the reference correlation frequency S_x is the ideal single tone resulting from (1) and the beat frequency S_b is the single tone resulting from subtracting the frequencies of the ideal linear chirp signals.

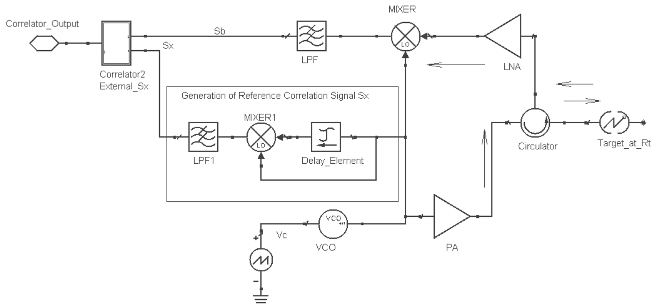

Figure 4. The block diagram of the LFM radar using a pre-formed reference correlation signal

The required reference frequency S_{xpre} is simply obtained by sampling the transmitted chirp and mixing it with a delayed version of itself with a delay corresponding to the required target range and passing the output through a LPF. The block diagram of the modified LFM radar employing the proposed technique is shown in “Fig. 4” as opposed to the basic LFM block diagram shown in "Fig. 2". The difference between the two systems is that the reference signal that is used for correlation is fixed and generated internally in the correlator (S_x) in the basic system, while it is generated using the actual chirp signal itself (S_{xpre}) then supplied to the correlator block to account for the chirp's non-linearity in the proposed system. This way we use the non-linearity of the chirp signal to eliminate its effect rather than working on producing a highly linear chirp signal. Note that the used correlator is a non-coherent correlator to extract the range information without taking the phase of the received signal into account. The correlation output for both systems is described in the results section.

It is worth mentioning that different target ranges can also be distinguished using different correlators with different reference correlation signals (S_{xpre1}, S_{xpre2},....,S_{xpreN}), where "N" is the number of distinguishable target ranges. These N reference signals are generated by mixing a sample of the transmitted chirp signal with "N" differently delayed versions of itself with each delay corresponding to one of the N detectable range bins then the outputs are passed through LPFs. Hence, we can determine the target range by correlating the received signal with each of the "N" generated reference signals and comparing the outputs of the N correlators.

As indicated above, the proposed solution needs an additional mixer, LPF and delay element, operating at high frequency, for each correlator (each detectable range). The problem of high frequency can be mitigated by down-converting the replica of the transmitted signal to a much lower frequency before delaying and mixing, relying on the fact that the beat signal depends on the difference frequency between the chirp and its delayed version rather than their absolute frequencies. This will relieve the requirements on the components to a great extent. Furthermore, at such a lower frequency the signal can be converted to digital and hence the delay and mixing can be performed easily by means of DSP (either software or hardware processing).

From the above discussion we can see that the proposed solution has the following advantages:

- A robust solution that is not affected by PVT variations or aging factor (real-time).
- Simple implementation that doesn't require complex algorithms or impractical hardware components.
- Does not degrade the system performance, i.e. does not add extra noise components to the output.
- Enable the system to have a better spurious performance by using a VCO rather than a DDS.
- Almost completely eliminating the non-linearity effect on the correlation output.

IV. RESULTS

In this section, the LFM radar system employing the proposed solution is simulated using MATLAB/Simulink. The results are compared to that of the same system without using the proposed solution to see the improvement in the correlation output in the presence of the VCO non-linearity.

First, simulations were performed for different amounts of non-linearity (different NLMs) on our proposed system as shown in "Fig. 4" using the same parameters as described in section II (f_c=2.4 GHz, B=150 MHz, T_b=10 us and R_t=R_x=10 m) . The resulting normalized correlation outputs are plotted versus different NLM values in "Fig.5". It is clear from "Fig. 5" that correlating with the pre-formed reference signal results in an ideal normalized correlation output of unity irrespective of the VCO non-linearity as long as the target range is identical to the correlator reference range (R_x=R_t=10 m in our case).

It is important to note that the target range detection and range resolution depend on the response of the correlator to different target ranges around the reference range of the correlator (R_x close to R_t). It can be shown that the ideal non-coherent correlation output, assuming linear frequency sweep, is related to the resulting beat frequency after mixing (f_b) by a sinc function with its maximum at the frequency of the reference correlation signal corresponding to the required target range (f_x). The relation is given by:

$$Output = Sinc\left(\pi\left(fx - fb\right)\times Tb\right) \qquad (3)$$

Knowing that the target range is linearly related to the resulting beat frequency f_b by (1), assuming linear frequency sweep, it is clear that correlation output is related to the target range by a sinc function centered at the required target range (Rt). From (3) we can see that the first zero crossing occurs at

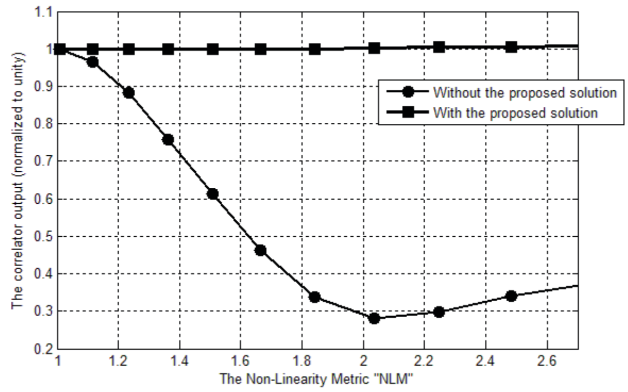

Figure 5. The normalized correlation versus Non-linearity Metric for basic LFM system and LFM system employing the proposed solution

(Δf=f_b-f_x=1/Tb) and hence the range resolution of the LFM radar can be directly calculated from (1) to be:

$$\Delta R = c/2B \qquad (4)$$

Equation (4) assumes a linear frequency sweep (linear VCO), but in case of a non-linear frequency sweep the resulting beat signal (S_b) has a non-constant frequency versus time. This varying frequency causes a corrupted correlation output as illustrated in the previous section. Also, the range deviation from the reference target range leads to a non-linear frequency deviation in the beat signal (not obeying (1)) and hence the correlation response is far from the above-mentioned sinc function.

"Fig. 6" shows different plots of the normalized correlation output versus target range for NLM=1, 1.6 and 2. The simulations were performed assuming the same system parameters as those used for "Fig. 5" and stated earlier in this section. Note that NLM=1 corresponds to an ideal linear chirp following the sinc function response as expected and NLM=2 corresponds to the worse degradation in the correlation output as indicated in "Fig. 3". It can be shown from "Fig. 6" how the simulated frequency sweep non-linearity has completely corrupted the correlation output response.

The same simulations were also performed on the system shown in "Fig. 4" employing the proposed solution by correlating the beat signal with the pre-formed reference signal that accounts for the VCO non-linearity. The results are plotted in "Fig. 7". It is clear that the proposed solution has drastically improved the system response to target ranges around the reference target range and made it close to the ideal sinc response. We should note that when the target range (R_x) deviates from the reference target range (R_t) there is still some non-linearity mismatch that exists between the actually resulting beat signal (S_b) and the pre-formed reference signal (S_{pre}), but this non-linearity mismatch can be neglected for small range deviations as indicated by the resulting plots.

The previous results indicate that the proposed solution has a superior performance that nearly eliminates the ambiguity in the radar range measurement resulting from the VCO non-linearity problem.

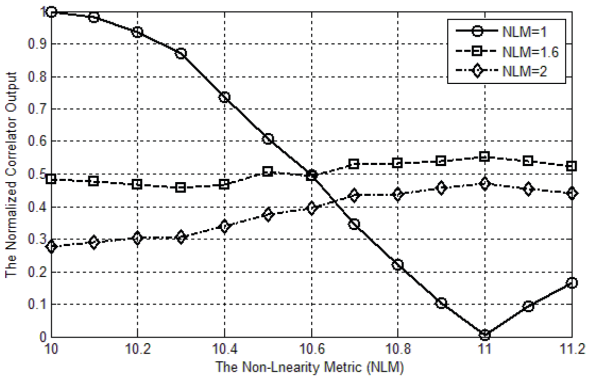

Figure 6. The normalized correlation output versus range without applying the proposed technique (Rt=10 m and ΔR=1 m) for different NLMs

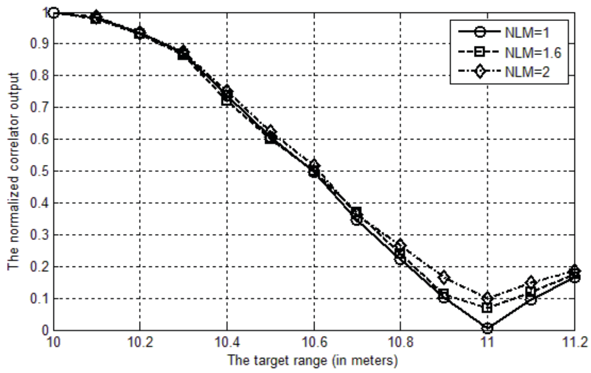

Figure 7. The normalized correlation output versus range when applying the proposed technique with (Rt=10 m and ΔR=1 m) for different NLMs

V. CONCLLUSION

A new solution for the problem of non-linear frequency sweep in LFM radars is presented. The solution relies on generating a pre-formed reference correlation signal that accounts for the VCO non-linearity. The simplicity and practicality of the proposed solution were demonstrated accompanied with its advantages over other existing solutions. Simulations supporting the efficiency of the solution are performed using MATLAB/Simulink and the resulting curves are demonstrated with brief comments.

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