Demonstration of Airport Runway FOD Detection System Based On Vehicle SAR

Xiaobiao Wu\textsuperscript{a}, Muyang Luo, Hemin Sun, Xin Xie, Changfei Wu

Air Force Early Warning Academy, Wuhan 430019, China

\textsuperscript{a}Xiaobiao\_wu@163.com

Abstract. In the background of detecting Foreign Object Debris (FOD) on the airport runway with conventional radar systems or optical systems, to solve the problems that the current detection technology of conventional radar is high frequency and high cost, and the optical system is vulnerable to environmental factors, this paper uses linear frequency modulated continuous wave (LFM-CW) signal in Ka band to detect FOD based on the Synthetic Aperture Radar (SAR) airport runway FOD detection system. Firstly, it is proved that the operating frequency of 36GHz is more suitable. Then demonstration that the use of LFM-CW can effectively reduce the system power. Finally, through the demonstration of the main technical indicators of the system, it is proved that the airport runway FOD detection system based on vehicle SAR can effectively detect objects with a height of 3cm and a cross-sectional area of $0.00051 \text{m}^2$ in a distance of 210 meters when the transmitting power is $25 \text{dBm}$ and the running speed is $61.2 \text{m/s}$. At this time, the detection probability is $0.9999$ and the false alarm rate is $10^{-12}$.

1. Introduction

Since the crash of the Air France Concorde in 2000, 113 people have been killed. The world has paid more and more attention to the threat of airport runway FOD for airport operation safety. Currently, there are four more classic airport runway FOD inspection systems designed for airports, including Tariser in the UK, FODetect in Israel, FODFinder in the US and IFerret in Singapore. The first three detection systems use conventional millimeter-wave radar to detect targets and use high operating frequencies to achieve high resolution. But high operating frequencies mean high power and high requirements of system design. The IFerret system is a pure optical device that can detect objects with a size of 2cm in weather conditions and light intensity. At the same, its limitations are also obvious. In rainy or snowy environments, system performance cannot be guaranteed. The SAR-based FOD detection system uses synthetic aperture technology to simulate the antenna array elements in the real linear antenna array by motion, thereby improving the azimuth resolution. Due to the technical characteristics of the SAR, the target scene can also be imaged [1].

SAR is an all-weather, all-day high-resolution imaging radar developed in recent decades. It is more advantages over conventional radar systems that achieves high resolution in the azimuth direction by means of signal processing. In view of the shortcomings of the above FOD detection system, based on the existing research results [1], this paper analyzes and demonstrates the working
frequency and signal form of the system, further analyzes the main technical indicators of the system. Finally, the effectiveness of the airport runway FOD detection system based on vehicle SAR is proved by simulation.

2. Institutional Argumentation
Due to the different operating frequencies of the radar system, electromagnetic waves may be specular or diffusely reflected on the ground. The condition for specular reflection is:

$$\Delta h \leq \frac{\lambda}{16 \sin \varepsilon}$$

Where $\Delta h$ represents the surface relief of the target area, $\lambda$ represents the operating wavelength of the system, and $\varepsilon = 1.4^\circ$ represents the angle between the radar transmit beam and the ground [1]. The target height of the system needs to be detected is 3cm [2], and the undulation of the airport runway surface is lower than $\Delta h = 0.5$cm. If the system emits a signal that produces diffuse reflection on the target and produces specular reflection on the runway surface, there is $1 cm \leq \Delta h \leq 2.5 cm$. From equation (1), we can see the range of operating frequencies required by the system:

$$\frac{c}{10^3 \cdot \Delta h \sin \varepsilon} \leq f \leq \frac{c}{10^2 \cdot \Delta h \sin \varepsilon}$$

From the calculation of formula (2), the operating frequency of the system is $25 GHz \leq f \leq 122.7 GHz$. At this time, the detection system emits electromagnetic waves that are diffusely reflected on the target surface, and specular reflection occurs on the runway surface. Since the components in the atmosphere attenuate electromagnetic waves, the attenuation is particularly severe in systems operating at frequencies greater than 20 GHz. The water vapor molecules have a fixed electric dipole, and the oxygen molecules have a fixed magnetic dipole. When the electromagnetic wave frequency coincides with the natural resonant frequency of oxygen and water vapor, a strong absorption occurs [3], so the Ka-band is selected. 36 GHz is the operating frequency of the system, at which time the absorption of electromagnetic signals by the atmosphere is minimal.

3. Signal Form Argument
The SAR system has two types of transmit signals, i.e., the LFM-pulsed signal and the LFM-CW signal. As shown in Fig 1.a, the LFM-pulsed signal is a low-frequency to high-frequency process, and the interval between pulse transmissions is called pulse repetition interval (PRI). As shown in Fig 1.b, the LFM-CW signal is signal modulation process from low-frequency to high-frequency, returned low-frequency again [4], where PRI represents the time of signal frequency from rising to restoring [5]. Based on these two signals, the form of the detection system antenna is also different. The antenna based on the LFM-pulsed signal is shown in Fig 2.b. After the system transmits the signal, the antenna is converted from the transmitting function to the receiving function to receive the echo of the target. The antenna based on the LFM-CW signal is as shown in Fig 2.a. The signal is continuously transmitted from the transmitting antenna, and the receiving antenna continuously receives the echo signal.
If the system transmits the chirp signal is:

$$s(t) = e^{j2\pi(f_0 + \frac{\alpha}{2}t^2)}$$

The variable $t$ is a fast time variable; $\alpha$ is the modulation frequency; $f_c$ is the center frequency, and the transmission frequency can be expressed as $f_t = f_c + \alpha t$. The received echo signal is mixed with a copy of the transmitted signal and input into a low-pass filter. Available output frequency:

$$\omega_{LFM-CW}(t) = \frac{d}{dt} [2\pi f_c \tau + 2\pi \alpha \tau t - \pi \alpha \tau^2]$$

There is a frequency $\omega_{LFM-CW}(t) = 2\pi \alpha \tau t$ at this time, where $\tau$ is the echo delay, and $\tau = 2R/c$, $R$ is the distance between the target and the SAR, and $c$ is the speed of light. Since the detection system is a near-field detection system, $R$ is only a few hundred meters, at which time $\tau$ will be very small, and the resulting frequency difference requires only a low sampling frequency. Based on the LFM-pulsed signal system, since the received chirp signal is mixed with the carrier, the output frequency is $((f_c - f_d) + \alpha \tau)$. It can be seen that the LFM-pulsed signal requires a higher sampling frequency than the LFM-CW signal.

![Fig. 1 LFM signal waveform](image1)

(a) LFM-pulsed signal  (b) LFM-CW signal

**Fig. 1** LFM signal waveform

If the system transmits the chirp signal by the system:
Where \( s_i(t) \) is the transmitted signal of the radar. The same LFM-pulse transmit signal power:

\[
P_{\text{LFM-pulsed}} = \frac{1}{\text{PRI}} \int_0^\tau |s_i(t)|^2 dt
\]

Where \( T \) is the pulse duration. It can be seen from the equations (3) and (4) that when the LFM-CW signal is used, since the PRI is larger than \( T \), more transmission power can be obtained.

Therefore, compared to LFM-pulsed, the system uses LFM-CW to achieve the same effect with lower power and lower sampling frequency [6]. Therefore, it is more advantageous to select the LFM-CW signal for the detection system application.

4. Main Technical Indicators Simulation and Demonstration

The FOD detection system of the vehicle SAR can not only overcome the shortcomings of the above system, but also has the advantages of small antenna size, low working frequency band and imaging of echo signals. After determining the system operating frequency and signal form, this section is based on the main technical indicators of the existing research demonstration system. According to the existing research, the system parameters determined are shown in Table 1:

| Table 1. Determined system parameters |
|--------------------------------------|
| System platform height | 4.4m | Maximum detection distance | 210m |
| operating frequency \( f \) | 36GHz | Minimum detection distance | 150m |
| Bandwidth \( B \) | 4.982GHz | Target cross-sectional area | 0.00051m² |
| PRI \( \tau \) | 2μs | The angle \( \phi \) | 1.4° |
| Cross-range resolutions | 1.7cm | Range resolutions | 3cm |

4.1. Pulse accumulation time

In theory, SAR can be accumulated for a long time, but in practical applications, in order to ensure the resolution of the radar, the on-board detection system must ensure that a distance resolution unit \( \rho_r \) is not moved during the accumulation time. Therefore, the pulse accumulation time \( t_0 \) must satisfy \( \nu_r t_0 \leq \rho_r \). As for the motion compensation and Doppler frequency shift in the pulse accumulation time, based on Dechirp's signal preprocessing method [7], the three factors mentioned above are analyzed, and \( t_0 \) the range of values obtained is:

\[
\frac{\Delta f}{\mu} \leq t_0 \leq \frac{\rho_r}{\nu_r}
\]

If the target is the Swerling I, at that time \( \tau=2\mu s \), because of the range of values \( \frac{\Delta f}{\mu} = \tau \) that can be accumulated \( 2 \times 10^{-6} \leq t_0 \leq 1.7 \times 10^{-2} / \nu_r \). For different platform speeds, the radar’s pulse accumulation time range is different. When the platform speed and time \( \nu_r = 4.25m/s \), \( \nu_r = 8.5m/s \), \( \nu_r = 17m/s \), the maximum pulse accumulation time is \( t_0=4ms \), \( t_0=2ms \), \( t_0=1ms \). Since the pulse repetition period is \( \tau=2\mu s \), the number of pulses that can be accumulated is \( n_p = t_0 / \tau \) 2000, 1000, and 500. Under the given conditions \( P_r = 0.9999 \), \( P_n = 10^{-12} \), obtain the required \( \text{SNR} \), use representation \( (\text{SNR})_{\text{eq}} \). The improvement factor expression derived from the Peebles experience has an accuracy of 0.8dB [8].
\[
\left[ I \left( n^p \right) \right]_{\text{log}} = 6.79 \left( 1 + 0.235P_d \left( 1 + \frac{\log \left( 1/P_{sc} \right)}{46.6} \right) \right) \log(n^p) \\
\left( 1 - 0.1401 \log(n^p) + 0.018310 \left( \log(n^p) \right)^2 \right)
\]

(8)

Fig 3 simulates the improvement of the accumulation factor as a function of the cumulative pulse number. From this we can see that the higher the pulse number, the larger the signal-to-noise ratio (SNR) improvement factor. When the pulse accumulation number is 500, the improvement factor is greater than 16dB due to the airport runway. The detection system is required to operate at a speed of 50 Km/h, so the system operating speed is selected to be 17 m/s, at which time the pulse accumulation number is 500 and the improvement factor is 16.13dB.

4.2. Receiver signal to noise ratio simulation demonstration

The proposed radar is a two-channel radar with separate transmit and receive. In order to obtain good azimuth resolution, the azimuth beam width of the antenna must be as small as possible. If a metal tube is used as the circular waveguide antenna, as shown in Fig 4, the antenna gain \( G_a \) can be obtained as follows:

\[
G_a = 10 \log_{10} \left( \frac{\pi D}{\lambda} \right)^2 = 20.55245 \text{dB}
\]

(9)

The radar receiving power is expressed as follows:

\[
P_r = \frac{P_s G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}
\]

(10)
Where \( P_t = 0.3W \) is the transmit power, the receive/transmit antenna gain is \( G_r = G_t = G \), the distance \( R \) from the radar to the target. Minimum received signal \( P_{r_{\text{min}}} = -101.39dBm \) in the maximum range of 210 meters. In the radar system, \( SNR = 18dB \) 99\% of the detection probability is usually guaranteed. If the receiver noise \( F_n = 7dB \) [9], the fast Fourier bandwidth \( f_m = 500Hz \) is, at room temperature \( T = 290k \), the Minimum Discernible Signal (MDS) at the receiving is:

\[
MDS = -174 + 10 \log f_m + F_n + SNR_{\text{min}} = -122dBm \tag{11}
\]

At this time, the minimum received signal is higher than the minimum detectable signal at the receiving end, which indicates that the receiver has the ability to detect the 0.00051m\(^2\) target within 210 meters. Based on accumulated pulse, the modified radar distance formula can obtain the (SNR) \( (SNR_0) \) of the received signal. The formula is as follows:

\[
SNR_0 = \frac{p_0G_rG_t\lambda^3\sigma I(\eta_0)}{(4\pi)^2 KT F_{op} B L_n R_{max}^2 C_B} \tag{12}
\]

\[\text{Fig. 5 SNR-Distance}\]

The \( L_n = 3dB \) is the total system loss. Fig 5 shows the simulation of the SNR with the distance between the platform and the target, the SNR of the system can be detected after 500 times of accumulation at 210 meters is \( SNR_0 = 25.6461dB \), and the SNR of a single pulse signal can be calculated to be 13.66461dB.

4.3. Signal to clutter ratio (SCR) simulation
The system emits a signal wavelength of \( \lambda = 0.83cm \), and the angle between the radar beam and the ground is \( \varepsilon = 1.4^\circ \). At this time, the surface area of the target area fluctuates to \( \Delta h \leq 2.13cm \), the target area surface produces specular reflection, and the FOD airport runway surface produces diffuse reflection. At this time, the system can receive the diffuse reflection. a clear echo.

The surface of the airport runway is composed of asphalt material. In the case of the grounding angle \( \varepsilon = 1.4^\circ \), there is no suitable theoretical or empirical model \( \sigma^h \), and accurate clutter analysis cannot be performed, so the required clutter scattering coefficient cannot be obtained. We can take an approximation to analyze \( \sigma^h = -50dB \) [10, 11]. At this time, the SCR:

\[
SCR = \frac{\sigma}{\sigma^h R\theta_b (C_T / 2) \sec \varepsilon} \tag{13}
\]

Where \( \sigma^h \) is the asphalt scattering coefficient, \( \theta_b \) is the antenna beam width, \( C_T / 2 \) is the distance resolution.
The known parameters are substituted into the formula (15), and the result is shown in Fig 6 as the simulation when the SCR is different from the target distance of the radar. At a maximum distance of 210 meters, \( \text{SCR} = 16.99 \text{dB} \). Compared with the SNR of 13.6461dB, the clutter power is not much different from the noise power when the signal power is the same. Therefore, the detection probability is verified only by the SNR [12].

4.4. Detection probability simulation

The detection probability \( P_d \) is that the signal sample \( s \) exceeds the threshold voltage in the case of noise plus signal. The formula is:

\[
P_d = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{s A}{\sqrt{\frac{2}{\psi^2}}} \exp \left( -\frac{s^2 + A^2}{\psi^2} \right) dr
\]

Where the orthogonal component of the noise is an uncorrelated zero-mean low-pass Gaussian noise with equal variance \( \psi^2 \), Radar signal amplitude is \( A \), Power is \( A^2 / 2 \), Single pulse \( SNR = A^2 / 2\psi^2 \), and \( (v^2 / 2\psi^2) = \ln(1 / P_o) \), That is, the probability of detection:

\[
P_d = Q \left[ \frac{A^2}{\sqrt{\psi^2}} \sqrt{2 \ln \left( \frac{1}{P_o} \right)} \right]
\]

Where \( Q \) is called the Marcum Q function [13]. As shown in Fig 7, the relationship between the SNR and the system detection probability, the false alarm probability is \( P_o = 10^{-5} \), and the detectable probability is 0.9999.

![Fig. 6 SCR-Distance](image-url)
5. Conclusion

This paper mainly demonstrates the operating frequency, signal form and main technical indicators of the airport runway FOD detection system based on vehicle SAR. Finally, the feasibility of the detection system is determined by simulation. Through analysis and simulation, the following conclusions are drawn:

1. SAR is easier to implement small antennas and high resolution than conventional radars, and the center frequency of 36 GHz is more suitable for detection methods based on vehicle SAR.

2. The chirped continuous wave signal can achieve the same effect as the pulse signal with less power and lower sampling frequency.

3. The airport runway FOD detection system based on vehicle SAR can effectively detect objects with height of 3cm and cross-sectional area of 20.00051m² in distance of 210m when the transmitting power is 25dBm and the running speed is 61.2m/s. At this time, the detection probability is 0.9999 and the false alarm rate is 10⁻¹².

References

[1] WU Xiaobiao, SUN Hemin, etc. A FOD Detection System Based on Vehicle SAR and Its Imaging Performance Analysis [J]. Journal of Air Force Warning Academy. 2018 (5).

[2] Guo Wei. Study on the characteristics of rain attenuation in Ka band [D]. Xidian University of Electronic Technology, 2011.

[3] András S, Baricz Á, Sun Y. The generalized Marcum SQ-$Q$-function: an orthogonal polynomial approach [J]. Acta Univ Sapientiae Math, 2011 (1) : 60-76.

[4] Michael I. Duersch, BYU MICRO-SAR: A very small low-power LFM-CW synthetic aperture radar, Brigham Young University, December 2004.

[5] K. El-Darymli, C. Moloney, E. Gill, P. McGregor, D. Power, "Design and implementation of a low-power synthetic aperture radar", Geoscience and Remote Sensing Symposium (IGARSS) 2014 IEEE International, pp. 1089-1092, 13–18 July 2014.

[6] G.L. Charvat, A.J. Fenn, B.T. Perry, "The MIT IAP radar course: Build a small radar system capable of sensing range Doppler and synthetic aperture (SAR) imaging", Radar Conference (RADAR) 2012 IEEE, pp. 0138-0144, 7–11 May 2012.

[7] ZHEN Boxiao, ZHANG Shouhong, Long-term Coherent Accumulation Method Based on Sparse Array Integrated Pulse Aperture Radar [J]. Journal of Electronics Science, 1998, 20 (4): 573-576.

[8] peebles Jr., P.Z , Radar Principles, John Wiley & Sons, Inc, 1998.

[9] Mehdi G, Miao J. Millimeter wave FMCW radar for Foreign object debris (FOD) detection at airport runways [C]// International Bhurban Conference on Applied Sciences & Technology. IEEE, 2012: 407-412.

[10] Ville Viikari, Timo Varpula and Mikko Kantanen, "Automotive Radar Technology for
Detecting Road Conditions. Backscattering Properties of Dry, Wet, and Icy Asphalt", EuMA Radar conference, October 200S, Amsterdam, The Netherlands.

[11] Eric S. Li, Member, IEEE, and Kamal Sarabandi," Low Grazing Incidence Millimeter-Wave Scattering Models and Measurements for Various Road Surfaces", IEEE Transactions on Antennas and Propagation, VOL. 47, NO. 5, MAY 1999.

[12] Mazouni, K.; Kohmura, A.; Futatsumori, S.; Yonemoto, N.; Dauvignac, I.; Pichot, c.; Migliaccio, C. , "77 GHz FM-CW radar for FODsn detection" EuRAD, 2010.

[13] FAA. AC 150/5220-24. Airport Foreign Object Debris Detection Equipment [R] 2009. 1-13.