Slow-Time MIMO in High Frequency Surface Wave Radar

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Abstract. High Frequency Surface Wave Radar (HFSWR) has been widely used for remote sensing and maritime target detection. However, the HFSWR system contains a huge antenna array for accurate angle measurement. Miniaturization of antenna array has been one of the most urgent problems in this field. Applying the Multiple-Input Multiple-Output (MIMO) technology to radar can effectively improve the angle estimation accuracy in the case of small aperture through virtual channels. Hence, the superiority of MIMO contributes to improve the performance of HFSWR system. Slow-time MIMO is a special form of MIMO radar through Doppler diversity, and it can operate at same time and same frequency. This paper introduces the experiment of slow-time MIMO in HFSWR system in recent days. The results validated on real data can prove the benefit of MIMO technology in angle estimating, and we analyze the specific impact of sea clutter, ionospheric clutter and radio interference for Slow-time MIMO HFSWR.

Keywords: High frequency surface wave radar · Slow-time MIMO · Aperture expanding · Beamforming · Clutter suppression

1 Introduction

The High Frequency Surface Wave Radar (HFSWR), which is applied on surface wave propagation, provides an excellent capability to detect ocean surface dynamical environment over-the-horizon [1]. And HFSWR operates in the High Frequency (HF) frequency band of 3 to 30 MHz. Nowadays, HFSWR systems has been widely applied in many fields, such as detecting the sea surface conditions, surveilling the large Exclusive Economic Zone(EEZ), as well as military defense [2]. Due to the large surveillance area, many countries apply the HFSWR to continuously supervise the maritime of activity within a nation's EEZ, which is a crucial question in protection of national sovereignty. At present, hundreds of HFSWRs have been deployed all over the world, and most of the typical HFSWR systems are lied close to offshore and apply the large array structures with aperture sizes of hundreds or even thousands of meters, which can occupy a large area of coastal. However, with the development of national economy, the coastal resources and environment become more precious than before. Obviously, the occupation of scarce coastal resources in a large area has become an important reason that limits the development of HFSWR system. Therefore, how to reduce the

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high land rental and construction cost is a hot research topic in the future development. With the excellent performance and distinctive design, Multiple-Input Multiple-Output (MIMO) antenna systems have the ability to markedly improve the performance of communication systems over single antenna systems. Multipath effect will adverse impact the signal quality in the transmission. Hence, the traditional antenna systems pay attention on eliminating multipath effects. However, the novelty of MIMO system is that it takes the opposite view. Specifically, MIMO explores the independence between signals at the array elements and applies the multipath effect to improve communication quality. In a MIMO system, the transmitter and receiver utilize multiple antennas to communicate simultaneously. MIMO systems often employ sophisticated signal processing techniques to significantly enhance reliability of signal, transmission range, and throughput. The transmitter uses these techniques to simultaneously send multiple radio frequency signals and the receiver recovers data from the radio frequency signals. As stated above, by transmitting different streams of information, MIMO communication systems solve the problems caused by fading from several irrelevant transmitters. Inspired by MIMO communication systems, Fishler et al. [3] proposed the MIMO radar, which also has the same advantages in multiple signal transmission. Specifically, in order to explore the radio cross section of target scintillations, the MIMO radar system transmits the different signals from some decorrelated transmitters. The receiver will receive a superposed signal that formed by independently faded signals, so the average signal to noise ratio (SNR) of the received signal is more or less constant. In this case, the MIMO radar system avoid the problem that received SNR contrasted sharply.

The HFSWR system and MIMO radar have their own superiority, so complementing them for each other becomes a natural choice. Many of the existing works have demonstrated that this combination is a promising approach for target detection in long range. In 2014, Dzvonkovskaya [4] proposed a new approach that applies MIMO technique to compact HF radar system WERA deployments and obtain positive economic benefits without degrading system detection performance. The WERA system adopts modular design, which can easily meet the requirements of practical application. Most of the signal processing steps are done by software, so this system can be easily adapted to different application. Initially, in the standard configuration of WERA receiving system has 12 receiving antennas and these receiving antennas are located in a linear array and their spacing is about one half of a radar wavelength. The test MIMO geometry of WERA system has 6 real antennas. These 6 real antennas are taken as real elements and other antenna elements are skipped [5]. The separation distance between the transmitters is L, which roughly 3 times of the radar wavelength. Therefore, the positions of virtual receiving antenna elements are placed after the real elements. The carrier frequency shift of the first and second transmitters is equal to one third of the distance cell frequency, which contributes to separate the echo between sea surface and targets in every real antenna. Windowed discrete Fourier transform is used to estimate Doppler frequency and windowed beamforming is used to estimate Angle. Because of the transmitted signals, the phase difference caused by transmitting antennas along with phase differences in receiving antennas can form a larger virtual array by a small number of antennas to proceed with the beamforming technique. In 2015, Jangal et al. [6] proposed a new HFSWR deployed for the European I2C project (i.e. Integrated

System for Interoperable sensors & Information sources for Common abnormal vessel behaviour detection & Collaborative identification of threat). The crucial improvement of ONERA's HFSWR is deploying key technologies as combination. These technologies are: employing proven hardware, slow rate equipment, real time processing, MIMO architecture, full digital system and possibility of located in rough terrain. The ONERA's HFSWR is deployed on Levant Island in the South East of France and applies Multi-carrier frequency technology (surface wave radar is operated at 5 and 9 MHz). Like other HFSWR systems, the important requirement of the Levant Island system is to deal with the Target to Clutter Mode(TCM) and reduce the radar cell means. For obtaining the aforementioned coverage on small and slow targets, The ONERA's HFSWR system increases the diversity and the array length. Simultaneously, ONERA's HFSWR system will increase the transmitting power and use FMCW mode instead of pulse mode to realize the detection of large target or fast target. In North America, A.M. Ponsford et al. [2] presented Canada's Third Generation High Frequency Surface Wave Radar System, which is a monostatic pulse Doppler radar. The radar is simultaneously operated by two independent frequencies in an interleaved pulse mode, and makes full use of time diversity and frequency diversity. For each frequency, the data collected on the thread is processed in multiple parallel paths optimized for different classes of ships.

However, none of the aforementioned methods is applicable to the large number of transmitting antennas. In 2006, Mecca et al. [7] proposed a MIMO method that in conventional radar waveforms are phase-coded to be orthogonal after Doppler processing at the receiver, i.e. in "slow-time". Slow-time MIMO has the advantages of high bandwidth efficiency, easy implementation, and doesn't need to modify the receiver before range pulse compression. Thanks to the advantage of Slow-time MIMO, many improvement approaches are proposed and applied in over horizon radar system. In the following study, Mecca et al. [8] presented beamspace multiple-input multiple-output space-time adaptive processing(STAP) to suppress radar clutter subject to multipath propagation between transmitter and receivers. In 2008, Frazer et al. [9] designed the Australian HILOW experiment to examine the MIMO radar concepts based on OTHR. Yu et al. [10] presented a technique for generating slow-time MIMO waveforms by using a low-cost passive frequency mixer and an existing (non-MIMO) radar structure. In this study, the concept of double-sideband orthogonal MIMO slow time radar and the experimental results of DUKE S-band radar test stand are introduced. In 2011, Rossum et al. [11] introduced article a novel waveform for MIMO radar, named Random Slow-Time Code Division Multiple Access (ST-CDMA). Compared with the conventional CDMA, the feature of ST-CDMA is that the waveforms of the different transmitters are orthogonal per burst. In fact, the typical MIMO-OTHR waveforms with existing coded modulation are not strictly orthogonal. Zhang et al. [12] presented slow time random phase coding waveform design based on Walsh matrix, which can improve the orthogonal performance of the coded waveform and the target detection capability of the radar system. In the meanwhile, in order to solve the problem that the autocorrelation performance of STRPC waveform encoded by Walsh matrix is unsatisfying, the MIMO-OTHR mismatch filtering can further improve the principal and sidelobe ratio of pulse pressure with a certain loss of mismatch filtering. Recently, the slow-time MIMO concept is employed into automotive radars, In the framework of Generalized Likelihood Ration Test (GLRT), Wang et al. [13] proposed an explicit signal model considering waveform separation residuals and presented a target detector based on Kronecker subspace. The precise theoretical analysis has verified the proposed target detection scheme.

Slow-time MIMO can operate at same time and frequency, which can save spectrum resources and do not have many extra hardware requirements. Due to the above advantages of Slow-time MIMO, it is suitable for HFSWR. In order to apply Slow-time MIMO to HFSWR, we have designed an experimental system, and conducted related experiment. This paper will introduce the experiment and results of slow-time MIMO in high frequency surface wave radar system in recent days. The rest of the paper is structured as follows. Section 2 introduces the signal model of slow-time MIMIO. Section 3 shows the experimental system and its configuration. Section 4 analyzed the results of the experiment, and a simple summary and outlook are given at the end.

2 Slow-Time MIMO Signal Model

Consider a MIMO radar system with M transmitters and N receivers. The transmitting signals are modulated by additional Doppler frequency in each pulse based on conventional pulse compression waveform, such as Linear Frequency Modulation (LFM). The q-th transmitting pulse of the m-th transmitter is given by

$$s_{mq}(t) = u(t)e^{j2\pi w_m q T_{\mathrm{pp}}} \tag{1}$$

where $u(t)$ is a conventional pulse compression waveform, $w_m, m = 1, 2, \ldots, M$ is the additional Doppler frequency of m-th transmitting signal, T_{pp} is the pulse repetition period.

Without loss of generality, LFM signal is taken as an example of $u(t)$ in this paper,

$$u(t) = \begin{cases} e^{j\pi K t^2} & 0 \le t < T_{\mathrm{pw}} \\ 0 & t \ge T_{\mathrm{pw}} \end{cases} \tag{2}$$

where $K = B/T_{\mathrm{pw}}$ is the modulation slope, B is the signal bandwidth, and T_{pw} is the pulse width. To divide the whole Doppler bandwidth into M orthogonal sub-channels whose bandwidth is f_{a}/M, w_m is defined as

$$w_m = \frac{f_{\mathrm{a}}}{2}\left(\frac{2m-1}{M} - 1\right) \tag{3}$$

where $f_{\mathrm{a}} = 1/T_{\mathrm{pp}}$ is the Pulse Repetition Frequency (PRF).

Consider a M elements uniform linear transmitting antenna array and a N elements uniform linear receiving antenna array. The transmitting steering vector and the receiving steering vector can be written as

$$\begin{aligned} \mathbf{a}(\theta) &= \begin{bmatrix} 1 & e^{-j2\pi d\sin(\theta)/\lambda} & \cdots & e^{-j2\pi(M-1)d\sin(\theta)/\lambda} \end{bmatrix} \\ \mathbf{b}(\varphi) &= \begin{bmatrix} 1 & e^{-j2\pi d\sin(\varphi)/\lambda} & \cdots & e^{-j2\pi(N-1)d\sin(\varphi)/\lambda} \end{bmatrix} \end{aligned} \tag{4}$$

where θ is the Direction Of Departure (DOD), φ is the Direction Of Arrival (DOA), d is the spacing between array elements, λ is the wave length of the operating frequency. Assume a far field target with a Doppler frequency f_{d}, and the DOD and DOA of the target is θ_{t} and φ_{t}. The echo of the target from n-th receiving antenna element in q-th pulse is

$$r_{nq}(t) = \sum_{m=1}^{M} s_{mq}(t) a_m(\theta_{\mathrm{t}}) b_n(\varphi_{\mathrm{t}}) e^{j2\pi f_{\mathrm{d}} q T_{\mathrm{pp}}} \tag{5}$$

where $a_m(\theta) = e^{-j2\pi(m-1)d\sin(\theta)/\lambda}$ is the phase shift of the m-th element in transmitting antenna array, and $b_n(\varphi) = e^{-j2\pi(n-1)d\sin(\varphi)/\lambda}$ is the phase shift of the n-th element in receiving antenna array. After pulse compression, we get

$$x_n(q) = \sum_{m=1}^{M} a_m(\theta_{\mathrm{t}}) b_n(\varphi_{\mathrm{t}}) e^{j2\pi w_m q T_{\mathrm{pp}}} e^{j2\pi f_{\mathrm{d}} q T_{\mathrm{pp}}} \tag{6}$$

When the frequency of targets is less than the frequency interval between w_m, we can separate echoes from different transmitters in Doppler domain.

3 Radar System Configuration

The MIMO radar experimental system used in this paper is site in Weihai, China. The system has a uniform linear array consisting of 8 transmitting-receiving antennas with 11.5 m spacing. Because our experimental MIMO System has 8 transmitters and 8 receivers, we can obtain 64 virtual channels and this design is shown in Fig. 1.

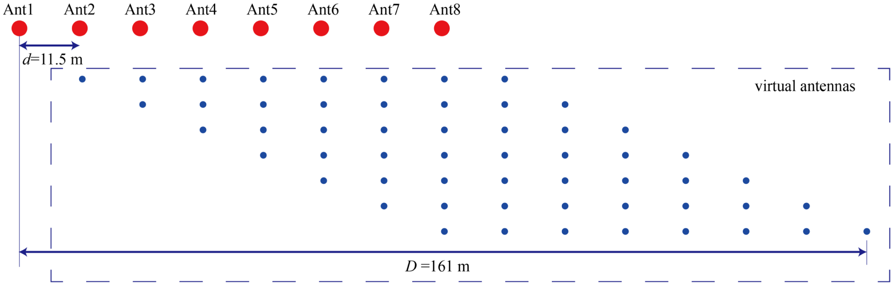

Fig. 1. The position of real antennas and virtual antennas

However, many virtual channels have the same phase shift, because the spacing between transmitting antenna elements is equal to the spacing of receiving antenna elements. So, the virtual array aperture is 161 m, which equivalents to a 15 elements linear antenna array.

The system can generate independent transmitting signals for 8 transmitters relying on a high-speed DAC module, so it can conveniently switch the working mode to single transmitter mode, phased array mode and MIMO mode. We obtained the transmit signals for slow-time mode whose parameters is shown in Table 1. The other working modes use similar parameters in this experiment.

Table 1. Transmitting signals parameters

Parameters	Value
Number of transmitters	8
Carrier frequency	4.7 MHz
Bandwidth	30 kHz
Transmit power	100 W
Pulse repetition period	55 ms
Doppler interval	2.27 Hz

4 Results and Analysis

4.1 Working in MIMO Mode

For further processing, the detection data is recorded after pulse compression. RD spectrum is obtained by Fourier transform in the slow-time dimension, as shown in Fig. 2. The 8 transmit signals are completely separated.

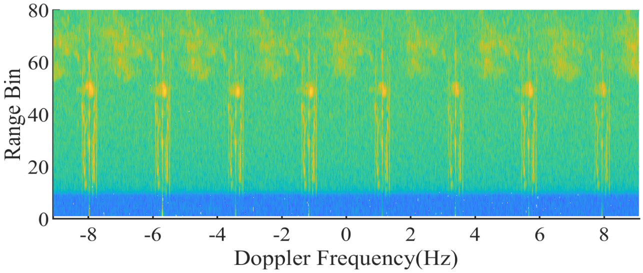

Fig. 2. RD spectrum with 8 transmitters in slow-time MIMO radar

Dividing the RD spectrum from each receiver into 8 equal parts, we can obtain the whole 64 virtual channels' data. Figure 3 shows the RD spectrum from one of the virtual channels.

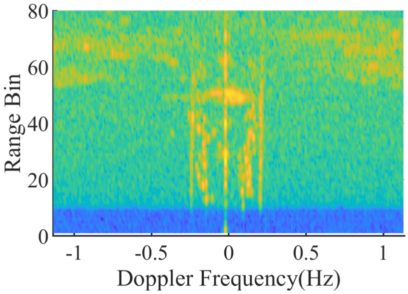

Fig. 3. RD spectrum in one of the virtual channels

In the experiment, we set the working mode of radar system as slow-time MIMO mode, phased array mode and single transmitter mode in turn. The time interval for switching the working mode is about 10 min, and the output powers of the transmitters remain unchanged during this process. Figure 4 shows the amplitudes of slow-time MIMO, single transmitter and phased array at a same range bin. The amplitude of Phased array mode is about 10 dB higher than that of slow-time MIMO and single transmitter. Meanwhile, slow-time MIMO and single transmitter have similar echo amplitudes.

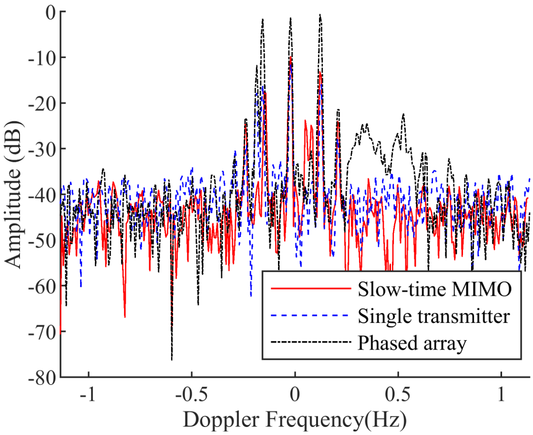

Fig. 4. Comparison of echo amplitudes of different radar working modes

4.2 Angle Estimation Performance

MIMO technology can improve the accuracy of angle measurement and the ability of angle resolution by expanding the aperture of the array. Figure 5 shows the beamforming results of a target echo when the radar system is working in slow-time MIMO mode. The blue line is the result of the scene that Ant1 transmits signal. The red line is the result of the scene that Ant1 and Ant8 transmit signals. The black line is the result of the scene that all antennas transmit signals. The main lobe width of the scene with 2 transmitting antenna elements and 8 transmitting antenna elements are almost the same, which is about half of the scene with one transmitting antenna element. Besides, the side lobe in scene with 8 transmitting antenna elements is lower.

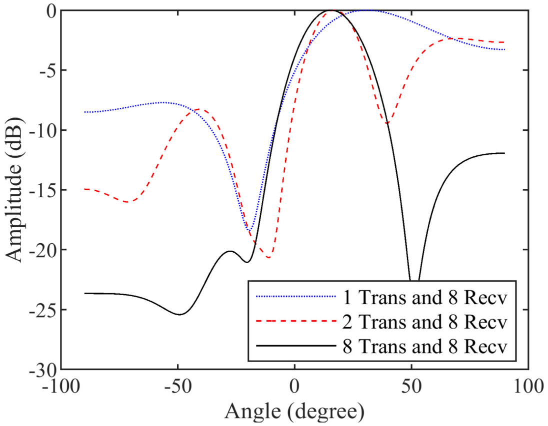

Fig. 5. Beamforming results of a target (Color figure online)

The range resolution capability of HFSWR is weak, and there may be multiple targets within the same range cell. When the speeds of the targets are similar, it is difficult to separate the targets with the small-aperture antenna array. Benefit from the aperture expanding by the MIMO technology, the ability to distinguish targets from different angles is enhanced. Figure 6 shows the results of two targets in a same range cell and Doppler cell, which can be separated in MIMO mode, but can’t be separated with single transmitter.

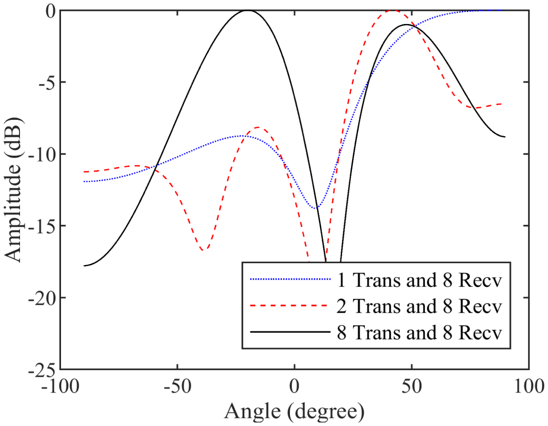

Fig. 6. Beamforming results of two targets with the same range and Doppler

4.3 Clutter and Interference

HFSWR has many clutters an interference such as sea clutter, ionospheric clutter, radio interference, etc. The sea clutter, mainly the first-order spectrum, has a low Doppler shift, located near the ship target echoes. So, the structure and characteristics of sea clutter in slow-time MIMO mode is similar to that in single transmitter mode. However, because of the slow-time MIMO mode has 64 independent virtual channels, the freedom degree and the amount of information that the slow-time MIMO mode can provide are square times that of the single transmitter mode, which has great significance for sea clutter detection and suppression.

Unlike sea clutter, ionospheric clutter may have a higher Doppler shift. Large-scale ionospheric clutter will repeat and overlap between Doppler sub-channels, shown in Fig. 7. The ionospheric clutter overlap will causes more severely affect in slow-time MIMO mode than in others, so the suppression of ionospheric is important in slow-time MIMO.

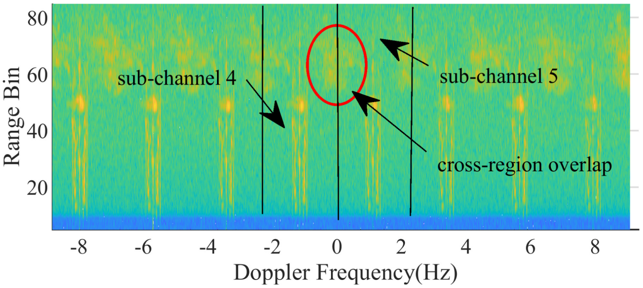

Fig. 7. Ionospheric clutter in cross-region

Contrary to ionospheric clutter, radio interference usually affects only a narrow bandwidth in Doppler domain. Figure 8 shows the RD spectrum with a simulated radio signal adding in. The radio interference affects only one transmit channel, rather than all channels.

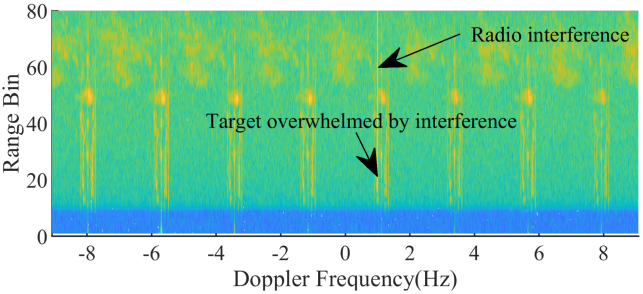

Fig. 8. Simulation radio interference add-in RD spectrum

Many virtual channels of slow-time MIMO are redundant, so deleting a part of them will not affect the detection performance seriously. Supposing a radio signal indenting from −10°, the beamforming result is affected by the interference, and the main lobe direction is shifted from 13.2° to −5.3°. After data deletion, the angle is restored to 13.2° with some side lobe elevation (Fig. 9).

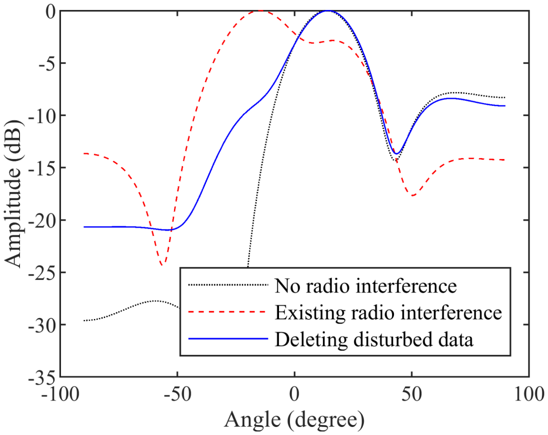

Fig. 9. Result of radio interference suppression by deleting disturbed data

5 Conclusion

This paper introduces the experiment of HFSWR based on slow-time MIMO. The experimental results have proved the practicability of slow-time MIMO in HFSWR. The MIMO technology can improve the performance of angle estimating, and the MIMO system (consists of 8 transmitting-receiving antennas) has more desired detection accuracy compared with the conventional system (consists of 1 transmitting antenna and 8 receiving antennas). In addition, the influence of interference and clutter on slow-time MIMO HFSWR is analyzed in this paper. And how to effectively suppress the clutter in MIMO HFSWR system is the following study in the future.

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