Effect of Carrier Frequency Estimation Error On Clutter Filtering For Magnetron Based Coherent Systems

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1 Introduction

Magnetron based radar systems are popular due to the high power values magnetrons can provide at a relatively lower cost. However, the main problem in magnetron based transmitters is that the magnetron output is not stable so that both the carrier frequency and the phase of the generated pulse are random, (Skolnik, 2008). The phase varies quite vastly from pulse to pulse. Although the carrier frequency varies from the intended carrier frequency to a lesser extent, the effects of such random variation may have to be accounted for in some systems.

The signals emanating from clutter patches are more or less stationary relative to the dwell time of meteorological radar. This fact helps radar designers filter out clutter signals through techniques, such as MTI processing, which are widely studied in the literature (Richards, 2014). However, all clutter filtering techniques need coherent reception since clutter filtering operations basically boil down to removal of the DC components in slow time. (Schleher, 2010). The incoming signals have to be phase aligned (and sometimes amplitude adjusted) in order to allow for coherent reception. A magnetron based transmitter generates its pulse with a random phase which can be corrected by a simple phase shift operation at the receiver as long as magnetron pulses are processed to extract their phases. In a similar fashion, carrier frequency offsets (CFO) may have to be determined and mitigated on the signals received in each pulse repetition interval.

In high resolution applications, the pulse duration is kept short, compromising the carrier frequency offset estimation accuracy, and a residual carrier frequency offset is always present. We report the effects of the residual CFO on pulse matched and mismatched filters in this study. MTI improvement factors for both approaches are presented.

2 Coherent Processing by Pulse Matched Filtering

The k^{th} pulse generated by the magnetron will be denoted by $p_k(t)$ which leads to the matched filtering with $p_k{}^*(-t)$ in order to maximize the signal to noise ratio at the receiver. One may note that the matched filter for each pulse is different than others.

We simplify the signal model to focus on the effects of CFO so that the magnetron output is $p_k(t) = p(t)e^{j\omega_k t}$ where $p(t)$ is the rectangular pulse and ω_k is the residual CFO for pulse k. The autocorrelation function of $p_k(t)$ can be written as $r_{p_k}(t) = p_k(t) * p_k{}^*(-t)$. The same function can be expressed in terms of the autocorrelation function of $p(t)$, $r_p(t)$, as $r_{p_k}(t) = r_p(t)e^{j\omega_k t}$.

For a scattering point with unity amplitude and delay of τ, it turns out that $r_{p_k}(t-\tau) = p_k(t-\tau) * p_k{}^*(-t) = r_p(t-\tau)e^{j\omega_k(t-\tau)}$ so that the matched filter peaks at $t = \tau$. Around the peak the absolute value of the matched filter has a triangular shape irrespective of the CFO value since $|r_{p_k}(t-\tau)| = |r_p(t-\tau)|$. The phase value is zero exactly at the peak point as desired, however the phase around the peak depends on the CFO as observed from $r_{p_k}(t-\tau) = r_p(t-\tau)e^{j\omega_k(t-\tau)}$. These observations can also be made on Figure *1* for a single point scatterer.

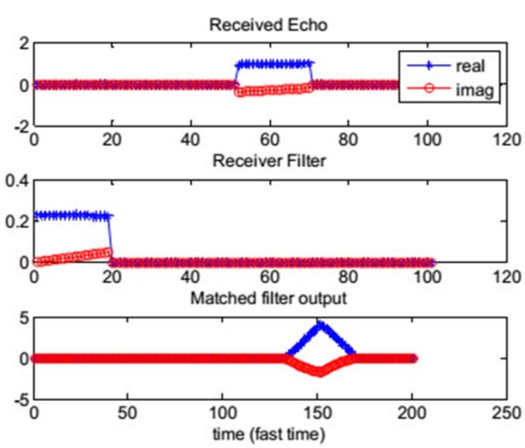

Figure 1: Output of pulse matched filter for a single scatterer. The scattering coefficient has unity amplitude and phase of -23 degrees. The residual CFO equals 80kHz.

As observed in the Figure *1* as well, the matched filter extends around the peak in a neighborhood of pulse duration T_{pulse}. Although the phase is zero at the peak, the phase varies in $\left[-\omega_k T_{pulse}, \omega_k T_{pulse,}\right]$ on the nonzero region around the peak. The pulse duration is, in general, around a few microseconds or smaller and the residual CFO is in the kHz range so that the $\omega_k T_{pulse}$ product is small, but nonzero. This small, but nonzero value, degrades the performance of MTI processing when high suppression values such as 40-50dB is demanded from MTI. The problem of MTI improvement factor loss is presented in more detail after the discussion of a second method for the coherent processing of magnetron output.

3 Coherent Processing by Pulse Mismatched Filtering

The output of magnetron can be considered as an uncoded pulse of a fixed duration. As in matched filtering based operation described earlier, the transmitted signal can be sampled by a secondary channel properly coupled to the transmitter output. The center frequency and the initial phase of the transmitted pulse can be estimated from the collected samples. With the assumption of small pulse-to-pulse carrier frequency deviation, it is possible to down-convert the pulses in a dwell by using an oscillator adjusted to a desired center frequency. With the assumption of simple pulse output for magnetron output; it is possible to process the incoming echoes through a filter whose impulse response is a simple rectangle function. This assumption neglects the transient behaviors at the beginning and end of the actual pulse; but can be considered to be acceptable for many systems. In this study we refer to this mode of operation, i.e. the utilization of the rectangle pulse as the receiver filter, as the mismatched filtering; since the receiver filter is not perfectly matched to the transmitted signal due to mentioned transients and carrier frequency offset.

Figure 2 shows the received signal for two discrete clutter points. It should be noted that the I-Q samples shown in this figure are not constant and vary during the duration of the pulse. This is due to the unaccounted carrier frequency offset. In Figure 3 the mismatched filter output is shown. In this figure, the filter output for two pulses is given. It can be noted that mismatched filter output have the same magnitude for all output samples; but have different phase values. This is due to different carrier frequency offset values for each pulse. If the mismatched filter outputs for each pulse are subtracted (MTI operation); the result (MTI output) is not identically zero.

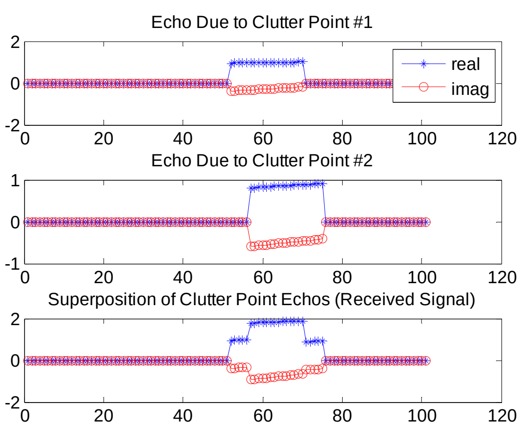

Figure 2: Return from two discrete clutter points

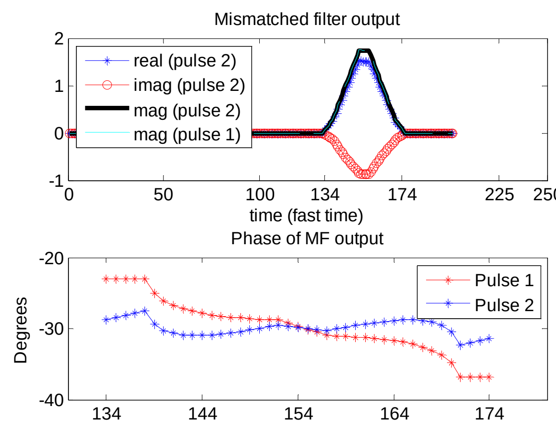

Figure 3: Mismatched filtered output

Figure 4 shows the amount of clutter suppression for the case shown in Figure 2 for both matched and mismatched filtering. The MTI suppression factor shown in this figure is defined as the ratio of the clutter average power before and after filtering. As an example, the MTI improvement factor of 60 dB corresponds to the reduction of voltage signal due to clutter by a factor of 10^{-3}. For the case shown in Figure 4, it can be seen that the maximum amount of suppression is at around the range cell with the index of 154. One can note from Figure 3 that the phase at this range for both pulses is almost the same; but not identical. In Figure 4, the effect of this nonidentical phase is observed through depiction of the MTI improvement factor where, (Skolnik, 2008).

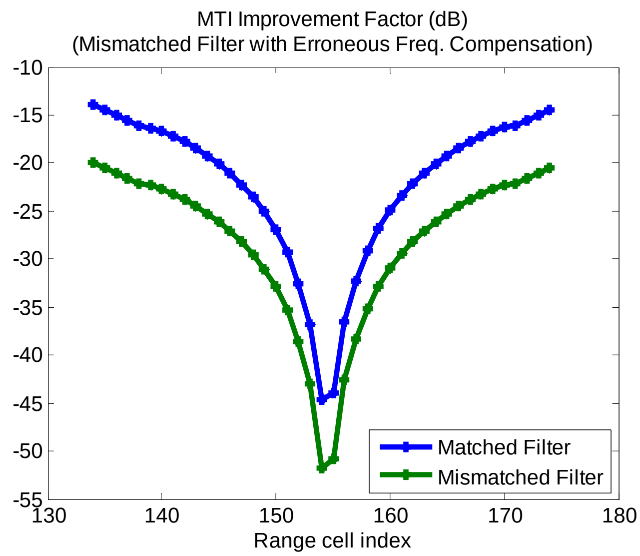

Figure 4: Return from two discrete clutter points

4 MTI Factor of Magnetron Based Systems For Homogeneous Gaussian Distributed Clutter

This section examines the MTI performance of a coherent system with magnetron transmitter utilizing suggested matched and mismatched filtered based techniques. Here, we assume that the clutter signal is complex Gaussian distributed with zero mean and unit variance and independently and identically distributed over all range cells. The magnetron pulse is assumed to have the duration of 0.4µ seconds and I-Q sampling rate is 45 MHz. It is assumed that the size of clutter patches is based on the sampling rate and each clutter patch corresponds to a unique range cell. Hence, a radar pulse occupies 0.4µ sec x 45 MHz = 18 range cells.

Figure 5 shows a typical clutter signal generated according to the mentioned statistics. For this realization, it can be noted that the clutter has a "spike" at range cell #19. Figure 6 shows the MTI improvement value when matched and mismatched is applied. It is assumed that there is a carrier frequency offset of 80 kHz between two pulses used in MTI processing. The improvement factor at the range cell #19 is high in comparison to its neighboring cells. This is due to the fact that the methods are capable of cancelling the component of the clutter signal (after filtering) due to range cell #19; but these methods can not totally eliminate the influence of clutter at the neighboring range cells. If we focus on range cell #30; it can be seen from Figure 5 that the clutter at that cell is weak. The poor improvement factor for this range cell is due to the domination of clutter signal at this cell by the clutter residing at cell #19 and, as seen before, the influence of neighboring cells cannot be totally cancelled due to the carrier frequency offset problem.

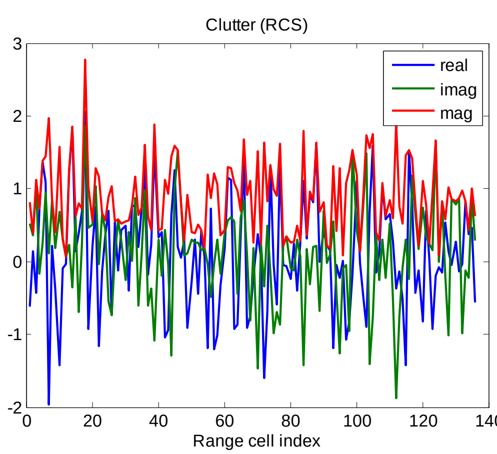

Figure 5: Generated clutter signal

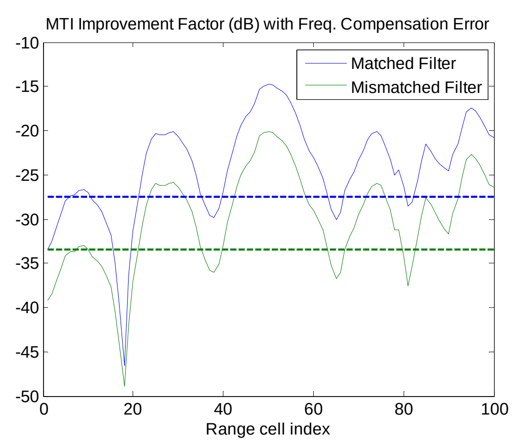

Figure 6: Mismatched filtered output

Figure 7 shows the results when the same experiment is repeated for different carrier frequency offset values. In this figure, the average MTI value of 500,000 simulations are given, 90% confidence intervals are also indicated.

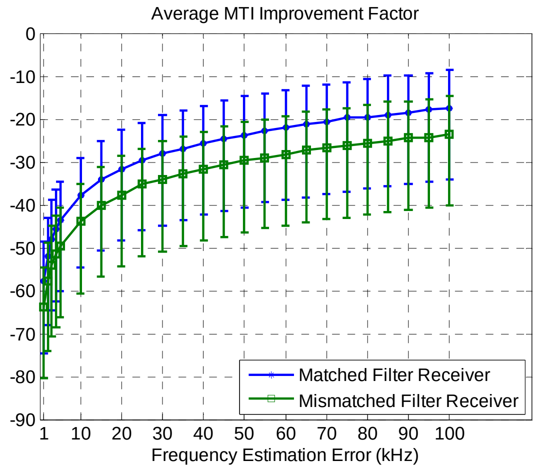

Figure 7: Average MTI factor (solid line) and 90% confidence intervals

5 Conclusions

We examine the MTI performance of two methods for the coherent processing of the magnetron output. It has been shown that the pulse-to-pulse center frequency deviation of the magnetron output can be an important limiting factor to reach high MTI values. We also note that the MTI processing method (single line canceller) examined in this work is limited to only two pulses. MTI filtering method utilizing higher number of pulses, such as the ones operating in the frequency domain, can suffer from higher losses. The pulse-to-pulse instability in the magnetron carrier frequency can also result in a blurred Doppler spectrum for discrete point-like targets. The results of this study indicate that the pulse-to-pulse frequency offset value should be minimized for a good performance. A practical suggestion can be the utilization of the average carrier frequency offset value of an earlier dwell (or a set of dwells) during the down-conversion of the next dwell by adjusting the local oscillator frequency accordingly.

References

Skolnik M. Radar handbook, Mc-Graw Hill, 2008.
Schleher D. MTI and Pulsed Doppler Radar with MATLAB. Artech House, 2010.
Richards M. Radar Signal Processing, McGraw-Hill, New York, 2014.