ICIC Express Letters
Part B: Applications
Volume **9**, Number **11**, November **2018**

ICIC International ©2018 ISSN 2185-2766
pp. 1109–1115

RESEARCH ON IONOSPHERIC CLUTTER EVALUATION MODEL OF HIGH-FREQUENCY SURFACE WAVE RADAR

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Received May 2018; accepted August 2018

Abstract. *High-frequency surface wave radar (HFSWR) played an important role in the coast defense. According to the problem that ionospheric clutter seriously affects the detection performance of the target, multi-parameters of ionospheric clutter in echo on the different frequencies are analyzed. Ionospheric clutter evaluation model based on multiple attribute decision making is put forward, and the optimum frequency is provided by the model solution to avoid ionospheric clutter. The method proposes a new solution to process the ionospheric clutter in HF surface wave radar.*
Keywords: HFSWR, Ionospheric clutter, Frequency selection, Multiple attribute decision making

1. **Introduction.** HFSWR has lots of advantages, such as anti-stealth, anti-ARM, and anti-interference. It can provide all-weather detecting and tracking of targets in exclusive economic zone all-weather [1]. So HFSWR is an ideal early warning radar. Moreover, HFSWR is widely used in sea-state remote sensing [2,3], sea surface pollution monitoring [4], ocean environment monitoring [5], resource development, typhoon monitoring [6], etc.

While HFSWR is detecting targets, it will be affected by ionospheric clutter, see clutter, ground clutter, radio frequency interference, meteor trails. Ionospheric clutter is caused by the reflection of ionosphere to electromagnetic wave, and it does not have specular reflection characteristics because of multi-layer and instability features of ionosphere. Because ionospheric clutter spreads in both range and Doppler domain, and it is non-stationary, the targets beyond 100 to 200 kilometers cannot be detected. Ionospheric clutter has become the domain bottleneck problem of HFSWR [1].

It is difficult to restrain the ionospheric clutter, because it is non-stationary, widely distributing, time-varying. Most existing algorithms did not fully consider the characteristics in time, frequency and spatial domain. There is not a method that can suppress the ionospheric clutter full considering various characteristics. On account of the close relationship between ionospheric clutter and radar frequency, optimum frequency is selected to avoid ionospheric clutter by ionospheric clutter evaluation model building and solving.

It is an important basis for frequency selection to monitor the multi frequency point of the ionospheric clutter, and evaluate the influence of the ionospheric clutter on the radar detection performance of each frequency point in various aspects, such as the intensity and the influence range. In this paper, an evaluation model of ionospheric clutter is established by using multiple attribute decision making method.

2. **Analysis of Measured Data of Ionospheric Clutter in HFSWR Echo.** Radar echo contains ship and aircraft target, see clutter, ground clutter, and background noise. In this paper, ionospheric clutter is regarded as the target to detect and identify from the echo [7]. Figure 1 shows the results of detection and recognition of ionospheric clutter

DOI: 10.24507/icicelb.09.11.1109

on four different frequencies (on the first row $f_1 = 3.776$MHz, on the second row $f_2 = 4.92$MHz, on the third row $f_3 = 5.14$MHz, on the fourth row $f_4 = 8.8$MHz). The clutter data on the same row are on different DOA (direction of arrival), which are $-30°$, $0°$, $30°$. According to Figure 1, ionospheric clutters on different DOA, on the same frequency, are different. Moreover, the clutters in echoes on different frequencies, which are from the

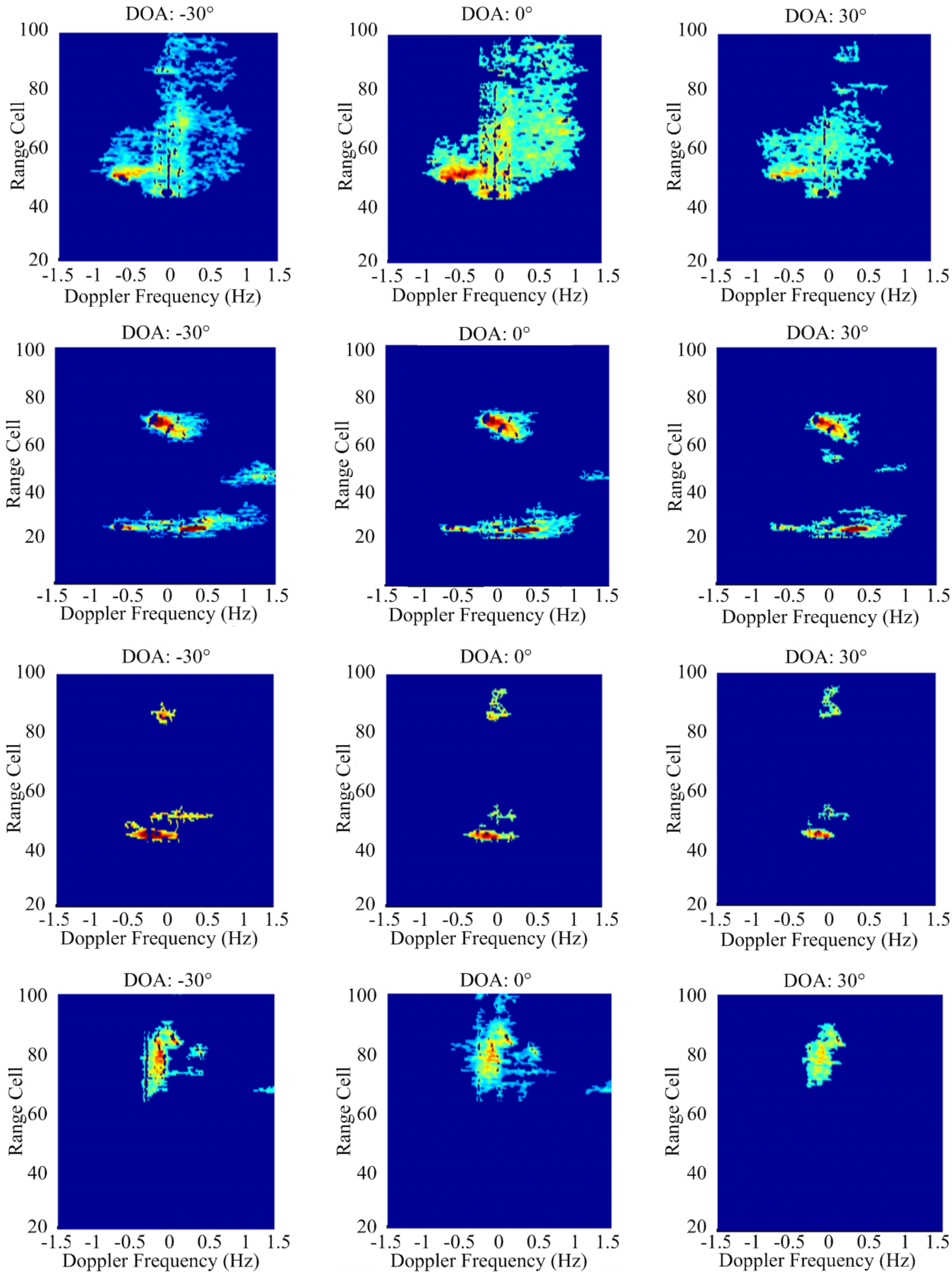

FIGURE 1. Detected ionospheric clutter of different directions and frequencies

same DOA, have different morphology, influence scope and strength. So, the optimum frequency cannot be selected according to only one DOA echo from different frequencies. It needs comprehensive consideration of various physical quantities of ionospheric clutter.

Define the physical quantities of ionospheric clutter. $\sigma_{\mathrm{RD\,max}}$ is the number of cells contaminated by ionospheric clutter in RD spectrum. $\sigma_{\mathrm{AD\,max}}$ is the number of cells contaminated by ionospheric clutter in AD spectrum. $\sigma_{\mathrm{AR\,max}}$ is the number of cells contaminated by ionospheric clutter in AR spectrum. V_{IC} is the number of cells contaminated by ionospheric clutter in ARD spectrum. $\overline{P}_{\mathrm{IC}}$ is average power of ionospheric clutter. $P_{\max}$ is the peak power of ionospheric clutter. $\overline{\mathrm{SCR}}$ is the average signal-to-clutter ratio. The quantities of the ionospheric clutter in Figure 1 is shown in Table 1.

Table 1. Calculation results of the ionospheric clutter petameters

f (MHz)	$\sigma_{\mathrm{RD\,max}}$	$\sigma_{\mathrm{AD\,max}}$	$\sigma_{\mathrm{AR\,max}}$	V_{IC}	$\overline{P}_{\mathrm{IC}}$ (dB)	$P_{\max}$ (dB)	$\overline{\mathrm{SCR}}$ (dB)
3.776	46543	446	3151	159279	−206.84	−148.76	18.64
4.92	11416	118	1470	34733	−178.90	−123.18	4.11
5.14	25705	273	1236	59655	−195.02	−145.14	6.03
8.8	14130	359	3152	45895	−182.44	−136.85	4.06

From Table 1, on the ARD spectrum, the ionospheric clutter in 3.776MHz echo pollutes the most cells, and the average power is the lowest. Meanwhile, the ionospheric clutter in 3.776MHz echo pollutes the least cells, and the power is the highest. To select the optimal frequency, the quantities above should be evaluated comprehensively. Multiple attribute decision making method is adopted to solve the problem.

3. **Establishment of the Ionospheric Clutter Evaluation Model.** The objective of ionospheric clutter comprehensive evaluation is to make accurate and scientific decision for radar operating frequency scheme. Scientific decision is based on the result of comprehensive analysis. The indexes include the influence scope, strength, frequency, etc. However, the optimal frequencies according to the influencing factors are not consistent. So, it is necessary to establish an ionospheric clutter evaluation model and comprehensively considerate the affecters above. Meanwhile, the optimum frequency is selected by quantization and evaluation of ionospheric clutter. Figure 2 shows the flow chart to select operating frequency by the ionospheric clutter evaluation model.

Firstly, according to the available frequency provided by the spectrum monitoring subsystem, a specific frequency plan is established. Secondly, the ARD 3D detection platform is established. The ionospheric clutter in the ARD spectrum at different frequencies is detected. The characteristics of the ionospheric clutter at different frequencies are evaluated synthetically, including the properties of the pollution range, the intensity and the ratio of the clutter to the clutter. Thirdly, the evaluation model of the ionosphere clutter is constructed. An evaluation model is built by associating different attributes with different frequency schemes. Finally, the optimal solution of ionospheric clutter estimation model is calculated by specific mathematical methods for a frequency scheme for radar operation.

Ionospheric clutter evaluation model based on multiple attribute decision making includes scheme set, attribute set and the determination of evaluation rule system of ionospheric clutter.

3.1. **Scheme set.** The scheme set of ionospheric clutter evaluation model is various alternative frequency schemes $F = \{f_1, f_2, \ldots, f_n\}$, where f_i is provided by the spectrum monitoring system of HFSWR. In the way, cochannel interference is avoided and the efficiency of clutter monitoring is improved.

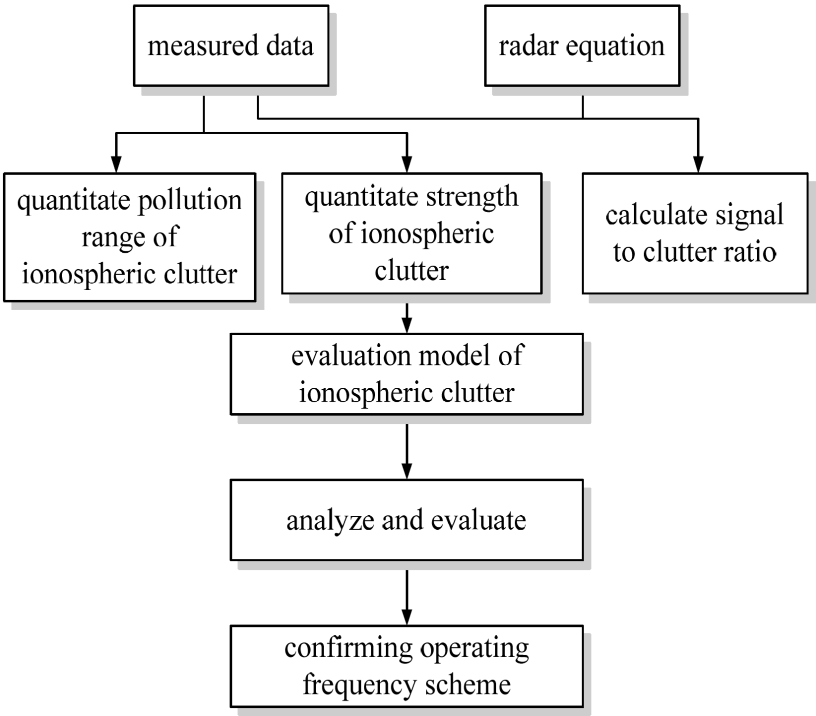

Figure 2. Flow of determination of radar work frequency

Table 2. Ionospheric clutter evaluating indicator result

Attribute value	Unit	Evaluation criteria
$\sigma_{\mathrm{RD\,max}}$	1	the smaller the better (cost type)
$\sigma_{\mathrm{AD\,max}}$	1	the smaller the better (cost type)
$\sigma_{\mathrm{AR\,max}}$	1	the smaller the better (cost type)
V_{IC}	1	the smaller the better (cost type)
$\overline{P}_{\mathrm{IC}}$	dB	the smaller the better (cost type)
$P_{\max}$	dB	the smaller the better (cost type)
$\overline{\mathrm{SCR}}$	dB	the larger the better (benefit type)

3.2. **Attribute set.** The attribute set of ionospheric clutter evaluation model is basis for ionospheric clutter. At different frequencies, it is considered about for the attribute set that the attribute set should evaluate all the important factors of ionospheric clutter and be computable for quantitative evaluation.

$$P = \left\{\sigma_{\mathrm{RD\,max}}, \sigma_{\mathrm{AD\,max}}, \sigma_{\mathrm{AR\,max}}, V_{\mathrm{IC}}, \overline{P}_{\mathrm{IC}}, P_{\max}, \overline{\mathrm{SCR}}\right\} \tag{1}$$

3.3. **Evaluation rule system.** Ionospheric clutters at different frequencies are different. Radar equation shows that echo power is diminished with the frequency increasing. However, the signal to clutter ratio is in connection with the intensity and polluted area of ionospheric clutter. The attribute cannot satisfy the unified frequency relation. Figure 3 shows the evaluation rule system of ionospheric clutter evaluation model based on multiple attribute decision making method.

It can be seen from the rule system shown in Figure 3 that the first layer is frequency scheme, and the characteristics of ionospheric clutter at different frequencies are different. The second layer helps to select the optimum frequency by the analysis of the characteristics including pollution range, clutter intensity, and radar power. The last layer is the attribute set, and the evaluation index of attribute set is shown in Table 2.

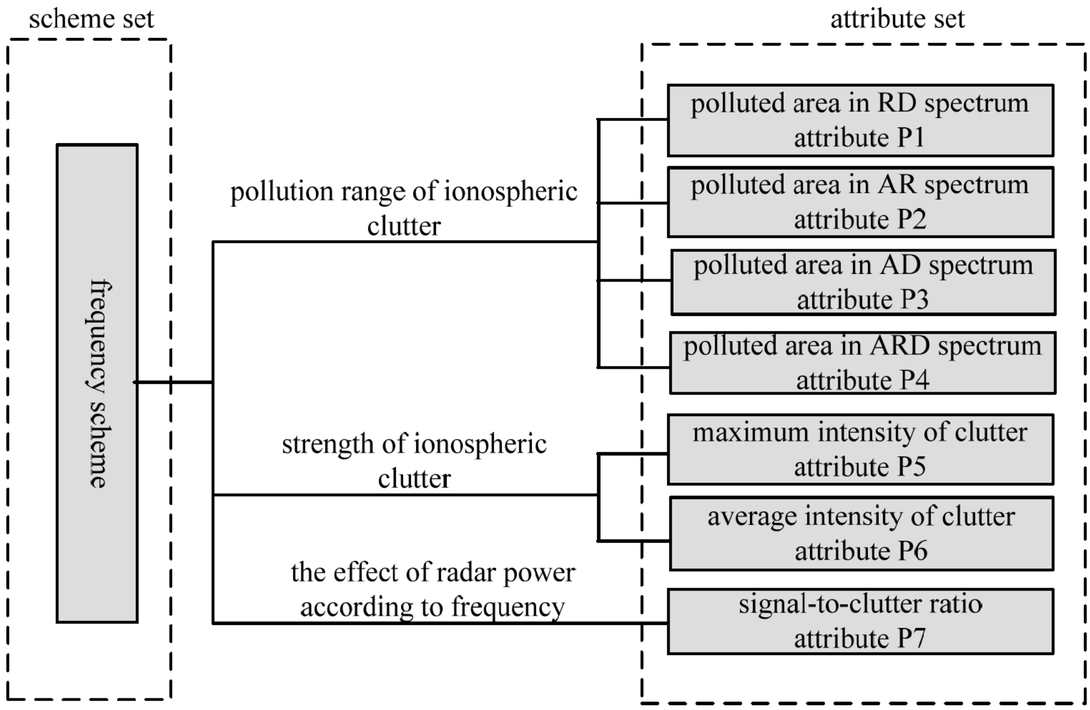

FIGURE 3. Graph of ionospheric clutter evaluation criteria system

The model solving method will be shown in Section 4.

4. **Model Solving Method Based on Weighted Sums.** Weighted sums algorithm is simple with clear principle. The basic steps of model solution by weighted sums are as follows.

Step 1 is to establish decision matrix. Decision matrix is the foundation of multiple attribute decision making. $\boldsymbol{F} = \{f_1, f_2, \dots, f_n\}$ is set as the scheme set, and attribute set is $\boldsymbol{P}_i = \{p_1(f_i), p_2(f_i), \dots, p_m(f_i)\}$. $p_j(f_i)$ is the attribute value of the ith scheme f_i acted by the jth attribute function. Then the decision matrix $\boldsymbol{D}$ is

$$\boldsymbol{D} = \begin{array}{c} \\ f_1 \\ f_2 \\ \vdots \\ f_n \end{array} \begin{array}{c} \begin{array}{cccc} \boldsymbol{P}_1 & \boldsymbol{P}_2 & \cdots & \boldsymbol{P}_m \end{array} \\ \begin{bmatrix} p_1(l_1) & p_2(l_1) & \cdots & p_m(l_1) \\ p_1(l_2) & p_2(l_2) & \cdots & p_m(l_2) \\ \vdots & \vdots & \cdots & \vdots \\ p_1(l_n) & p_2(l_n) & \cdots & p_m(l_n) \end{bmatrix} \end{array} \tag{2}$$

Step 2 is standardization of decision matrix. The attribute types in decision matrix are various and have different dimensions. It makes that the various attributes cannot be measured together, so it is necessary to normalize the attribute values. Linear transformation algorithm is adopted to realize the normalization of decision matrix. If the element d_{ij} in decision matrix belongs to the benefit type, the larger value $d_{ij} = p_j(f_i)$ is better. Meanwhile, if the element d_{ij} in decision matrix belongs to the cost type, the smaller value $d_{ij} = p_j(f_i)$ is better. Then the elements in normalized matrix $\boldsymbol{Z}$ of $\boldsymbol{D}$ are

$$\begin{cases} z_{ij} = d_{ij}/d_j^{\max} & j \in M^+ \\ z_{ij} = 1 - d_{ij}/d_j^{\max} & j \in M^- \end{cases} \tag{3}$$

Then all the elements have the same trend (the larger value is better), and the absolute value is from 0 to 1.

Step 3 is to determinate the weight matrix by information entropy method. First, evaluating matrix Q is calculated, and the evaluation value q_{ij} of $p_j(f_i)$, which is the jth attribute of the ith scheme, is defined as follows

$$q_{ij} = \frac{d_{ij}}{\sum_{i=1}^{n} d_{ij}} \quad i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots m \tag{4}$$

where n is the number of schemes, and here it represents the frequency number, and m is the number of attributes.

The weight ω_j of the attributes is calculated by the information deviation de_j of the attribute. The entropy E_j, information deviation de_j, and weight ω_j of the jth attribute are defined as follows,

$$\begin{aligned} E_j &= -k \sum_{i=1}^{n} q_{ij} \ln q_{ij} \\ de_j &= 1 - E_j \qquad\qquad i = 1, 2, \ldots, n;\ j = 1, 2, \ldots m \\ \omega_j &= \frac{de_j}{\sum_{j=1}^{m} de_j} \end{aligned} \tag{5}$$

where $k = 1/\ln m$ is constant.

The ionospheric clutter attribute entropy vector, information deviation, and weight vector are calculated by evaluating matrix shown in (5). The results are shown in Table 3.

Table 3. Attribute entropy, information deviation and weight vector of ionospheric clutter

	$\sigma_{\text{RD max}}$	$\sigma_{\text{AD max}}$	$\sigma_{\text{AR max}}$	V_{IC}	$\overline{P}_{\text{IC}}$	$P_{\max}$	$\overline{\text{SCR}}$
E	0.8907	0.9340	0.9401	0.8616	0.9988	0.9982	0.8304
de	0.1093	0.0660	0.0599	0.1384	0.0012	0.0018	0.1696
ω	0.2000	0.1209	0.1097	0.2533	0.0022	0.0034	0.3105

Step 4 is calculation of taxis indexes. The taxis indexes C_i of multiple attribute decision making based on weighted sums are

$$C_i = \sum_{j=1}^{m} \omega_j z_{ij} \tag{6}$$

where ω_j is the weight value of the jth attribute, and z_{ij} is the jth attribute of the ith scheme.

The frequency schemes are sorted by the values of indicated values, and the scheme with the larger value is better.

According to calculation the sorting index vector C of the ionospheric clutter shown in Figure 1 is

$$C = \begin{array}{c} \begin{matrix} f_1 & f_2 & f_3 & f_4 \end{matrix} \\ [0.3105 \quad 0.0685 \quad 0.1004 \quad 0.0676] \end{array} \tag{7}$$

The sorting result of the alternative frequencies is

$$f_1 \succ f_3 \succ f_2 \succ f_4 \tag{8}$$

where $\succ$ means the left scheme is better than the right one. So f_1 is the optimal frequency by comprehensive consideration of the various attributes of ionospheric clutter.

5. **Conclusion.** The analysis of measured data of ionospheric clutter in radar echo shows that the parameters, such as the ionospheric clutter contaminating range cells, doppler cells, range, and strength, are different at different operating frequencies. The ionospheric clutter evaluation model is built, and the optimal operating frequency is selected by solution of the model. The method can not only quantitatively evaluate the ionospheric clutter but also recommend the optimum frequency to HFSWR to avoid ionospheric clutter to maximum extent.

Because ionospheric clutter is time varying, it is better to avoid ionospheric clutter by selecting frequency. For potential future research, we will explore the prediction algorithm of ionospheric clutter based on the established clutter estimation model.

Acknowledgment. The authors would like to express their great thanks to the support of the National Natural Science Foundation of China (61801196), the Natural Science Foundation of Higher Education Institutions of Jiangsu Province (17KJB510014), and China Postdoctoral Science Foundation (2015M571898). The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

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