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Effect of DRFM Phase Response on the Doppler Spectrum of a Coherent Radar: Critical Implications and Possible Mitigation Techniques

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ABSTRACT

In this research, the critical implications of the phase response of a Digital Radio Frequency Memory (DRFM) based repeater system on the Doppler spectrum of a modern, coherently processing radar system (e.g. pulsed Doppler radar) are presented. It is shown that, in addition to the desired Doppler term due to the simulated movement of the repeated echo, the spectrum exhibits a number of unwanted terms which result in spurious responses in the processed radar data set. The radar could exploit these effects to identify the echo as a DRFM-based repeater jammer. When a DRFM is used in the testing of radar equipment the radar system performance will be incorrectly inferred. The paper concludes with a possible mitigation scheme.

INTRODUCTION

Digital Radio Frequency Memories (DRFMs) are the next generation of repeater jammers that utilise state-of-the-art digitisers, allowing the radar waveform to be sampled, stored and repeated coherently with a digitally controlled, variable time delay that can be adjusted in real-time. The deployment of DRFM-based repeaters in Electronic Attack (EA) and Hardware-In-the-Loop (HWIL) simulator systems is well known, e.g. [**1**]. Dyck [**2**] qualitatively specified the performance requirements for high resolution DRFM-based EA systems from a modern radar perspective. Küsel *et al*. [**3**] and Greco, Farina *et al*. [**4**] have analysed and quantified the Continuous Wave (CW) spectral purity for the different DRFM encoding architectures and range gate pull-off deception techniques. Greco and Farina showed that the spectral impurities due to phase quantization are by far the dominant effect.

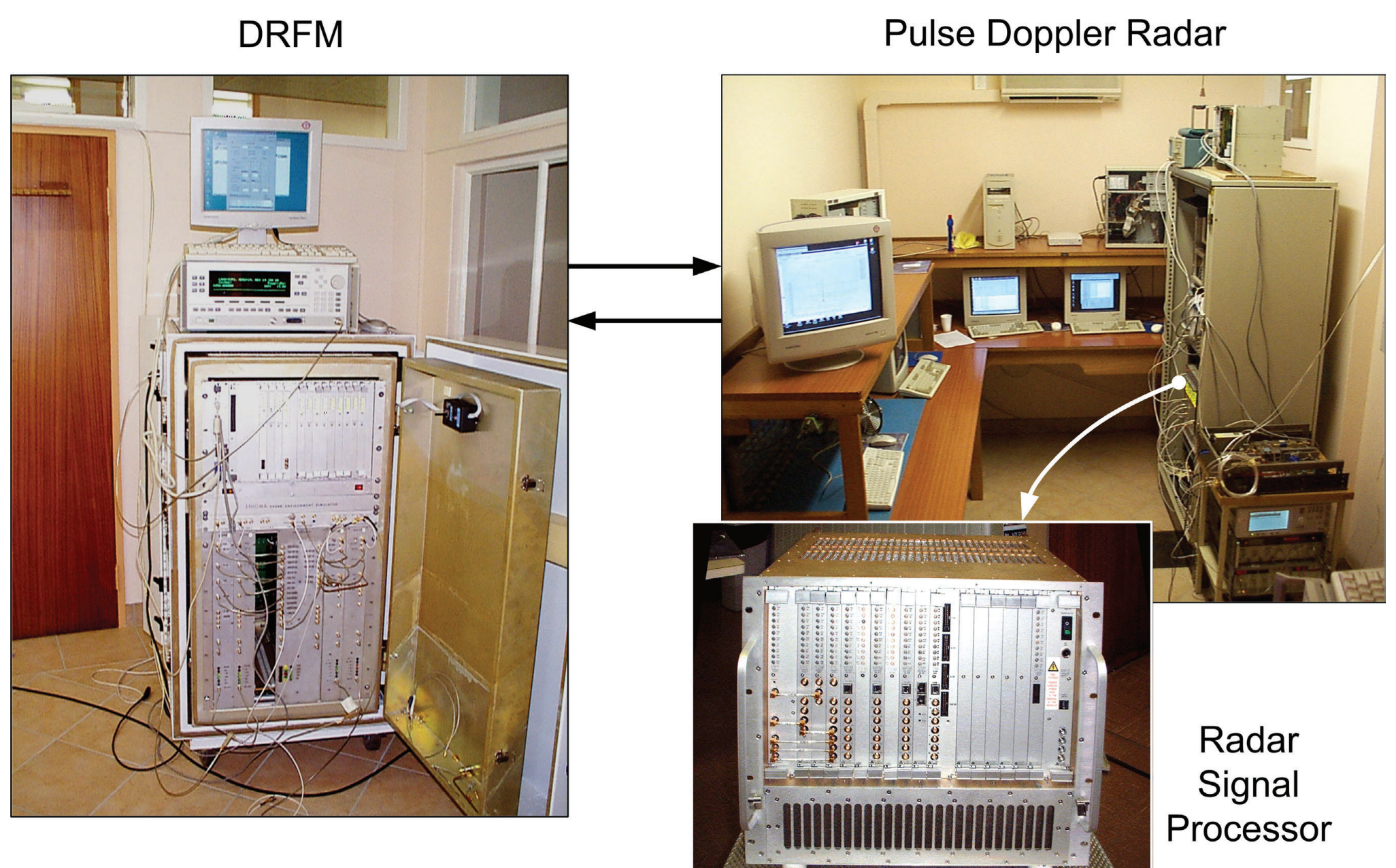

Figure 1: Laboratory setup of pulse Doppler radar and DRFM

This research investigates the effect of the DRFM's discrete time delay (range delay) resolution, and transitions between these discrete delays, on the signal processor of modern radar. The paper will present a theoretical analysis of this effect as well as simulation results and laboratory measurements conducted using a radar and a DRFM system (**Figure 1**). In conclusion a mitigation technique for the abovementioned effects is suggested.

SYSTEM DESCRIPTION

Figure 2 depicts a system level block diagram of a generic radar-DRFM interaction. The radar generates the transmit waveform at baseband (I and Q channels) using a Digital-to-Analog Converter (DAC). This signal is up-converted to RF by a single analog mixing stage. Next, the waveform is received by the DRFM-based system antenna and is down-converted to the Intermediate Frequency (IF) of the DRFM. After being digitised, stored (delayed) and repeated, the waveform is up-converted using a frequency shifted version of the LO to generate the required Doppler shift. This waveform is received by the radar, coherently down-converted and sampled by means of two Analog-to-Digital Converters (ADCs). The radar then applies pulse compression and Doppler filtering to the digitised sample train.

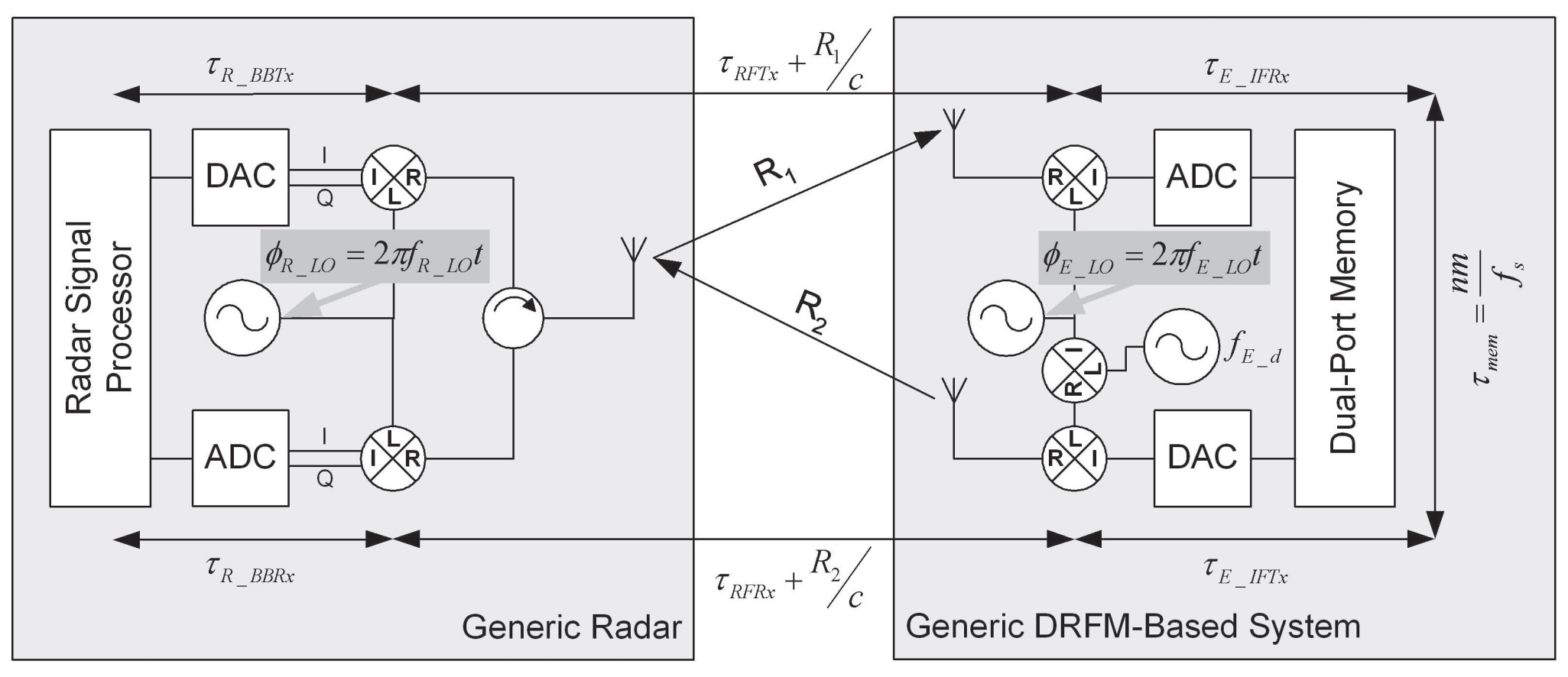

Figure 2: Block diagram of generic radar and DRFM-based system

THEORETICAL DERIVATION OF THE RADAR SYSTEM DOPPLER SPECTRUM

The only physical components that can influence the radar phase response are the mixers. The phase response for radar pulse q in the coherent processing interval can be expressed as

$$\phi_{R\_BB\_Rx} = 2\pi f_{E\_LO}\left(t_{E\_tx} - t_{E\_rx}\right) - 2\pi f_{R\_LO}\left(t_{R\_rx} - t_{R\_tx}\right) + 2\pi f_{E\_d} t_{E\_tx} \quad , \tag{1}$$

where f_{E_LO} is the LO frequency of the DRFM-based system, f_{E_d} is the required Doppler shift, $t_{R\_rx} - t_{R\_tx}$ is the time delay between radar transmission and reception and $t_{E\_tx} - t_{E\_rx}$ is the time delay induced by the DRFM. The transmission time instant of the DRFM is denoted by t_{E_tx}. For a DRFM sampling at f_s samples/second:

$$t_{R\_rx} - t_{R\_tx} = \tau_{C1} + \left(R_1 + R_2\right)c^{-1} + nmt_s \;\; ; \;\; t_{E\_tx} - t_{E\_rx} = \tau_{C2} + nmt_s \;\; ; \;\; t_{E\_tx} = \tau_{C3} + R_1 c^{-1} + nmt_s + q\tau_{PRI} \quad , \tag{2}$$

where T_{PRI} is the radar's pulse repetition interval, $t_s = 1/f_s$, mt_s is the DRFM time delay resolution, n is the DRFM offset between the read and write pointers in m sample steps, and T_{c1}, T_{c2} and T_{c3} are constant time delays that can be calculated as:

$$\tau_{C1} = \tau_{RFTx} + \tau_{E\_IFRx} + \tau_{E\_IFTx} + \tau_{RFRx} \;\; ; \;\; \tau_{C2} = \tau_{E\_IFRx} + \tau_{E\_IFTx} \;\; ; \;\; \tau_{C3} = \tau_{RFTx} + \tau_{E\_IFRx} + \tau_{E\_IFTx} \quad . \tag{3}$$

Substituting (2) into (1) yields:

$$\phi_{R\_BB\_Rx} = \phi_C + 2\pi\left[-f_{R\_LO}\left(R_1 + R_2\right)c^{-1} + nmt_s\left(-f_{R\_LO} + f_{E\_LO} + f_{E\_d}\right) + f_{E\_d} R_1 c^{-1} + f_{E\_d} q\tau_{PRI}\right] \quad , \tag{4}$$

where ϕ_c is a constant phase induced by the constant time delays in (3). The term $f_{E\_d}.q.T_{PRI}$ produces the required Doppler peak at f_{E_d} after Doppler processing. Apart from the Doppler term and the constant phase term, ϕ_c, all other terms are unwanted.

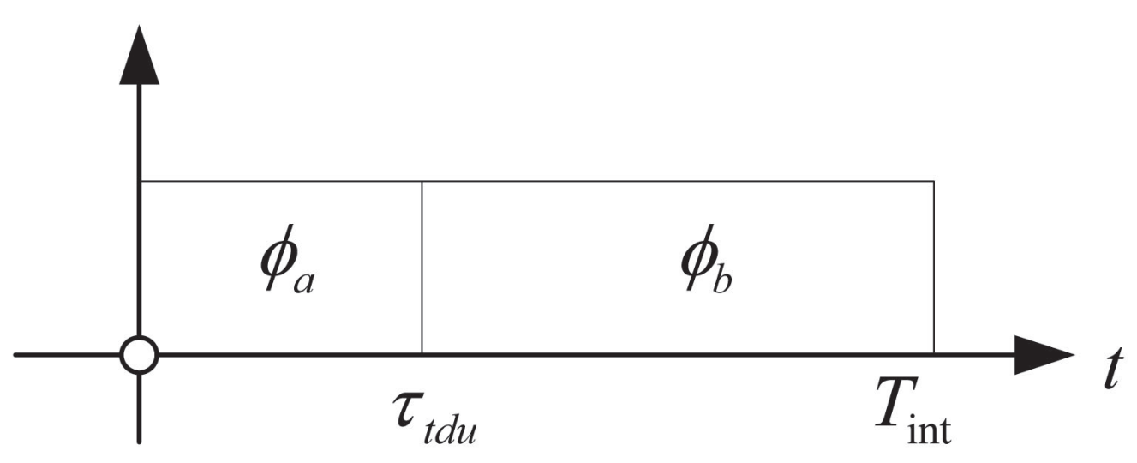

Figure 3: Phase transition occurring within the radar's coherent integration interval

The following analysis will focus on the effects of changing the DRFM time delay during the radar's coherent integration time for the stationary platform case. The total DRFM time delay, nmt_s, is controlled by the offset, n, between the read and write pointers of the dual-port memory and is updated at a rate T_u (typically 1- 2 ms).

DOPPLER PROCESSOR RESPONSE FOR A SIMULATED CONSTANT RADIAL VELOCITY TARGET

The following analysis focuses on the effects of changing the DRFM time delay during the radar's coherent integration time when both the DRFM and radar systems are stationary.

The continuous Fourier transform [5], of this time domain effect can be calculated as:

$$g(f) = \exp\left[j\phi_a - j\pi(f - f_d)\tau_{tdu}\right] \times \tau_{tdu}\,\text{sinc}\left[(f - f_d)\tau_{tdu}\right] + \exp\left[j\phi_b - j\pi(f - f_d)(T_{int} + \tau_{tdu})\right] \times (T_{int} - \tau_{tdu})\,\text{sinc}\left[(f - f_d)(T_{int} - \tau_{tdu})\right] \tag{5}$$

From (5) it can be seen that the radar's Doppler spectrum will consist of the sum of two sinc() spectra, $g_{\phi a}(f)$ and $g_{\phi b}(f)$. Examples of the amplitude spectra for the interactions between these two functions are shown in **Figure 4** for different relative phases ϕ_b-ϕ_a, with f_{E_d} = 1 kHz, T_{int} = 5 ms and T_{tdu} = 1.7 ms.

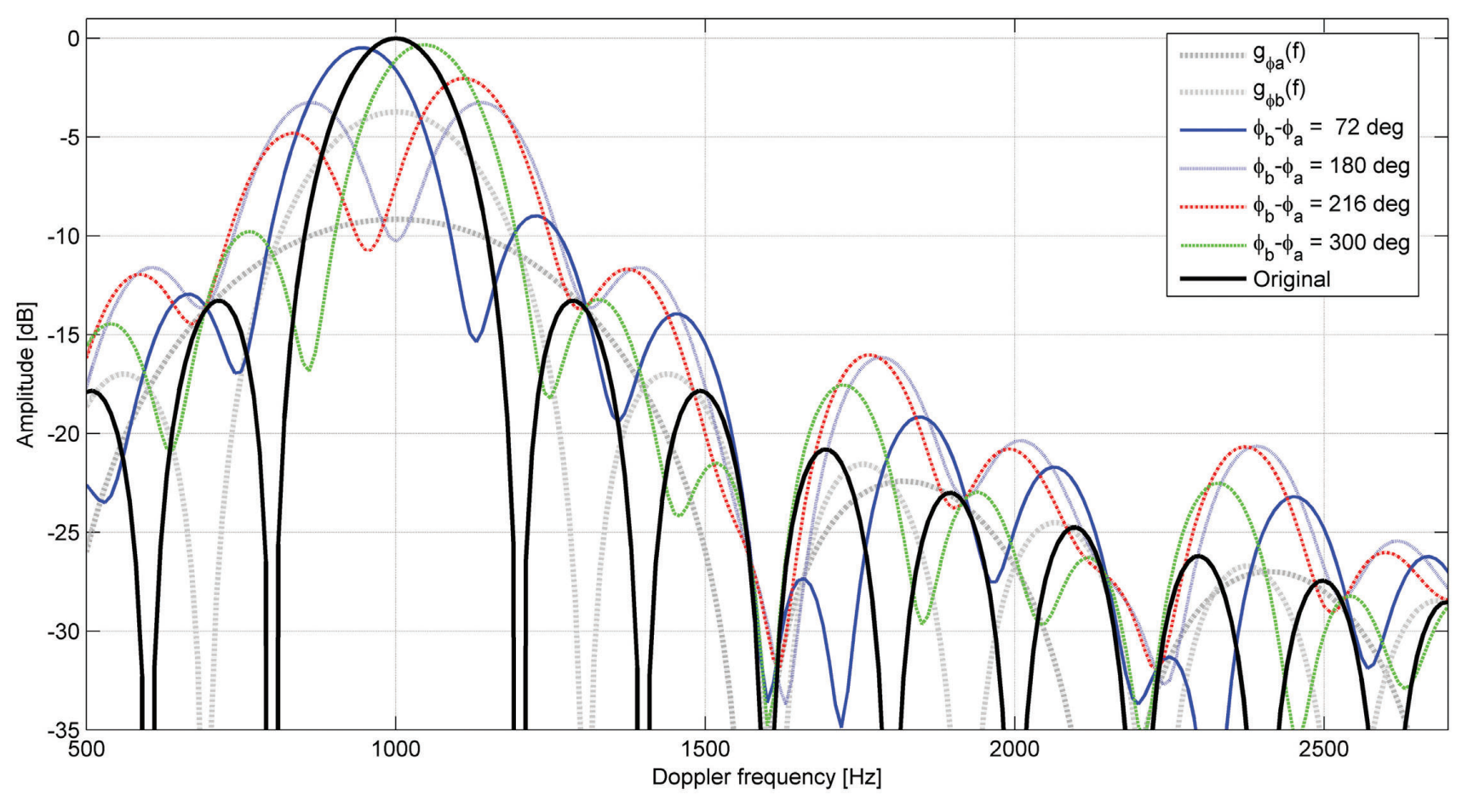

Figure 4: Example of interaction between the two interfering terms caused by the phase discontinuity.

The interaction causes effects in the Doppler domain such as broadening of the main lobe, cancellation of the peak, elevated sidelobe levels and a shift in the Doppler peak position. The contour plot in **Figure 5** further illustrates this effect for phase differences ϕ_b-$\phi_a \in [0,2\pi)$. It is evident that the Doppler peak shifts away from the desired Doppler frequency of 1 kHz.

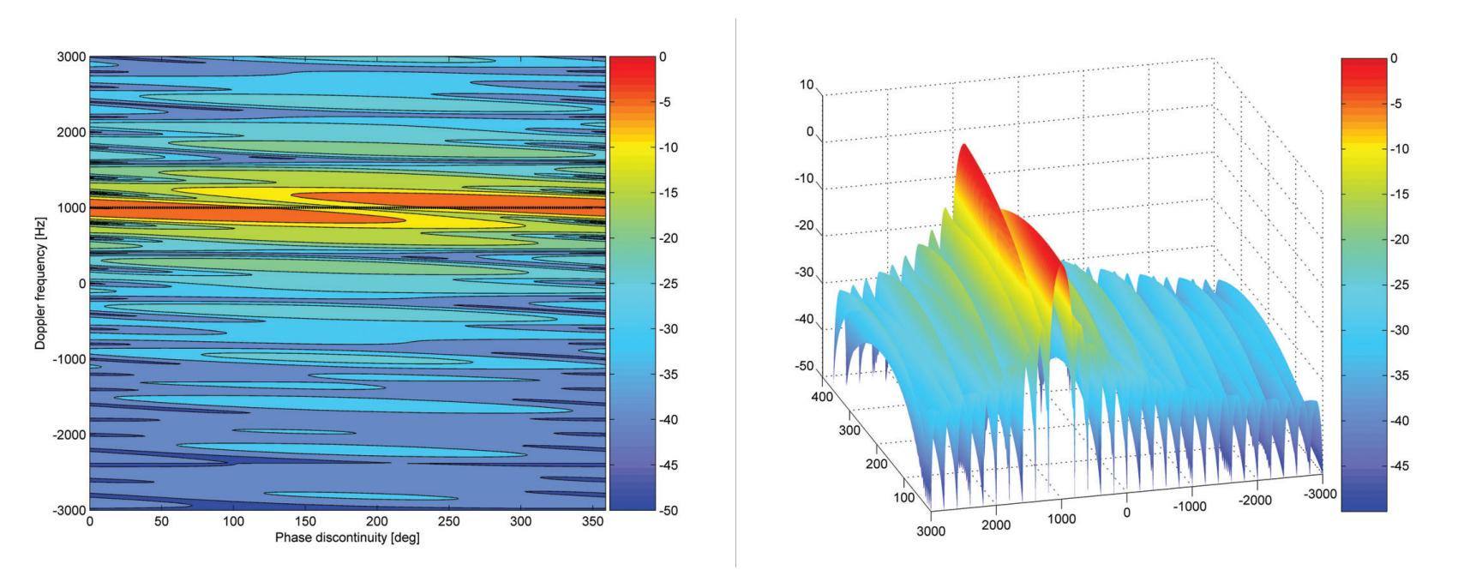

Figure 5: Example of interaction between the two interfering terms caused by the phase discontinuity.

HARDWARE IN THE LOOP TESTS

To complement the preceding theoretical analysis, laboratory measurements were made with a pulsed-Doppler Radar Signal Processor (RSP), transmitting at 9 GHz, integrated with a HWIL DRFM-based simulator system.

The RSP transmitted 64 pulses per burst. The DRFM simulated an inbound target at 650 m/s. The DRFM's update rate was 1 ms with a delay resolution mt_s = 16 ns. This configuration yielded f_{E_d} = 39 kHz (aliased to 3 kHz by the RSP). To establish a reference the DRFM was initially configured not to perform time delay updates and the subsequent Range-Doppler (RD) map produced by the RSP is shown in **Figure 6** (a).

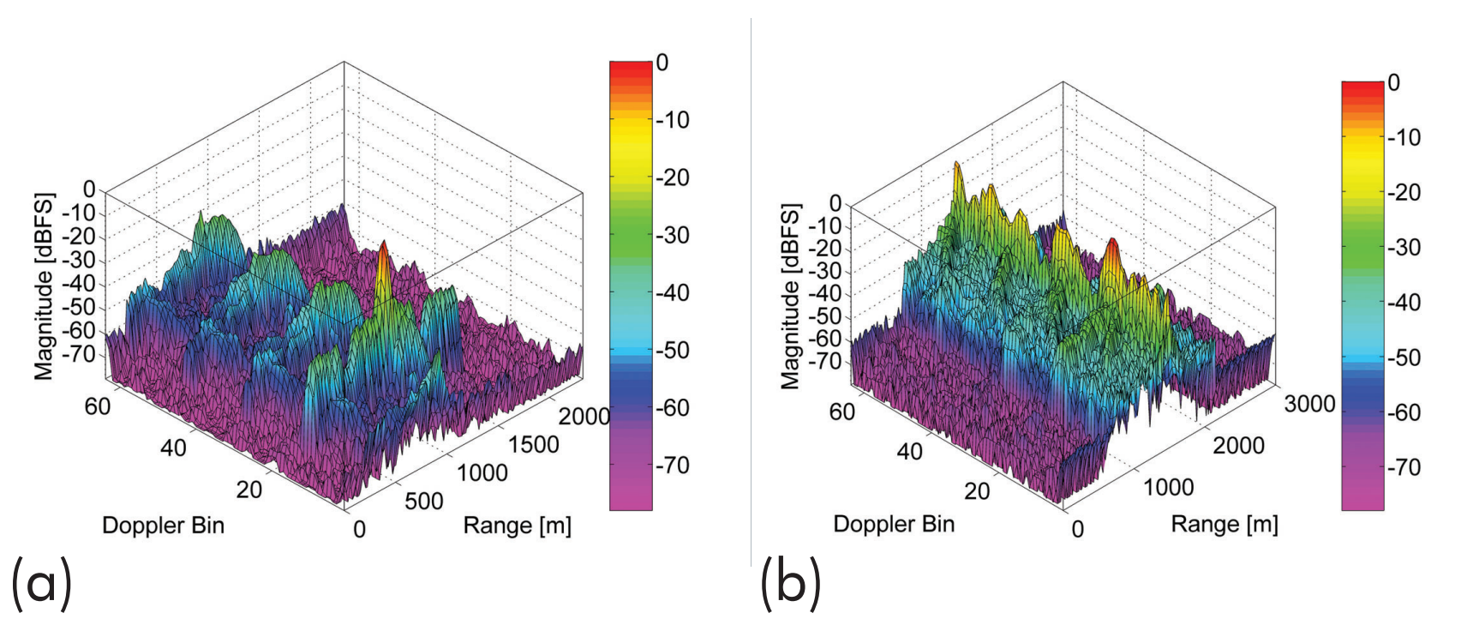

Figure 6: Range-Doppler map of a HWIL generated target without time delay updates (a) and with time delay updates (b).

The simulated target response is clearly visible with characteristic range sidelobes in the order of -30 dBc and Doppler sidelobes in the order of -33 dBc (see **Figure 7**). The latter sidelobes are due to the spurious response of the DRFM's RF stages. The RD map after activation of time delay updates is shown in **Figure 6** (b). It is clear that the range sidelobes are not severely affected but the Doppler sidelobes are significantly affected. **Figure 7** shows the Doppler responses of the range bins containing the simulated target's peak.

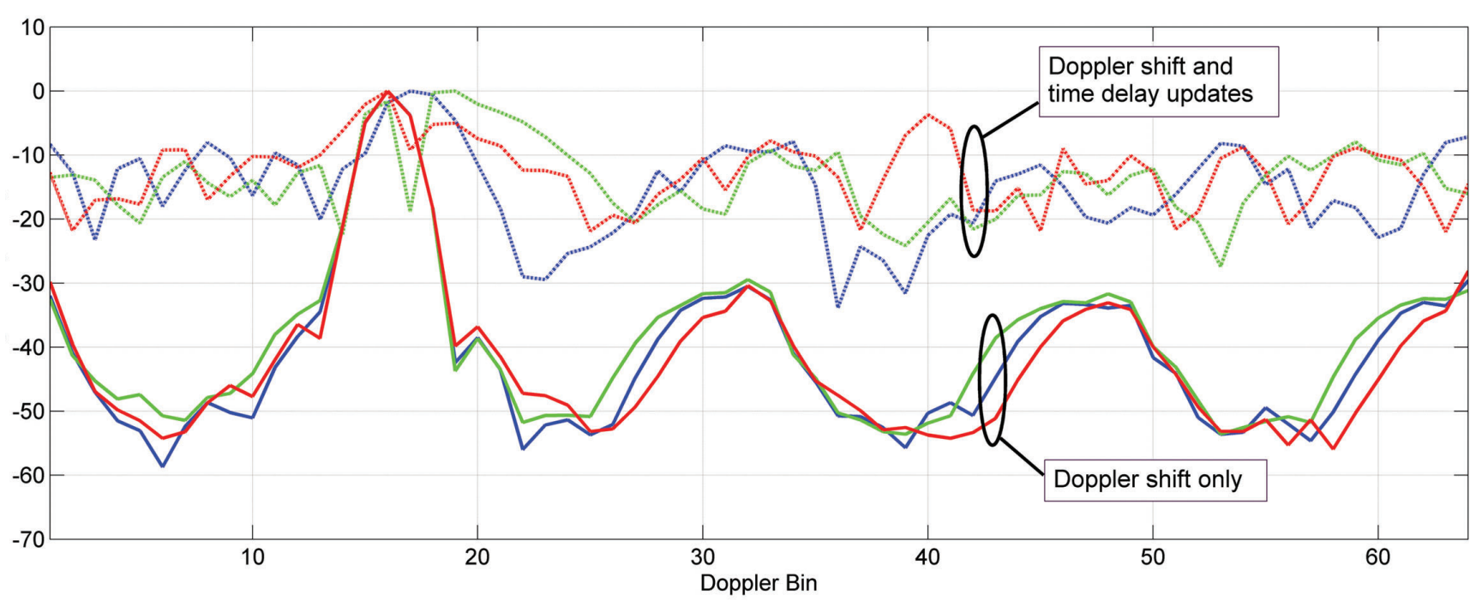

Figure 7: Doppler response of DRFM generated target with and without time delay updates

It is evident that the Doppler peak is frequency shifted, somewhat broadened and the sidelobes significantly increased to a level of approximately -10 dBc. This confirms the hypothesis that time delay updates in DRFM-based systems detrimentally affect the coherent radar system's Doppler response.

EFFECTIVE COMPENSATION FOR PHASE DISCONTINUITIES

For a stationary radar and DRFM, the induced phase error, $\phi_e = 2\pi\Delta nmt_s\left(f_{E\_LO} + f_{E\_d} - f_{R\_LO}\right)$, depends on the change in DRFM time delay, the Doppler shift frequency and the LO frequencies of both the radar and DRFM-based systems. Except for the radar LO frequency, all the other terms are known. The phase change can thus be calculated and compensated for by adjusting the instantaneous phase of the DRFM's transmit oscillator or by the addition of a digital phase shifter. The effectiveness of this compensation is determined by the achievable phase shift accuracy and the oscillator's phase stability. It is also necessary to accurately estimate the radar's transmit frequency. The maximum frequency estimation error associated with a given phase error can be shown to be $\max\{|f_{err}|\} = \max\{|\phi_e|\}(2\pi\Delta nmt_s)^{-1}$. If a phase error of $\pi/16$ is acceptable, the required frequency estimation error for a DRFM with mt_s = 16 ns is approximately 1.95 MHz, which is within reach of the current state-of-the-art ESM systems.

CONCLUSION

The effect of DRFM time delay updates on the radar's Doppler response have been investigated. It was shown that the phase discontinuities induced by the delay updates result in elevated Doppler sidelobes, peak broadening and even peak cancellation. The theoretical analysis was confirmed with HWIL laboratory tests, proving that this effect has to be considered when designing modern DRFM-based systems. A technique for the mitigation of these effects was presented and analysed.

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