Modified GIT model for predicting wind-speed behavior of low-grazing-angle radar sea clutter*

Zhang Yu-Shi(张玉石)[a)†], Zhang Jin-Peng(张金鹏)[b)], Li Xin(黎 鑫)[b)], and Wu Zhen-Sen(吴振森)[a)]

[a)] *School of Physics and Optoelectronic Engineering, Xidian University, Xi'an* 710071, *China*
[b)] *China Research Institute of Radiowave Propagation, Qingdao* 266107, *China*

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A modified GIT model for describing the variational trend of mean clutter reflectivity as a function of wind speed is proposed. It uses two slope adjustment factors and two critical wind-speed factors to define and adjust the increasing slope of reflectivity with respect to wind speed. In addition, it uses a constant factor to compensate the overall amplitude of clutter reflectivity. The performance of the modified GIT model has been verified on the basis of the L-band low-grazing-angle radar sea clutter data. The results are in good agreement with the experimental data, indicating that the model is more effective in predicting the wind-speed behavior of clutter reflectivity than the conventional GIT model, especially for lower and higher wind speeds. We believe that the proposed model can provide deeper insights into the relationship between radar sea clutter reflectivity and sea state conditions.

Keywords: GIT model, low grazing angle, radar sea clutter

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1. Introduction

Radar sea clutter refers to the backscatter returned from a patch of sea surface illuminated by a radar wave. At certain instances, the backscatter clutter is considered to be a potential source for remote sensing of the ocean surface as well as the atmospheric conditions above.[1–3] However, in many other cases, for example, maritime surveillance applications, the backscattered clutter is regarded as undesirable, as it often interferes with the intended target signals and immerses the targets, leading to missed detection or false alarms.[4,5] In the case of airborne or surface radars that typically operate at low grazing angles, the sea clutter has a heavier impact on the target signals as 'sea spikes' emerge and become common at a low grazing angle.

With a good understanding of the nature and behavior of the clutter, good target detection performance can be realized by adopting appropriate signal processing techniques within the radar.[6] Therefore, in the recent years, considerable attention has been given to analyzing the characteristics of sea clutter, particularly at low grazing angles. Thus far, several studies have performed both experimental data analysis and modeling of low-grazing-angle (LGA) sea clutter, including mean clutter reflectivity,[5] amplitude statistics,[7] Doppler spectra,[8] and temporal and spatial correlations.[9] On the basis of the LGA sea clutter data obtained by radars working in VHF, UHF, L, S and X-bands of MIT Lincoln Laboratory, Chan[10] presented a detailed analysis of the mean clutter reflectivity, amplitude distribution and spectral characteristics of sea clutter. According to this study, the mean clutter reflectivity measured in low sea states is different from that predicted by the typical models, GIT and SIT. Similarly, on the basis of the LGA sea clutter data measured by an L-band multi-channel radar near Kangaroo Island in South Australia, Dong *et al.*[11] investigated the trend of the mean clutter reflectivity as a function of the range (or grazing angle). According to their study, with an increase in range, clutter reflectivity decreases at a rate of r^4 (r is the range). This does not agree with predictions by the typical clutter models.[12] Lately, Ward,[5] in his new book, systematically summarized the current status of research on sea clutter over the years, thereby providing deeper insights into the theory and modeling techniques of sea clutter.

With regard to clutter modeling, most of the studies reported so far concentrate on the amplitude characteristics of the clutter. To this end, several typical models, such as the GIT, TSC, and HYB models[13,14] have been developed to describe mean clutter reflectivity. Recently, Gregers-Hansen *et al.*[15] proposed a new empirical LGA sea clutter reflectivity model, referred to as the NRL model, on the basis of the measured sea clutter data summarized by Nathanson.[16] This model is found to agree better with the measured data. Although the above-mentioned models are widely used in radar research, they do not always agree with the data from many experiments. More importantly, these models do not agree among themselves, especially at low grazing angles. This discrepancy could be attributed to an inadequate understanding of the relationships between the models and the radar parameters, as well as sea surface conditions. The main surface parameters of the sea affecting mean clutter reflectivity include wave height,

*Project supported by the National Natural Science Foundation of China (Grant No. 61172031).
†Corresponding author. E-mail: zhang10695@126.com
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wind speed and wind direction relative to the radar line-of-sight angle. Some clutter data, such as that used in the development of the GIT model, indicate that the mean clutter reflectivity is predominantly a function of wind speed, rather than wave height.[17] In the present study, we have modeled the relationship between the mean clutter reflectivity and the wind speed, aiming to assist the analysis of radar performance under different sea state conditions.

To the same end, some earlier studies have investigated the wind-speed behavior of mean sea clutter reflectivity. For example, Wetzel[18] performed an extensive survey of the sea clutter data reported by several studies and described the general law of mean sea clutter reflectivity as a function of wind speed in medium grazing angles. According to that study, the mean clutter reflectivity is related to the wind speed in the form of a power function. Furthermore, by fitting some L-band measured clutter data, Sarkar *et al.*[19] presented a polynomial model as well as the corresponding model parameters for mean clutter reflectivity as a function of wind speed at grazing angles varying from 30° to 90°. However, the above-mentioned studies on clutter reflectivity mainly concentrated on medium or high grazing angles, while the relationship between clutter reflectivity and wind speed at low grazing angles has not received comparable attention.

Therefore, in the present study, we have proposed a modified GIT model for predicting the wind-speed behavior of low-grazing-angle radar sea clutter. This model contains two critical wind-speed factors and two slope adjustment factors that are used to adjust the increasing slope of reflectivity with respect to wind speed. In addition, the model features a constant factor to adjust the overall amplitude of the clutter reflectivity. These factors depend on the actual radar scattering systems, and can be determined by fitting the experimental data. The introduction of these factors would facilitate better modeling of the wind-speed behavior of mean clutter reflectivity at low and high wind speeds, when compared with the conventional GIT model. The performance of our modified GIT model has been validated by predicting the wind-speed behavior of the low-grazing-angle L-band radar sea clutter and by comparing the results with the predictions of the conventional GIT model.

2. Performance analysis of the conventional models for determining wind-speed behavior of sea clutter

Previous studies of the characteristics of sea clutter as a function of wind speed usually sought the best linear fit between the scattering coefficient and the logarithm of the wind speed. This relationship is usually expressed as a power function. The conventional mean clutter reflectivity models, such as GIT, TSC, HYB, and NRL, can be used to describe the wind-speed behavior of sea clutter by fixing all parameters except wind speed.

Both the GIT and TSC models incorporate a wind speed factor to describe the effects of wind speed on the clutter reflectivity. According to the GIT model,[20] the mean sea clutter reflectivity (i.e., scattering coefficient) for low frequencies (< 3 GHz) is expressed as follows:

$$\sigma^0_{\mathrm{H}}(\mathrm{dB}) = 10\log[3.9\times10^{-6}\lambda\phi^{0.4}G_{\mathrm{m}}G_{\mathrm{u}}G_{\mathrm{w}}], \quad (1)$$

$$\begin{aligned}\sigma^0_{\mathrm{V}}(\mathrm{dB}) &= 10\log[3.9\times10^{-6}\lambda\phi^{0.4}G_{\mathrm{m}}G_{\mathrm{u}}G_{\mathrm{w}}] \\ &\quad -1.73\ln(h_{\mathrm{a}}+0.015)+3.76\ln(\lambda) \\ &\quad +2.46\ln(\varphi+0.0001)+22.2,\end{aligned} \quad (2)$$

where λ is the radar wavelength (in meters), φ is the grazing angle (in radians), h_{a} is the average wave height (in meters), G_{m} is the interference factor, G_{u} is the wind direction factor, and G_{w} is the wind speed factor.

The interference factor is based on the interference between a direct ray and a surface reflected ray, the amplitude of which is modified by surface roughness. The wind direction factor is based on the upwind–downwind ratio and the grazing angle, which increases with a decrease in grazing angle. The expressions of these two factors can refer to Ref. [20]. The wind speed factor describes the effect of sea state on clutter reflectivity, which can be expressed as

$$G_{\mathrm{w}} = \left[\frac{1.94V_{\mathrm{w}}}{1+V_{\mathrm{w}}/15.4}\right]^{qw}, \quad (3)$$

with

$$qw = 1.1(\lambda+0.015)^{-0.4}, \quad (4)$$

where V_{w} is the wind speed in meters per second. For a fully developed sea, the wind speed and the average wave height are interrelated as

$$V_{\mathrm{w}} = 8.67h_{\mathrm{a}}^{0.4}. \quad (5)$$

According to this relationship, mean clutter reflectivity depends solely on either wind speed or wave height.

In the TSC model, the wind speed factor that is used to account for the sea state effect is given as

$$G_{\mathrm{w}} = \left[\frac{V_{\mathrm{w}}+4}{15}\right]^{A}, \quad (6)$$

with

$$A = 2.63A_1/(A_2A_3A_4) \quad (7)$$

and

$$\begin{aligned}&A_1 = \left[1+(\lambda/0.03)^3\right]^{0.1}, \quad A_2 = \left[1+(\lambda/0.1)^3\right]^{0.1}, \\ &A_3 = \left[1+(\lambda/0.3)^3\right]^{\phi^{0.6}/3}, \quad A_4 = 1+0.35\phi^{0.6},\end{aligned} \quad (8)$$

where all the parameters have the same meaning as those in Eqs. (3) and (4). Unlike the GIT model, the wind speed factor for the TSC model can be seen to depend on both λ and

φ. The expression of clutter reflectivity predicted by the TSC model has been reported elsewhere.[13]

In both the HYB and the NRL model, the sea state level is an input parameter. Therefore, determining the wind-speed behavior of the predicted clutter reflectivity is possible by using the relationship between the wind speed and the sea state. This relationship can be expressed as

$$V_{\mathrm{w}} = 2.15SS^{1.04}, \tag{9}$$

where SS represents the sea state level. Here, the NRL model is notably derived by averaging a large number of sea clutter data points with different wind directions, eliminating the wind direction factor. Details on the forms of these two models are explained in Refs. [16] and [21].

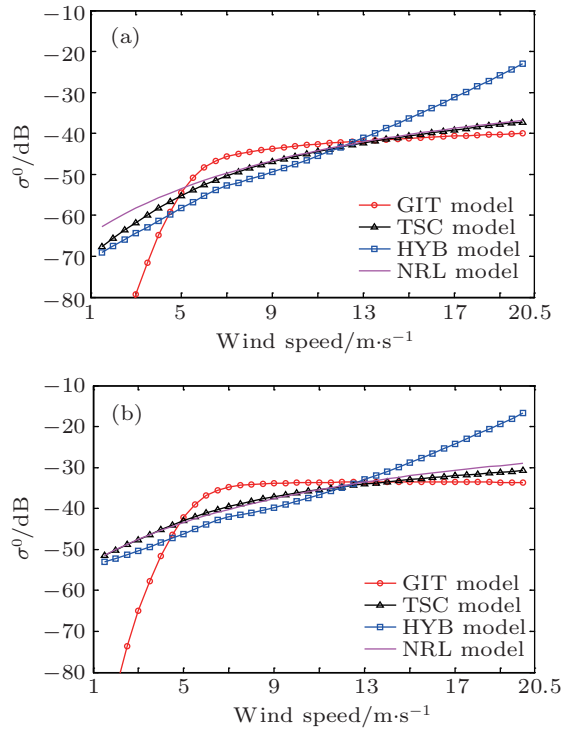


Fig. 1. (color online) Mean sea clutter reflectivity as a function of wind speed, as predicted by conventional sea clutter models, (a) HH-Pol and (b) VV-Pol.

In order to compare the wind-speed behaviors of the radar sea clutter reflectivity predicted by these conventional models, we fixed all the parameters except wind speed and then intently analyzed the effect of the wind speed on the model predictions. Figure 1 shows the mean clutter reflectivity as a function of wind speed as predicted by these conventional clutter models. The corresponding radar frequency is 1.34 GHz (L band), the grazing angle is 4° and the wind direction is upwind. The following inferences can be observed by comparing these results: (i) the wind-speed behaviors of the clutter reflectivity predicted by these models differ from each other, particularly for low and high wind speeds, (ii) the predicted clutter reflectivity of the GIT model at low wind speeds is significantly smaller than that of the other models, and (iii) the clutter reflectivity predicted by the TSC, HYB, and NRL models tends to increase with an increase in wind speed. However, according to the GIT model, the clutter reflectivity is predicted to approach a constant value when the wind speed is larger than a critical value. Given these considerations, the conventional models, are certainly not sophisticated in modeling the wind-speed behavior of the LGA radar sea clutter. Therefore, developing an improved model to describe the clutter reflectivity as a function of wind speed with a freely adjusted slope at low and high wind speeds is imperative.

3. Modified GIT model for the wind-speed behavior of sea clutter

3.1. Model formulation

As mentioned above, developing an improved model that can predict the clutter reflectivity with a wind-speed behavior between those predicted by conventional models is highly desirable. Such a model is expected to be robust in modeling the clutter reflectivity for many sea surface scattering systems. Given the fact that the GIT model is capable of predicting a relatively small reflectivity at low and high wind speeds, in the present study, we modified the wind speed factor of the GIT model to freely model the increasing slope of reflectivity within these wind speed intervals.

Accordingly, the wind speed factor for the modified GIT model can be expressed as

$$\begin{aligned} G_{\mathrm{w}}^{\mathrm{m}} = & \left[\frac{1.94V_{\mathrm{w}}}{1+V_{\mathrm{w}}/15.4} + \exp\left[\rho_1\left(v_1^{\mathrm{c}} - V_{\mathrm{w}}\right)\right]\right. \\ & \left. + \ln\left[\exp\left[\rho_2\left(V_{\mathrm{w}} - v_2^{\mathrm{c}}\right)\right] + 1\right]\right]^{1.1/(\lambda+0.015)^{0.4}}, \\ & \rho_1 > 0, \quad \rho_2 > 0, \quad v_2^{\mathrm{c}} > v_1^{\mathrm{c}} > 0, \end{aligned} \tag{10}$$

where V_{w} and λ have the same meanings as in Eq. (3). In Eq. (10), two terms have been introduced to adjust the increasing trend of $G_{\mathrm{w}}^{\mathrm{m}}$, and in turn the clutter reflectivity. The first term is $\exp\left[\rho_1\left(v_1^{\mathrm{c}} - V_{\mathrm{w}}\right)\right]$, which represents an increment with a relative slope of ρ_1, when the wind speed V_{w} is lower than a critical value v_1^{c}. The second term, $\ln\left[\exp\left[\rho_2\left(V_{\mathrm{w}} - v_2^{\mathrm{c}}\right)\right] + 1\right]$, represents an increment with a relative slope of ρ_2, when the wind speed V_{w} is larger than a critical value v_2^{c}. The logarithmic form of this term ensures the lowering of the increment per unit of the wind speed with increase in wind speed. This pattern is typical of much experimental clutter data.

The wind direction factor G_{u} in the GIT model (Eqs. (1) and (2)) provides the dependence of reflectivity on the radar line-of-sight direction with respect to the wind/wave direction. According to the study reported by Long,[20] the typical difference of mean clutter reflectivity along two arbitrary directions is within 3 dB. Sometimes it is assumed to be unity to avoid

complexity. We also deal with it in this manner in the modified model. For the interference factor $G_{\rm m}$, because we mainly focus on modeling the wind-speed behavior of clutter reflectivity, it is also set as unity in the modified GIT model.

Accordingly, considering the modified wind speed factor given by Eq. (10), the modified GIT model for the wind-speed behavior of LGA radar sea clutter at low frequencies (<3 GHz) can be expressed as

$$\sigma^0_{\rm H}({\rm dB}) = 10\log[3.9\times10^{-6}\lambda\phi^{0.4}G_{\rm w}^{\rm m}]+C, \quad (11)$$

$$\sigma^0_{\rm V}({\rm dB}) = 10\log[3.9\times10^{-6}\lambda\phi^{0.4}G_{\rm w}^{\rm m}] - 1.73\ln\left[(V_{\rm w}/8.67)^{2.5}+0.015\right]+3.76\ln(\lambda) +2.46\ln(\phi+0.0001)+22.2+C, \quad (12)$$

where the constant C (in decibels) is introduced to compensate the overall amplitude of reflectivity. This factor, as well as the slope adjustment factors ρ_1 and ρ_2 and the critical wind speeds $v_1^{\rm c}$ and $v_2^{\rm c}$ used in Eq. (10) are the five new parameters we introduced to modify the conventional GIT model. For different radar systems and sea conditions, the above-mentioned factors have different values that can be determined by fitting the corresponding experimental data. In this way, the modified model will be more flexible in describing the wind speed behaviors of reflectivity with regard to different radar scattering systems. Another advantage of the modified model is that it retains the relationships between σ^0 and the parameters of the conventional GIT model, such as radar wavelength and grazing angle. These relationships have received widespread acceptance.

3.2. Performance validation

Before validating the performance of the modified GIT model, we first investigated the effect of each newly introduced parameter on the predicted wind-speed behavior of the clutter reflectivity. Figure 2 shows the variations in the L-band clutter reflectivity of the modified GIT model obtained by changing one of the model parameters while keeping the other four parameters constant. As can be seen from Fig. 2, only the variable parameter has varying values, while the other parameters have fixed values of $\rho_1=0.3$, $\rho_2=3.0$, $v_1^{\rm c}=3.0$ m/s, $v_2^{\rm c}=9.0$ m/s, and $C=0.0$. In this example, the grazing angle is 4°. By comparing the curves shown in each subfigure, it can be observed that a) the slope adjustment factors ρ_1 and ρ_2 can sensitively adjust the increasing rate of the clutter reflectivity when the wind speed is lower than a critical value $v_1^{\rm c}$ (3.0 m/s here) and higher than another critical value $v_2^{\rm c}$ (9.0 m/s here), respectively; b) the critical wind speeds $v_1^{\rm c}$ and $v_2^{\rm c}$ successfully control the critical values of the wind speed, beyond which the increasing slope of σ^0 will be adjusted. Accordingly, these four newly introduced parameters can be accepted as valid for the modified GIT model.

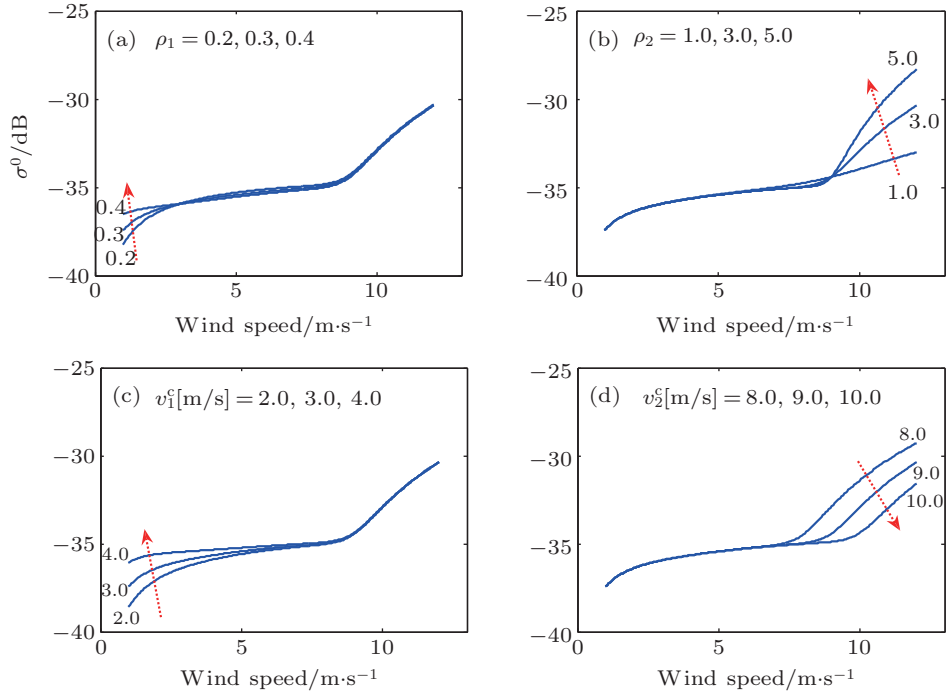


Fig. 2. (color online) Wind speed behaviors of mean clutter reflectivity predicted by the modified GIT model with different (a) slope adjustment factors ρ_1, (b) slope adjustment factors ρ_2, (c) critical wind speeds $v_1^{\rm c}$, and (d) critical wind speeds $v_2^{\rm c}$.

We have validated the performance of the proposed modified GIT model and derived the corresponding model parameters on the basis of the experimental data collected by the sea clutter observation radar of the China Research Institute of Radiowave Propagation. The observation radar works in the L-band with HH and VV polarizations, and can work in different range resolutions with grazing angles ranging from 1.5° to 6.5°. It is set on a shore platform 100 m above the mean

sea level in Qingdao, facing the Yellow Sea with an azimuth angle of 201° (Fig. 3). In the present study, 216 sets of the measured clutter data of VV polarization with a range resolution of 3 m are chosen to exhibit the wind speed behavior of the clutter reflectivity of this radar scattering system. The grazing angles for these data range from 2.71° to 4.24°. The wind speeds and wind directions (i.e., the angles relative to the radar beam) recorded simultaneously with these clutter data are shown in Fig. 4. As is seen, the wind speed covers a large interval between 0.1 m/s and 11.1 m/s, which corresponds to the sea state level $1 \sim 5$. The wind directions for these sets of data are different from each other, and hence we do not consider this factor in modeling the reflectivity, as expected by the modified GIT model.



Fig. 3. (color online) Location of the L-band clutter observation radar.

The ability of the modified GIT model to predict the wind-speed behavior of L-band clutter reflectivity in VV polarization is shown in Fig. 5. The five parameters introduced in the modified model are optimized using the PSO algorithm.[22]

Comparing the wind-speed behavior shown in the figures, it can be observed that (I) the σ^0 value of the experimental data has an increase faster when the wind speed is larger than approximately 9 m/s. This tendency of σ^0 as well as that for the other wind speeds are predicted well by the modified GIT model; (II) the σ^0 value determined by the conventional GIT model is appropriate at high wind speeds; however, its increasing trend does not agree with the experimental data. Moreover, for wind speeds lower than 6 m/s, the GIT model predicts a much smaller value of σ^0, which deviates significantly from the experimental data. Therefore, with the five new parameters of Eq. (10), the modified GIT model can be concluded to model the wind-speed behavior of sea clutter reflectivity better than the conventional GIT model.

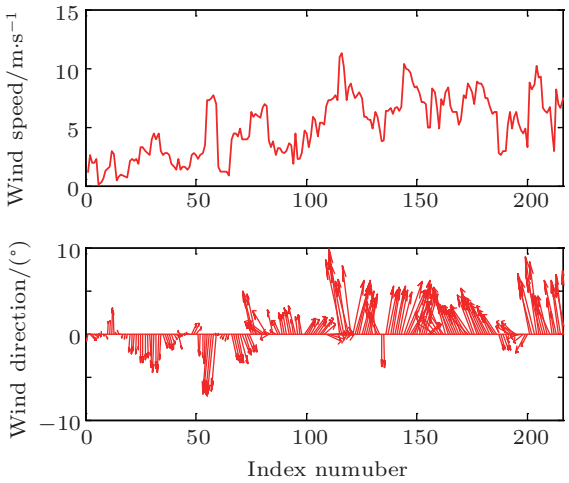


Fig. 4. (color online) Wind conditions simultaneously recorded with the clutter data.

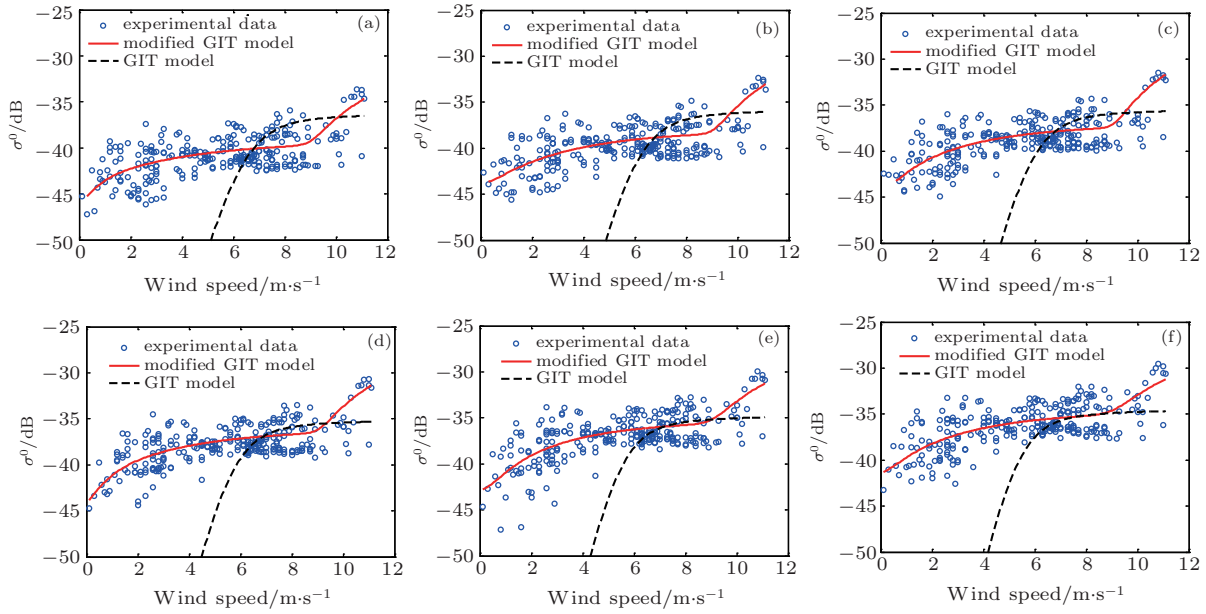


Fig. 5. (color online) Comparisons of the wind-speed behavior of mean clutter reflectivity between the experimental data, modified GIT model, and conventional GIT model: (a) grazing angle=2.71°, (b) grazing angle=3.02°, (c) grazing angle=3.31°, (d) grazing angle=3.6°, (e) grazing angle=3.93°, and (f) grazing angle=4.19°.

As shown in Fig. 5, the wind-speed behavior determined by the modified GIT model is notably slightly different for the six grazing angles. In simple terms, the newly introduced parameters are a function of the grazing angle. This dependency must be considered when modeling the wind-speed behavior for different radar scattering geometries. In modeling this behavior of L-band sea clutter reflectivity with VV polarization (Fig. 5), the optimized values of the five new parameters of the modified GIT model as functions of the grazing angle are shown in Fig. 6. The slope adjustment factors ρ_1 and ρ_2 are seen to be strong functions of the grazing angle, as variations on the order of 10^{-1} will result in relatively large shifts of the model's curves. Given the fact that the critical wind speeds v_1^c and v_2^c change slowly with the grazing angle, we can use a constant (e.g., the mean value) in modeling the wind-speed behavior for a certain radar scattering system, irrespective of the grazing angle. The constant C, which affects the overall amplitude of the clutter reflectivity, increases approximately linearly with the grazing angle from -3 dB to 0 dB. Therefore, it must be properly optimized to ensure the precision of the predicted clutter reflectivity by the modified GIT model.

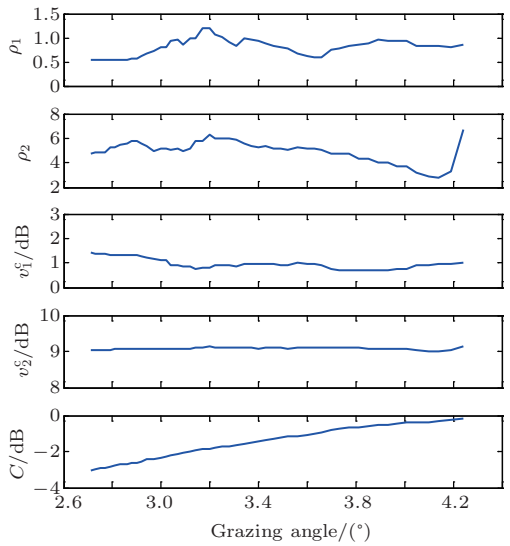


Fig. 6. (color online) Optimized values of the five new parameters of the modified GIT model.

4. Conclusions

Wind speed is one of the most important factors determining mean sea clutter reflectivity. A comparison of the performance of four conventional clutter models in describing the wind-speed behavior of clutter reflectivity shows that these models perform differently, and they do not agree well with the experimental data. Therefore, in the present study, we have proposed a modified GIT model to describe the wind-speed behavior of radar sea clutter, wherein five new parameters are introduced to adjust the increasing slope of reflectivity as a function of the grazing angle, as well as to increase the overall magnitude of reflectivity. The performance of the modified GIT model has been validated on the basis of different sets of experimental clutter data collected using LGA sea clutter observation radar. The results agree well with the experimental data, indicating the efficacy of the modified model in predicting the trends of clutter reflectivity with respect to wind speed, i.e. the wind-speed behavior, especially at low and high wind speeds. For a certain radar scattering system, three new parameters of the model, namely, the slope adjustment factors ρ_1 and ρ_2 and the constant C, are validated as strong functions of the grazing angle. However, the other two parameters, namely, the critical wind speeds v_1^c and v_2^c, do not depend on the grazing angle. Therefore, in applying the modified model, the former three parameters should be determined by optimizing the experimental data at each grazing angle, while determining the latter two parameters at one grazing angle is sufficient. Further studies are underway to validate the model using more sea clutter data in other radar bands, measured at a wider range of wind speeds.

Acknowledgments

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