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An Improved MTI filter for Ground Clutter Reduction in UAV Classification

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ABSTRACT

In recent years, Unmanned Aerial Vehicles (UAVs) have increasingly been used in many civil applications. However, they also pose a significant threat in restricted zones. Radar can be used to detect and discriminate UAVs. Due to the low flying altitude of the UAVs, it is found that the radar signals also include some unwanted echoes, reflected by building, ground, trees and grasses etc. Consequently, it has not been possible to get the clean UAVs characteristics for further classification. In this paper, the MTI filter is applied to cancel the ground clutter and based this, an improved MTI filter is further proposed. Compared with the traditional MTI filter, the improved one significantly enhances ground clutter rejection capability while maintaining most of the target power. As the result, the cleaner UAVs classification characteristics can be obtained. The effectiveness of the proposed method has been verified by an experimental CW radar dataset, collected from a helicopter UAV.

Keywords: Ground Clutter Reduction, Highpass FIR Filter, MTI Filter, UAV Classification, Helicopter UAV

1. INTRODUCTION

In recent years, the Unmanned Aerial Vehicles (UAVs) have become widely available and are more and more popular used in many areas, such as news broadcasting, environmental monitoring, and particularly common in defense, for example: spying, reconnaissance and even attack etc. With the growing number of the UAVs being developed and used, they form a great threat to a restrict zone. Therefore, it is necessary to detect and further discriminate them. Considering most UAVs have rotary parts, either fixed-wing propeller UAVs or rotary-wing helicopter UAVs, these rotary parts show different kinematic characteristics, resulting in different Doppler modulation details (also called micro-Doppler characteristics), thereby presenting a possibility of effective classification.[1-2]

In this paper, a ground-based continuous wave (CW) radar is employed to detect and classify the UAVs. However, since the most of the UAVs fly at low altitude, in order to detect them the radar's elevation observational direction cannot be very high. Consequently, the radar will unavoidably receive some unwanted echoes, reflected from the buildings, grounds, trees and grasses etc. Such echoes are generally called ground clutters. In signal processing of the CW radar experimental data, it is found that the presence of this ground clutter may greatly affect the acquisition of the clean micro-Doppler characteristics of the UAVs, and further cause the failure in its classification. Therefore, it is necessary to firstly remove the ground clutter and increase the signal to clutter plus noise ratio (SCNR), in order to benefit the subsequent classification.

So far, many of the methods for removing clutters, interference and noise have been proposed, i.e. Least Mean Square (LMS)[3], Adaptive Maximum Entropy Method (MEM)[3], and Moving Target Indicator filter (MTI) [3-4]. Since the transmitting signal of CW radar is single-tone continuous wave signal, the traditional MTI filters with different orders could be applied to various arbitrary lengths of CW radar data. In general, a low order traditional MTI filter can work on very short Coherent Integration Time, while a high order requires it to work on relative longer Coherent Integration Time. The maximum ground clutter rejection bandwidth and the sharpness of the roll off at the cutoff frequency are determined by the order of the traditional MTI filter. If a higher order filter is adopted, a wider band of clutter will be rejected, which leads to better ground clutter cancellation but with, at the same time, the cancellation of some of the target signal also[5]. In this paper, an improved MTI filter is proposed based on both the finite impulse response(FIR) filter design theory and the classic Parks-McClellan algorithm. The improved MTI filter has a flat passband for enhancing the ground clutters rejection while maintaining the target signal power as much as possible.

This paper is organized as follows. In section 2, a traditional MTI filter will be designed and applied to the experimental CW radar data collected from a helicopter UAV. In Section 3, an improved MTI filter will be designed and its performance will be compared with that of the traditional MTI filter, in terms of the cancellation capability of the clutter, SCNR enhancement and cleanness of the UAVs classification characteristics. Section 4 concludes this paper.

2. A TRADITIONAL MTI FILTER FOR CLUTTER REDUCTION

In a radar system, stationary clutters such as echoes received from the ground or building always have zero Doppler frequency or very low Doppler frequencies. Hence, the traditional MTI filter can be applied to reduce the clutter power.

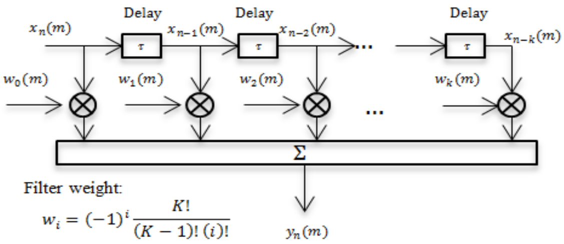

Figure 1. A traditional MTI filter.

Fig. 1 shows the processing structure of the traditional MTI filter. It can be regarded as a delay-line canceller, in which τ is the delay time, w is filter weight, and K is filter order[6]. When the filter order K of the traditional MTI filter increases, the null near zero Doppler frequency will be deeper and wider (i.e., better ground clutter cancellation). However, the filter amplitude response becomes more unevenly distributed, which may lead to the reduction of the target power as well. Hence, the selection of K is a trade-off between stopband attenuation and passband flatness.

TABLE I HELICOPTER UAV SPECIFICATIONS

Model	Mikado Logo 600
Type	Helicopter
No.of rotors	2 (main, tail)
Length of main blade(mm)	1350

In this section, a traditional MTI filter, with $K = 2$, is applied to the experimental data of CW radar to remove the ground clutter. The selection of $K = 2$ is because when $K = 1$, the strong ground clutter still exists. When $K \geq 3$, signal for the slow moving target, e.g. walking person, bicycle etc., will also be removed, which leads to inaccuracy in target classification. The real dataset is provided by Thales Nederland, in which the CW radar is operating at 9.7GHz with the sampling rate of 192kHz. In addition, a helicopter UAV is used as the radar target for data collection. The specifications of the helicopter UAV are shown in TABLE I.

2.1 Time/Frequency Domain analysis before using the traditional MTI filter

Fig. 2 illustrates the original time-domain echo of the helicopter UAV. When the main blade of the helicopter is perpendicular to the radar line-of-sight, the strength of the blade echo will reach the maximum. Such strong blade echo is called blade flash. In Fig.2, five blade flashes, corresponding to five periodical small peaks, can be observed. However, due to the presence of the ground cutter, the blade flash has very low SCNR. The quantitative analysis shows that the SCNR in Fig. 3 is only 5 dB. And the uncleaned blade echo of the helicopter may also further cause the failure of its classification. Fig. 3 shows the corresponding results in frequency domain. There is strong ground clutters near the zero Doppler frequency.

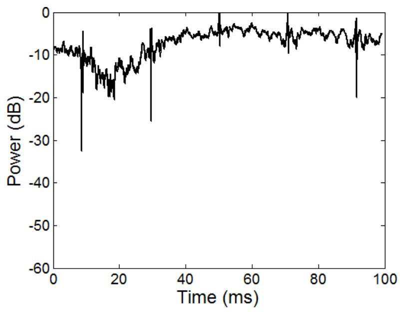

Figure 2. Time Domain Analysis before traditional MTI.

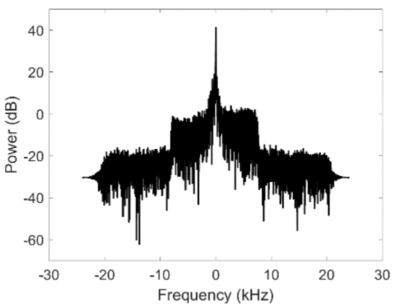

Figure 3. Frequency Domain Analysis before traditional MTI filter.

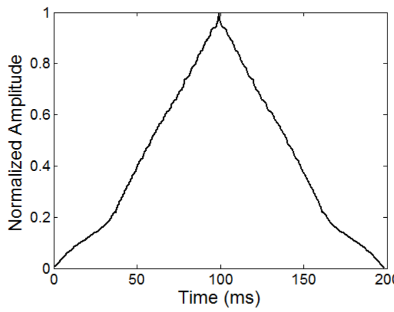

Figure 4. Auto correlation Analysis before traditional MTI.

The blade flash signal can be considered as a kind of periodical signal and the auto correlation is a common method to estimate the period of the periodical signal. The auto-correlation analysis is performed and the result is shown in Fig. 4. It is seen that due to the low SCNR, it is actually hard to observe the periodicity of the blade flashes from the original time-domain echo.

2.2 After using the traditional MTI filter

Traditional MTI filter is widely used in radar signal processing since it has an advantage in ground clutter cancellation. In this section, a traditional MTI filter with $K = 2$ was chosen to apply to the same original time domain echo as discussed previously. Figs. 5-6 indicate time and frequency domain analysis after using traditional MTI filter. It seems that the five blade flashes are clear and distinguishable. Moreover, the strong ground clutters located at zero frequency is attenuated. But these qualitative analyses did not seem to be very persuasive. In order to obtain the quantitative analysis result for the traditional MTI filter, SCNR analysis is considered. In Fig. 5, the SCNR is calculated to be 25.97dB, which is about 21dB higher than the original signal. Therefore, the traditional MTI filter significantly enhanced the performance in ground clutters cancellation.

In addition, Fig. 7 shows auto correlation analysis result. Unlike Fig. 4, a strong periodic characteristic caused by blade flash signal is observed. Afterwards the blade rotation period is calculated as the distinguishing feather for the UAVs classification. Since the Helicopter UAV employed contains two main blades, each time the rotor rotates 360°, there are two blade flash peaks detected by the CW radar. Therefore, the blade rotation period is twice the time interval between the highest and second highest normalized amplitude, i.e. $20.6ms \times \quad 2 = 51.2ms$.

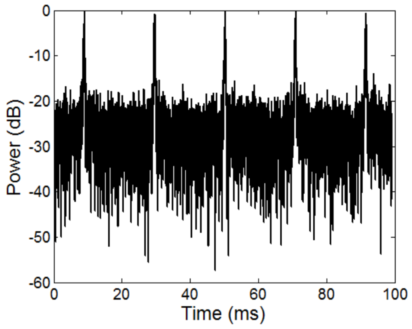

Figure 5. Time Domain Analysis after traditional MTI.

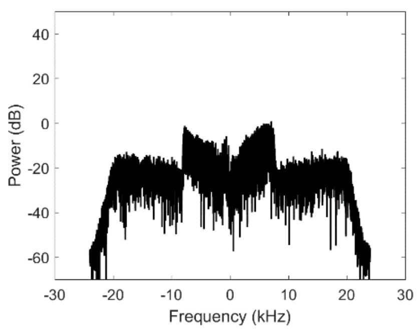

Figure 6. Frequency Domain Analysis after traditional MTI filter.

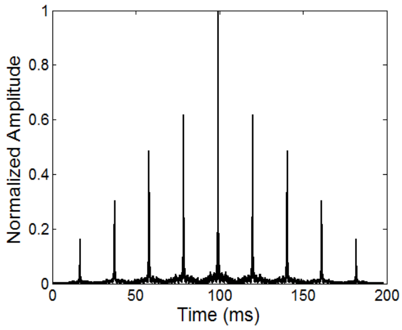

Figure 7. Auto correlation after traditional MTI filter.

3. AN IMPROVED MTI FILTER FOR CLUTTER REDUCTION

The former result for the traditional MTI filter shows an advantage in reducing the ground clutters, nevertheless it contains the shortcoming of affecting target signal near to zero frequency. It seems that the design of a digital filter can overcome that shortcoming and further enhance the performance in filtering ground clutters. The improved MTI filter is a wide-band high-pass linear phase FIR filter. The normalized stopband edge ω_s must be chosen very small in order to remove clutter at zero frequency. The normalized passband edge ω_p should also be very small for minimum distortion. However, such a FIR filter has an extremely high filter order. Thus, we shall relax ω_p to a somewhat larger value. The improved MTI filter is designed using MATLAB function $firpm$ which implements the Parks-McClellan algorithm[7]. The transfer function $H(z)$ of the filter is shown as (1), where M is the filter order and $h(0)$, $h(1)$, …, $h(M)$ are the filter coefficients. The filter order is chosen as $M = 30$, and $\omega_p = 0.12\pi$ and $\omega_s = 10^{-9}\pi$ are used in our design. The coefficients of the designed filter are listed in Table II. Only half of the coefficients are listed because the impulse response of the designed filter is symmetric. The improved MTI filter is analyzed and compared in terms of time domain, frequency domain, auto correlation, spectrogram and filter magnitude responses as below. Fig. 8 presents the result of the amplitude-frequency response analysis. It can be observed that the improved MTI filter has an advantage in minimizing the effect of the target signal near zero frequency while removing the ground clutters, since it has about 20 dB more attenuation in stopband than that in traditional filter. Moreover, it also has a narrower transition band and flatter pass band than the other filter.

$$H(z) = \sum_{n=0}^{M} h[n]z^{-n} \quad (1)$$

TABLE II COEFFICIENTS OF THE DESIGNED FIR FILTER

h(0)	-0.005738	h(4)	-0.016409	h(8)	-0.036102	h(12)	-0.053489
h(1)	-0.006050	h(5)	-0.020921	h(9)	-0.041144	h(13)	-0.056081
h(2)	-0.008919	h(6)	-0.025812	h(10)	-0.045848	h(14)	-0.057685
h(3)	-0.012382	h(7)	-0.030928	h(11)	-0.050029	h(15)	0.941767

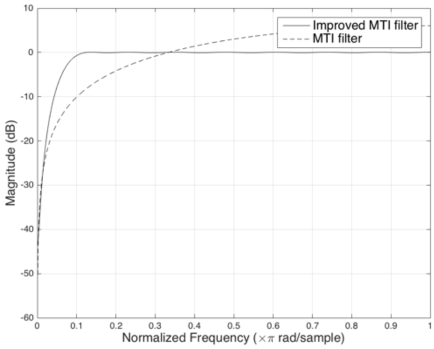

Figure 8. Comparison of traditional and improved MTI filter in terms of magnitude response.

Figs. 9 to 11 illustrate the results for the improved MTI filter in terms of time domain/ Frequency domain analysis, autocorrelation analysis and spectrogram analysis. As shown in Figs. 9 and 10, it is obvious that both filters perform well in ground clutters cancellation and provide clean blade flash signal. Nevertheless, the quantitative analysis result shows that the improved MTI filter has 1.82 dB higher in SCNR than that in the traditional. Fig. 11 illustrates auto correlation analysis after passing through the improved MTI filter. Although it shows a periodic characteristic in Fig. 11, it should be noted that the improved MTI filter has the higher normalized amplitude, reading 0.7 (for the second highest blade flash signal), than that 0.6 in traditional MTI filter. From the discussion, one may conclude that the Helicopter blade flash signal is stronger after the ground clutters cancellation using improved MTI filter than the traditional one.

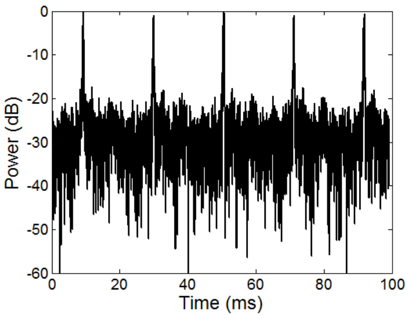

Figure 9. Time domain analysis after passing through an improved MTI filter.

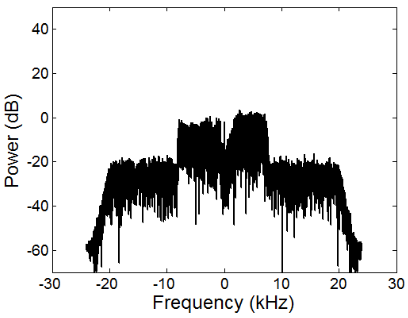

Figure 10. Frequency domain analysis after passing through the improved MTI filter.

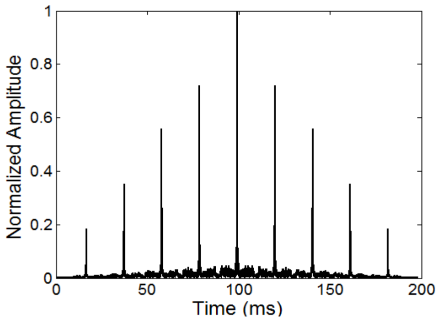

Figure 11. Auto correlation analysis after passing through the improved MTI filter.

Next, a brief introduction and result of spectrogram analysis for both filters will be provided and compared. In order to obtain excellent UAVs classification result, clear micro-Doppler signatures are required to be extracted from the spectrogram. The spectrogram can be calculated through applying Short-Time Frequency Transform (STFT) on the time-frequency(TF) domain radar echo. The same X band CW radar echo for the Helicopter UAV is used as discussed previously. The advantages of using X band CW radar in this study are the following: firstly, good time resolution spectrogram can be obtained. Secondly, distinguishing features will be extracted from micro-Doppler signature for the UAVs classification.

Figs. 12 to 14 present a spectrogram analysis of CW radar data before and after passing through the traditional and improved MTI filter. As shown in Fig. 12, spectrogram of original signal presents very strong ground clutters at zero velocity. Thereby, both a traditional and an improved MTI filter were applied to remove the ground clutters. Afterwards, the performances for both filters will be further discussed in three aspects: firstly, it can be seen that both of them performs well in removing the ground clutters. Secondly, it can be observed that spectrogram for the improved MTI filter has clearer background than the traditional one. Furthermore, as shown in Fig. 13, although it seems that the ground clutters near to zero Doppler axis are removed, it is obvious that blade flash signal (target signal) is also broken into upper and lower parts after doing ground clutter cancellation. However, as shown in Fig. 14, each blade flash signal is almost a continuous line, which shows clearer micro-Doppler signature of Helicopter UAV target signal. As discussed in the previous sections, the improved MTI filter outperform traditional MTI filter for its higher SCNR and clearer micro-Doppler signature.

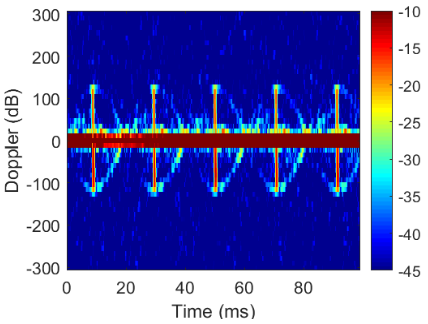

Figure 12. Spectrogram of original CW radar data.

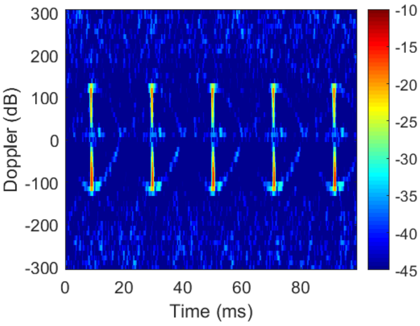

Figure 13. Spectrogram after passing through the traditional MTI filter.

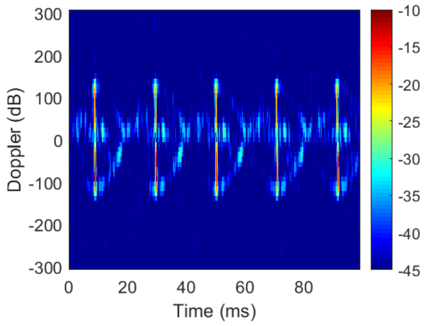

Figure 14. Spectrogram after passin through the improved MTI filter.

4. CONCLUSION

We have presented the design of an improved MTI filter, which is able to notch a very narrow band near the zero frequency while maintaining most of the target power. When compared with the traditional MTI filter, it can be observed that the improved MTI filter has better performance in attenuating ground clutters, in terms of time/frequency domain analysis, autocorrelation analysis as well as the spectrogram analysis. The enhanced SCNR of radar micro-Doppler signatures will facilitate the classification of unmanned aerial vehicles (UAVs).

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