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Synthetic Aperture Radar with OFDM-CP for Image Enhancement

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Abstract: The existing linear frequency modulated (LFM) (or step frequency) and random noise synthetic aperture radar (SAR) systems may correspond to the frequency hopping (FH) and direct sequence (DS)spread spectrum systems in the past second and third generation wireless communications. Similar to the current and future wireless communications generations, in this paper, we propose OFDM SAR imaging, where a sufficient cyclic prefix (CP) is added to each OFDM pulse. The sufficient CP insertion converts an inter-symbol interference (ISI) channel from multi paths into multiple ISI-free sub channels as the key in a wireless communications system, and analogously, it provides an inter-range-cell interference(IRCI) free (high range resolution) SAR image in a SAR system. The sufficient CP insertion along with our newly proposed SAR imaging algorithm particularly for the OFDM signals also differentiates this paper from all the existing studies in the literature on OFDM radar signal processing. Simulation results are presented to illustrate the high range resolution performance of our proposed CP based OFDM SAR imaging algorithm.

Keywords: Inter-Range-Cell Interference (IRCI), Cyclic Prefix (CP), Orthogonal Frequency-Division Multiplexing (OFDM), Swath Width Matched Pulse (SWMP), Synthetic Aperture Radar (SAR) Imaging, And Zero Side Lobes.

I. INTRODUCTION

The Use of multiple transmitters is of a great interest in the synthetic aperture radar (SAR) community. It provides an increase of degrees of freedom and dramatically improves SAR imaging performance when combined with multiple receivers, also-called multiple-input multiple-output (MIMO) constellation. However, the waveform design for multiple transmitters has been the most important and challenging issue in realizing the MIMO SAR concept. Particularly for space borne SAR, aside from the orthogonality between waveforms for simultaneous multiple pulse transmissions, a constant envelope of the wave form is desired, considering the high power amplifier (HPA) in transmitters. The HPAs in space borne SAR systems operate in saturation in order to generate the maximum output power and to ensure a stable output power level for amplitude variations in the HPA input signal. A significant envelope variation of waveform therefore yields a clipping effect on the output waveform, and the orthogonality can be broken. This letter presents a novel waveform scheme to meet the aforementioned requirements, based on the principle of orthogonal frequency division multiplexing (OFDM) proposed.

In OFDM systems, an available signal bandwidth is divided into multiple subbands, which is specified to be narrower than the channel coherence bandwidth, in order to avoid the frequency selective channel effect. The OFDM signaling is also paid attention for SAR applications, and recently, SAR processing techniques for OFDM waveforms were introduced. A major problem of the typical OFDM signal (mainly in space borne SAR) is the fast variation of the signal envelope. We resolve the problem by combining the OFDM principle with chirp waveforms. Therefore, the basic idea behind the proposed waveform scheme is to exploit both the orthogonality of subcarriers and intrinsic characteristics of traditional chirp waveforms. To deal with the side lobe issues from the non-ideal autocorrelations across the range cells in the conventional SAR systems, we have proposed a sufficient cyclic prefix (CP) based orthogonal frequency division multiplexing (OFDM) SAR imaging for single transmitter radar systems. By using a sufficient CP, zero range side lobes and inter-range-cell interference (IRCI)free range reconstruction can be achieved, which provides an opportunity for high resolution range reconstruction. As it has been explained, the major differences between our proposed CP based OFDM SAR and the existing OFDM SAR systems are in two aspects.

One is that a sufficiently long CP is used at the transmitter and the CP should be as long as possible when the number of range cells in a swath is large. The other is the SAR imaging algorithm at the receiver, which is not the matched filter receiver by simply treating the CP based OFDM signals as radar waveforms as what is done in the existing OFDM radar systems. With these two differences, the key feature of an OFDM system in communications applications of converting

an inter symbol interference (ISI) channel to multiple ISI free sub channels is analogously obtained in our proposed CP based OFDM SAR imaging as IRCI free range reconstruction among range cells in a swath. In this paper, we consider a frequency-band shared statistical radar range reconstruction using OFDM signals with sufficient CP by generalizing the CP based OFDM SAR imaging from single transmitter and receiver to multiple transmitter and receiver radar systems called "OFDM radar." With our newly proposed CP based OFDM radar, all the signal waveforms from all the transmitters have the same frequency band and thus the range resolution is not sacrificed and the same as the single transmitter radar. Furthermore, their arbitrarily time delayed versions are still orthogonal for every subcarrier in the discrete frequency domain and therefore, the spatial diversity from all the transmitters can be collected the same as the frequency division radar.

In addition to the two differences mentioned above for single transmitter and receiver CP based OFDM radar systems with the all the existing OFDM radar systems, the orthogonality in the time domain under arbitrarily time delays between different transmitters have not been considered in the existing OFDM radar systems where IRCI exists not only among range cells in a swath but also among the transmitters. In this paper, IRCI free is achieved among both range cells in a swath and all the transmitters. The importance of using chirp waveform in the proposed scheme is emphasized in the following issues: First, one can easily achieve the constant envelope of time domain waveforms aforementioned, which leads to a maximum efficiency of the transmitter modules of a phased-array antenna. Second, the chirp spectrum approaches a rectangular shape as the time–bandwidth product increases so that its spectral efficiency and signal-to-noise ratio can be maximized. Finally, one can further exploit the linear frequency–time characteristics of chirp in signal processing. It makes it easy to combine the proposed scheme with existing SAR processing algorithms, such as the de-chirp-on-receive technique. Focusing on a dual transmit antenna scenario, we develop the novel waveform scheme consisting of the modulation and demodulation algorithm, based on the conventional OFDM processing, and validate its potential.

Special attention has to be paid to the demodulation since the classical OFDM de-modulation assumes that the delay length of a received signal is shorter than the length of the cyclic prefix (CP), but a SAR echo signal is generally much longer than the transmitted pulse length. In this letter, we present a demodulation strategy for such a long SAR signal. Another difference for OFDM communications systems and CP-based OFDM SAR systems is as follows. It is known in communications that, for an OFDM system, a Doppler frequency shift is not desired, while the azimuth domain (or cross-range direction) in a SAR imaging system is, however, generated from the relative Doppler frequency shifts between the radar platform and the scatterers. One might ask how the OFDM signals are used to form a SAR image. This question is not difficult to answer. The range distance between the radar platform and image scene is known, and the radar platform moving velocity is known too. Thus, the Doppler shifts are also known, which can be used to generate the cross ranges similar to other SAR imaging techniques and can be also used to compensate the Doppler shift inside one cross range and correct the range migration.

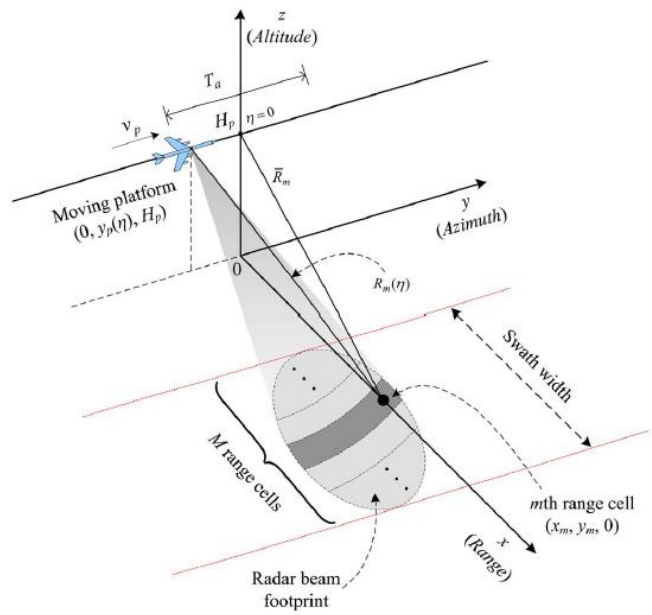

Fig.1. Monostaticstrip map SAR geometry.

This paper is organized as follows. In Section II, OFDM Chirp Modulation .In Section III, we present some simulations to illustrate the high-range resolution property of the proposed CP-based OFDM SAR imaging and also the necessity of a sufficient CP insertion in an OFDM signal. In Section IV, we conclude this paper and point out some future research problems.

II. OFDM CHIRP MODULATION

A. Principles

The basic idea behind the proposed technique is to exploit the orthogonality of discrete frequency components, i.e., subcarriers. This means that the orthogonality of waveforms is independent of the types of input sequences. Assume the input sequence (spectrum) **S** [$\bar{p}$] with N discrete spectral components, which are separated by 2Δf as shown in Fig.2. First, the input sequence **S** [$\bar{p}$] is interleaved by Nzeros, which is $\mathbf{S}_1$ [p] in Fig. 2, and then, the interleaved input sequence is shifted by Δ_{ffor} the second data sequence $\mathbf{S}_2$[p].These data sequences are transformed into the time domain by the 2N-point inverse discrete Fourier transform (IDFT), which is the OFDM modulation. As a result, we obtain two waveforms modulated by two orthogonal subcarrier sets that are mutually shifted by Δ_f. Thus, their demodulation must be performed by 2N-point DFT. It must be emphasized that both the sets contain 2N subcarriers but use only N subcarriers to carry the input data, respectively.

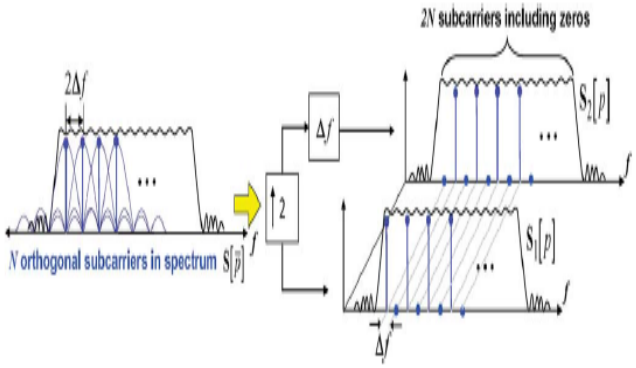

Fig.2. Two orthogonal OFDM chirp waveforms are generated by zerointerleaving and shift of a single chirp spectrum as an input sequence.

B. Signal Model

As aforementioned, a chirp signal spectrum is used for the OFDM modulation in this work. The chirp signal spectrum, as input complex data, is obtained by

$$S[\bar{p}] = F\{s[n]\} = F\{exp\,(j.\pi.K_r.(nT_s)^2)\} \quad \textbf{(1)}$$

where s[n] denotes the discrete time samples of a complex chirp signal with the length of N, F{·}is the Fourier transform operator, T_s is the sampling interval, and K_r is the chirp rate, which is a ratio between the signal bandwidth B and the chirp duration T_p(K_r= B/T_p). Using (1), we generate two input data sequences by the zero interleaving and shift as follows:

$$S_1[p] = [S[0], 0, S[1], 0 \ldots, S[N-1], 0] \quad \textbf{(2)}$$

$$S_2[p] = [0, S[0], 0, S[1], \ldots, 0, S[N-1]] \quad \textbf{(3)}$$

Where p = 0, 1, 2, . . . , 2N − 1. Both data sequences contain total 2N components, respectively. Therefore, they are modulated by 2N-point IDFT. According to the Cooley–Tukey algorithm, the DFT/IDFT can be performed by separate transforms with respect to the odd and even components of the input. Since the even components in **S**1 are zeros, the inverse Fourier transform of S_1 [p] is equivalent to that of S [$\bar{p}$]. Substituting $\bar{p}$for p/2, the modulated waveform s1 is given by

$$S_1[n] = \sum_{p=0}^{N-1} S[\bar{p}]\,.\,exp\left(j\,\frac{2\pi}{N}\bar{p}n\right) \quad \textbf{(4)}$$

Where n = 0, 1, 2, . . . , 2N − 1. Since the inverse Fourier transform of S [$\bar{p}$] is s[n] with the period of N, s_1[n] can be expressed by a repetition of s[n] over the length of 2N

$$s_1[n] = s[n].rect\left[\frac{n}{N}\right] + s[n-N].rect\left[\frac{n-N}{N}\right] \quad \textbf{(5)}$$

In the same way, using (p + 1)/2 = $\bar{p}$+ (1/2), the other modulated waveform s_2 is derived as

$$s_2[n] = exp\left(j\,\frac{\pi}{N}n\right)\sum_{p=0}^{N-1} S[\bar{p}]\,.\,exp\left(j\,\frac{2\pi}{N}\bar{p}n\right) \quad \textbf{(6)}$$

and using s[n], it can be also described as

$$s_2[n] = \left(s[n].rect\left[\frac{n}{N}\right] + s[n-N].rect\left[\frac{n-N}{N}\right]\right).\exp\left(j\frac{\pi}{N}n\right) = s_1[n].exp\left(j\frac{\pi}{N}n\right) \quad \textbf{(7)}$$

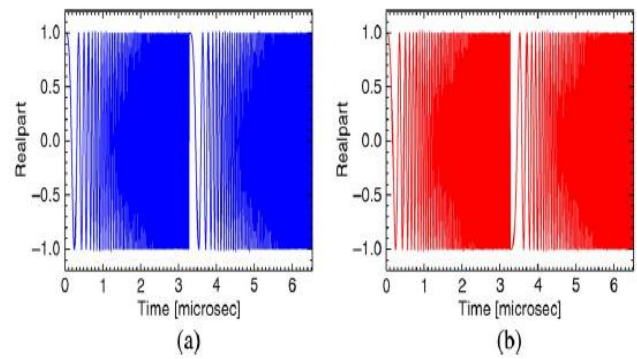

Fig.3. Real parts of OFDM chirp waveforms in time domain with 50-MHzbandwidth and N = 4096. The phase change in s2(t) due to the sub carrieroffset must be remarked in comparison with s1(t). (a) s1(t). (b) s2(t).

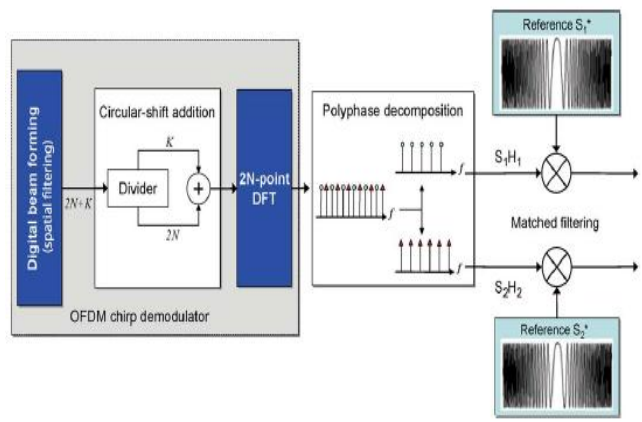

Fig.4. Generic schematic of the proposed OFDM demodulator followed by the poly phase decomposition and parallel matched filters for the range compression.

By introducing t = nT_s and Δ_f= 1/2NT_s, it is noticed that both waveforms are distinguishable by the subcarrier offset Δ_f. These modulated OFDM waveforms are converted to analog forms by a digital-to-analog converter. The OFDM waveforms in the time domain are plotted in Fig.3. Due to the zero inter leaving in the spectrum, the peak power level of the waveforms will be reduced. However, according to Parseval's theorem, the total energy of the input sequence is conserved. Using the aforementioned signal model, the OFDM waveforms can be also directly produced in the time domain. The time domain generation is valuable since a band-limited input sequence can cause an overshoot in time domain waveforms as shown in Fig.4.

III. SIMULATIONS AND PERFORMANCE DISCUSSIONS

This section is to present some simulations and discussions for our proposed CP-based OFDM SAR imaging. The simulation strip map SAR geometry is shown in Fig. 1. The

azimuth processing is similar to the conventional strip map SAR imaging[3] as shown in Fig. 5(a). For computational efficiency, a fixed value of R_c located at the center of the range swath is set as the reference range cell as in [3]. Then, the range cell migration correction(RCMC) and the azimuth compression are implemented in the whole range swath using R_c. For convenience, we do not consider the noise in this section as what is commonly done in SAR image simulations. For comparison, we also consider the range Doppler algorithm using LFM and random noise signalsas shown in the block diagram of Fig. 5. Since the performance of a step frequency signal SAR is similar to that of an LFM

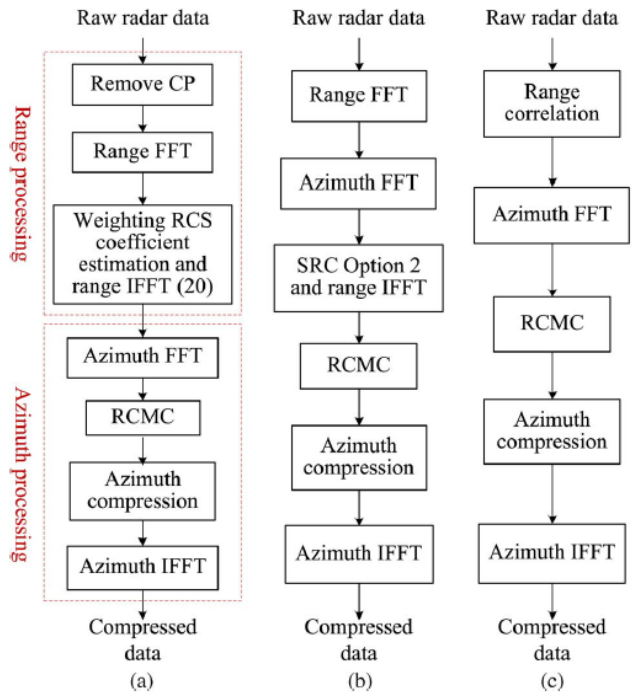

Fig.5. Block diagram of SAR imaging processing. (a) CP-based OFDMSAR. (b) LFM SAR. (c) Random noise SAR and conventional OFDM SAR.

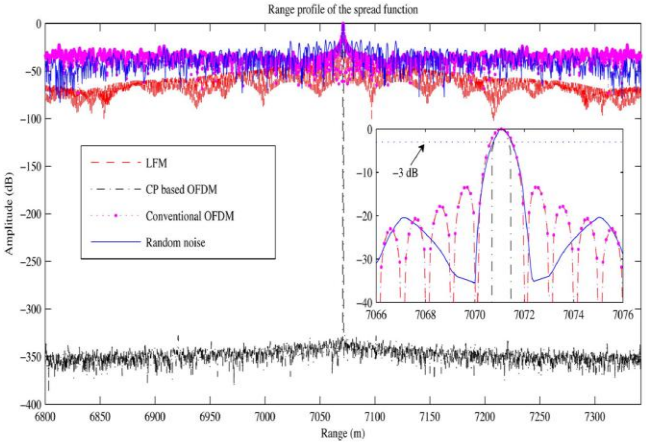

Fig.6. Range profiles of the point spread function.

signal SAR, here, we only consider the LFM signal SAR in our comparisons. In Fig. 5(b), the secondary range compression is implemented in the range and azimuth frequency domain, the same as Option 2 in [2, Ch. 6.2]. In Fig. 5(c), the range compression of the random noise signal and the conventional OFDM signal are achieved by the correlation between the transmitted signals and the range time domain data. Notice that the difference of these three imaging methods in Fig. 5 is the range compression, while the RCMC and azimuth compression are identical.

The simulation experiments are performed with the following parameters as a typical SAR system: PRF = 800 Hz, the bandwidth is B = 150 MHz, the antenna length is La = 1 m, the carrier frequency f_c = 9GHz, the synthetic aperture time is T_a = 1 s, the effective radar platform velocity is v_p= 150 m/s, the platform height of the antenna is H_p= 5 km, the slant range swath center is R_c= 5√2 km, the sampling frequency f_s= 150 MHz, and the number of range cells is M = 96 with the center at R_c. For the convenience of FFT/IFFT computation, we set T = (512/150) μ_s≈ 3.41 μ_s; then, the number of subcarriers for the OFDM signal is N = 512. The CP leng this 95 that is sufficient, and the CP time duration is TGI =(95/150) μ_s≈ 0.63 μ_s. Thus, the time duration of an OFD Mpulse is T_o= (607/150) μ_s≈ 4.05 μ_s. The complex weight vectors over the subcarriers of the CP-based OFDM signal and the conventional OFDM signal are set to be vectors of the binary PN sequence of values −1 and 1. Meanwhile, for the transmission energies of the three SAR imaging methods to be the same, the time durations of an LFM pulse, a conventional OFDM pulse, and a random noise pulse are also 4.05 μs. A point target is assumed to be located at the range swath center. Without considering the additive noise, the normalized range profiles of the point spread function are shown in Fig. 6, and the details around the main lobe area are shown in its zoo min image. It can be seen that the side lobes are much lower for the CP-based OFDM signal than those of the other three signals, while the 3-dB main lobe widths of the four signals are all the same.

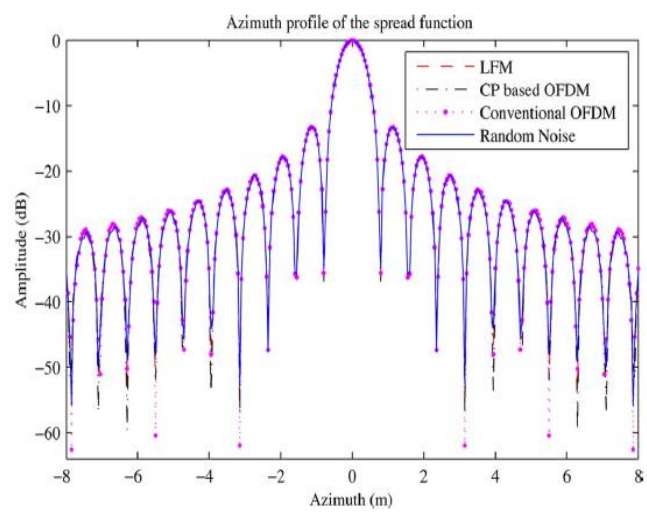

Fig.7. Azimuth profiles of the point spread function.

The normalized azimuth profiles of the point spread function of the three methods are shown in Fig. 7. The results show that the azimuth profiles of the point spread function are similar for all the four signals of LFM, CP-based OFDM, conventional OFDM, and random noise. We then consider an

extended object with the shape of a tank constructed by a few single point scatterers, and the original reflectivity profile is shown as Fig. 8(a). The results indicate that the imaging performance using the CP-based OFDM SAR is better than that of the other three signals. Specifically, the boundaries of the extended object are observed to be less blurred by using the CP-based OFDM SAR imaging. In Fig. 8(f), we also consider the imaging of the tank with our proposed method when the CP length is zero and the transmitted OFDM pulse is the same as the conventional OFDM pulse as a remark, comparing Fig. 8(e) and (f), one may see that the SAR imaging performance degradation is significant when the CP length is zero. This is because our proposed range reconstruction method in the receiver, as mentioned, is for CP-based OFDM SAR imaging and different with the traditional matched filter SAR imaging method. Thus, sufficient CP should be included in the transmitted OFDM pulse to achieve IRCI-free range reconstruction.

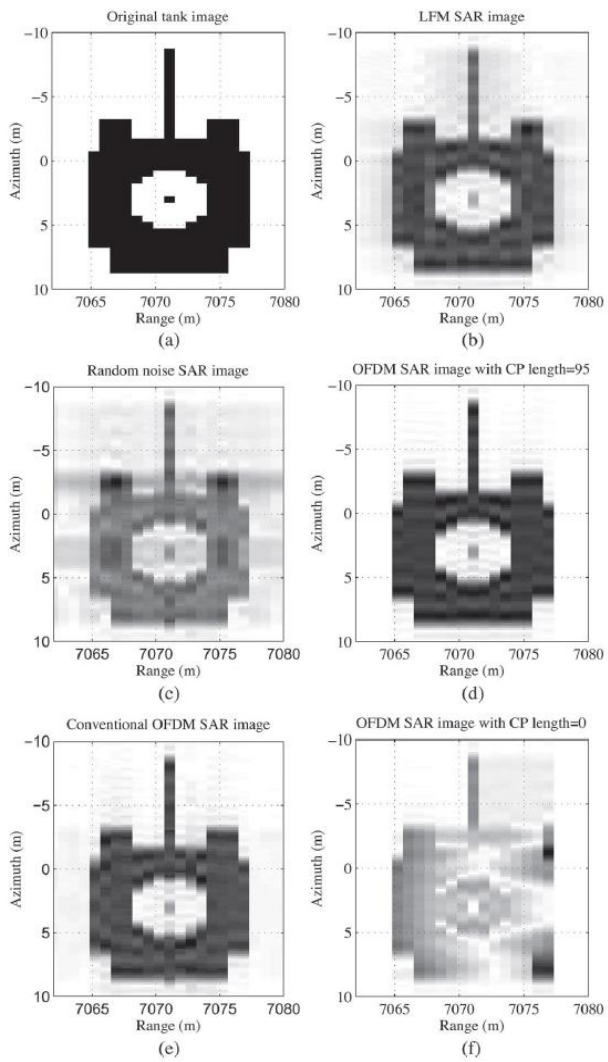

Fig.8. Imaging results of simulated reflectivity profile for a tank. (a) Original tank. (b) LFM SAR. (c) Random noise SAR. (d) OFDM SAR with sufficient CP. (e) Conventional OFDM signals SAR. (f) CP-based OFDM SAR withCP length = 0.

We next consider the importance of adding a sufficient CP in our proposed CP-based OFDM SAR imaging. We consider a single range line (a cross range) with M = 96 range cells; targets are included in 18 range cells, the amplitudes are randomly generated and shown as the red circles in Fig. 9,and the RCS coefficients of the other range cells are set to be zero. The normalized imaging results are shown as the blue asterisks. The results indicate that the imaging is precise when the length of CP is 95, i.e., sufficient CP length, in Fig. 9(a),and the amplitudes of the range cells without targets are lower than −300 dB, which is due to the computer numerical errors. With the decrease of the CP length, the imaging performance is degraded, and the IRCI is increased. Specifically, the zero amplitude range cells become nonzero anymore, and some targets are even submerged by the IRCI as shown in Fig. 9(b)and (c).We also show the imaging results with the conventional OFDM SAR image as in Fig. 9(d). The curves in Fig. 9(d)indicate that some targets are submerged by the IRCI from other range cells. In Fig. 9, we notice that, when the CP lengths are95 and 80 (as in Fig. 9(a) and (b), respectively), the imaging performances of our proposed method outperform that of the conventional OFDM SAR image in Fig. 9(d).

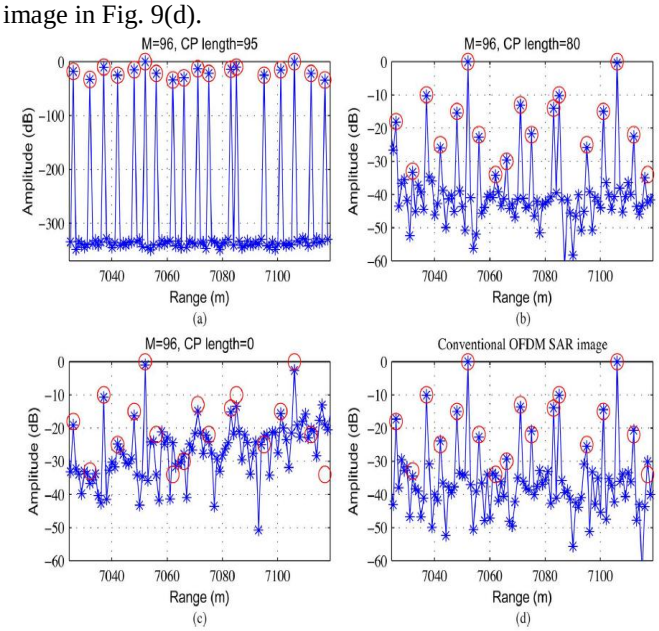

Fig.9. Range line imaging with different CP lengths. Red circles denote the real target amplitudes, and blue asterisks denote imaging results.

However, the imaging performance with zero length CP is worse than that of the conventional OFDM SAR image, although they have the same transmitted OFDM waveform, which is again because our proposed range reconstruction method at the receiver is different from the conventional method. It also further indicates that a sufficient CP is important for our proposed CP-based OFDM SAR imaging. We also consider a single range line (a cross range) with M range cells, in which the RCS coefficients are set as gm= 1,m = 0,…,M−1. After the CP-based OFDM SAR imaging with different lengths of CP, we calculate the mean square errors (MSEs) between the energy normalized imaging results and

the original RCS coefficients gm. The results are achieved from the average of 1000 independent Monte Carlo simulations and are shown in Fig. 10. The curves suggest that the performance degradation occurs when the length of CP is less than M − 1, i.e., insufficient. The MSE is supposed to be zero when the CP length is M − 1 that is sufficient. However, one can still observe some errors in Fig. 10, which is because errors may occur by using a fixed reference range cell R_c in the imaging processing (i.e., RCMC and azimuth compression), and the wider swath (or a larger M) causes the larger imaging error. Thus, the MSE is slightly larger when M is larger.

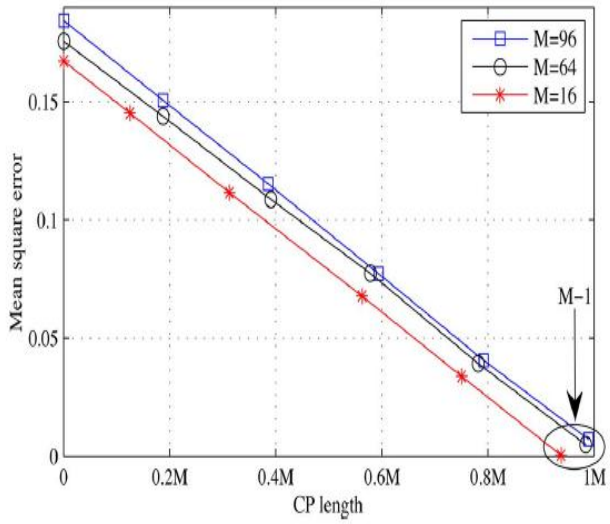

Fig.10. MSEs for insufficient CP lengths.

IV. CONCLUSION

In this letter, we proposed a novel waveform scheme, based on the principle of OFDM technique combined with conventional chirp waveforms. Regarding a typical space borne SAR scenario, this letter dealt with the demodulation scheme combined with DBF and verified it by simulation. In this paper, we proposed a novel frequency-band shared and sufficient CP based OFDM radar range reconstruction method by using our newly proposed and designed OFDM pulses that are in the same frequency band but orthogonal each other for every subcarrier in the discrete frequency domain. This range reconstruction algorithm with the orthogonality of the OFDM signals can provide the advantage of avoiding the interference between different transmitters, even when there are time delays among the signals from different transmitters, and achieving the full spatial diversity. Meanwhile, due to the sufficient CP insertion to each pulse with the zero head and tail values in the discrete time domain, the range reconstruction is IRCI free and the proposed system does not have the energy redundancy. Our proposed range reconstruction is a joint pulse compression and pulse coherent integration, after which the SNR was analyzed. We then proposed four design criteria for multiple OFDM pulses.

To achieve the orthogonality for every subcarrier in the discrete frequency domain across multiple transmitters, complex orthogonal designs were adopted, with which only non-zero-valued OFDM pulses for the first transmitter are needed to be designed. To maximize the SNR, a closed form solution was proposed by using the par unitary filter bank theory. Considering the tradeoff between the PAPR and the SNR degradation within the range reconstruction, we also proposed an MICF joint OFDM pulse design method to obtain OFDM pulses with low PAPRs and insignificant SNR degradation. We finally presented some simulations to demonstrate the performance of the proposed OFDM pulse design method. By comparing with the frequency band shared radar using poly phase code waveforms and frequency division radar using LFM waveforms, we provided some simulations to illustrate the advantage, such as the full spatial diversity and free IRCI, after the range reconstruction, of the proposed OFDM radar.

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