Anti-Jamming Technology of SAR Seeker for Forward Squint of Aircraft

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Abstract. The SAR seeker has the capability of detecting all day long and all-weather. The imaging guidance of SAR can revise the error of inertial navigation, greatly improved the precision of the aircraft. However, the SAR seeker is vulnerable to interference from the other side, which affects imaging and guidance capability. In this paper, the basic principle, model and jamming effect of common noise, FM jamming and pulse jamming are given on the basis of introducing the working principle of SAR seeker. On this basis, this paper focuses on the anti-noise and anti-pulse jamming technology and interference principle of the SAR seeker with forward squint. After analysis, the anti-jamming principle is feasible, and it has the engineering application ability, and can be applied to the aircraft. In addition, from the point of view of the overall design of aircraft, some anti-jamming ideas of SAR seeker are given.

1. Introduction
At present, with the development of guidance detection technology, users have higher and higher requirements for the accuracy of aircraft in complex environment, and the accuracy mainly depends on the navigation and guidance precision of the aircraft. The error of the own device in inertial navigation will gradually accumulate over time, which can’t meet the requirements of long-time high-precision flight. The Synthetic Aperture Radar (SAR) seeker has full-time, all-weather detection capability. The imaging guidance using SAR can correct the error of inertial navigation, which greatly improves the accuracy of the aircraft.

As a wireless transceiver device, the SAR is exposed to the same area for long time during use, and is easily detected by the other party, so that the interference is interfered by the other party [1]. The interference modes for SAR radar include noise interference, pulse interference, frequency shift interference, chaff interference and convolution interference [2]. With the development of electronic countermeasure technology, the interference to SAR radar has become a focus of current research. For example, Li Tian gave a SAR coherent suppression interference method based on amplitude modulation[3], and Fang Ming gave a SAR Doppler shift frequency intermittent sampling and forwarding interference method[4].

In the face of severe interference situations, research on anti-jamming at home and abroad has become an important development trend. However, current research on SAR anti-jamming mainly focuses on spaceborne SAR [5]. For the aircraft using the squint SAR imaging system, the interference means are different from the spaceborne SAR, so the anti-interference measures are also different. Jiang Siyuan proposed a method to resist frequency shift interference[6]. In this paper, the corresponding anti-jamming measures are proposed for noise FM interference and pulse interference. From the mode of use of the aircraft, several ideas for anti-interference of SAR seeker are proposed.
2. Squint SAR imaging technology

2.1 Spatial design of forward squint SAR space
In the northeast celestial coordinate system, the spatial geometry of the squint SAR imaging is shown in Fig. 1 [7]. Let 0\( _m \) = 0 phase is the center of SAR, located at point A, The coordinate position is (0,0,\( _0H_0 \)). The aircraft is at speed \((V_x', V_y', V_z')\), The acceleration is \((A_x, A_y, A_z)\), O point is the center of the imaging scene, The coordinates is \((x_0, y_0, z_0)\), Move to point B at time \(t_m\), The instantaneous coordinates is
\[
\left( V_x t_m + \frac{A_x t_m^2}{2}, V_y t_m + \frac{A_y t_m^2}{2}, H_0 + V_z t_m + \frac{A_z t_m^2}{2} \right).
\]

![Figure 1. Spatial geometry model of squint SAR imaging](image)

2.2 Front squint SAR signal model
Suppose the expression of the chirp signal sent by the SAR is:
\[
s(t) = w_r(\hat{t}) \exp \left( j 2\pi \left( f_0 \hat{t} + \frac{k t^2}{2} \right) \right) (1)
\]

In formula 1, \(w_r(\bullet)\) is the window function of the linear frequency modulation (LFM) signal, \(k\) is frequency modulation slope, \(f_0\) is carrier frequency.

The fundamental frequency signal of the point target received by the radar is in the fast time-azimuth slow time domain (\(\hat{t} - t_m\) domain) is:
\[
s_r s_a(\hat{t}; t_m) = w_r \left( \hat{t} - \frac{2R(\hat{t}_m)}{c} \right) w_a(t_m) \exp \left[ j \pi k \left( \hat{t} - \frac{2R(\hat{t}_m)}{c} \right)^2 \right] \exp \left[ -j \frac{4\pi R(t_m)}{\lambda} \right] (2)
\]

In formula 2, \(R(\hat{t}_m)\) is the instantaneous slant distance from the target to the radar, \(w_a(\bullet)\) is the azimuth window function of the radar, \(t_m\) is the azimuth slow time, \(\hat{t}\) is the distance of the fast time, \(c\) is Speed of light, \(\lambda = c / f_0\) is the wavelength corresponding to the center frequency.

According to the bandwidth of the radar echo frequency, the time width after the azimuth pulse compression can be calculated:
According to the radar imaging theory, the azimuth time width is multiplied by the velocity component of the reference point, and the azimuth resolution of the target can be obtained \( \rho_\alpha \). The speed of the reference point is \((v_x, v_y, v_z)\), instantaneous speed is \( V = (v_x^2 + v_y^2 + v_z^2)^{1/2} \). Therefore, the azimuth resolution can be obtained as:

\[
\rho_\alpha = \Delta T V = \frac{\Delta \lambda}{4R_\alpha \Delta T}\frac{\Delta r}{2V_\alpha \Delta T_\alpha}
\]  

(4)

It can be seen that the shorter the wavelength, the longer the imaging accumulation time, the faster the speed and the higher the resolution; the short wavelength and high speed flight can increase the Doppler bandwidth, which is easy to cause azimuth Doppler blurring, and the pulse repetition frequency needs to be increased. But increasing the pulse repetition frequency is easy to cause distance blur.

3. Front squint SAR interference technology

3.1 Noise FM interference

The model of the noise FM interference signal is:

\[
p(t) = \exp \left( j2\pi k_m n(\tau) d\tau \right)
\]

Half power bandwidth is:

\[
B_{\text{noise}} = 2\sqrt{2 \ln 2} k_m \sigma = 2.35 k_m \sigma
\]

(6)

It can be seen that the interference bandwidth depends on the power of the modulated signal \( \sigma^2 \) and Tuning rate \( k_m \). After the noise-modulated interference signal is pulse-pressed, the signal is still distributed in the form of Gaussian distribution around the target echo. Because the spectrum of \( p(t) \) is continuous, the output of Gauss noise FM jamming signal is connected by pulse compression, which can only form blocking jamming and cannot form deceptive jamming.

The parameters of LFM signal are: pulse width \( T_p = 5\text{ms} \), bandwidth \( B = 1\text{MHz} \); Modulation noise bandwidth \( B_n = 3.27\text{kHz} \), power \( \sigma = 1 \), \( m_\omega = 100 \), \( k_m = 3.3 \times 10^6 \). The simulation results are shown in Figure 2.

(a) Amplitude frequency characteristics of noise FM jamming
In Fig. 2, because \( m_\mu \gg 1 \), the half power bandwidth of the \( P \) of the jamming signal is:

\[
B_{\text{noise}} = 2\sqrt{2}\ln 2k_{\text{fm}}\sigma = 2.35k_{\text{fm}}\sigma = 0.77\text{MHz}
\]

The time range of interference signal coverage is:

\[
T_r = B_{\text{noise}} / K = 3.9\text{ms}
\]

The red in figure (b) is the result of compression of the original LFM signal, and the blue is the result of compression after noise modulation, \( J/S \) is 20\,dB, the increase of signal to noise ratio can achieve complete suppression effect.

### 3.2 Pulse jamming

The model of pulse jamming noise signal is [2]:

\[
n(t) = \sum_{-\infty}^{\infty} \text{rect}(t + nT)Ae^{j2\pi f_0t}
\]

\[
\text{rect}(t) = \begin{cases} 1 & (-\tau / 2 \leq t \leq \tau / 2) \\ 0 & \text{otherwise} \end{cases}
\]

\( T \) is pulse repetition period; \( n \) is integer; \( A \) is the noise amplitude, obeys the normal Gauss distribution, and \( f_0 \) is the center of frequency.

Considering that the pulse width of jamming signal is far less than the pulse width of target signal, the pulse repetition period of jamming signal is also far less than the radar pulse repetition period. In this way, a number of jamming pulses will be included in the radar receiving a target pulse. Therefore, the power of the jamming signal will be concentrated in a short time, and the spectrum of the pulse jamming can be regarded as covering the whole signal frequency domain and Doppler frequency domain.

The target signal power of radar is \( P_n \), the average power of jamming signal is \( P_j \), the average power of the pulse in the jamming signal is \( P_j \), the signal to noise ratio of radar signal is:

\[
\text{SNR} = \frac{P_n}{P_j} = \frac{P_j}{\gamma P_j} = \frac{P_j}{\gamma P_j}
\]

\( \gamma = \frac{\tau}{T} \) is the duty cycle of pulse jamming signal.

The ratio of average power to signal power in the jamming signal pulse can be obtained:

\[
\frac{P_j}{P_j} = \frac{1}{\text{SNR} \gamma}
\]
4. Squint SAR anti-jamming technology

4.1 Anti-noise FM jamming technology

Noise FM jamming is a commonly used jamming mode. Aiming at this jamming mode, anti-jamming technology generally includes side-lobe blanking, dual-channel cancellation and variable polarization technology. This paper analyzes the ability of suppressing noise FM jamming from the angle of increasing pulse repetition rate.

The Doppler bandwidth of spacecraft SAR seeker is small, usually only tens of hertz, so the pulse repetition frequency of spacecraft SAR seeker can be much larger than its Doppler bandwidth. Improving pulse repetition rate can not improve azimuth resolution, but it can increase the number of accumulated pulses and help to improve signal-to-interference ratio. Different from the range, the azimuth signal is directly sampled, and the sampling frequency is the pulse repetition frequency. Generally, the jamming signal is non-coherent in azimuth, and the bandwidth of the jamming energy in the whole Azimuth frequency domain is much wider than the Doppler bandwidth of the target. The azimuth bandwidth of the jamming signal is much wider than that of the radar, so in the azimuth signal received by the radar, the pulse repetition frequency is PRF, and the jamming signal is evenly distributed between -PRF/2 and PRF/2. The Doppler bandwidth of the target signal is smaller than that of the pulse repetition rate. If the noise power after distance compression is $j_P$, Target signal power is $Pt$, The Doppler bandwidth of the target signal is $Bd$, The SNR is in the range of signal bandwidth (i.e. azimuth compression):

$$
SNR_0 = \frac{Pt \cdot PRF}{j_P \cdot Bd}
$$

(12)

It can be seen that the signal-to-noise ratio of radar after azimuth compression is proportional to the PRF of radar pulse repetition frequency, so increasing PRF can greatly improve the signal-to-noise ratio of imaging and play an anti-jamming role.

4.2 Anti-pulse jamming technology

According to formula (11), the time domain interference sweeping technology can be carried out from the following aspects, and the signal processing algorithm against impulse interference can be obtained:

- a) Identify interference based on received signal waveform;
- b) Calculate the average amplitude of the signal and set the amplitude threshold;
- c) Zeroing the sample points above the threshold;
- d) Imaging the processed signal.

The signal form of radar after jamming is:

$$
s(t) = \sum_{n=0}^{\infty} rect(t + nT)A e^{j2\pi ft} + s_j(t)
$$

(13)

With the above anti-jamming technology, the radar signal form is:

$$
s(t) = [\sum_{n=0}^{\infty} rect'(t + nT + T/2)]s_j(t)
$$

(14)

Set $r(t) = \sum_{n=0}^{\infty} rect'(t + nT + T/2)$, The spectrum of $r(t)$ is

$$
R(\omega) = \sum_{m=-\infty}^{\infty} \frac{2\sin ma_0 \tau_0}{m} \delta(\omega - m\omega_0)
$$

(15)

In formula 15 $\omega_0 = 2\pi/T$, $\tau_0 = T - \tau_0$. When the interference signal duty cycle is 0.5, The even number of M is at zero. The Fourier transformation of $s(t)$ is:

$$
S(\omega) = S_j(\omega) * R(\omega)
$$

$$
= \sum_{m=-\infty}^{\infty} \frac{2\sin ma_0 \tau_0}{m} S_0(\omega - m\omega_0)
$$

(16)
Because $S_0(t)$ is a chirp signal:

$$S_0(e^{j\omega t}) \rightarrow s_0(t - m \frac{\omega_0}{2\pi k})$$ (17)

$K$ is the frequency modulation slope. According to the ambiguity function of LFM signal, after anti-jamming signal processing, we can get the compressed signal as follows:

$$g(t) = 2T_p \sum_{n=-\infty}^{\infty} \sin c(m\omega_0 \tau_n) \sin c\left(B_p(t - m / T_k)\right)$$ (18)

The above analysis shows that adopting time domain interference cleaning technology can enhance the ability of SAR to resist pulse jamming.

5. Conclusion

With the development of complex battlefield electromagnetic environment, the anti-jamming performance of spacecraft SAR has attracted more and more attention. Improving the anti-jamming capability of the forward squint SAR of aircraft plays an important role in enhancing the operational efficiency of aircraft. Starting from the working principle of aircraft forward squint SAR, based on introducing noise FM interference and pulse interference, this paper proposes anti-jamming measures such as improving pulse repetition frequency and time domain interference sweeping technology. At the same time, this paper puts forward some anti-jamming ideas based on the use mode of aircraft for further research.

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