Abstract

In airborne radar, it is important to reject clutter signals to detect targets of interest. High pulse repetition frequency (HPRF) waveform provides robust detection performance in a clutter environment by separating clutter signals from the target echo signals in a Doppler frequency domain, but it suffers from range ambiguity. The range ambiguity in HPRF can be resolved by frequency modulation (FM) ranging. However, the Doppler frequencies of both the clutter and target echo signals change linearly with the range due to changes in the carrier frequency in FM ranging. In such a case, the target echo signal can be rejected by a conventional clutter rejection frequency even if it is not masked by a clutter signal. This paper proposes an optimum clutter rejection frequency for FM ranging airborne radar by considering the Doppler frequency spread in FM ranging. The optimum clutter rejection frequency is derived by calculating the maximum Doppler frequency of the spread clutter signal caused by FM ranging. The simulation and flight test results verify that the proposed clutter rejection frequency is the optimum value that can improve the detection capability of FM ranging airborne radar.

Key Words: Airborne radar, Clutter rejection, FM ranging, FMICW

I. INTRODUCTION

In airborne radar, clutter signals with Doppler frequencies that correspond to the radar platform speed are received. Such clutter signals can degrade the detection range performance of the radar by reducing the signal to clutter and noise ratio (SCNR). Thus, a high pulse repetition frequency (HPRF) waveform is often used to improve the detection range of the radar due to its clutter-free characteristic in the target velocity (or the Doppler frequency) range of interest [1].

However, since HPRF is ambiguous in range, it is required to resolve the range ambiguity for measuring the target's slant range. One method for resolving the range ambiguity in HPRF is frequency modulation (FM) ranging [2-5]. In FM ranging, the carrier frequency of each transmit pulse is linearly increased or decreased based on its chirp rate (also called frequency modulated interrupted continuous wave (FMICW)) and the range is measured from the difference between the carrier frequency of the transmitted pulse and that of the received pulse.

Unlike pulses with a fixed carrier frequency, the Doppler frequency of a target echo or a clutter signal changes linearly with the range due to changes of the carrier frequency in FM ranging. More specifically, the clutter signal spreads in Doppler frequency domain depending on the chirp rate of FM. Thus, conventional clutter rejection in the Doppler frequency band of a pulse Doppler radar is not suitable for FM ranging radar (as described in Section II).

In [4-7], HPRF waveform with FM ranging has been designed considering the spread of clutter Doppler frequency, but no guideline for an optimum clutter rejection frequency design is provided. In this paper, clutter rejection method for FM ranging airborne radar considering the Doppler frequency spread to improve the detection performance of airborne radar. Specifically, the optimum clutter rejection frequency is derived in a closed range is measured from the difference between the carrier frequency of the transmitted pulse and that of the received pulse.

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form by calculating the maximum Doppler frequency of the spread clutter signal caused by FM ranging.

This paper is organized as follows: in Section II, the Doppler frequency spread phenomenon in FM ranging is reviewed. Then, in Section III, the optimum clutter rejection frequency for a given radar environment is derived, and the detection performance improvement is analyzed through simulation examples. In Section IV, the flight test result is provided, and the paper is summarized in Section V.

II. DOPPLER FREQUENCY SPREAD IN FM RANGING

For conventional pulse Doppler radar, the carrier frequency of each transmit pulse is constant, as shown in Fig. 1(a). On the other hand, the carrier frequency changes linearly in FM ranging, as shown in Fig. 1(b). The chirp rate (the rate of carrier frequency change) $k$ can be positive or negative depending on the radar system design. Usually, a positive value of $k$ is preferred since the spread of the clutter Doppler frequency does not intrude into the Doppler frequency band of interest [5]. The following example provides a simple illustration for how Doppler frequencies of clutter and target signal change depending on $k$. Fig. 2 shows a situation where the radar platform is moving with velocity $v_r$ and the radar is illuminating its main beam (or mainlobe) toward a target moving with velocity $v_{tgt}$ at range $r_{tgt}$. The main beam steering angle with respect to the platform velocity vector is $\psi_s$. If the projection angle of the target velocity vector toward the radar is $\theta$, then the Doppler frequency of the target echo $f_{tgt}$ is given as

$$f_{tgt} = \frac{2v_{tgt} \cos \theta}{\lambda}$$

(1)

where $\lambda$ is the wavelength of the radar waveform.

To satisfy clutter-free condition for detecting the target, it is required to perform signal processing for only the signal with frequency that is higher than the maximum Doppler frequency of clutter, $f_{slc,max}$ (i.e., reject the signal with a frequency lower than $f_{slc,max}$). Without FM ranging ($k = 0$), $f_{slc,max}$ is given as follows after compensating the radar platform velocity.

$$f_{slc,max} = \frac{2v_r}{\lambda} \left(1 - \cos \psi_s \right)$$

(2)

Therefore, the optimum clutter rejection frequency $f_{rej} = f_{slc,max}$, and the clutter-free condition is satisfied as long as $f_{tgt} > f_{slc,max}$ regardless of the target range. Suppose that the range of the target varies from $r_2$ to $r_1$ with the constant Doppler frequency ($f_i = f_{tgt}$ where $i = 1, 2$) as shown in Fig. 3(a) where both mainlobe clutter (MLC) and sidelobe clutter (SLC) are presented with the target. The target echo is kept in the clutter-free region independent of the range change. However, when $k > 0$, the Doppler frequencies of both the clutter and target signals are linearly reduced with range. Thus, $f_i$ is no more independent of $r_i$, but is given as

$$f_i = f_{tgt} - \frac{2kr_i}{v_0}$$

(3)

where $v_0$ is the speed of light. As shown in Fig. 3(b), when the target is at $r_2$, the target cannot be detected if $f_{rej}$ is kept as $f_{slc,max}$ since $f_2 < f_{slc,max}$. After the target approaches close enough so that its Doppler frequency is higher than $f_{slc,max}$ the clutter-free condition is satisfied. For instance, the target can be detected when
it is at \( r_1 \) since \( f_1 > f_{\text{slc, max}} \). To detect the target at \( r_2 \) when \( k > 0 \), it is required to find the new rejection frequency to avoid clutter.

### III. OPTIMUM CLUTTER REJECTION FREQUENCY FOR FM RANGING AIRBORNE RADAR

To satisfy clutter-free condition when \( k > 0 \), the optimum rejection frequency can be found as follows. The Doppler frequency of clutter \( f_c \) at angle \( \psi \) with respect to the platform velocity vector and range \( r \), when \( k > 0 \) is given as (without compensating the radar platform velocity)

\[
f_c(\psi, r) = \frac{2v_r \cos \psi}{\lambda} - \frac{2kh_r}{c_0}\]

When the radar platform height is \( h_r \), \( r \) can be expressed as

\[
r_c = \frac{h_r}{\sin \theta_d}\]

where \( \theta_d \) is a depression angle (with respect to the platform velocity vector) toward clutter. The maximum Doppler frequency in the same clutter range is given when azimuth angle is zero, i.e., \( \psi = \theta_d \). Thus, by letting \( \theta_d = \psi \) and substituting \( \sin \psi \) to \( \rho \), from (4) and (5), \( f_c \) is given as a function of \( \rho \) as follows.

\[
f_c(\rho) = \frac{2v_r}{\lambda} \sqrt{1 - \rho^2} - \frac{2kh_r}{c_0}\]

Fig. 4 shows \( f_c \) as a function of \( \rho \) when \( k = 5 \text{ MHz} \), \( h_r = 10,000 \text{ ft} \), velocity \( v_r = 200 \text{ m/s} \), and \( \lambda = 0.03 \text{ m} \). The value of \( \rho \) at maximum \( f_c \) can be found as a root of the derivative of \( f(\rho) \) as follows.

\[
\frac{df_c(\rho)}{d\rho} = \frac{2kh_r}{c_0\rho^2} - \frac{2v_r\rho}{\lambda\sqrt{1-\rho^2}}
\]

\[
\rho^6 + \alpha \rho^2 - 1 = 0
\]

where \( \alpha = \left(\frac{kh_r}{c_0 v_r}\right)^2 \). Since (8) is a form of depressed cubic,

\[
\rho^2 = \left(\frac{a}{2} + \sqrt{\frac{a^2}{4} + \frac{a^2}{27}}\right) + \left(\frac{a}{2} - \sqrt{\frac{a^2}{4} + \frac{a^2}{27}}\right)^{\frac{1}{3}}
\]

Finally, \( \psi \) for the maximum Doppler frequency of clutter, \( \psi_{\text{c,max}} \) is given as

\[
\psi_{\text{c,max}} = \sin^{-1}(\rho)
\]

and from (6) and (11), the optimum clutter rejection frequency for \( k > 0 \) is given as follows after compensating the radar platform velocity.

\[
f_{\text{req}} = \frac{2v_r}{\lambda} \left(\cos \psi_{\text{c,max}} - \cos \psi_s\right) - \frac{2kh_r}{c_0\sin \psi_{\text{c,max}}} \]

The following simulation examples show how \( f_{\text{req}} \) calculated from (12) can improve the detection performance when \( k > 0 \).

Assuming that the radar platform altitude \( h_r = 10,000 \text{ ft} \), velocity \( v_r = 200 \text{ m/s} \), and the radar beam steering angles in azimuth and elevation (\( \theta_{\text{az}}, \theta_{\text{el}} \) = \( 30^\circ, -15^\circ \)), the clutter signals in range-velocity domain with backscattering coefficient shown in Fig. 5 have been generated as in Fig. 6 for \( k = 0 \), \( 5 \text{ MHz/s} \), and \( 10 \text{ MHz/s} \) respectively. The clutter signal has been calculated for \( 50 \times 50 \text{ m}^2 \) range cell, and the detailed process for the clutter signal generation is in [8], and is not provided in this paper for
brevity. Note that noise has not been considered for the simulation. Also, to provide more intuitive information, the signals have been provided not in range-Doppler domain but in range-velocity domain.

In Fig. 6, the red dashed lines indicate the velocity corresponding to \( f_{\text{slc,max}} \) from (2). As described in the previous section, it is shown in Fig. 6(a) that \( f_r = f_{\text{slc,max}} \) when \( k = 0 \). In this case, \( f_r = 2.181 \text{ kHz} \) which corresponds to the rejection velocity \( v_r = 32.69 \text{ m/s} \) when the carrier frequency is 10 GHz. Thus, the echo signal from any target with a velocity higher than \( v_r \) can satisfy the clutter-free condition regardless of its range.

However, as \( k \) increases, the range of the target that satisfies the clutter-free condition is reduced. In Fig. 6(b) and (c), the green dotted lines indicate the range of the target echo signal with velocity \( v_t = 60 \text{ m/s} \). If the rejection frequency is kept as \( f_{\text{slc,max}} \) for \( k = 5 \text{ MHz/s} \), then the maximum range at which the echo signal can be processed is \( r_{\text{max}} = 54.61 \text{ km} \), which is indicated as the point (a) in Fig. 6(b). In other words, if the target is located farther than \( r_{\text{max}} \), it cannot be detected. By setting \( f_r \) as the frequency that can be calculated by (12), \( r_{\text{max}} \) can be increased. In Fig. 6(b), \( f_r \) is calculated as 1.098 kHz which corresponds to \( v_r = 16.46 \text{ m/s} \) (\( v_r \) is indicated as the yellow dashed line) and as a result, \( r_{\text{max}} \) is increased to 87.08 km, which is indicated as the point (b) in Fig. 6(b).

A similar situation is observed for the case when \( k = 10 \text{ MHz} \), as shown in Fig. 6(c). For the same target with velocity \( v_t = 60 \text{ m/s} \), \( r_{\text{max}} = 32.69 \text{ km} \) (the point (a)), when \( f_r = f_{\text{slc,max}} \), but \( r_{\text{max}} \) is increased to 53.16 km (the point (b)) when \( f_r = 0.456 \text{ kHz} \) which corresponds to \( v_r = 6.84 \text{ m/s} \).

IV. FLIGHT TEST RESULTS

In this Section, the flight test results to verify the proposed clutter rejection frequency are provided. The test scenario is shown in Fig. 7(a). An ownship (radar platform) flies from north to south (heading 180°) at altitude \( a_{\text{own}} = 12 \text{ kft} \) with ground velocity \( v_{\text{own}} = 184 \text{ m/s} \), while a target, starting from approximately 130 km away from the ownship, flies from south to north (heading 0) at altitude \( a_{\text{tgt}} = 12.4 \text{ kft} \) with ground velocity \( v_{\text{tgt}} \) approximately −61.5 m/s.
The slant range of the target from the radar and its radial velocity are shown in Fig. 7(b) and (c), respectively. During the test, the radar attempts to detect the target with HPRF waveform using FM ranging. In this paper, the detailed waveform parameters such as PRF, carrier frequency, and chirp rate are not disclosed for security reasons.

At first, the radar attempted to detect the target (i.e., direct the beam toward the target) when the target slant range $r_{tgt} = 127.8 \text{ km}$ and $v_{tgt} = -61.5 \text{ m/s}$, as marked with red x symbols in Fig. 7(b) and (c) (point (A)). Then, the radar attempted to detect the target again when the target slant range $r_{tgt} = 126.8 \text{ km}$ and $v_{tgt} = -61.3 \text{ m/s}$, as marked with red o symbols in Fig. 5(b) and (c) (point (B)). For each point, the received echo signals in range-Doppler domain after matched filtering and Doppler processing are shown in Fig. 8 and 9. The frequencies correspond to $f_{slc,max}$ and $f_{ej}$ are shown with dashed red and yellow lines, respectively. It is observed that, while the red lines are displaced from the maximum Doppler frequency of the clutter signals, the yellow lines are located at the maximum Doppler frequency of the clutter signals, proving that $f_{ej}$ is the optimum clutter rejection frequency.

At the point (A), the clutter rejection frequencies calculated from eq. (2) and (12) are $f_{slc,max} = 8.547 \text{ Hz}$ and $f_{ej} = -929.851 \text{ Hz}$, respectively. The received echo signal in range-Doppler domain after matched filtering and Doppler processing is shown in Fig. 8(a) and (b). Fig. 8(a) shows the entire range-Doppler domain (with range from 0 to unambiguous range, and Doppler frequency from $-0.5\text{PRF}$ to $0.5\text{PRF}$), while Fig. 8(b) is a close-up for the Doppler frequency around the clutter rejection frequencies. The target echo is not visible since it is within clutter region.

Fig. 7. The flight test scenario: (a) flight trajectories of the ownship and target, (b) target slant range, and (c) target radial velocity.

Fig. 8. The echo signals in range-Doppler domain for the point (A): (a) whole range-Doppler domain and (b) close-up for the Doppler frequency around the clutter rejection frequencies. The target echo is not visible since it is within clutter region.
a close-up of Fig. 8(a) for Doppler frequency around the clutter rejection frequencies. Since the target echo is within clutter region, it is not visible and cannot be detected even if the radar rejects the signals with Doppler frequencies lower than $f_{o,p}$.

At the point (B), the target has the similar velocity but is closer to the radar compared to the point (A). The clutter rejection frequencies calculated from eq. (2) and (12) are $f_{slc,max} = 7.333$ Hz and $f_{rej} = -930.111$ Hz, respectively. The received echo signal in range-Doppler domain after matched filtering and Doppler processing is shown in Fig. 9(a) and (b). Unlike the case of the point (A), the target echo is now visible since it is in clutter-free region. If the clutter rejection frequency is set as $f_{slc,max}$ (shown with the red dashed line), the target cannot be detected even when it is in the clutter-free region. On the other hand, by setting the clutter rejection frequency as $f_{rej}$, the target can be detected while rejecting the undesired clutter signals sufficiently.

V. CONCLUSION

In this paper, the optimum clutter rejection frequency selection for FM ranging airborne radar considering the Doppler frequency spread to improve the detection performance of the radar has been proposed. The optimum clutter rejection frequency is derived with a closed form by calculating the maximum Doppler frequency of the spread clutter signal due to FM ranging. By simulation and flight test, it has been verified that the proposed clutter rejection frequency matches with the maximum Doppler frequency of the clutter signals, and that the target which cannot be detected when the clutter rejection frequency is set as $f_{slc,max}$ can be detected by replacing the frequency as $f_{rej}$.

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REFERENCES

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