MIMO SAR PROCESSING WITH AZIMUTH NONUNIFORM SAMPLING

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1. ABSTRACT

This paper analyses ambiguity suppression caused by MIMO SAR azimuth nouniform sampling. Two methods are analyzed: azimuth spectrum reconstruction algorithm and minimum mean square error (MMSE) imaging algorithm. The azimuth spectrum reconstruction algorithm can reconstruct the scene with fine resolution, while the nonideal orthogonality of multi-channel encoding waveforms causes orthogonal ambiguous in SAR imaging. The MMSE imaging algorithm can perfectly eliminate this ambiguous energy, while it requires high SNR.

2. INTRODUCTION

The synthetic aperture radar (SAR) is an active microwave remote sensing imaging tool providing high resolution image and is becoming more and more important in military monitoring and earth observation. SAR technique is under steady development to meet the versatile demands of different users. The recently proposed multiple-input multiple-output (MIMO) is a configuration that multi apertures are used for both transmission and receiving [1], and it is often combined with digital beamforming techniques. MIMO SAR can greatly improve the performance of traditional SAR and foresee wide range of SAR working modes, such as high-resolution wide-swath, ambiguity suppress and 3D imaging, etc. In MIMO SAR orthogonal waveform are generated and transmitted by multi antennas. While MIMO SAR imaging, the azimuth signals from multiple receivers should be effectively separated and rearranged. The rearranged azimuth signals are used to construct the full Doppler spectrum. To achieve uniform azimuth sampling intervals, a strict restriction is posed on the systems pulse repetition frequency (PRF) and platform velocity (V): V divided by PRF is just half of the total antenna length. This is often unsatisfied and the azimuth ambiguity appears. To suppress this ambiguity, a spectrum filtering algorithm is introduced to reconstruct the spectrum of uniform sampling [2] [3]. However, due to the nonideal orthogonality of encoding waveforms, the reconstructed result is degraded. In this paper, we analyses the performance of spectrum reconstruction algorithm of MIMO SAR and introduce MIMO SAR MMSE imaging algorithm. Based on system imaging geometry, MMSE imaging algorithm uses statistical properties of the targets and noise to optimally estimate the radar cross section (RCS) of the scene [4]. It takes full advantage of increased power brought by multi-transmitting and multi-receiving channels. Especially, algorithm based on MMSE avoids the problems of orthogonal ambiguity, because the it models the overall transmitted and received signals.

3. MIMO SAR SYSTEM MODEL

As shown on Fig. 1, a MIMO SAR system uses all its subapertures to transmit orthogonal waveforms and to receive echoes. Antennas regularly compactly spaced at a plane are mounted in the radar platform which moves with the velocity of V along the direction of Y axis. The coordinate origin is set at the geometric center of antenna array at the slow time $t = 0$.The coordinate of ground point target X can be expressed as $X = (x, y, -h)$. The location of geometric center of antenna center at time t is $(0, vt, 0)$. The numbers of subapertures of along track and across track is N_l and N_h respectively and total number of subaperture is $N = N_l N_h$. L and H are length and height of each subaperture. So the range history for (i, k) subaperture transmission and (l, m) subaperture receiving can be written as

$$\begin{aligned} r_{iklm}(t, X) &= r_{ik}(t, X) + r_{lm}(t, X) \\ &= \sqrt{h^2 + \left((i - (N_l + 1)/2)\, L + vt - x\right)^2 + \left((k - (N_h + 1)/2)\, H - y\right)^2} \\ &\quad + \sqrt{h^2 + \left((l - (N_l + 1)/2)\, L + vt - x\right)^2 + \left((m - (N_h + 1)/2)\, H - y\right)^2} \end{aligned}$$

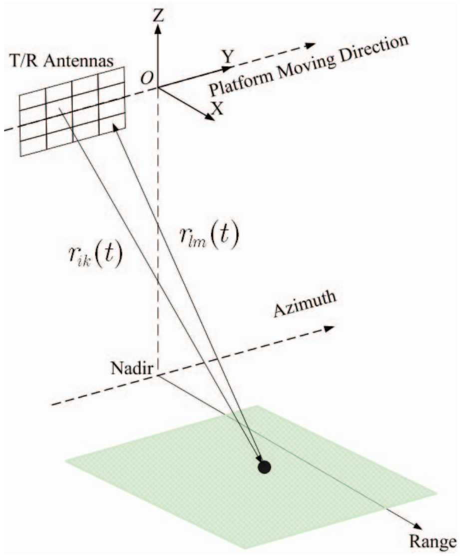

Fig. 1. Geometry of MIMO SAR.

If we denotes the waveform transmitted by (i, k) subaperture as $p_{ik}(\tau)$ wave velocity of light in vacuum as $c_0$and electromagnetic wavelength as λ, the signal received by (l, m) aperture is the linear superposition of echoes from all other transmitted antennas and can be expressed as

$$s_{lm}(\tau, t, X) = \sum_{k=1}^{N_l} \sum_{i=1}^{N_h} \frac{1}{r_{ik}(t, X) r_{lm}(t, X)} \exp\left(-j\frac{2\pi}{\lambda} r_{iklm}(t, X)\right) p_{ik}\left(\tau - \frac{r_{iklm}(t, X)}{c_0}\right)$$

In practice, the echoes of receivers are the sum of all echoes from all scattering point in the illuminated area and noise, so the digital data of (l, m) subaperture at slow time t and fast time τ is

$$d_{lm}(\tau, t) = \sum_X r_0(X) s_{lm}(\tau, t, X) \Delta A + n_{lm}(\tau, t)$$

where $r_0(X)$ is the RCS at location X, A is the illuminated area, and $n_{lm}(\tau, t)$ is the receiving noise.

4. MIMO SAR IMAGING

4.1. Azimuth Spectrum Reconstruction Algorithm

In MIMO SAR system, the number of space sampling increases largely because there are much more transmitting and receiving antennas. Before MIMO SAR imaging, the azimuth signals from multiple receivers should be effectively separated and rearranged. Waveform for a unique transmission-receiving channel can be distilled by matched filtering which can be accomplished when range compression is processed, and the other orthogonal waveforms are suppressed. For a MIMO SAR system having N_l subapertures in azimuth, the number of effective phase centers is $2N_l - 1$. Effective phase center is defined as the geometry center of phase centers of transmitting antenna and receiving antenna, and the received signals from this channel can be viewed as the signal transmitted and received by a sole antenna located at this virtual phase center. After multi-channel signal separation, the azimuth signals are rearranged as the order of effective center to reconstruct the full Doppler spectrum. If the previous mentioned rigid requirement is not satisfied

$$\frac{V}{PRF} \neq \frac{N_l d}{2}$$

the azimuth samplings will be nonuniform and azimuth ambiguity appears. Based on multi-channel signal sampling theorem, if the total azimuth samples are not less than that needed by Nyquist sampling theorem and the effective phase centers used for spectrum are not coincident, the unambiguous azimuth spectrum can be perfectly reconstruct[1]. This reconstruction condition can be expressed as

$$(2N_l - 1)PRF \geq Ba$$
$$\frac{V}{PRF} \neq nd \, (n = 1, \cdots, N_l - 1)$$

4.2. MMSE Imaging Algorithm

From MIMO SAR system model depicted in part 3, the entire recorded data of multi-channel can be expressed using matrix-vector notation

$$\mathbf{d} = \mathbf{S}\mathbf{r} + \mathbf{n}$$

where, $\mathbf{d}$ is the receiving data vector formed by data of multi receiving channels, $\mathbf{S}$ is the unit scattering matrix, $\mathbf{r}$ is complex RCS vector and $\mathbf{n}$ is complex noise.The MMSE filter can be expressed as [4]

$$\mathbf{W}_{\text{MMSE}} = r^2 \mathbf{S}^{\text{H}} \big(r^2 \mathbf{S}\mathbf{S}^{\text{H}} + \mathbf{K}_n\big)^{\sim 1}$$

where, $r = \mathbf{E}(\mathbf{r}^H \mathbf{r})$ is the expected value of the squared RCS magnitude for each target and $\mathbf{K}_n = \mathbf{E}(\mathbf{n}^H \mathbf{n})$ is the noise covariance matrix; $(\cdot)^{\text{H}}$ and $(\cdot)^{\sim 1}$ denotes matrix conjunction and pseudoinverse operation respectively.

5. SIMULATION RESULTS

In this section, we present some simulation results for a MIMO SAR system using 2 antennas for both transmitting and receiving. The up and down chirps are chosen as the encoding waveforms. As the effective phase center after azimuth sample rearranged is 3 times as much as the monostatic system, the PRF can be reduced by a factor of 3 and swath width expands 3 times correspondently.

6. CONCLUSION

Due to the stringent restriction posed on system's PRF, the azimuth nonuniform sampling is often inevitable in MIMO SAR implement. Spectrum reconstruction algorithm based on multi-channel signal sampling theorem can reconstruction the azimuth signal with uniform sampling via multi-channel filtering. The noideal orthogonality of waveforms causes ambiguous energy when range compression is processed, and this ambiguous energy will appears in azimuth spectrum reconstruction as the form of white noise and degrade the final SAR image. While another opportunity is the usage of MMSE imaging algorithm of MIMO SAR, which is based on the system model taking the whole encoding waveform into account. It can reconstruct the scene with fine resolution. The only disadvantage is that it is sensitive to noise, and well performance requires high SNR.

7. REFERENCES

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