A New Cyclic Iterative Correction Algorithm for Retrieving Sea Surface Wind Speed Based on a Multilayer-Medium Model

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ABSTRACT At high sea conditions, e.g., typhoons and hurricanes, the sea surface waves break and produce foams, spray droplets, and bubbles, which are collectively known as whitecaps. Whitecaps covering the rough sea surface greatly absorb the electromagnetic pulses emitted by satellite remote sensors, such as altimeters, scatter-meters, and the Surface Waves Investigation and Monitoring (SWIM). Thus, the whitecaps reduce the sea surface backscattering, which results in the sea surface wind speed being overestimated, an error that is particularly prevalent at high wind speeds. Many algorithms of retrieving wind speeds can retrieve effectively sea surface wind speed when the wind speed is less than 15m/s, but the bias of retrieving wind speed is become bigger and bigger when wind speed is more than 20m/s. In order to eliminate the effect of whitecaps on retrieving the sea surface wind speed at high wind speeds (>15m/s), we propose a Cyclic Iterative Correction Algorithm (CICA). Firstly, a four-layer medium with including whitecaps is established. Secondly, the effect of whitecaps is calculated. Finally, the retrieving and correcting wind speed is continuously repeated. The ultimate goal is to remove the whitecaps’ influence on the backscattering coefficient and re-correct the overestimated wind speed until it reaches a constant value. The wind speeds measured by SWIM were corrected by using CICA, and then were compared with buoy measurements. Those comparisons show that using CICA can improve the wind speed inversion accuracy to 1.5 m/s, an improvement that is particularly evident in high sea conditions.

INDEX TERMS Oceanic remote sensing, Windspeed retrieval, Multilayer-medium model, High sea conditions, Whitecaps, Cyclic Iterative Correction, SWIM

I. INTRODUCTION
Over the past 50 years, rapid development of satellite observation technology has accelerated the pace of marine observation worldwide. Historically, traditional instruments, such as the radar altimeter[1-6] and scatter-meter[7], have been successfully used to survey sea surface wind speed and obtain data with an acceptable accuracy of 2m/s, but only after the data have been subjected to numerous and various corrections[8-14]. Furthermore, advances in scientific research methodology and development of marine science applications have brought about higher requirements for observation accuracy and space-time resolution of remote sensors on marine observation satellites. Surface Waves Investigation and Monitoring (SWIM)[15-16] is a new Centre National d’Etudes Spatiales (CNES) ku-band (13.575 GHz) real aperture radar instrument that is based on spaceborne radar altimeter technology at nadir. SWIM was aboard the China France Oceanography Satellite (CFOSAT), which was launched on October 29, 2018, and can be used to invert the backscatter coefficient (σ°), wind speed (U₁₀), and other related ocean parameters. SWIM retrieves the sea surface wind speed via a double-parameter Neural Network algorithm, with an accuracy of 2 m/s. However, the accuracy of retrieving surface wind speed is not so satisfying at some high sea conditions, such as typhoons, hurricanes and heavy rain which generates a substantial amount of whitecaps (foam, spray droplets, and bubbles) on the sea surface. In general, when the sea surface wind speed reaches 7 m/s, whitecaps begin to generate and cover the sea surface. It has been established that the whitecaps will cause microwave
signals to be attenuated and sea surface wind speed to be overestimated. To date, more than 10 types of wind speed inversion geophysical model functions (GMF)[1,2,5,6,17-19] have been published worldwide, all of which neglect the effect of whitecaps because those models are almost obtained at low or moderate wind speeds, at which conditions whitecaps are not generated at all or so small and thin that they can be neglected and thus the accuracy of 1.7 - 2.0 m/s stays the same all longer at present [6,20]. Eight representative sea surface wind speed inversion GMFs are summarized and compared in Table 1.

### Table 1. The selected model functions for retrieving wind speed

| GMF        | Scholar       | Derivation method            | Scope of U (m/s) | Matching method | Matched data | RMSE m/s |
|------------|---------------|-----------------------------|------------------|-----------------|--------------|----------|
| BR         | Brown (1981)  | Statistical regression      | 1-18             | GEOS-5          | 184          | 1.74     |
| SB         | Brown (1981)  | Smoothing BR                | 2-18             | --              | --           | 1.84     |
| CM         | Challen&Close (1985) | Statistical regression | 4-14             | Satellite      | 1967        | 2.37     |
| GS         | Goldhirsh & Dobson (1995) | Smoothing BR | 2-18             | --              | --           | 1.82     |
| CW         | Challen & Watts (1986) | Weighted regression | 0-20             | Satellite      | 240000      | 2.30     |
| WC         | Wittenberg & Kelton (1991) | Matching CW wind speed probability distribution | 0-20             | Satellite      | --          | 1.90     |
| YG         | Young (1995)  | Statistical regression      | 20-40            | GHP forecasting model | 192        | 2.0      |
| LF         | Leuter (1996) | Statistical regression      | Uniqua- l       | TOPAS-Scat     | 17004       | 1.75     |

The root mean square error (RMSE) of these eight wind speed inversion methods listed in Table 1 is various from 1.7m/s to 2.4 m/s. It is obvious that RMSE of those models’ wind speed inversion can be stabilized below 2 m/s [20]. Based on the data in Table 1, all the representative wind speed inversion methods can get satisfying results when the wind speed is less than 20 m/s except that Young(YG)[2] is the only recognized inversion method of high wind speed(20-40m/s). They are empirical mode function inversion method, and their accuracy of retrieving sea surface wind speed is mainly depend of the situ data. In order to improve the accuracy of retrieving sea surface wind speed sea states(e.g. significant wave height(SWH)) should be considered and several double-parameter models with SWH and sigma(0) are presented[18]. Another retrieval method is about semi-empirical and theoretical model presented by Zhao and Toba(ZT)[5] in 2003. ZT model includes mean square slope(MSS) and sea states et al. To this day, the accuracy of retrieving high wind speed is not satisfying is because the situ data at high wind speed is very scarce besides various complex sea surface conditions and the buoy limitation, and also actual high wind speed observed by buoy becomes unreliable.

In recent decades, scholars have been working to improve the retrieval accuracy of sea surface wind speed. There are mainly the following two aspects:

Firstly, try to consider various factors to improve the accuracy of wind speed inversion. Considering sea states, corrections[8-14] and other parameters such as wave age[5] and MSS[5,21], those measured parameters at a double frequency(Ku and C band) are introduced into the geophysical model functions(GMF)[21]. In [22] GMF of sigma(0) and SWH at Ku and C bands are expressed by

\[
U_{10} = a_0 + a_1 \sigma_{Ku}^2 + a_2 \sigma_{C}^2 + a_3 \sigma_{Ku} + a_4 \sigma_{C} \sigma_{Ku}^2 + a_5 \sigma_{C} \sigma_{C}^2 + a_6 \sigma_{Ku} + a_7 \sigma_{C} + a_8 \sigma_{Ku}^2 + a_9 \sigma_{C}^2 + a_{10} \sigma_{Ku}^2
\]

where \(a_i (i=0,1,2,\ldots,8)\) is constant defined by the matched data, \(U_{10}\) is sea surface wind speed at 10 m height from sea surface, \(\sigma_{Ku}\) and \(\sigma_{C}\) are Ku and C band backscatter coefficient of sea surface, SWHKu and SWHC are SWH values of sea surface measured by Ku and C band, respectively. Equation(1) not only considers influences of SWHKu and \(\sigma_{Ku}\), but also consider nonlinear effects of these parameters on \(U_{10}\). Since the electromagnetic scattering at C band is different from those at Ku band, equation (1) considers the effect of rainfall[8-14] in a certain degree.

In addition to this, Multi-source data joint[23] is introduced to consider more influencing factors of the high wind speed inversion. Besides of \(\sigma_{0}\) and SWH measured by the satellite altimeter[24], the brightness temperature(\(T_b\)), water vapor(\(W_V\)) and liquid water content(\(W_L\)) measured by the microwave radiometer[25-26] are incorporated into GMF in order to consider the rainfall effect and some other high wind conditions. In [25] the multi-parameter linear regression model with \(\sigma_{Ku}/\sigma_{C}\) and \(\sigma_{Ku}/\sigma_{C}\), but also consider nonlinear effects of these parameters on \(U_{10}\). Since the electromagnetic scattering at C band is different from those at Ku band, equation (1) considers the effect of rainfall[8-14] in a certain degree.

Secondly, In order to get high wind speed measurements and consider more relevant factors, Global Navigation Satellite Systems reflection (GNSS-R) technology(C band) has been developed to retrieve sea surface wind speed[]. Meanwhile, SAR technology and SAR image technology are developed to retrieve sea surface wind speed[30-37] recently. Its fundamental principles of retrieving sea surface wind speed are to depend on relationships between backscattering coefficient (or received power or SAR image power) and wind speed, or relationships between the received power waveform and wind speed[38-40]. In view of the huge amount of data, artificial neural network technology[40] is introduced for training to establish the model of scattering power, or power waveform and sea surface wind speed. These models mainly depend on the relationships between the sea surface wind speed and those relative parameters(scattering power or waveform) at C band. And also the scattering mechanism (scattering angle, polarity, time delay and et al)[40] is so complex that the improvement
of the accuracy of retrieving wind speed is still 1.5m/s or more than. The effects of rainfall and whitecaps still exist although rainfall and whitecaps have little attenuation of the electromagnetic scattering at C band.

Under high sea conditions, the sea surface will be covered with whitecaps [41], which changes its roughness and reflectivity. These whitecaps absorb the electromagnetic pulses emitted by satellite remote sensors instead of scattering them. As a result, the microwave signals received by remote sensors, such as SWIM and altimeter are very weak, with little or even deadlock echo energy, which then negatively influences the sea surface wind speed inversion accuracy [42]. It is known that these GMFs are well suitable for retrieving sea surface wind speeds at low and moderate wind speeds, but do not perform well at high wind speed due to the whitecaps’ effect. Monahan et al. [43] and Bondur et al. [44] proposed an empirical relationship between the whitecaps’ coverage and wind speed. However, Anguelova and Webster [45] reported that in addition to wind speed, whitecap coverage is also related to numerous other environmental factors, such as seawater temperature, salinity, material composition, wind duration, and atmosphere temperature, etc. In the paper those conditions and influencing factors of whitecaps generation are not studied. Here the effect of whitecaps on the sea surface backscattering, by which the sea surface wind speeds are retrieved, will be studied and calculated in terms of a multilayer medium model. Using the scattering theory of layered media, Zheng et al.[41] concluded that the effect of whitecaps on altimeter measurements cannot be ignored in high sea conditions, and correct Brown’s wind speed model in terms of a three-layer medium scattering model. In fact, this method by Zheng et al.[41] can do well for some analytical models but can not for empirical models. In the other hand, Zheng et al.[41] neglected the effect of spray droplets. Herein, the whitecaps’ effect was calculated in terms of a four-layer medium scattering model to correct the sea surface wind speed based on the data from SWIM. The presented Cyclic Iterative Correction Algorithm(CICA) can correct the analytical models and also correct those empirical models to remove the effect of whitecaps on retrieving sea surface wind speeds. In the end, the results were compared with buoy data, which demonstrated that this implementing correction improved the accuracy of retrieving sea surface wind speed by 0.5 m/s (2 to 1.5 m/s).

In this article, the microwave reflectivity of a whitecap-covered sea surface was quantitatively calculated based on the electromagnetic field theory, and then the whitecaps’ effect on the remote sensor’s echo pulse was subsequently evaluated. Furthermore, the relationship between whitecaps and sea surface wind speed was investigated and the backscattering attenuation caused by the presence of whitecaps was analyzed. In addition, the accuracy and applicability of several wind speed retrieval models were investigated and compared with each other. Finally, in order to eliminate completely these effect of whitecaps at high wind speeds a new CICA was presented and applied to data measured by SWIM. the results were validated against buoy data to find its accuracy in retrieving and correcting sea surface wind speed.

II. THE EFFECT OF WHITECAPS ON SEA SURFACE BACKSCATTERING

Herein, a four-layer medium model was established to calculate the backscattering from the rough sea surface. The calculated results would be applied to correct the retrieved wind speed.

A. THE FOUR-LAYER MEDIUM AND ITS REFLECTIVITY

As described above, under high sea conditions (wind speed > 7 m/s), sea surface waves begin to break and generate a large amount of whitecaps which covers the sea surface and absorbs the electromagnetic pulses emitted by the satellite remote sensors. In general, it has been illustrated that whitecaps reduce the sea surface backscattering, resulting in overestimated wind speed. Foams are comprised of seawater and air, with air potentially accounting for 94% -97% of the foam [41,46]. When the wind speed reaches 25 m/s, more than a third of the sea surface is covered with foams and spray droplets [47]. The physical properties of foams and spray droplets are different from those of seawater and air, it is an example for the reflectivity. Moreover, the thickness and coverage of foams and spray droplets will also affect the sea surface backscattering.

Figure 1 depicts a four-layer medium model with a three-interface surface. As an example, the sea surface is covered by spray droplets and foams at high sea conditions. The top surface \( z_1 \) separates free space (or the air) from a homogenous medium (spray droplets dielectric constant \( \varepsilon_0 \), permeability \( \mu_0 = \mu_1 \)); The second surface \( z_2 \) separates spray droplets, with layer thickness \( d_1 \), from another homogenous medium (foams dielectric constant \( \varepsilon_2 \), permeability \( \mu_2 = \mu_3 \)); and the bottom surface \( z_3 \) separates the foams, with layer thickness \( d_2 \), from the bottom half space (sea water dielectric constant \( \varepsilon_3 \), permeability \( \mu_3 = \mu_0 \)). It is obvious that \( z_2 = z_1 + d_1 \) and \( z_3 = z_1 + d_1 \) are valid because spray droplets and foams all float on the sea water.
Similarly, the reflection coefficient of an incident wave with parallel polarization (or called as TM wave) can be derived from electromagnetic theory and mathematically given as:

$$R_{TM} = \frac{H^r_{TM}}{H^i_{TM}} = \frac{R_{a} + R_{b} e^{jkz} + R_{c} e^{2jkz} + R_{d} e^{3jkz}}{1 + R_{a} e^{jkz} + R_{b} e^{2jkz} + R_{c} e^{3jkz}}$$

where

$$R_{m(n+1)} = \frac{1 - \mu_{m} k_{z(n+1)}}{1 + \mu_{m} k_{z(n+1)}} \quad m=0,1,2$$

and $H^i_{TM}$ is the amplitude of the incident field intensity, and $H^r_{TM}$ is the amplitude of the reflected magnetic intensity. Thus the total reflectivity of a whitecap-covered sea surface can be mathematically expressed as:

$$R_{r} = \left| R_{TM} \right|^2$$

Equation(12) can be used to obtain the electromagnetic scattering characteristics of the four-layer medium model, by setting $\theta = 0^\circ$ at the SWIM nadir and $R_{TM} = R_{TM}$. When only a foam layer exists (Figure 2), as the foam layer increases to 5 cm (Figure 3a), the sea surface reflectivity gradually decreases to $\approx 0.0445$ and the sea surface wind speed reaches 45 m/s (Figure 3b). The oscillations in the descending reflectivity curve are a product of the electromagnetic wave being absorbed by the foam layer. The foam can decrease the sea surface backscattering coefficient ($\sigma^b$) by $\approx 11.4$ dB, resulting in the radar encountering blind spots at high sea conditions. Figures 4a and b show that when the thickness of the spray droplets layer reaches 36.75 cm and the sea surface wind speed is about 7 m/s, the sea surface reflectivity and backscattering coefficient ($\sigma^b$) will rapidly decrease to $\approx 0.238$ and $\approx 4.07$ dB, respectively. Figures 5a and b present the trend observed when foam and spray droplets are jointly considered, and clearly show that the sea surface reflectivity begins to descend from 0.608 to 0.2336 when the sea surface wind speed reaches 7 m/s. Thus, the sea surface backscatter coefficient ($\sigma^b$) will decrease by $\approx 4.154$ dB. These results demonstrate that the effect of whitecaps should not be neglected when the sea surface wind speed is more than 7 m/s.
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B. THE BACKSCATTERING OF A WHITECAP-COVERED SEA SURFACE

Whitecap-coverage is defined as the proportion of sea covered by whitecaps relative to the visible sea surface area. Whitecaps begin to develop on the sea surface when wind speed reaches 7 m/s. Moreover, the whitecap-coverage grows larger and thicker as a function of increasing sea surface wind speed ($U_{10}$). As such, understanding the relationship between the degree of whitecap-coverage and wind speed ($U_{10}$) and calculating the backscattering coefficient ($\sigma^b$) of a whitecap-covered sea surface are pivotal to the development of an accurate and applicable correction for the wind speed retrieval.

The presence of any whitecap-coverage will affect the electromagnetic backscattering from the rough sea surface. Currently, there are two kinds of whitecap models: 1) analysis model—analyzes the energy lost by the breaking wave, in this case, the waveform’s effective slope serves as the input independent variable; and 2) empirical model—applies statistical methodology formulas, in this case, wind speed serves as the input independent variable. For the purposes of this study, the empirical model was deemed more suitable for correcting the wind speed ($U_{10}$) and was selected for use. Table 2 and Figure 6 depict the relationships between the whitecap-coverage ($C$) and wind speed ($U_{10}$). Note that when the wind speed is more than 7 m/s, the whitecap coverage percent significantly increases in Figure 6. Thus, the influence of whitecaps on wind speed inversion must be considered. In order to comprehensively consider the impact of whitecaps on wind speed retrieving, a geometric mean solution was selected to analyze the relationships between the whitecap-coverage ($C$) and wind speed ($U_{10}$):

\[
C = (4.4 \times U_{10}^2 + 1.35 \times 10^{-6} U_{10}^{1.4} + 1.55 \times 10^{-7} U_{10}^{1.75}) + 1.7 \times 10^{-8} U_{10}^{3.52} + 7.75 \times 10^{-6} U_{10}^{3.211} + 2.95 \times 10^{-7} U_{10}^{3.32} + 3.84 \times 10^{-8} U_{10}^{4.41}/7\quad U_{10} \leq 20\text{ m/s (13a)}
\]

\[
C = (7.75 \times 10^{-8} U_{10}^{3.211} + 2.95 \times 10^{-7} U_{10}^{3.32} + 3.84 \times 10^{-8} U_{10}^{4.41})/3,\quad 20\text{ m/s} < U_{10} \leq 35\text{ m/s (13b)}
\]

\[
C = 3.84 \times 10^{-6} U_{10}^{4.41},\quad 35\text{ m/s} < U_{10} < 40\text{ m/s (13c)}
\]

Table 2  The relationships between whitecap-coverage ($C$) and wind speed ($U_{10}$)

| Scholar(s)          | $C$         | $U_{10}$ (m/s) |
|---------------------|-------------|----------------|
| Blanchard [1963]    | 4.4 $\times$ $10^{-4} U_{10}^2$ | 5.1–20.6       |
| Monahan [1971]      | 1.35 $\times$ $10^{-4} U_{10}^{1.4}$ | 4–10          |
| Toba et al. [1973]  | 1.55 $\times$ $10^{-4} U_{10}^{1.75}$ | <20           |
| Tang [1973]         | 7.75 $\times$ $10^{-4} U_{10}^{0.231}$ | <35           |
| Wu [1979]           | 1.7 $\times$ $10^{-4} U_{10}^{0.52}$ | <20           |
| Monahan et al. [1980] | 2.95 $\times$ $10^{-4} U_{10}^{0.52}$ | <35           |
| Monahan et al. [1980] | 3.84 $\times$ $10^{-4} U_{10}^{0.41}$ | <40           |
C. WIND SPEED INVERSION

In general the sea surface wind speed inversion can be obtained using GMF, which defines the relationships between the sea surface wind speed \( U_{10} \) and geophysical parameters such as the backscattering coefficient \( \sigma^0 \), or significant wave height (SWH)[18], etc. Since 1980’s there have been several traditional methods for obtaining sea surface wind speed \( U_{10} \). In figure 7 several algorithms are plotted with relationships between wind speeds \( U_{10} \) and backscattering coefficients \( \sigma^0 \). Note that all the presented algorithms show that sea surface wind speed \( U_{10} \) increases as the backscatter coefficient \( \sigma^0 \) decreases. At wind speed \( U_{10} < 10 \text{ m/s} \), all the presented algorithms depict consistent results, which is particularly evident around 7 m/s. However the differences among these algorithms become progressively larger as the sea surface wind speed \( U_{10} \) increases until it reaches 20 m/s—i.e., high sea conditions. As such, these algorithms do not accurately obtain high wind speeds. It is obvious that almost all the algorithms agree well in the range of 7-10 m/s, and converge together, but when the wind speed is more than 10 m/s, they begin to disperse, and also the difference is become bigger and bigger with the wind speed increasing. It is illustrated that the accuracy of retrieving sea surface wind speed is not so the same good at high wind speeds as at low or medium wind speeds. Almost all algorithms can do well when the wind speed is less than 10 m/s, but begin to show a big bias compared with buoy data when the wind speed is more than 10 m/s. One reason is that a great deal of whitecaps is generated at high wind speeds while there are few whitecaps on sea surface at low or moderate wind speeds. Thus many algorithms are not suitable for retrieving high wind speeds. Those whitecap absorption reduces the sea surface backscatter coefficient \( \sigma^0 \), which results in the estimated sea surface wind speed being higher than it is in reality. The another reason is that the measured data is scarce at high wind speeds. Now only one algorithm is known as the High Wind Speed Empirical Algorithm\([20-40\text{ m/s}]\), namely YG algorithm[2,50] presented by Young in 1993, which can be applied for retrieving high wind speeds under high sea conditions, as shown in figure 7.

In 1986 considering effect of spray and foam R.M. Gairola et al presented the corrected DMF[41]

\[
\sigma^0 = R_s(1 - C) + R_C\left[ \ln U_{10} + b \right] \tag{16}
\]

Where

\begin{align*}
\alpha &= 0.010, \quad b = 0.012, \quad U_{10} \leq 7 \text{ m/s} \tag{17} \\
\alpha &= 0.85, \quad b = -0.145, \quad U_{10} > 7 \text{ m/s} \tag{18}
\end{align*}

Equation (14) corrected by the effect of whitecaps with a three-layer medium model and a four-layer medium model is plotted in Figure 8. When the sea surface wind speed is more than 15 m/s, the reflectivity of the three-layer model is 0.038 and closer to zero while the reflectivity of the four-layer model is 0.24. It is obvious that the four-layer medium model is closer to practices (or Young model and Brown model) than the three-layer medium in Figure 8. In this paper, the four-layer medium model will be applied for correcting the retrieved wind speed.
These parameters (including $a_1, b_1, a_2, b_2, a_3, b_3$) are defined by net training. Equations (19) ~ (23) can be expressed as a two-parameter (SWH and $\sigma^0$) inversion algorithm [18] as follows:

$$U_{10}(i) = a_0 + a_1 \text{SWH} + a_2 \sigma^0 + a_3 \text{SWH}^2 + a_4 \sigma^2$$

where parameter $a_y$ can be obtained by matching wind speed data, and $i$ or $j=0,1,2$ represents the first and the second power of the corresponding parameters, respectively. Similarly, Equation (19) ~ (23) and parameters are obtained by matching wind speed data at low or moderate wind speeds, and are not suitable for retrieving high wind speeds. That is to say, equation (24) is established by the measurements by buoys at low or moderate wind speeds and is not proper for retrieving the sea surface wind speed at high wind speeds because the data including the case of high wind speed is scarce or the wind speeds measured by buoys at high wind speeds are unreliable. And thus the high wind speeds retrieved by equation (24) need to be corrected by eliminating the effect of whitecaps to improve the accuracy of retrieving high wind speeds.

**III. THE NEW CYCLIC ITERATIVE CORRECTION ALGORITHM FOR RETRIEVING WIND SPEED($U_{10}$)**

In general, model functions which are currently being applied are usually obtained from these measurements or situ data at low or moderate wind speed—scenarios in which the whitecaps’ effect can be neglected. However, whitecaps—including spray droplets and foams—will significantly cover the sea surface when the wind speed is more than 7 m/s, and are particularly prevalent when the wind speed is $> 20$ m/s shown in figure 6. These whitecaps covered the sea surface, resulting in the reduction of the sea surface backscattering coefficient. As a result, the retrieved wind speed based on the backscattering coefficient is larger than the actual wind speed and the error progressively enlarges as the wind speed increases. Therefore, it is necessary to eliminate the whitecaps’ effect in order to improve the wind speed inversion accuracy, especially at high sea states (i.e., high wind speed).

In this paper we propose a new cyclic iterative correction algorithm of retrieving wind speed to eliminate those whitecaps’ effect, as described below:

1) The sea surface wind speed ($U_{10}(0)$), measured by SWIM, was selected to obtain the whitecaps’ coverage at the measured point. It is expressed as:

$$C(i) = f(U_{10}(i-1))$$

where $i=1,2,3,..., f(U_{10}(i-1))$ can be obtained in terms of Equation (13).

2) The whitecaps’ coverage $C(i)$, obtained in Equation (13) was substituted into Equation (14) and (15) to obtain the backscattering coefficient attenuation ($\Delta \sigma^0(i)$).

3) The backscattering coefficient attenuation ($\Delta \sigma^0(i)$) was added to the backscattering coefficient $\sigma^0(i)$ measured by SWIM to obtain the corrected backscattering coefficient ($\sigma^0(i)$).

4) The corrected backscattering coefficient ($\sigma^0(i)$) and the SWH measured by SWIM were substituted into Equation (19) or Equation (24) to obtain the corrected wind speed ($U_{10}(i)$).

5) The corrected wind speed ($U_{10}(i)$) was then input into step (1) to obtain the new whitecaps’ coverage ($C(i)$) again.

The process was repeated until the backscattering coefficient ($\sigma^0(i)$) reached a stable value (i.e., the difference between two successive steps was less than a given infinitesimal value). To a large extent, these loop iterations successfully eliminated the effect of whitecaps on the sea surface backscatter coefficient, and thus correct the overestimated wind speed. The new CICA lies in equation (26), it is different from $\sigma^0(i+1)=\sigma^0(i)+\Delta \sigma^0(i)$.

The effect of whitecaps on SWH will be neglected in this paper [41].

**IV. VALIDATION AND APPLICATION OF THE NEW CYCLIC ITERATIVE CORRECTION ALGORITHM**

**A. WIND SPEED CORRECTION**

SWIM Tracks of July, August, September and October in 2019 are chosen, as shown with red lines in figure 9. And Positions of buoy are denoted by red triangles in figure 10.
A large amount of original data is shown in Figure 11(a) noted by blue points (501169 points). In order to correct high wind speeds these original data is arranged from the small to the large values and plotted in Figure 11(b) noted by a red line (red dots look like a line). The horizontal axis is the number of data and the vertical axis is the wind speed. In this paper the wind speeds with being more than 10m/s are chosen. In figure 12(a) and figure 12(b) the measured data from SWIM are arrayed and plotted by red solid line (red dots). Those data corrected by the new CICA are shown by black * sign in Figure 12(a) (106032 sampling points) and Figure 12(b) (24091 sampling points). However, the distribution of those red dots is not uniform, after these dots (wind speeds) are corrected, those dots will move down a different distance (corrected values) and constitutes that picture plotted by * sign. The picture can be understood from Figure 11. In figure 12 the red line (red dots) represents the original measured data which is arrayed from the small to the large values according to the wind speeds. The amount of data (red dots) is equal to the corrected ones noted by black * sign.

Figure 11 The original measurements from SWIM are chosen. In figure 12(a) and figure 12(b) the measured wind speeds are from 10m/s to 15m/s, the bias of the corrected data from the original ones is 0.3548m/s, which is illustrated that the effect of whitecaps is so small that it can be neglected although the improvement of the new presented algorithm on retrieving wind speed can be obtained in a certain degree. In figure 12(b) the wind speeds are from 15m/s to 20m/s.
20m/s, the bias of the corrected data from the original ones is 1.1427 m/s, which is illustrated that the effect of whitecaps is so obvious that it cannot be neglected, and the improvement of the new algorithm on retrieving wind speed has been obtained to a large extent.

Table 3 Several measured values and corrected values

| Original value (m/s) | Corrected value (m/s) |
|---------------------|-----------------------|
| 7.3379              | 7.2966                |
| 8.8415              | 8.94546               |
| 9.1812              | 9.130756              |
| 9.4406              | 9.170027              |
| 9.5683              | 9.159193              |
| 9.6481              | 9.640864              |
| 10.1963             | 10.01745              |
| 10.292              | 9.817895              |
| 10.4492             | 9.188013              |
| 10.7285             | 9.630819              |
| 12.2541             | 9.828452              |
| 12.4451             | 9.816329              |
| 12.5004             | 9.569241              |
| 13.8533             | 9.727822              |
| 13.9352             | 9.715949              |

Similarly, some original measured data from SWIM and the corrected ones by the new algorithm are shown in Table 3, the difference between them is become larger and larger with the wind speed increasing. Firstly, let original values arrayed from the small to the large value and plotted, as shown in Figure 13.

B. COMPARED WITH BUOY DATA

The CFOSAT satellite data were matched to the buoy data with a matching time window of 30 min and a space window of 50 km. The NDBC buoy data used in this study were provided by NOAA (National Oceanic and Atmospheric Administration). Those positions are shown in Figure 10. Those data from SWIM during several months such as July and August are shown in figure 13, which are more than 10 m/s. Before corrected by the new CICA, RMSE of those measured wind speeds compared with the corresponding buoy wind speeds is 2.15 m/s and the mean bias is 1.69 m/s as shown in figure 13. After corrected by the new CICA, RMSE of wind speeds measured by SWIM is reduced to 1.38 m/s and the bias is also reduced to 0.91 m/s as shown in figure 14. It is obvious that the correction is very large.

In addition to the above, the data from SWIM and NDBC during September and October is also studied. It has been established that the sea surface waves break and produce foams and spray droplets, when the wind speed is ≥ 7 m/s. Similarly, to eliminate the whitecaps’ effect, herein, the new CICA was applied to correct those wind speeds with being more than 7 m/s. After invalid data were filtered out, the relationships between the measured wind speed and backscatter coefficient were analyzed for each point. The relationships were shown in figure 15, where the backscatter coefficient (\( \sigma^0 \)) is inversely related to wind speed (\( U_{10} \)). It is to say, the radar cross-section (\( \sigma^0 \)) is a decreasing function of wind speed. Obviously, there are few data of wind speed greater than 15 m/s, that is, there are few data of higher wind speed.
V. CONCLUSIONS

In this article, a four-layer medium model including foams was established to calculate the backscatter coefficient. When the incident angle was 0°, and the sea surface was covered with only the foam layer, the sea surface reflectivity gradually decreased from 0.608 to ~ 0.0445. In the other hand, the thickness of foam layer increased to 5 cm when the sea surface wind speed reached 45 m/s. This foam can cause RMSE and bias were reduced by 5.8% and 56%, respectively, relative to the original values. It is also obvious that the improvement of correcting high wind speeds such as being more than 12 m/s. In summary, the new CICA proposed herein can effectively improve the wind speed inversion accuracy, especially high wind speeds.

Note that after applying CICA, the RMSE of the measured wind speed ($U_{10}$) corresponding to the buoy wind speed ($U_{true}$) was reduced to 1.13 m/s and the bias reduced to 0.14 m/s. As shown, the overestimated high wind speeds ($U_{10} >12$ m/s) are corrected and become much smaller, while low or moderate wind speeds ($U_{10} <12$ m/s) almost maintained their original value, as shown in Figure 18. After applying the wind speed ($U_{10}$) iterative correction, the
the sea surface backscatter coefficient ($\sigma^0$) to decrease by $\sim 11.4$ dB, resulting in radar blind spots at high sea conditions. When the sea surface wind speed was $\geq 7$ m/s, a four-layer medium model with having the spray droplets layer was established to calculate the backscattering coefficients. The spray droplets layer can have a thickness of $36.75$ cm and cause the backscattering coefficient to decreased rapidly from $0.608$ to $0.238$. Namely, the sea surface backscattering coefficient ($\sigma^0$) decreased to $4.07$ dB. Overall, when the sea surface wind speed was $\geq 7$ m/s, the sea surface reflectivity began to rapidly decrease and the sea surface backscattering coefficient also decreased. The whitecaps’ effect should not be neglected when the sea surface wind speed is $\geq 7$ m/s. As such we proposed a new Cyclic Iterative Correction Algorithm for correcting the sea surface wind speed, specifically at high wind speeds, and discussed in detail the steps for carrying out the wind speed correction. Finally, the new proposed algorithm was applied to retrieve and correct sea surface wind speed measured by SWIM. By comparing the corrected results with the buoy data provided by NDBC the new algorithm can reduce the RMSE and bias by $58\%$ and $56\%$, respectively, relative to the original values. It can obtain a conclusion that the new proposed algorithm was applied to retrieve and correct sea surface wind speed in terms of the measured data is less than $1.5$m/s after corrected by the new Cyclic Iterative Correction Algorithm. These results are in good agreement with both the theoretical concepts and empirical data discussed herein and demonstrate that the new algorithm can effectively remove the whitecaps’ influence on high wind speed inversion, and thereby improve its accuracy. Results form an additional study concerning whitecaps’ effect on SWH will be published in a future article.

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