

# The Spectrum of a Digital Radio Frequency Memory Linear Range Gate Stealer Electronic Attack Signal

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*Abstract*— In this paper, we examine the spectrum of a digital radio frequency memory (DRFM) linear rate gate stealer (RGS) electronic attack (EA) signal. The spectrum has two noticeable characteristics. The first is a small, yet measurable, center frequency shift from the input center frequency. The second is the presence of harmonics (spectral lines) of significant magnitude centered on either side of the shifted center frequency. The primary source of these spectral characteristics is the discrete nature of the DRFM. We develop expressions to predicted the center frequency shift and the locations of the harmonics as function of the radar and DRFM parameters. These spectral characteristics should be of interest to radar and EA engineers since they could potentially effect system performance. Signal intelligence analysts should also find these spectral characteristics of interest since they provide additional clues for assessing EA systems.

## I. INTRODUCTION

In a pulse radar system, the target range is tracked automatically using a split range gate system consisting of an early range gate and a late range gate [1, 176-177]. The early and late range gates are contiguous in time (range) and are approximately one pulsewidth wide. The combination of the early and late range gates is referred to as the range tracking gate. The range tracking point is the center of the range tracking gate (i.e., the joint between the early and late range gates). Initially, the position of the range tracking gate is set using range information obtained during search operations. After placing the range tracking gate over the target, a control loop is used to continuously adjusted the range tracking point to center the range tracking gate on the target. The error signal used in the control loop is based on the difference between the energy in the early and late range gates. The control loop is designed to balance the energy level between the early and late range gates. That is, as the target moves in range, the energy levels in the early and late range gates are not equal and the resulting error signal is used to reposition the range tracking gate in an attempt to balance the energy between the gates.

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The target's range and velocity, as well as the azimuth and elevation angles to the target, play a critical role in successfully engaging the target. Typically, an electronic attack (EA) system or jammer is employed on the target to deny the radar target information (range, velocity, azimuth and elevation angles) or to inject false target information into the radar. The range gate stealer (RGS) technique is one of the most fundamental EA techniques used to deny accurate range information to the radar. With the RGS technique, the EA system transmits a pulse of radio frequency (RF) energy that initially arrives at the radar time coincident with the target pulse. That is, both the jamming and target pulses are initially present in the range tracking gate. After a short period of time coincidence, the EA system begins to continuously delay the jamming pulse (RGS signal) with respect to the target pulse. The delayed jamming pulse attempts to draw the range tracker off the true target. If successful, the range tracker tracks the false (jamming) target until the EA system turns off the RGS signal. Without the RGS signal in the range tracking gate, the radar breaks range lock and initiates a search for the true target. The use of RGS to cause range break locks will complicate and hamper the successful engagement of the target. Several methods exist for generating RGS signals, with the most recent method using DRFM devices.

A DRFM EA system consist of five primary components: down converter, analog-to-digital converter (ADC), memory, digital-to-analog converter (DAC), and up converter. The basic operation of the DRFM is as follows. The received radar signal is down converted and sampled by the ADC. The samples are then stored in memory. The samples are later recalled from memory, passed through the DAC, up converted, and transmitted. Once the radar signal is stored in memory, the radar signal parameters can be manipulated by changing the stored samples and recalled at anytime to produce a wide range of EA signals. For the relatively simple case of linear RGS, the DRFM EA system retransmits a copy of the radar pulse with a linearly increasing time delay with respect to the received radar pulse. Due to its digital nature,

the DRFM can only delay the pulse in discrete steps (time delay resolution) at discrete time intervals (update rate). The discrete time delay resolution and update rate of the DRFM introduce two noticeable spectral characteristics. The first is a small, yet measurable, center frequency shift from the input center frequency. The second is the presence of harmonics (spectral lines) of significant magnitude centered on either side of the shifted center frequency. In this paper, we examine these DRFM linear RGS spectral characteristics.

The remainder of this paper is organized as follows. In Section II, we develop expressions to predict the size of the center frequency shift and the location of the harmonics. In Section III, we provide simulation results to verify the expressions presented in Section II. Finally, we give some concluding remarks in Section IV.

## II. ANALYSIS

Let  $x(t)$  be the signal input to the EA system, then output signal  $y(t)$  during RGS operations is given by

$$y(t) = x(t - c(t)), \quad (1)$$

where  $c(t)$  is the time delay function that determines the amount of delay between the received and transmitted signals. Ideally, the time delay function of a linear RGS signal is a linear continuous function of time. That is, the ideal linear RGS time delay function is given by

$$c(t) = c_i(t) = \alpha t, \quad (2)$$

where  $\alpha$  is the delay (pull-off) rate. Due to its discrete nature, a DRFM based EA system must approximate the ideal time delay function with a piece-wise continuous function of time (i.e., a stair step function). The time delay function of the DRFM based RGS signal can be written as

$$c(t) = c_d(t) = \beta \sum_n u(t - nT_c), \quad (3)$$

where

$$u(t) = \begin{cases} 1; & \text{if } t \geq 0, \\ 0; & \text{otherwise.} \end{cases}$$

Figure 1 depicts the ideal and DRFM time delay functions. The step size ( $\beta$ ) and step length ( $T_c$ ) are determined by the time resolution and update rate of the DRFM and the linear RGS parameter  $\alpha$ . The DRFM time delay resolution ( $t_d$ ) and update rate ( $t_s$ ) are set at the factory based on realistic target dynamics and radar specifications. The time delay resolution is selected such that at each update the jamming target pulse does not move outside the range tracking gate of the radar. Once the time delay resolution is set, the update rate is set to achieve the maximum jamming target range rate or pull-off rate (i.e.,  $\alpha_{\max} = t_d/t_s$ ). Thus, in general,  $\beta = t_d$  to

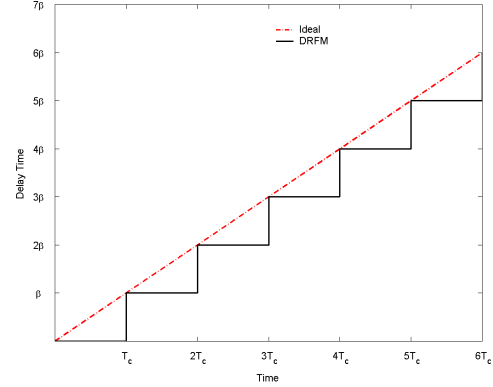


Fig. 1. Notional time delay functions for the ideal and DRFM linear RGS cases.

ensure that jamming target pulse does not move outside the range tracking gate and  $T_c$  is a multiple of  $t_s$  such that  $\beta/T_c \leq \alpha$ . That is,

$$T_c = \lceil t_d/(t_s \alpha) \rceil t_s, \quad (4)$$

where  $\lceil \cdot \rceil$  denotes the next larger integer operation.

For pulse radar systems, the input signal to the DRFM is a sinusoid modulated by a pulsed waveform. We ignore the pulsed waveform in the following analysis since it simply causes a replication of the spectrum at the pulse repetition frequency and an overall shaping of the spectrum. Thus, the input signal to the DRFM can be considered to be a sinusoid and the output linear RGS is given as

$$\begin{aligned} y(t) &= e^{j2\pi f_0(t - \beta \sum_n u(t - nT_c))} \\ &= \underbrace{e^{j2\pi f_0 t}}_{\text{carrier}} \underbrace{e^{-2\pi f_0 \beta \sum_n u(t - nT_c)}}_{\text{phase change}}, \end{aligned} \quad (5)$$

where  $f_0$  is the transmit frequency of the radar. We observe from Eqn. (5) that the discrete time delay updates of the DRFM linear RGS signal represent discrete changes in phase of the output signal relative to the input signal. The phase change per update cycle is

$$\Delta\phi = -2\pi(f_0\beta - \lfloor 2f_0\beta \rfloor + \lfloor f_0\beta \rfloor), \quad (6)$$

where  $\lfloor \cdot \rfloor$  denotes the next lower integer operation. We note that these phase changes occur every  $T_c$  seconds. Thus, the output signal is a sinusoid with a time varying phase, which translates into a frequency shift of the output signal relative to the input signal. The frequency shift of the output signal relative to the input signal is [2, 280]

$$f_s = \frac{\Delta\phi}{2\pi\Delta t} = \frac{-(f_0\beta - \lfloor 2f_0\beta \rfloor + \lfloor f_0\beta \rfloor)}{T_c}. \quad (7)$$

As noted earlier, the phase changes occur every  $T_c$  and

thus, we can write the output signal in the following general form:

$$y(t) = \sum_n p_n(t) \delta(t - nT_c). \quad (8)$$

Using the Fourier transformation relationship [3, 129]

$$\sum_n \delta(t - nT) \Leftrightarrow 1/T \sum_m \delta(f - m/T), \quad (9)$$

we conclude that the spectrum of the DRFM linear RGS will have harmonics (spectral lines) spaced  $f_c = 1/T_c$  Hertz apart. Thus, the DRFM spectrum will have spectral lines at

$$f = f_0 + f_s \pm n f_c, \quad (10)$$

where  $n$  is an integer. The DRFM related parameters  $\beta$  and  $T_c$  and the radar transmit frequency  $f_0$  determine the frequency shift  $f_s$  and the spacing of the harmonics  $f_c$ .

### III. SIMULATION RESULTS

To verify the validity of the above analysis, we present the results of several computer simulation runs. For the results presented here, the sample rate is 10 KHz (a generic airborne pulse Doppler medium pulse repetition frequency), each coherent processing interval (CPI) is 1024 samples or 102.4 msec, the amplitude weighting is a Hanning function, and the frequency offset (Doppler shift) is 4000 Hz. The RGS profile is separated into three CPIs. The first CPI has only samples with no time delays (i.e., the DRFM's discrete nature does not effect the spectrum). The second CPI contains 512 samples of no delay and 512 samples with the staircase delay. The third CPI contains 1024 samples with the staircase delay. The simulation also zero padded the 1024 samples after windowing to 2048 samples. The combination of a 10 KHz sampling rate and a 2048 complex FFT gives a frequency bin spacing of 4.8828125 Hz ( $= 10000 \text{ Hz}/2048$ ) and 3 dB filter bandwidth of 4.3 Hz. However, the Hanning window broadens the 3 dB filter bandwidth to approximately 7.3 Hz [4]. The DRFM and radar transmit frequency parameters for the simulation are as follows:

**Case 1:** walk time of 10 sec, delay time of 10 usec, update rate of 1.5 msec, time delay resolution of 4.44 nsec and center frequency of 9.655 GHz ( $\alpha = 10 \text{ usec}/10 \text{ sec} = 1 \times 10^{-6}$ ),

**Case 2:** walk time of 8 sec, delay time of 6 usec, update rate of 1.5 msec, time delay resolution of 4.44 nsec and center frequency of 9.655 GHz ( $\alpha = 6 \text{ usec}/8 \text{ sec} = 0.75 \times 10^{-6}$ ),

**Case 3:** walk time of 10 sec, delay time of 10 usec, update rate of 1.5 msec, time delay resolution of 4.44 nsec and center frequency of 9.68468 GHz ( $\alpha = 10 \text{ usec}/10 \text{ sec} = 1 \times 10^{-6}$ )

Figure 2 shows the spectrum for Case 1. From Eqn. (7), the predicted frequency shift is 29.29 Hz and the frequency shift from Fig. 2 is 28 Hz. From Eqn. (4),  $T_c =$

4.5 msec which yields a harmonic spacing of 222.22 Hz. Figure 2 (CPI 3) shows a left and right harmonic spacing of 219 Hz and 224 Hz, respectively. Figure 3 shows the spectrum for Case 2. From Eqn. (7), the predicted frequency shift is 22.97 Hz and the frequency shift from Fig. 3 is 22 Hz. From Eqn. (4),  $T_c = 6.0$  msec which yields a harmonic spacing of 166.67 Hz. Figure 3 (CPI 3) shows a left and right harmonic spacing of 165 Hz and 166 Hz, respectively. Figure 4 shows the spectrum for Case 3. An examination of Figure 4 reveals the absence of a frequency shift or harmonics. The absence of a frequency shift or harmonics is due to the fact that the combination of DRFM parameters and radar transmit frequency for Case 3 yields a  $2\pi$  phase change per update cycle or equivalently, a zero phase change per update cycle. That is, the Case 3 DRFM linear RGS signal can be considered to have a constant phase. In general, we observe excellent agreement between the predicted and simulation results.

### IV. CONCLUSION

In this paper, we demonstrated that the spectrum of a DRFM linear RGS signal is not a clean copy of the radar signal as conventional wisdom (RGS techniques only attack the time domain process) might imply. The discrete nature of the DRFM for linear RGS techniques causes a small center frequency shift and harmonics within the Doppler processing band of the radar. The size of the center frequency shift and the strength and location of the harmonics is depended on the radar, DRFM and RGS parameters. These spectral harmonics should not be ignore by the radar and EA systems engineers since they could potentially effect system performance. For example, the DRFM linear RGS harmonics basically act as a narrowband noise source which could trigger the wrong (radar engineer perspective) or unintended (EA engineer perspective) response from the radar. The presence of the spectral harmonics also provides the signal intelligence analyst with additional clues for assessing threat EA systems. Finally, additional work should be done to expand the analysis and computer simulation to include parabolic RGS techniques along with an investigation to determine if the discrete nature of the DRFM impacts other EA techniques, such as velocity gate stealers.

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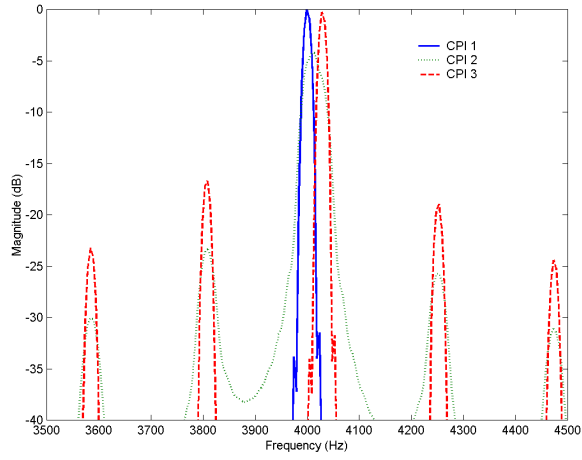


Fig. 2. Spectrum of a DRFM linear RGS signal with Case 1 parameters.

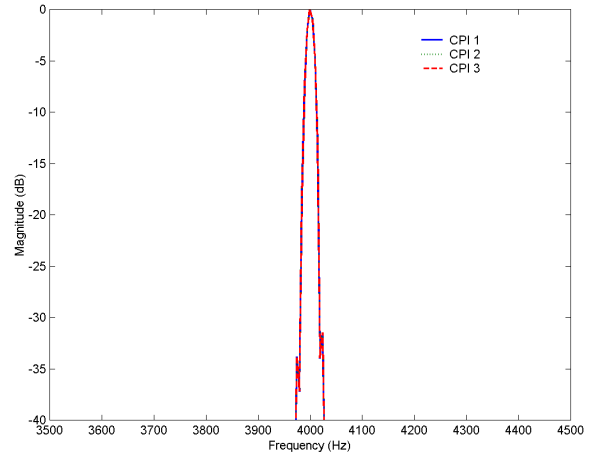


Fig. 4. Spectrum of a DRFM linear RGS signal with Case 3 parameters.

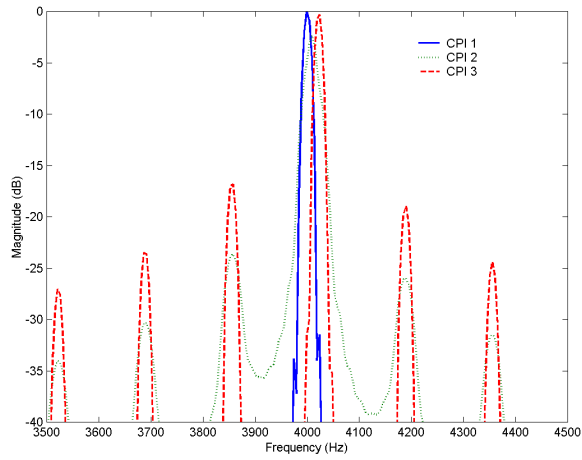


Fig. 3. Spectrum of a DRFM linear RGS signal with Case 2 parameters.