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Using alpha-phase modulation method to solve range ambiguity for high frequency surface wave radar

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ABSTRACT

A new type of high frequency surface wave radar (HFSWR) system consisting of a close-range detection using surface wave path and a long-range detection using skywave path are proposed in this paper. An important portion of this system is to design a signal that can detect longer distance targets, which is the main content of this paper. To minimize the changes to the existing radar system, this paper phase-modulates the original transmitted signal to mitigate range ambiguity. This method is applicable to all kind of single pulse repetition frequency (PRF) original transmitted signal and can manage the received signal in the region of eclipse (where the received signal is incomplete). The simulation results of different original transmitted signals (constant-frequency pulse and P4 phase-coded signals) verify that the long-range target can be correctly detected through this method. Finally, the real data collected at Weihai, China is processed. Comparing the flight information of Automatic dependent surveillance-broadcast (ADS-B) at the time when the data was recorded, two tracks that match the actual flight information in course and positions were found near 900 km (Shuozhou), flying to Hohhot.

1. Introduction

The application of hybrid sky–surface propagation mode is a popular research trend for expanding the surveillance coverage of high frequency radar. The most studied is a kind of high frequency radar configuration consisting of a skywave transmission path and a surface wave reception path [1]. This type of radar system places a transmitter inland and places several (or one) receivers on shore or on board, with some flexibility but still limited by the transmitter's coverage region. Actually, High Frequency Surface Wave Radar (HFSWR) also contains skywave and surface wave propagation paths simultaneously, so we propose a new HFSWR system that uses surface wave path to detect close-range targets and uses skywave path to detect long-range targets. Of course, this does not mean that there are only two propagation modes. In fact, there should be four propagation modes irrespective of ionospheric stratification as shown in Fig. 1. However, this article only discusses whether it is possible to detect the long-range targets and how to detect them, so the propagation mode of the target echo is not being studied.

Obviously, the long-range targets' echo will exceed the pulse repetition period, causing range ambiguity if the radar's original transmitted signal remains unchanged. Therefore, changing the parameters of the transmitted signal or solving range ambiguity is necessary for the detection of long-range targets. This article tends to solve range ambiguity which can be easily applied to the existing radar system. Moreover, the HFSWR is usually a monostatic radar, where the receiver and transmitter operations are interleaved, which will result in incomplete reception of the target echo, i.e. range eclipse. In traditional HFSWR, range eclipse only affects the detection of targets near the radar that is not the interested detection area. However, using range ambiguity resolution method to detect long-range targets will produce range eclipse problems in the interested area, so the range eclipse problems also need to be considered for long-range targets detection.

There have been many studies on the range ambiguity resolution for various radar, mainly from two main directions. The first is to transmit multiple PRF signal and then use solution algorithms to calculate the unambiguous range, which is typically used for High Pulse Repetition Frequency (HPRF) Radar. The main solution algorithms include Chinese remainder theorem [2], remainder table method [3] and one-dimensional method [4], etc. The method using multiple PRF signal also suitable for medium-PRF radar where we use the clustering algorithm as the solution algorithms [5]. However, this method is computationally intensive. To improve the

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calculating speed, reference [6] proposes a new solution algorithm that first estimates a set of fuzzy distance number of wavelengths through the lattice theory, and then implements the estimation of the true distance in the framework of maximum likelihood estimation. In addition, the method using multiple PRF signal will be affected by the range eclipse problems due to the relatively high duty cycle [7]. To reduce the loss caused by range eclipse, references [8] and [9] have proposed some effective solutions.

The second one is to use diverse pulse signals, including inter-pulse amplitude weighting signals, phase-coded signals and frequency-coded signals etc. [10]. One of the most widely applied is the phase-coded signals. References [11] and [12] use a set of M unique pulses to solve range ambiguity. In paper [13], random phase and systematic phase-coded waveforms are employed to solve range ambiguity. Ultra Wide Bandwidth (UWB) Radar [14] and weather radar [15] usually use inter-pulse cyclic phase coding to solve range ambiguity. For synthetic aperture radar (SAR), paper [16] uses two-dimensional phase-coding, and paper [17] uses pulse phase coding and two-pulse cancellation to solve range ambiguity. The phase-coded signals are also affected by range eclipse, which can result in incomplete received signal and then destroy the correlation characteristics of the signal. To solve this problem, reference [18] proposes a kind of code set that can maintain a higher peak-to-sidelobe ratio when receiving incomplete codes within the region of eclipse, and reference [19] uses inter-pulse phase coded high PRF spike pulse signal, which can avoid large range eclipse coverage. Recently, frequency-coded signal is widely applied to solve the range ambiguity problems for imaging radar, for example, SAR [16,17,20,21]. Reference [22] applies random stepped frequency (RSF) signal, and then searches the unambiguous range by imaging using the reference signal with different time-delay. Reference [23] establishes the match filter, and obtains the unambiguous range by match filtering. In recent years, there have been some other kinds of new methods to solve range ambiguity in SAR, such as the methods based on Chinese remainder theorem (CRT) [24], robust CRT [25] and compressed sensing (CS) theory [26].

The first method using multiple PRF signal is suitable for narrow pulses generally. However, HFSWR signal needs wide pulses and higher duty cycle signals to ensure high transmission power and detection range beyond the horizon. In addition, this method needs a large amount of calculations and its extended unambiguity range is determined by the multiple pulse repetition frequency. The second method using diverse pulse signals is generally difficult to solve range ambiguity when the received signals are incomplete because the correlation of code is broken. Its extended unambiguity range usually is determined by the code's length.

The Alpha-phase modulation method proposed in this paper can use wide pulses and higher duty cycle signals and can also solve range ambiguity in the region of eclipse. Moreover, the method can be easily applied to the existing radar system and maintain the same detection performance as the original transmitted signal processing within close range. In addition, the original transmitted signal could be any single PRF signal, and we can choose signals that still maintain good performance in incomplete situations as the original transmitted signal. The unambiguity detection range of this method can be arbitrarily extended according to the limitation provided in section 3.3. The computational complexity of this method is small. Compared to the original signal processing flow of HFSWR, only a series of multiplications and a series of filters are needed.

First, we define a modulation factor α and construct an additional phase modulation item $\psi(\alpha)$ to modulate the original signal to form a new transmitted signal. Then, the received signal is pre-demodulated by the demodulation item ϑ before the range and Doppler processing. Thus, the target echo of different transmitted pulse will be shift to different frequency bands after Doppler processing, and then after a series of filter, the target's real distance could be calculated correctly. However, this method will occupy the effective Doppler range of the original signal, which is related to the modulation factor α and the multiple N of the detection range that you want to expand, so we give the selection criteria of the modulation factor Alpha in Section 3.3.

This article first introduces the new HFSWR system and analyzes its feasibility in Section 2. Then the theory and processing flow of the range ambiguity resolution method, and the selection criteria of the value of modulation factor α are demonstrated in Section 3. Finally, in Section 4, the simulation results of the constant-frequency pulse signals and P4 phase coded signals verify that this method can correctly detect the target within the area of range ambiguity and eclipse. Moreover, through processing the actual data collected in Weihai, China, we find two suspected aircraft tracks of flying to Hohhot near 900 km (Shuozhou), China compared to the flight information of Automatic dependent surveillance-broadcast (ADS-B).

Notation:

L_0	the length of ground wave path;
R	the Earth radius;
θ	the radiation elevation angle
α	the modulation factor
ϑ	the demodulation item
ψ	the additional phase modulation item
$R_{\max}$	the maximum unambiguity range of the existing HFSWR
L	the target's real distance
L_m	the target's measurement distance
T_r	the pulse width
T_p	the pulse repetition period
T	the pulse accumulation period
$s(t)$	the original transmitted signal

2. Introduction of the new HFSWR system

In this paper, we propose a new type of high frequency surface wave radar (HFSWR) system consisting of a close-range detection using surface wave path and a long-range detection using skywave path. The antenna pattern of HFSWR is not completely along the sea surface, so that the skywave path also exists in HFSWR, which is the theoretical basis of the new HFSWR system. As shown in Fig. 1, there are four propagation modes in the new HFSWR system without considering ionospheric stratification, and mode 4-SS propagate the farthest. This paper only studies how to detect long-range targets, so the propagation mode of target echo is not considered. Next, we analyze the propagation characteristics of mode 1-GG with the lowest propagation distance and mode 4-SS with the longest propagation distance (Mode 2 and 3 can also detect farther distances than the existing HFSWR, which is not described in detail in this article).

2.1. Analysis of the radiation elevation angle

The main differences between the two propagation modes are the radiation elevation angle (the angle between the radiation direction and the zenith direction) and the propagation attenuation. Mode 1-GG consist of a surface wave transmission path and a surface wave reception path, so its radiation elevation angle is 90 degrees. While mode 4-SS includes a skywave transmission path and a skywave reception path whose radiation elevation angle changes with the ground distance. The elevation angle of mode 4-SS θ is calculated based on the geometric relationship between the ground wave path and the skywave path: