Vol 14 No 6, June 2005
1009-1963/2005/14(06)/1259-06

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

A microwave emissivity model of sea surface under wave breaking*

Wei En-Bo(魏恩泊)† and Ge Yong(葛 勇)

Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

(Received 3 December 2004; revised manuscript received 5 February 2005)

With the effective medium approximation theory of composites, a remedial model is proposed for estimating the microwave emissivity of sea surface under wave breaking driven by strong wind on the basis of an empirical model given by Pandey and Kakar. In our model, the effects of the shapes of seawater droplets and the thickness of whitecap layer (i.e. a composite layer of air and sea water droplets) over the sea surface on the microwave emissivity are investigated by calculating the effective dielectric constant of whitecaps layer. The wind speed is included in our model, and the responses of water droplets shapes, such as sphere and ellipsoid, to the emissivity are also discussed at different microwave frequencies. The model is in good agreement with the experimental data of microwave emissivity of sea surface at microwave frequencies of 6.6, 10.7 and 37GHz.

Keywords: microwave emissivity, effective medium approximation, whitecaps, wave breaking
PACC: 9210, 7260, 5235H

1. Introduction

Wave breaking driven by a strong wind generates a composite layer (i.e. whitecaps: sea spray and bubbles) of water droplets and air over the sea surface. This whitecap layer and the roughness of sea surface have a profound effect on the microwave remote sensing of the sea water physical properties and the geometrical characteristics of sea surface, e.g. temperature, salinity, concentrations of the organic substance and micro-sized sand particles, through the microwave emissive and scattering mechanism.[1−3] Recently, the effects of whitecaps on the emissivity have attracted much attention in ocean remote sensing because it is found that, in the practical observations of microwave remote sensing, the broken waves enhance the emissivity of sea surface, and then increase the microwave brightness of the sea surface at higher sea state. In order to correct the whitecaps effects and to give a reasonable estimation of sea surface temperature from the remote sensing data, a number of models have been given to investigate the emissivity of sea surface under wave breaking on the basis of the microwave emissive theory and microwave experimental data by many authors, such as the semi-empirical models proposed by Stogryn,[4] Pandey and Kakar,[5] Koepke,[6] Smith,[7] Huang and Jin[8] and the theoretical models proposed by Droppleman,[9] Rosenkranz and Staelin,[10] and Guo *et al.*[11] All of the theoretical models have investigated qualitatively the microwave radiation transfer properties of sea surface with active wave breaking based on the electromagnetic scattering and thermal emission theories. The semi-empirical models were derived from the experimental data of ocean remote sensing and applied to inverse quantitatively the physical parameters of sea surface water.

For the ocean whitecap layer of sea surface, one kind of thermal emission models was proposed by the effective medium approximation theory of composites, where the dielectric constant of whitecap layer was calculated by using a two-phase mixture of air and seawater droplets. This pioneering idea was proposed by Droppleman,[9] who investigated the effects of sea surface foam on the temperature of microwave brightness by regarding the randomly covered foam as a uniform layer of air and seawater droplets. Subsequently, Rosenkranz and Staelin[10] developed the method to discuss the microwave emissivity of ocean foam with

*Project supported by the National Natural Science Foundation of China (Grant Nos 40476062, 10374026) and the National High Technology Development Program of China (Grant No 2002AA639270).

†E-mail: ebwei@ms.qdio.ac.cn

a model of a series of thin films parallel to the sea surface. These models seem to be quite difficult to match with the experimental data owing to the roughness of sea surface driven by strong wind. It is well known that, in terms of effective medium approximation theory, the shapes of particles and the volume fraction of inclusion particles have important effects on the effective dielectric responses of composites. Therefore, to improve the effective medium approximation model under wave breaking, two factors of the whitecap layer should be included in the emissivity model as well as the roughness of sea surface and coverage fraction of whitecaps. One is the thickness of the whitecap layer. The other is the shape of water droplets in the whitecap layer. In order to go further into the method for dealing with the effects of both whitecap layer and roughness of sea surface on microwave emissivity, in this paper we shall propose a remedial model on the basis of the empirical microwave emissivity model given by Pandey and Kakar,[5] who took into consideration the roughness and whitecaps of sea surface,[4] to investigate the microwave emissisivity of sea surface under wave breaking in passive remote sensing. In our model, we have taken into account the factors of wind speed, thickness and coverage fraction of whitecap layer, the shapes of water droplets and the roughness of sea surface.

2. Remedial microwave emissivity model

In the case of roughness and whitecaps of sea surface with broken waves, Pandey and Kakar proposed a microwave emission model by analysing the microwave measurement,[5]

$$e_p(\theta) = (1-w)[e_{sp}(\theta) + e_{rp}(\theta)] + we_{wp}(\theta), \qquad (1)$$

where p denotes the horizontal (h) or vertical (v) polarization, and θ is the incidence angle in degrees and$w$ is the whitecap coverage. e_{sp}, e_{rp} and e_{wp} are contributions to emissivity due to specular sea surface, surface roughness and whitecaps, respectively,

$$\begin{aligned} e_{sp} =& 1 - r_{sp}, \\ e_{\rm rh} =& U\gamma^{1/2}(A + B\theta^2)/T_s - 0.00065\gamma, \\ e_{\rm rv} =& U\gamma^{1/2}(a + be^{c\theta})/T_s - 0.00065\gamma, \end{aligned}$$

where $A = 1.15 \times 10^{-1}$, $B = 3.8 \times 10^{-5}$, $a = 1.17 \times 10^{-1}$, $b = -2.09 \times 10^{-3}$, $c = 7.32 \times 10^{-2}$, $r_{sh} = \left|(\cos\theta - \sqrt{\varepsilon_i - \sin^2\theta})/(\cos\theta + \sqrt{\varepsilon_i - \sin^2\theta})\right|^2$, $r_{sv} = \left|(\varepsilon_i \cos\theta - \sqrt{\varepsilon_i - \sin^2\theta})/(\varepsilon_i \cos\theta + \sqrt{\varepsilon_i - \sin^2\theta})\right|^2$, ε_i is the dielectric constant of sea water. U, γ and T_s are the wind speed (m / s), microwave frequency (GHz) and temperature (Kelvins) of sea surface water, respectively. In Pandey and Kakar's model, the emission term e_{wp} was a function of sea surface temperature, microwave frequencies and the incidence angle, which was obtained by fitting the measured data. However, there are no important physical oceanography parameters of whitecaps included in the whitecaps emission term, e_{wp}, such as the whitecaps thickness, the volume fraction and the shapes of water droplets. In order to correct this term with physical oceanography parameters, we develop the effective medium method to take into account microwave emissivity of whitecaps regions, e_{wp}. The microwave emissivity of whitecaps layer can be calculated by regarding the whitecaps layer as a homogeneous composites layer of air and ellipsoidal seawater droplets. If the ellipsoidal water droplets have a random distribution of orientation in air host, the effective microwave dielectric constant $\varepsilon_{\rm m}$ of the composites layer can be obtained by the following equation:[12]

$$\begin{aligned} \varepsilon_{\rm m} =& \varepsilon_{\rm h} + \frac{1}{3} f_i(\varepsilon_i - \varepsilon_{\rm h}) \\ & \times \sum_{u=a,b,c} [1 + A_u(\varepsilon_i/\varepsilon_{\rm h} - 1)]^{-1}, \end{aligned} \qquad (2)$$

where ε_i and $\varepsilon_{\rm h}$ are the dielectric constants of seawater droplets and air, respectively , and $\varepsilon_{\rm m}$ is the dielectric constant of the mixture of sea water droplets and air in whitecaps. The dielectric constant of seawater droplet is obtained by Debye formula,[13] which is related to the temperature, microwave frequencies and salinity. f_i is the volume fraction of water droplets, and A_u is the depolarization factors of ellipsoidal droplets,

$$\begin{aligned} A_u =& \frac{abc}{2} \int_0^\infty (u^2 + s)^{-1} \\ & \times [(a^2 + s)(b^2 + s)(c^2 + s)]^{-1/2} {\rm d}s, \end{aligned}$$

where a, b and c are the semi-axes of the ellipsoid particles along x-, y- and z- directions. The maximum uniform thickness $\delta_{\rm max}$ of the whitecaps layer is estimated by significant wave height,[14] $\delta_{\rm max} = H_s/5$, where $H_s = 0.3U_{10}^2/g$ is the significant wave height related to the ten metres high wind speed U_{10}. Therefore, the maximum volume fraction of water droplets in the whitecap layer is $f_{i-\rm max} = w\delta_{\rm max}$.

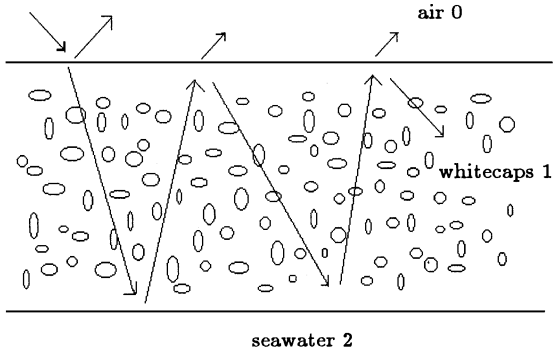


Fig.1. The geometry of whitecaps in our model.

For the layered medium of whitecaps, the emissivity of the uniform plane of whitecap layer can be calculated by the reflectivity r_{wp} under the Kirchhoff thermal equilibrium condition, i.e. $e_{wp} = 1 - r_{wp}$. In order to calculate the reflectivity of the layered whitecap medium, we assume that an incident microwave with wavelength λ and radiant intensity $L(\lambda)$ is reflected and transmitted at the whitecap layer (see Fig.1). Interfaces 1 and 2 are the upper surface of whitecap layer and sea surface, respectively. For the first time of the microwave incidence on interface 1, the reflected intensity of incident microwave is $LR_{p01}(\theta)$, where $R_{p01}(\theta)$ represents the reflectivity of the microwave transmitted from the air (subscript 0) to the whitecap layer (subscript 1), and the meanings of p and θ are given in Eq.(1). Here, we note that when the reflectivity is calculated by the Fresnel reflection coefficients, the dielectric constant of whitecap layer is estimated by Eq.(2). Subsequently, transmissive intensity is $LT_{p01}(\theta)$, where T_{p01} is the transmissivity from air to whitecaps layer, θ is the incident angle, which is connected with the angle of transmission θ_t by Snell's law, and the transmissivity T_{p01} can be calculated by the Fresnel coefficients. The transmissive microwave transmitting in the whitecap layer decreases because the dielectric constant of the whitecap layer has a non-zero imaginary part, and the decrease coefficient τ of the whitecap layer is related to the thickness of layered medium δ, $\tau = \exp(-2\omega n'\delta/\cos(\theta_t)c)$, where ω and c are the angular frequency of microwave and the speed of light, respectively. n' is the imaginary part of refractive index of whitecap composite layer. When the transmissive microwave arrives at the sea surface, its intensity is $LT_{p01}\tau$, and then it is reflected by the sea surface through the whitecap layer up to the upper surface of whitecaps and its intensity is $LT_{p01}\tau^2 R_{p12}$, where R_{p12} is the reflectivity from the whitecap layer to sea surface (subscript 2). So, the first transmissive intensity from the whitecap layer into air is $LT_{p01}\tau^2 R_{p12}T_{p10}$, where T_{p10} is the transmissivity from the whitecap to air. For the second time, the microwave reflected down by the upper surface of whitecap layer is decreased and reflected by whitecap layer and the sea surface, respectively. Thus, the intensity of microwave into the air is $LT_{p01}\tau^4 R_{p12}^2 R_{p10}T_{p10}$. For the k-th times, the intensity of incident microwave from the whitecaps into air is $LT_{p01}\tau^{2k}R_{p12}^k R_{p10}^{k-1}T_{p10}$. Therefore, the total radiant intensity is

$$L_{\rm tr} = L\left(R_{p01} + \sum_{k=1}^{\infty} T_{p01}T_{p10}R_{p10}^{k-1}R_{p12}^k\tau^{2k}\right).$$

Finally, we have the reflectivity $r_{wp} = L_{\rm tr}/L$ and the microwave emissivity of the whitecap layer $e_{wp} = 1 - r_{wp}$.

3. Comparison with experimental data

In order to compare our remedial model of whitecap layer with the measured data, two kinds of whitecaps coverage formulas are used in Eq.(1). One is Huang's empirical expression obtained from the observation data,[8]

$$w = 11.12\mathrm{e}^{0.063U_{19.5}} - 16.23, \quad (U_{19.5} \geq 7\mathrm{m/s}). \quad (3)$$

The other is Wu's formula obtained by the energy equilibrium of wave breaking and experimental data,[15]

$$w = 1.7 \times 10^{-6}U_{10}^{3.75} \quad ,(U_{10} \geq 7\mathrm{m/s}). \quad (4)$$

The maximum thickness of whitecaps layer is related to the wind speed over sea surface, so we can define the thickness, δ, $0 < \delta \leq \delta_{\max}$. At the sea surface temperature 285K and the salinity 35, Pandey and Kakar have obtained the Seasat-SMMR observation data of emissivity for various wind speeds and microwave frequencies at an incident angle 48.8°. Here we will use these data to compare our remedial model with Pandey and Kakar's empirical and Huang's model,[8] and to discuss the effects of droplet shapes and thickness of microwave on the emissivity of whitecaps layer at microwave frequencies.

From Figs.2 to 7, for different wind speeds, our results obtained using the present model for both vertical and horizontal emissivities are shown and compared with the Seasat-SMMR observation data at microwave frequencies 37, 10.7 and 6.6GHz, respectively.

In these figures, the solid square represents Seasat-SMMR observation data. For the maximum thickness of whitecaps, the solid lines with trigon and star denote our results of spherical droplets obtained using Huang's and Wu's whitecap coverage formulae, respectively, and the dashed lines with loop and star are our results in ellipsoidal models using Huang's and Wu's whitecap coverage formulae, respectively. The solid line is the emissivity of sea surface without whitecap layer, i.e. $w = 0$ in Eq.(1). For the whitecap layer thickness, $\delta = \delta_{\max}/e$, our results of the spherical model obtained from Huang's whitecap coverage formula are denoted by dashed lines in these figures. Comparing our results with those of Pandey and Kakar in Fig.2[5] and of Huang in Fig.5,[8] we can see that our simple spherical model with $\delta = \delta_{\max}/e$ is in good agreement with their empirical models. For both horizontal and vertical polarizations in our model, the horizontal emissivity is better and much more sensitive to wind speed than the vertical one by comparing them with the data. It seems that Wu's and Huang's whitecap coverage formulae give respectively the lower and upper bounds of the horizontal emissivities obtained in our model, compared with the measured data. With increasing wind speed, the thickness of whitecap layer increases, and the emissivity of sea surface under wave breaking condition increases also for both whitecap coverage formulae. So the thickness of whitecaps layer enhances the emissivity of sea surface. For the shapes of the seawater droplets, we have given the prolate ellipsoid eccentricity ($a = b$, $c = 1.25a$), $\alpha = [1 - (a/c)^2]^{1/2} = 0.6$. From Figs.2 to 7, it is clear that the emissivity is very sensitive to the shape of water droplets at the microwave frequencies, and the difference between the spherical and ellipsoidal droplets increases with the decrease of microwave frequency. It may result from the fact that, for a given volume of droplets, the emissive areas or lengths of ellipsoid particles with random orientations are larger than those of spherical ones. However, in the effective medium approximation, it is valid for the mixed dielectric response of composites if the microwave length is larger than the average radius of the water droplets. In fact, the radii of ocean droplets produced by wave breaking are almost less than a millimeter. It is why there is not any important difference between spherical and ellipsoidal models for higher microwave frequencies (see Fig.2 for 37GHz). Therefore, our effective medium approximation is valid for the microwave frequencies less than about 37GHz if we use our model to predict the average size of water droplets from remote sensing data.

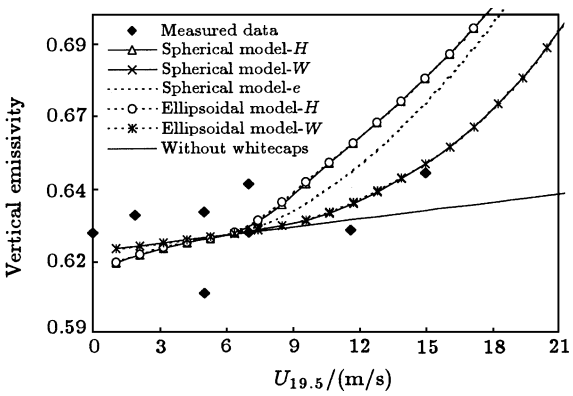


Fig.2. Vertical emissivity of our model at microwave frequency 37GHz and radiation incidence angle θ=48.8°.

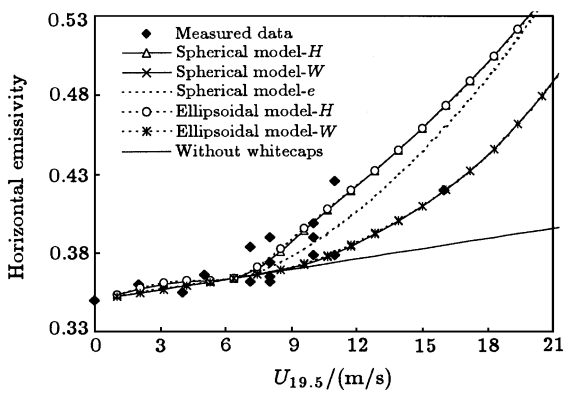


Fig.3. Horizontal emissivity of our model at microwave frequency 37GHz and radiation incidence angle θ=48.8°.

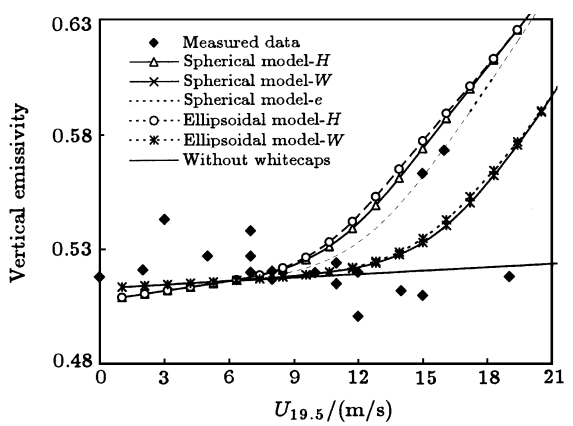


Fig.4. Vertical emissivity of our model at microwave frequency 10.7GHz and radiation incidence angle θ=48.8°.

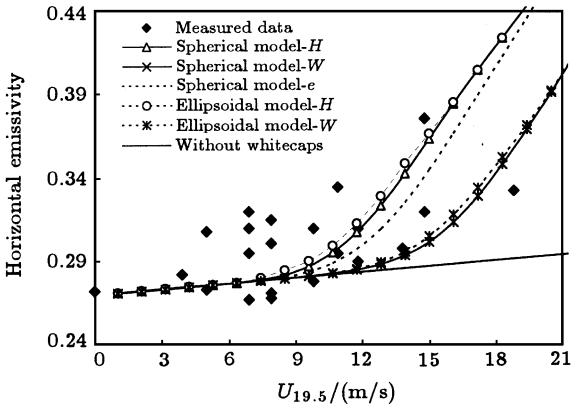


Fig.5. Horizontal emissivity of our model at microwave frequency 10.7GHz and radiation incidence angle θ=48.8°.

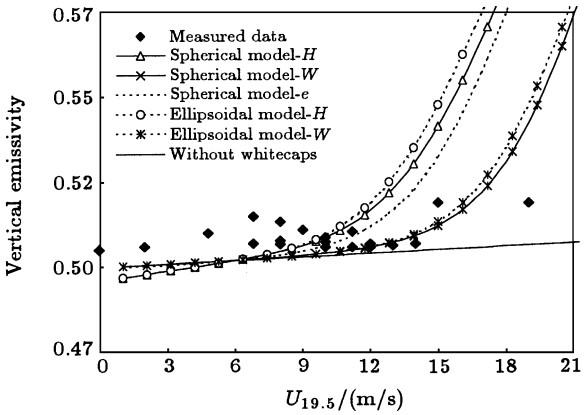


Fig.6. Vertical emissivity of our model at microwave frequency 6.6GHz and radiation incidence angle θ=48.8°.

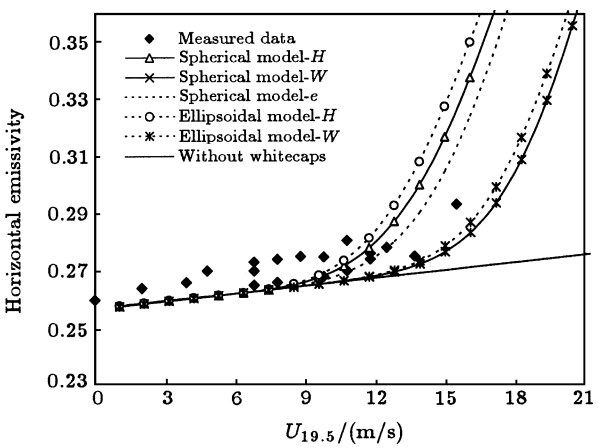


Fig.7. Horizontal emissivity of our model at microwave frequency 6.6GHz and radiation incidence angle θ=48.8°.

4. Conclusion and discussion

The empirical emissivity model proposed by Pandey and Kakar[5] is remedied on the basis of the effective medium approximation of whitecaps composite layer by taking into consideration the physical parameters of whitecaps, such as the thickness and the shapes of droplets. At strong wind speeds ($U \geq 7$m/s), this remedied model is useful for the practical application of ocean remote sensing. It is in good agreement with Huang's and Pandey's empirical models. In our model, the parameters of droplet shapes and the thickness of whitecap layer are included, and the emissivity of the model of ellipsoidal droplets is larger than that of the spherical model; and the emissivity increases with the increase of the thickness of whitecaps. Because of the sensitivities of the model to the thickness and the shape of droplets, it seems that it may be possible to estimate the thickness of whitecaps or the mean radius of droplets from thermal emissivity at a lower microwave frequency (below a microwave frequency of 37GHz by comparing with the experimental data.) if we know the number distribution of droplets per unit volume of whitecaps or the whitecap thickness, through inversing the mixed dielectric response of whitecaps from the remote sensing data. Of course, the mixed dielectric constant of whitecaps is related to the distribution of particles in the host space, such as snow, soil particle, air hole in sea ice and so on. It is also one of the major objectives of ocean and land remote sensing to estimate the mean radius of the inclusion particles.[16,17] In addition, the effective medium approximation can be applied to deal with the complex boundary condition of microwave transfer equation in remote sensing.[18]

References

[1] Wu S T and Fung A K 1972 *J. Geophys. Res.* **77** 5917

[2] Fung A K and Lee K K 1982 *IEEE J. Oceanic Eng.* **7** 166

[3] Jin Y Q and Kong J A 1984 *J. Appl. Phys.* **55** 1364

[4] Stogryn A 1972 *J. Geophys. Res.* **77** 1658

[5] Pandey P C and Kakar R 1982 *IEEE J. Ocean Eng.* **OE-7** 135

[6] Koepke P 1986 *Remote Sensing Signatures of Whitecaps, Ocean Whitecaps and Their Role in Air Sea Exchange Processes* edited by E. C. Monahan and G. MacNiocaill (Norwell, MA: Reidel) 251

[7] Smith P M 1988 *IEEE Trans. on Geoscience and Remote*

Sensing **26** 541
[8] Huang X Z and Jin Y Q 1995 *IEE Proc.—Microwave Antennas and Propagation* **142** 109
[9] Droppleman J D 1970 *J. Geophys. Res.* **75** 696
[10] Rosenkranz P W and Staelin D H 1972 *J. Geophys. Res.* **77** 6528
[11] Guo J *et al* 2001 *IEEE Trans. on Geoscience and Remote Sensing* **39** 1019
[12] de Loor G P 1956 *Appl. Sci. Res.* B **11** 310
[13] Klein L A and Swift C T 1977 *IEEE Trans. on Antennas and Propagation* **25** 104
[14] Yuan Y L, Hua F and Pan Z D 1988 *Sci. Chin.* B **10** 1084 (in Chinese)
[15] Wu J 1979 *J. Physical Oceanography* **9** 1064
[16] Schmugge T J and Jackson T J 1992 *IEEE Trans. on Geoscience and Remote Sensing* **30** 757
[17] Shao J *et al* 2003 *IEEE Trans. on Geoscience and Remote Sensing* **41** 1879
[18] Jin Y Q, Zgang J R and Zhao R Y 1992 *Int. J. Remote Sensing* **13** 2801