Frequency Agility MIMO-SAR Imaging and Anti-Deception Jamming Performance

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Abstract

Imaging proceduce for frequency agility multiple-input multiple-output synthetic aperture radar (MIMO-SAR) in presence of deception jamming is proposed, where the radar, at each pulse repetition interval (PRI), emits a waveform by one antenna, and the transmitted baseband signals are modulated with step carrier frequencies in successive PRIs. System model and signal model of both target echo and jamming were analyzed. Imaging procedure flow of frequency agility MIMO-SAR was expounded, a signal recombination technique was presented, enables the MIMO-SAR to achieve high resolution imagery. Frequency agility MIMO-SAR imaging in deception jamming scenarios was simulated at the end. Experiment results are used to show the validity of the introduced concepts.

1. Introduction

The ECM and ECCM of SAR are the important content in the electronic warfare domain. One very effective strategy on suppressing the effect of a digital radio frequency memory (DRFM) repeat jammer is based on the concept of pulse diversity. In [1], a method is proposed where the diversified pulses are phase-perturbed, i.e., a phase shift is introduced to linearly frequency modulated (LFM) signals. A method by random initial phase and polarity of chirp rate jittered of the transmitted LFM pulses is proposed in [2], The output signal-to-jamming ratio is enhanced by making the jamming not get all the gains of matching filters. A method to generate the complex modulation LFM signal using the slope wobble in different pulse repetition interval (PRI) is introduced in [3], because the modulated form of the LFM signal in different PRI is not known to the jammer, which destroys the correlation of the jamming signal and the SAR transmitted signal in the current PRI. The method is also adopted in [4]. These chirp rate jittered methods needs the chirp rate changing in every PRI. Chaotic binary code signal is introduced in SAR by Zheng [5], in the same year, a new SAR signal of chaotic phase modulated intra-pulse and random coded inter-pulse is proposed depending on the characteristic of extreme initial value sensitivity and pseudo-randomness and multidimensional hyper-chaos [6-8], whereas the generation of chaos signal is difficult in practice.

The pulse diversity method is useful to suppress the deception jamming, and applying it into MIMO-SAR system will improve the ECCM capability of the radar. Other than the chirp rate jittered or transmitted waveforms varied methods, this paper introduces a frequency agility MIMO-SAR system, where the radar, at each PRI, emits a baseband LFM signal by one antenna, receives the echoes using all the antennas with coherent demodulation, and the transmitted signals are modulated with step carrier frequencies in successive PRIs.

2. Frequency Agility MIMO-SAR System Model

For implementing the scheme, which transmits a different carrier frequency signal in each PRI, the MIMO-SAR system works with switched local oscillators (LO) mode. The transmitter's configuration and timing diagram of frequency agility MIMO-SAR is illustrated in Fig.1 and Fig.2.

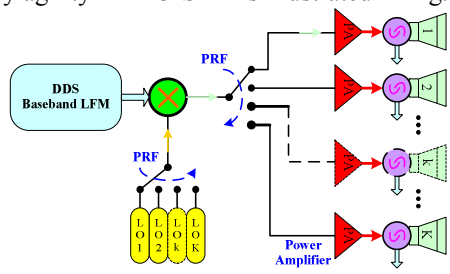

Fig. 1 Configuration of frequency agility MIMO-SAR transmitter

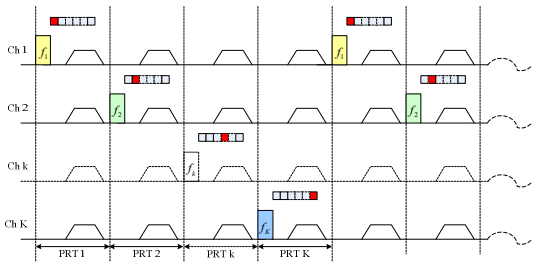

Fig. 2 Timing diagram of frequency agility MIMO-SAR

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Fig. 1 shows the structure of MIMO-SAR transmitter, where the radar, transmits different carrier frequency LFM signal in each PRI controlled by pulse repetition frequency (PRF). The corresponding LO and transmitting channel are selected based on system PRF in the current PRI. Direct digital synthesizer (DDS) generates baseband LFM signal and then transmits to the mixer. Through modulation and power amplify, the modulated signal emits to the targets scene. The rectangular group displays in horizon donates the azimuth antenna apertures, as shown in Fig. 2, darken one represents the transmitting aperture in the current PRI. For achieving high resolution imagery, the spacing of adjacent carrier frequencies is designed equal to the subband bandwidth. The subband synthesis principle of frequency agility MIMO-SAR is shown in Fig. 3.

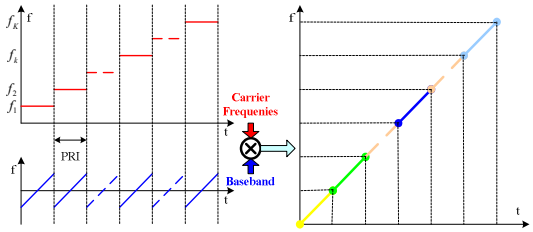

Fig. 3 Subband synthesis principle

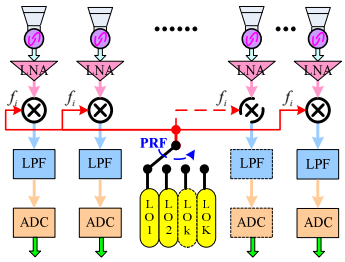

Fig. 4 The receiver front-end frame

MIMO-SAR system emits the same baseband LFM signals modulated by different carrier frequencies in each PRI, thus a broadband signal can be synthesized by multiple sub-echoes received in several PRIs, which can be used to achieve high range resolution imagery. All the channels receive the echoes by coherent demodulation in each PRI. The principle diagram of frequency agility MIMO-SAR receiver is shown in Fig. 4.

2.1 System Signal Model with Deception Jamming

Nowadays, the mostly deception jammer is designed based on the DRFM, and the false imagery jamming is an effective method to confuse SAR processor, whereas, it needs complex computation and longer processing time, thus let the processing time of DRFM jammer as T_{jam}. The transmitted signal of frequency agility MIMO-SAR in the current PRI is represented by

$$q_k(t) = \exp\left\{ j2\pi f_k t + j\pi K_r \tau^2 \right\} \tag{1}$$

where $f_k = f_0 + (k-1)\Delta f$, f_0 is the carrier frequency of the initial azimuth channel, k is the serial number of the current transmitting channel, Δf is the spacing between adjacent carrier frequencies.

While, the received echo reflected off the real targets by the ath azimuth aperture in current PRI is

$$\mathbf{r}_a(t) = \sum_{p=1}^{P} \sigma_p \exp\left\{ j2\pi f_k (t-\tau_p) + j\pi K_r (\tau-\tau_p)^2 \right\} \tag{2}$$

where P donates the total numbers of the scatterers in imaging scene. $\tau_p = \left(R_{k+1,p} + R_{a,p}\right)/c$ represents the corresponding delay of scatterer p. $R_{k+1,p}$ is the distance between $k+1^{\text{th}}$ antenna azimuth aperture and the scatterer p, and the distance between the scatterer and k^{th} antenna azimuth aperture is donates as $R_{a,p}$.

Supposing the DRFM jammer is located in imaging scene, the intercepted waveform is

$$I(t) = \exp\left\{ j2\pi f_k (t-\tau_i) + j\pi K_r (\tau-\tau_i)^2 \right\} \tag{3}$$

where $\tau_i = R_{k,i}/c$ is the transmission delay between k^{th} antenna azimuth aperture and the jammer I.

The jamming signal transmitted by the DRFM jammer is

$$\mathbf{J}(t) = \left[\exp\left\{ -j2\pi f_k \tau_i + j\pi K_r (\tau-\tau_i)^2 \right\} * \mathbf{h}(\tau, t_m) \right] \cdot \exp\left(j2\pi f_k t \right) \tag{4}$$

where $\mathbf{h}(\tau, t_m)$ represents the modulation function of the jammer.

Then the received jamming signal of the ath antenna azimuth aperture can be formulated as

$$\mathbf{J}(t)=\left[\exp\left\{-j2\pi f_k\tau_J+j\pi K_r(\tau-\tau_J)^2\right\}*\mathbf{h}(\tau,t_m)\right]\cdot\exp(j2\pi f_k t) \tag{5}$$

where $\tau_J=\tau_i+\tau_i'+T_{jam}=\left(R_{k,i}+R_{a,i}\right)/c+T_{jam}$ donates the transmission delay of jamming signal.

The total received echo of the ath antenna azimuth aperture in current PRI is written as

$$\begin{aligned}\mathbf{S}_a(t)=\mathbf{r}_a(t)+\mathbf{J}(t)&=\sum_{p=1}^{P}\sigma_p\exp\left\{j2\pi f_k(t-\tau_p)+j\pi K_r(\tau-\tau_p)^2\right\}\\&+\left[\exp\left\{-j2\pi f_k\tau_J+j\pi K_r(\tau-\tau_J)^2\right\}*\mathbf{h}(\tau,t_m)\right]\cdot\exp(j2\pi f_k t)\end{aligned} \tag{6}$$

Consider the jamming delay time $\tau_J>PRI$, the jamming can't enter the receiver by the filter, while, the delay time $\tau_J<PRI$, the partial jamming energy received by the radar, we discuss this condition in the following.

2.2 Frequency Agility MIMO-SAR Imaging

The carrier frequencies of transmitted signals are changed depend on the system PRF, so the azimuth phase of the received echoes will be discrete. For achieving high resolution imagery, the data received by all channels should be recombined base on PRF firstly, and then reconstruct the recombined data to make the azimuth data sampling uniformly. The subband synthesis method is introduced in processed data to get a broadband signal in the sequence step, and the high resolution imagery can be achieved at the last. The imaging processing flow chart is shown in Fig. 5.

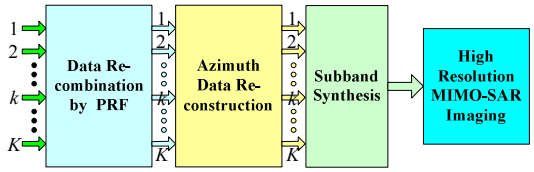

Fig. 5 The flow chart of frequency agility MIMO-SAR imaging

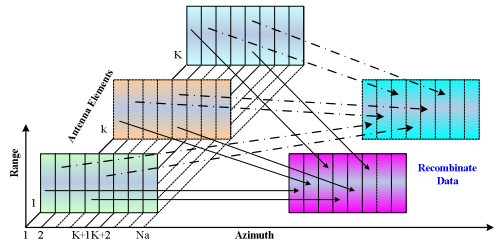

Fig. 6 Recombination principle of the collected data

The uniformly sampling reconstruction of the azimuth data can be accomplished after all the collected data is recombined. The recombination principle is shown in Fig. 6. From the above, the imaging procedures of frequency agility MIMO-SAR are given as follows: 1) The collected data is recombined along the azimuth direction, the principle is shown in Fig. 6. 2) Solve the Doppler blur by reconstruction filter-bank method for every recombined sub-echo. 3) Synthetic a broadband signal by subband synthesis technique processed in time or frequency domain. 4) R-D algorithm is applied to the synthesized data for high resolution imaging.

3. Simulation Results

The echo data of frequency agility MIMO-SAR is simulated for analyzing the proposed method. System parameters are listed in Table 1.

Table 1. System parameters of frequency agility MIMO-SAR

Symbol	Parameter	Value	Symbol	Parameter	Value
H_s	Satellite height	514.8 km	θ_{inc}	Beam incident angle	38°～42°
f_c	Center frequency	9.65 GHz	h_{ant}	Antenna height in elevation	0.88 m
B_r	Sub-signal bandwidth	50 MHz	l_{ant}	Antenna length in azimuth	4 m
T_P	Pulse width	5 μs	N_{az}	Elements number in azimuth	3
Δf	Carrier frequency spacing	50 MHz		Deception jamming template	Island

For the sake of lowering the computational burden, targets scene inversion from coast imagery with 1 m resolution got by TerraSAR-X, whose size is 0.7km×0.7km. The coast scene is shown in Fig. 7.

Island imagery is used as the deception imagery template, DRFM jammer modulates the intercepted radar signals with the template information to form deception jamming. The imaging results of multifrequency MIMO-SAR and frequency agility MIMO-SAR in presence of deception jamming are shown in Fig.8 and Fig. 9 separately.

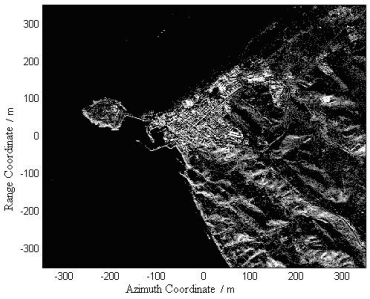

Fig. 7 Imaging scene acquired by TerraSAR-X

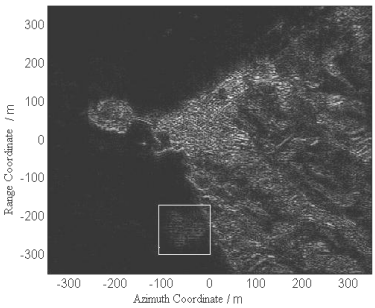

Fig. 8 Imaging of multifrequency MIMO-SAR

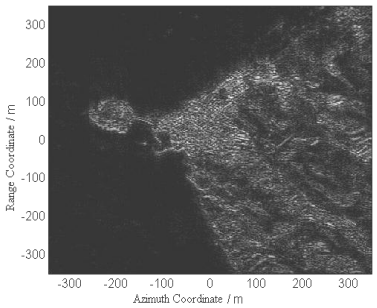

Fig. 9 Imaging of frequency agility MIMO-SAR

The multifrequency MIMO-SAR, transmits step frequency signals with all the azimuth antennas at the same time, and collects the return echoes by all the antennas. The imaging result with deception jamming is shown in Fig. 8. This system transmits the same waveform in the successive PRIs, the jamming signals and the echo reflected off the real targets can't be separated in the imaging processing, so the false targets is formed, which is labelled with rectangle in the Fig. 8. Fig. 9 demonstrates the anti-deception jamming performance of the frequency agility MIMO-SAR, where the spectrum overlap degree between target echo and deception jamming is 5%. Here, we use structure similarity index to estimate the anti-jamming performance. The structure similarity is 0.477 for multifrequency MIMO-SAR imagery, and the structure similarity is 0.936 for frequency agility MIMO-SAR imagery. The estimate results show that the frequency agility MIMO-SAR system has remarkable anti-deception jamming performance, profiting from the combination of pulse diversity and frequency agility technique.

4. Conclusion

MIMO SAR system employs multiple antennas to transmit signals, and receives echoes also by multiple antennas, which improves notably the ability of accessing to ground information and becomes a hot issue of SAR research domain in recent years. Advanced ECCM techniques are the precondition for its future application. This paper introduces the pulse diversity method and frequency agility technique in SAR and proposes a frequency agility MIMO-SAR system, which transmits signals and receives return echoes by switched LO mode. The proposed system has three advantages: 1) It is convenient to implement in practice since its simple principle, 2) it can achieve high resolution imagery compared with traditional single channel SAR, and 3) deception jamming signals can be suppressed for improving survive ability of the radar system. The operation principle and imaging flow are expounded, and simulation experiments are performed to validate the anti-deception jamming capability of the frequency agility MIMO-SAR.

5. References

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