The intrapulse beamsteering radar based on OFDM Chirp signals

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Abstract. The OFDM (Orthogonal Frequency Division Multiplexing) technique is widely used in communication field due to the great waveform diversity and anti-fading ability of OFDM signals. Because of the similarity of radar system and communication system, The OFDM radar has gradually emerged as a new system radar in recent years. At the same time, Intrapulse beamsteering system is a kind of multi-dimensional waveform encoding, which can improve the transmitting efficiency and multi-mission performance of radar. So, this paper proposes a new radar operating mode with the combination of the OFDM chirp signals and the intrapulse beamsteering in elevation, that is the combination of waveform orthogonality and beam orthogonality, we can also call it “double insurance”, which can greatly improve the emission efficiency and the system performance. Especially the interference suppression and the robustness to terrain undulation. The simulation results at the end of the paper prove the feasibility and advantages of the proposed operating mode.

1. Introduction

The Synthetic aperture radar (SAR) has been widely used in military and civil fields due to its advantages of all-weather, all day capabilities and high resolution. However, With the increasing requirement of radar performance and efficiency, many new SAR systems have emerged in recent years. Multiple-input multiple-output Synthetic Aperture Radar (MIMO SAR) system is one of them. MIMO technique was first used in communication engineering to solve multi-path effect [1]. Afterwards, J. Ender from German High Frequency Physical Laboratory proposed the application of MIMO technique in SAR system [2], MIMO SAR mainly has two advantages: flexible beam-pattern design, a high degree of freedom and the improved resolution [3].

However, the design of emission waveform is a difficulty in MIMO SAR system. OFDM (Orthogonal Frequency Division Multiplexing) technique is widely used in the field of high-speed wireless communication due to its excellent anti-frequency selective fading performance [4]. Because of the similarity of the radar system and communication system. Krieger of the German space agency generalized the short-term shift-orthogonal (STSO) waveforms and Orthogonal frequency-division Modulation Chirp (OFDM Chirp) waveforms, and analyzed the feasibility and consistency of their application in SAR system [5]. In 2013, J.Kim proposes a novel waveform scheme of the spaceborne MIMO SAR system based on the OFDM chirp signals, where the modulation and demodulation process of OFDM Chirp signals and signal processing flow are given [6].

Multidimensional Waveform Encoding (MWE) is a new digital beamforming technique for SAR remote sensing, and the intrapulse beamsteering in elevation is one example of MWE, which enables a wide image swath and high resolution. It also can reduce the transmission power and PRF requirement...
of the radar system [7]. The detailed working principle and method will be introduced in the following sections.

Therefore, this article proposes a novel radar operating mode with the combination of OFDM chirp signals and the intrapulse beamsteering in elevation, give full play to the advantages of these two techniques, finally simulation experiments are carried out to verify the system feasibility.

2. Intrapulse beam steering in elevation

Intrapulse beamsteering in elevation is one example of multidimensional waveform encoding, which can realize wide swath irradiation with multiple narrow beams with high gain.

![Figure 1. Schematic diagram of intrapulse beamsteering](image)

As shown in Figure 1, we can divide a wide swath into several small subswaths. In a PRT, we can transmit a number of narrow beams, and each one corresponds to a subswath. If we scan from the far end of the swath to the near end, the radar echoes from different subswaths will overlap at the receiving end, which will bring range ambiguity.

A common and feasible method for separating the mixed waveforms from different subswaths is the digital beamforming (DBF) on receive [8,9], where we use the difference of the DOA (direction of arrival) of echoes from different subswaths to construct a spatial filter. These processing can be performed on the ground without the loss of radar data information [10].

This radar operating mode has the following advantages:
- The length of receiving window is shortened, the duty ratio of transmitting signal can be increased, and the echo SNR and system operating distance can be improved;
- Different transmitting bandwidths are used for different subpulses, so that different subswath have different range resolution, thus obtaining flexible multi-range resolution.
- By means of phase weighting, the gain of the antenna in each subswath is uniform, avoiding the gain attenuation of the swath edge.
- In the elevation, using array weighting to form narrow beams, the antenna gain is higher and the requirement of radiation peak power for a single T/R module is reduced.

3. OFDM chirp signal modulation

The basic idea behind the OFDM technique is to exploit the orthogonality of discrete frequency components. As is shown in Figure 2, here we take three orthogonal OFDM waveforms for example, based on the frequency data of a modulate signal, we can get three non-overlapping signals by adding zero in frequency domain, which ensures the orthogonality of the three waveforms in frequency domain. Then the OFDM signals can be generated by performing an IDFT on these three frequency datas.
In this paper, a chirp signal spectrum is used for the OFDM modulation, the chirp signal spectrum can be written as:

\[ S[\bar{p}] = DFT[s[n]] = DFT[\exp(j\pi K_r (nT_s)^2)] \]  

(1)

where \( s[n] \) denotes the discrete time samples of a chirp signal with the length of \( N \), \( T_s \) is the sampling interval, and \( K_r \) is the chirp rate, then we can obtain three frequency data by zero-padding:

\[
\begin{align*}
S_1[p] &= \{S[0], 0, 0, S[1], 0, 0, \ldots, S[N-1], 0, 0\} \\
S_2[p] &= \{0, S[0], 0, 0, S[1], 0, \ldots, 0, S[N-1], 0\} \\
S_3[p] &= \{0, 0, S[0], 0, 0, S[1], \ldots, 0, 0, S[N-1]\}
\end{align*}
\]  

(2)

where \( p = 0, 1, 2, \ldots, 3N-1 \), Both data sequences contain \( 3N \) points, and they are completely orthogonal in the frequency domain. Then we perform \( 3N \)-point IDFT on them respectively, finally we can get the time domain form of the orthogonal signals by DAC (Digital-to-Analogue Conversion):

\[
s_t(t) = \text{rect}\left(\frac{t}{T_p}\right) s(t) + \text{rect}\left(\frac{t-T_p}{T_p}\right) s(t-T_p) + \text{rect}\left(\frac{t-2T_p}{T_p}\right) s(t-2T_p)
\]  

(3)

\[
s_2(t) = (\text{rect}\left(\frac{t}{T_p}\right) s(t) + \text{rect}\left(\frac{t-T_p}{T_p}\right) s(t-T_p) + \text{rect}\left(\frac{t-2T_p}{T_p}\right) s(t-2T_p)) \cdot \exp(j2\pi \Delta f \cdot t)
\]  

(4)

\[
s_3(t) = (\text{rect}\left(\frac{t}{T_p}\right) s(t) + \text{rect}\left(\frac{t-T_p}{T_p}\right) s(t-T_p) + \text{rect}\left(\frac{t-2T_p}{T_p}\right) s(t-2T_p)) \cdot \exp(j2\pi 2\Delta f \cdot t)
\]  

(5)

Where \( s_t \) is the time domain chirp signal with the period of \( T_p \), \( \Delta f = 1/3T_p \) is the frequency we shift in zero-padding. So here we get the time domain modulation forms of OFDM chirp signals, \( s_t \) is composed of three Chirp signals, \( s_2t \) and \( s_3t \) are constructed by adding a different phase term to \( s_t \).

4. OFDM chirp demodulation based on intrapulse beamsteering

For the conventional OFDM demodulation, the signal processing flow chart is shown in Figure 3(a),
Figure 3. (a) The conventional flow chart of demodulation; (b) The flow chart of proposed mode.

Where the DBF processing is to divide the echo data into several narrow signals to meet the OFDM orthogonality constraint, which is that the swath time delay $T_d$ should be less than $T_p$, that is to say $K \leq N$ [6]. The circular-shift addition is to ensure the integrity of the subswath information and the unification of DFT/IDFT points [6]. Finally, we can use the orthogonality of OFDM signals to separating the mixed waveforms in frequency domain.

Here we propose a new radar mode with the combination of the OFDM chirp signals and the intrapulse beamsteering in elevation. The new signal processing flow chart is shown in Figure 3(b), assuming there are three subswaths that meet the orthogonality constraint, the three OFDM chirp signals are used as the three transmit signals, which irradiate three subswaths respectively.

We can use the orthogonality of OFDM signal waveforms to separate the echoes from different subswaths instead of DBF. So, the DBF processing here can be used for energy accumulation and interference suppression after waveforms separation, here we choose the Linear Constraint Minimum Variance (LCMV) criterion to do DBF processing:

$$\begin{align*}
\min_{\mathbf{w}} P_{\text{out}} &= E[\mathbf{X}^H] = \mathbf{w}^H \mathbf{R}_x \mathbf{w} = \mathbf{w}^H \mathbf{R}_x \mathbf{w} + \mathbf{w}^H \mathbf{R}_{i,a} \mathbf{w} \\
\text{s.t.} \quad &\mathbf{w}^H \mathbf{C} = \mathbf{f}^H
\end{align*}$$

Where $\mathbf{C} = [A(\theta_1), A(\theta_2), \ldots, A(\theta_L)]$ is the steering vector matrix, $L$ is the number of constraints $\mathbf{f}^H = [1, 0, 0, 0, \ldots, 0]$ is a constraint vector, we can set the $i$-th element of $\mathbf{f}$ to 1 and the others to 0 so that we can obtain the echo signal with the DOA angle of $\theta_i$ and suppress the interference echoes from other directions. The optimal spatial filter is given by:

$$\mathbf{w}_{\text{opt}} = \mathbf{R}_x^{-1} \mathbf{C} (\mathbf{C}^H \mathbf{R}_x^{-1} \mathbf{C})^{-1} \mathbf{f}$$

Many interference signals can be suppressed by the DBF in elevation, such as signal leakage caused by the nonideal antenna pattern, finally, we splice the processed signals of the three subswaths together to get the result of the whole swath, and the earth observation with low transmission power requirements, low disturbance, high resolution and wide swath is realized. The simulation experiment is carried in the next section, which can prove the feasibility and advantages of the proposed novel radar operating mode.
5. Simulations

5.1. Ideal antenna pattern
First, a 1-dimensional simulation is carried out, we assume that the antenna pattern is ideal, which means that we can achieve complete truncation of the transmitted beam and the targets in other subswaths will not be irradiated, the simulation parameters and targets setting are given by Table 1 and Table 2:

Table 1. Simulation parameters.

| Parameters               | Value       | Parameters            | Value       |
|--------------------------|-------------|-----------------------|-------------|
| Platform height          | 600Km       | Antenna height        | 5m          |
| Carrier frequency        | 5.6GHz      | Subaperture numbers   | 10          |
| Signal bandwidth         | 200MHz      | Subswath 1            | (620Km,623Km)|
| Pulse width (a chirp signal) | 20us     | Subswath 2            | (623Km,626Km)|
| Number of subswaths      | 3           | Subswath 3            | (626Km,629Km)|

The simulation result without DBF is shown in the Figure 4 below, the results show that the proposed algorithm is feasible and can accurately locate the targets position. As it is the ideal antenna pattern, there is no interference signal, so we can get the ideal result without spatial filtering.

Figure 4. The results of ideal antenna pattern.

5.2. Nonideal antenna pattern
However, it is impossible to realize completely truncated antenna pattern in practical application, the echoes from the targets in other subswaths will also be received, but will be truncated by the receiving window, which will destroy the integrity of the OFDM chirp signals so that the orthogonality cannot be maintained. This will lead to signal leakage to other subswaths and bring interference signals, so we need to do DBF processing to suppress the interference signals. Here we use the following formula to calculate the antenna pattern:
The simulation results are shown in the Figure 5 above, we can clearly see the suppression effect of DBF processing on the interference signals.

5.3. Fault tolerance to terrain undulation
As we all know, although we think of the earth in theory as an ideal sphere, in reality the ground has terrain undulation, the terrain undulation will bring the error of the targets’ DOA. So, the DBF processing that takes advantages of the DOA information will be affected. However, the radar system proposed not only uses DBF technology but also orthogonal waveforms, which is unaffected by the terrain undulation. Therefore, here we add a height error to each target and compare the result with the conventional intrapulse beamsteering system using LFM signals and OFDM chirp signals. Notice that we should keep the pulse width and bandwidth consistent.

Figure 6. Comparison of LFM signal and OFDM chirp signal (with terrain undulation)
Here we set a random height error of (0,300m) for each target, as we can see in the Figure 6, both LFM and OFDM chirp signals can be used to locate the actual position of the targets, but we can clearly see that there are less and lower interference amplitudes when using OFDM chirp signals, we can control the interference at an ideal level, below -50dB. However, the interference level can be higher than -20dB if we use LFM signals, which is unacceptable in practical application. In general, the radar mode proposed has a good fault tolerance for height error and terrain undulation.

5.4. 2-dimensional simulation
Finally, we consider the 2-dimensional simulation to verify the feasibility of the proposed radar operating mode, to simplify the computation, we set up two subswaths, targets setting is given in Table 3 below.

| Point targets | Coordinate(range,azimuth) | Point targets | Coordinate(range,azimuth) |
|---------------|---------------------------|---------------|---------------------------|
| A1            | (621.8Km, 300m)          | B1            | (623.1Km, 350m)          |
| A2            | (621.8Km, -300m)         | B2            | (623.1Km, -350m)         |
| A3            | (621.4Km, 300m)          | B3            | (623.5Km, 350m)          |
| A4            | (621.4Km, -300m)         | B4            | (623.5Km, -350m)         |
| A5            | (621.6Km, 0m)            | B5            | (623.3Km, 0m)            |

Figure 7. (a) Imaging result without DBF; (b) Imaging result After DBF.

The results in Figure 7 show the excellent performance of the proposed radar operating mode, with the combination of OFDM chirp signals and DBF in elevation, we can accurately locate the targets position and suppress the interference signal to a very low degree.

6. Conclusion

This article proposes a new radar operating mode with the combination of OFDM chirp signals and intrapulse beamsteering in elevation. It means that the waveform orthogonality and beam orthogonality are combined. As a result, the radar system performance can be improved a lot. Especially the Anti-interference capability and the tolerance for height error of targets. Finally, the simulation experiments can verify that the proposed system’s feasibility and superiority.

Reference

[1] Bliss, D. W. , Forsythe, K. W. , Hero, A. O. I. , & Yegulalp, A. F. . (2002). Environmental
issues for mimo capacity. IEEE Transactions on Signal Processing, 50(9), 2128-2142.
[2] Ender J. (2007) MIMO SAR. International Radar Symposium, Cologne, Germany, 580-588.
[3] Wang, W. Q. (2011). Space–time coding mimo-ofdm sar for high-resolution imaging. IEEE Transactions on Geoscience & Remote Sensing, 49(8), 3094-3104.
[4] Christian Lueders. (2005). Theory and Applications of OFDM and CDMA. John Wiley.
[5] Krieger, & Gerhard. (2014). Mimo-sar: opportunities and pitfalls. IEEE Transactions on Geoscience & Remote Sensing, 52(5), 2628-2645.
[6] Kim, J. H., Younis, M., Moreira, A., & Wiesbeck, W. (2013). A novel ofdm chirp waveform scheme for use of multiple transmitters in sar. IEEE Geoscience and Remote Sensing Letters, 10(3), 568-572.
[7] Krieger, G., Gebert, N., & Moreira, A. (2008). Multidimensional waveform encoding: a new digital beamforming technique for synthetic aperture radar remote sensing. IEEE Transactions on Geoscience & Remote Sensing, 46(1), 31-46.
[8] Younis, M., Fischer, C., & Wiesbeck, W. (2003). Digital beamforming in sar systems. IEEE Transactions on Geoscience & Remote Sensing, 41(7), 1735-1739.
[9] Gebert, N., Krieger, G., & Moreira, A. (2009). Digital beamforming on receive: techniques and optimization strategies for high-resolution wide-swath sar imaging. Aerospace & Electronic Systems IEEE Transactions on, 45(2), p.564-592.
[10] He, F., Ma, X., Dong, Z., & Liang, D. (2014). Digital beamforming on receive in elevation for multidimensional waveform encoding sar sensing. Geoscience & Remote Sensing Letters IEEE, 11(12), 2173-2177.