Estimating of RCS of Ionosphere for High Frequency Surface Wave Radar

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Abstract. High Frequency Surface Wave Radar (HFSWR) has been shown to provide enhanced performance in over the horizon detection of targets and sea states remote sensing by the returns of targets and ocean surface. Meanwhile, HFSWR can also receive ionospheric echoes reflected by the ionosphere, which severely affect the radar detection performance. In this paper, the radar cross section (RCS) of ionosphere for HFSWR is estimated, which would help quantify the impact of the ionosphere to radar system and the performance of clutter mitigation techniques. Simulations are provided to illustrate the effect of parameters including radar operating frequency, scale size of irregularities, aspect angle and detection range on the RCS of ionosphere.

Keywords: High Frequency Surface Wave Radar · Ionosphere · RCS

1 Introduction

High Frequency Surface Wave Radar (HFSWR) uses the sea-surface diffraction character of vertically polarized wave which can achieve long ranges detection due to low attenuation over the highly conductive sea surface. Ideally, a perfect conductive plane consisting of sea surface is infinite in coverage area, thus making transmitted wave entirely travel along the sea. However, considering the actual antenna pattern characteristics, poor ground and array error, partial energy is radiated into sky and reflected by ionosphere. Finally the echoes arrived at radar receiver in various paths, interfering target detection severely as ionospheric clutter [1, 2]. The ionospheric clutter primarily restricted the detection performance of HFSWR. Therefore, in order to analyze and simulate the effect of ionosphere on radar system, it is necessary to establish the estimation of radar cross section (RCS) of ionosphere for HFSWR.

It is convinced that the ionospheric clutter of HFSWR mainly occur from coherent scattering between electromagnetic wave and irregularities caused by plasma instabilities. The theory of ionospheric coherent scattering was initially proposed by Booker [3], which demonstrates that the major contribution to the scattered field is given by a spatial spectrum component of electron density fluctuations whose period along the propagation direction, scale size satisfies the Bragg scatter conditions producing

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constructive interference at the refraction point. According to collective scatter theory [4], the backscattered ionospheric echoes come from a large number of ionosphere irregularities inside the Effective Scatter Volume (ESV), which is formed by the intersection of the antenna beam with the ionosphere. The coherent scattering theory has been used in HFSWR to obtained several ionosphere parameters [5]. In this study, we develop the RCS of ionosphere in detail and intensively analyze the effect of each variable on RCS for HFSWR, which would help quantify the impact of the ionosphere to radar system and the performance of clutter mitigation techniques.

In this paper, firstly the generalized radar range equation for distributed target as ionosphere is established. Then the RCS of ionosphere is obtained by coherent scattering theory. Simulations illustrate the effect of each parameter on RCS of ionosphere and indicate the key contributions to the RCS of ionosphere.

2 Modeling RCS of Ionosphere for HFSWR

The classical radar equation for a monostatic HFSWR is defined as

$$P_{\mathrm{r}} = \frac{P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}} \lambda^2}{(4\pi)^3 R^4 L_{\mathrm{s}}} \sigma \tag{1}$$

where P_{r} is the received power; P_{t} is the transmitted power; G_t is the transmitter antenna gain; G_{r} is the receiver antenna gain; σ is RCS; λ is the radar wavelength; R is the target range; L_s is the system loss.

2.1 Range Equation for Ionosphere

The ionospheric scatters should be modeled as distributed scattering from a three-dimensional volume rather than a single point scatter. Because of the distributed characteristics and the gain of the antenna varies with (θ, φ), G_t and G_{r} should be replaced by $G_t(\theta, \varphi)$ and $G_r(\theta, \varphi)$, respectively, that accounts for the effect of antenna power pattern on the power density radiated in a particular direction (θ, φ).

Considering the scattering from an incremental volume dV located at range and angle coordinates (R, θ, φ) (the incremental RCS of volume element is $d\sigma$ square meters), the incremental backscattered power from dV can be expressed as

$$dP_{\mathrm{r}} = \frac{P_{\mathrm{t}} G_{\mathrm{t}}(\theta, \phi) G_{\mathrm{r}}(\theta, \phi) \lambda^2}{(4\pi)^3 R^4 L_{\mathrm{s}}} d\sigma(R, \theta, \phi) \tag{2}$$

Then the total received power is obtained by integrating over all space

$$P_{\mathrm{r}} = \frac{P_{\mathrm{t}} \lambda^2}{(4\pi)^3 L_{\mathrm{s}}} \int_V \frac{G_{\mathrm{t}}(\theta, \phi) G_{\mathrm{r}}(\theta, \phi)}{R^4} d\sigma(R, \theta, \phi) \tag{3}$$

In Eq. (3), the volume of integration V is all of three-dimensional space. However, only scatters within a single resolution cell volume dV contribute significantly to the radar. Therefore, a more appropriate form of the generalized radar range equation can be given by

$$P_r = \frac{P_t \lambda^2}{(4\pi)^3 L_s} \int_{\Delta V(R,\theta,\phi)} \frac{G_t(\theta,\phi) G_r(\theta,\phi)}{R^4} d\sigma(R,\theta,\phi) \tag{4}$$

where $\Delta V(R,\theta,\phi)$ is the volume of the resolution cell at coordinates (R,θ,ϕ). Suppose the distribution of ionospheric irregularities evenly distributed throughout the volume. We defined η as RCS per cubic meter, or volume reflectivity, then

$$d\sigma = \eta dV \tag{5}$$

Here η is also the reflectivity of effective scatter volume (ESV) which is formed by the intersection of radar beam with ionosphere. For the antenna having an elliptical beam with azimuth and elevation beam widths θ_3, ϕ_3, the resolution cell volume $\Delta V(R,\theta,\phi)$ can be approximately expressed as

$$\Delta V(R,\theta,\phi) = \frac{\pi}{4} R^2 \Delta R \theta_3 \phi_3 \approx R^2 \Delta R \theta_3 \phi_3 \tag{6}$$

where ΔR is the range resolution, θ_3, ϕ_3 are the 3 dB beam widths in azimuth and elevation. Thus, the RCS of volume can be obtained:

$$\sigma = R^2 \Delta R \theta_3 \phi_3 \eta \tag{7}$$

Considering the attenuation of electromagnetic wave propagation in ionosphere and using approximation [6], we can reduce Eq. (3) to the range equation for ionosphere scatters:

$$P_r = \frac{P_t \lambda^2 G_t G_r \Delta R \theta_3 \phi_3 \eta}{(4\pi)^3 R^2 L_s L_p} \tag{8}$$

2.2 ESV Reflectivity

According the Bragg scatter conditions for monostatic backscatter:

$$\lambda_{irr} = \frac{\lambda_{radar}}{2} \tag{9}$$

where λ_{irr} is the scale size of ionosphere irregularities, which means the scale size of irregularities between 5–50 m can be observed by HFSWR. For the magnetic plasma in the ionosphere region, irregularities at these scale sizes are highly anisotropic and aligned with the geomagnetic field $\vec{\boldsymbol{B}}$. The reflectivity of ESV depends on the direction, electron density and scale size of the irregularities, etc. which can be expressed as [7]:

$$\eta = f(k, v_d, \phi, \alpha, l, f_{e,i}, \overline{\Delta N_e}, N_e) \tag{10}$$

where $\boldsymbol{k}$ is the radar wave-vector in the medium, v_d is the drift velocity of irregularities, ϕ is the flow angle, i.e. the angle between radar wave-vector and drift velocity, α is the aspect angle i.e. the complement of the angle between $\overrightarrow{k}$ and $\vec{\boldsymbol{B}}$, l is the scale length of irregularities, $f_{e,i}$ is the electron and neutral collision frequency, $\overline{\Delta N_e}$ is the average level of the electron density fluctuations, N_e is the electron density of irregularities. Assuming that the magnitude of electron density fluctuations has linearly relationship with the electron density, which also consistent with experimental results [8]. For convenience of discuss, Eq. (10) can be reduced to [9, 10]

$$\eta \propto N_e^2 \exp\{-2k^2(l_{\parallel}^2\alpha^2 + l_{\perp}^2)\} \tag{11}$$

where $l_{\parallel,\perp}$ is the scale size of irregularities along and across the external magnetic field $\overrightarrow{\boldsymbol{B}}$, respectively. Equation (10) is based on the assumption that $l_{\parallel} \gg l_{\perp}$ and $kl_{\parallel} \gg 1$ so that η appears peak when $\alpha = 0^{\circ}$, namely $\overrightarrow{k} \perp \overrightarrow{\boldsymbol{B}}$ which means the major contribution to the backscattered field is only a small region of ESV.

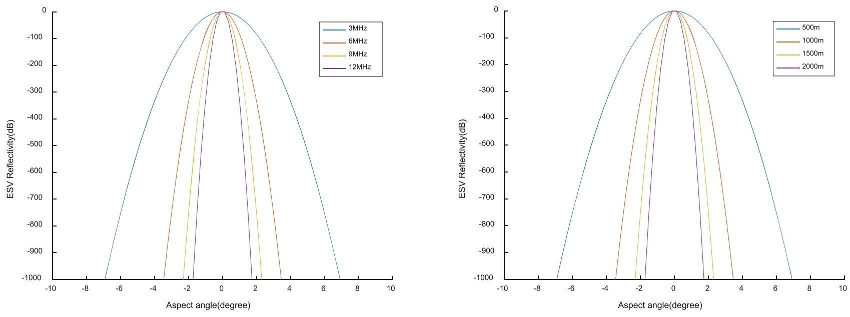
In summary, our analysis reveals that the backscatter ionospheric clutter of HFSWR should be dominated by the specific ionospheric region in which the wave vector is near perpendicular to the electromagnetic field in simplified situation.

3 Simulations and Analysis

This section presents the results of simulations testing the theory developed in the previous sections. Figure 1 shows the effect of each variable in Eq. (11) on ESV reflectivity. In Fig. 1(a), we choose parameter $l_{\parallel} = 1000$ m to simulate the ESV reflectivity vary with different frequencies limited to the radar resolution. Figure 1(b) shows the ESV reflectivity vary with different scale size of irregularities. Figure 2 shows ESV reflectivity in three-dimensional with four specific frequencies.

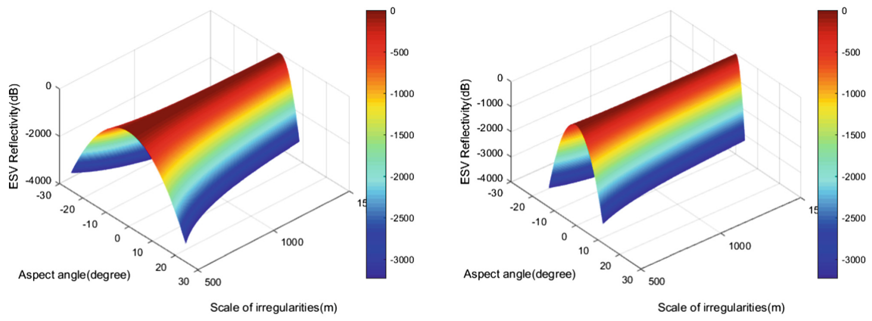
We can see that the ESV reflectivity appears a very strong peak near $\alpha = 0^{\circ}$ and rapid declines in other incident angles. The higher the frequency is, the more obvious this phenomenon is. Based on the above observation, we can draw a conclusion that the major contribution to the backscattered field is only the region of ionosphere where wave vector is perpendicular to the major axis of field-aligned, regardless of frequency and scale size of irregularities.

We choose different radar operating frequencies to simulate RCS of ionosphere, but they are almost the same. In Fig. 3, the radar frequency is 3 MHz. It is obvious that the RCS of ionosphere do not change with the detection range, only depended on aspect angle. Therefore, the RCS of ionosphere for HFSWR should be dominated by the specific ionospheric region in which the direction of wave vector approaches the normal to the external magnetic field.

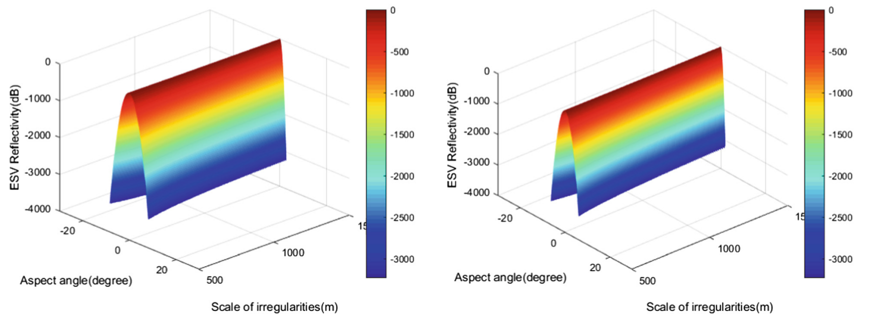


(a) $l_{\|} = 1000m$ (b) $f_0 = 6M$

Fig. 1. Effect of each variable in Eq. (11) on ESV reflectivity.



(a) $f_0 = 3M$ (b) $f_0 = 6M$



(c) $f_0 = 9M$ (d) $f_0 = 12M$

Fig. 2. 3D ESV reflectivity varies with different radar operating frequencies, aspect angle and scale size of irregularities along the external magnetic field.

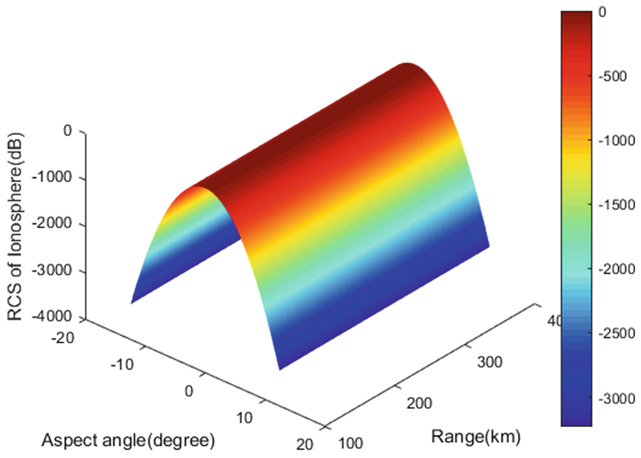


Fig. 3. RCS of ionosphere varies with radar range and aspect angle.

4 Conclusions

The main purpose of this paper is to reveal the physical mechanism of RCS of ionosphere for HFSWR. The purpose of this work arose from the need of quantify impact of the ionosphere to radar system. Firstly we obtained the generalized radar range equation for the ionosphere and the RCS of ionosphere. Then we used coherent scattering theory to analysis the major contribution to RCS of ionosphere, i.e. the reflectivity of effective scatter volume in the case of simplification. Simulations illustrate the effect of each parameter on the reflectivity of ESV and found out the key contribution to the reflectivity of ESV is only the aspect angle, rather than other parameters, such as radar frequency, scale size of irregularities or detection range.

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References

1. Chan, H.C., Hung, E.K.: An investigation in interference suppression for HF surface wave radar. Technical report, Ottawa (1999)
2. Sevgi, L., Ponsford, A., Chan, H.C.: An integrated maritime surveillance system based on high-frequency surface-wave radar, part I: theoretical background and numerical simulations. J. IEEE. Antenn. Propag. Mag. **43**(4), 28–43 (2001)
3. Booker, H.G.: A theory of scattering by nonisotropic irregularities with application for radar reflections from aurora. J. Atmos. Terr. Phys. **8**, 2004–2221 (1956)
4. Rytov, S.M., Kravtsov, Y.A., Tatarskii, V.I.: Principles of Statistical Radiophysics. Springer, New York (1988)

5. Xuguang, Y., Changjun, Y., et al.: The vertical ionosphere parameters inversion for high frequency surface wave radar. J. Int. J. Antenn. Propag. **3**, 1–8 (2016)
6. Mark, A.R.: Fundamentals of Radar Signal Processing. New York (2005)
7. Schlegel, K.: Coherent backscatter from ionospheric E-region plasma irregularities. J. Atmos. Solar-Terr. Phys. **58**, 933–941 (1996)
8. Haldoupis, C., Nielsen, E., Schlegel, K.: Dependence of radar auroral scattering cross section on the ambient electron density and the destabilizing electric field. Ann. Geophys. **8**(3), 195–211 (1990)
9. Walker, A.D.M., Greenwald, R.A., Baker, K.B.: Determination of the fluctuation level of ionospheric irregularities from radar backscatter measurements. Radio Sci. **22**, 689–705 (1987)
10. Ponomarenko, P.V., Stmauirice, J.P., et al.: Refractive index effects on the scatter volume location and Doppler velocity estimates of ionospheric HF backscatter echoes. Ann. Geophys. **27**(11), 4207–4219 (2009)