The Effect of Whitecaps on the Parameters Measured by Altimeter

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Abstract. Under the impact of offshore rocks or high sea states such as typhoons, cyclone and so on, the sea water breaks into foams or is spilled into the air and becomes droplets. These foams and droplets cover the sea surface, which will attenuate or even absorb the electromagnetic wave emitted by the altimeter, and will affect the altimeter's measurements such as the sea surface height (SSH), the significant wave height (SWH) and the sea surface backscattering coefficient $\sigma_0^0$. In this paper, the effect of sea foams and droplets on parameters measured by altimeter: backscattering coefficient $\sigma_0^0$, SSH and SWH and so on, is studied by means of electromagnetic scattering theory analysis, numerical calculation and simulation. Some data and error correction tables of some parameters are given, which are beneficial to business error correction.

Introduction

Under the impact of offshore rock and land, or on high sea conditions such as typhoon and hurricane, the sea water breaks and sprays into the air to form the surface whitecaps (including foams and droplets)[1-3]. The white foams has a strong attenuation and absorption effect[4-5] on the electromagnetic wave emitted by the satellite radar altimeter (referred to as the altimeter) of detecting the marine dynamic environment. As a result, parameters such as sea surface height, significant wave height and backscattering coefficient $\sigma_0^0$ measured by the altimeter are affected[4]. Both domestic and foreign scholars have studied the attenuation effect of foams on electromagnetic wave in details[6-9]. However, the effect of droplets and foams on sea surface height (SSH) and significant wave height (SWH) has not been fully studied, nor have the operationalized error correction tables been provided. In this paper, electromagnetic scattering theory and electromagnetic calculation method are used to calculate the attenuation characteristics of droplets and foams on the altimeter electromagnetic pulse. Secondly, the sea surface echo is simulated to analyze the influence of foams on the significant wave height measured by altimeter.

The Effect of Whitecaps

The Model of Whitecaps

When the sea wind speed is more than 7m/s, the air is involved into the sea water and at the other hand the sea water is thrown into the air. And thus the whitecaps including foams and droplets will cover the sea surface. The electromagnetic pulse emitted by the altimeter firstly passes through the atmosphere, and then plunges into the droplets and foams layer on the sea surface, and finally onto the seawater layer. Due to the influence of environmental factors such as the surface wind speed, tide and ocean current and so on, these three interfaces are random rough surfaces, for example the interface between the atmosphere and droplets layer, the interface between the droplets and foams layer and the interface between the foams and seawater’s layer. Of course, these three rough surfaces are mainly related to sea surface wind speed[1-2,10], and related each other. In order to study conveniently we assume that the three rough surfaces have the same RMS height and correlation length. The model with four medium layers and three rough surfaces is shown in figure 1. It is known that a rough
surface model is mainly defined by sea spectrum, root mean square height and correlation length. In figure 1 the multi-layer rough surface model is about the gaussian distribution and has the same RMS and correlation length. It is also obvious that the mean square root height of rough sea surface increased with the increase of sea surface wind speed. On the contrary, as sea surface wind speed decreases, the root-mean-square height of rough sea surface decreases and the correlation length decreases. In order to simplify the calculation and workload, this paper mainly studies the electromagnetic scattering characteristics of one-dimensional multilayer rough surface model, as shown in figure 2. Figure 2(a) is a one-dimensional rough surface profile, Figure 2(b) and figure 2(c) are local electromagnetic incident reflection physical models.

Figure 1. Two-dimensional rough surfaces.  
Figure 2. One-dimensional rough surface profile.

The Calculation of Whitecaps

It is known that the sea surface coverage and thickness of the foam layer and droplet layer are mainly related to sea surface wind speed $U_{10}$ (wind speed at 10m above sea level) in addition to the physical properties of sea water such as temperature and salinity[6]. There exists an empirical relationship between the thickness of foam layer $d_1$ and the thickness of foam layer $d_2$ [11-12]:

$$d_1 = 0.0075U_{10}^2$$

$$d_2 = \begin{cases} 0.004 & U_{10} \leq 7\text{m/s} \\ 0.004 + (U_{10} - 7) \times 0.0012 & U_{10} > 7\text{m/s} \end{cases}$$

According to the electromagnetic scattering theory of layered medium[4,13], the total electromagnetic reflection coefficient $R$ of the multilayer medium model shown in figure 2(b or c) can be given as

$$R = \frac{R_{01} + R_{01}R_{12}R_{23}e^{-j2k_{zm}d_2} + R_{12}e^{-j2k_{zm}d_1} + R_{23}e^{-j2k_{zm}d_1-j2k_{zm}d_2}}{1 + R_{01}R_{23}e^{-j2k_{zm}d_2} + R_{01}R_{12}e^{-j2k_{zm}d_1} + R_{01}R_{23}e^{-j2k_{zm}d_1-j2k_{zm}d_2}}$$

where $k_{zm}^2 = k_m^2 - (k_0\sin\theta)^2$, $m=1,2$. For the horizontal polarization(or TE) wave, the reflection coefficient $R$ is defined by the ratio of the reflected electric field intensity $E_0^-$ to the incident electric field intensity $E_0^+$, namely $R = E_0^- / E_0^+$ and

$$R_{m(m+1)} = \frac{1 - \frac{\mu_m k_z(m+1)}{\mu_{m+1} k_{zm}}}{1 + \frac{\mu_m k_z(m+1)}{\mu_{m+1} k_{zm}}}$$

$$R_{m(m+1)} = \left(1 - \frac{\mu_m k_z(m+1)}{\mu_{m+1} k_{zm}}\right) / \left(1 + \frac{\mu_m k_z(m+1)}{\mu_{m+1} k_{zm}}\right)$$
where \( m=0,1,2 \). For the vertical polarization wave (or TM wave), the reflection coefficient \( R \) is defined by the ratio of the reflected magnetic field intensity \( H_0^- \) to the incident magnetic field intensity \( H_0^+ \), namely \( R = H_0^- / H_0^+ \), and

\[
R_{m(m+1)} = \left( 1 - \frac{\varepsilon_m k_z (m+1)}{\varepsilon_{m+1} k_m} \right) / \left( 1 + \frac{\varepsilon_m k_z (m+1)}{\varepsilon_{m+1} k_m} \right)
\]  

(5)

where \( m=0,1,2 \). In terms of equation (3) the electromagnetic scattering characteristics of foams and droplets can be calculated and analyzed.

**The Effect of Foams and Droplets on the Scattering of Rough Sea Surface**

The generation of foams and droplets is mainly related to wind speed. The static sea surface with zero wind speed has no whitecaps covering. The electromagnetic wave (Ku band 13.9GHz) reflectivity (reflection coefficient square \( R^2 \)) can reach about 0.607 with no whitecaps covering the sea surface, as shown in Figure 3. When there exists only the foam layer, the reflectivity of the sea surface gradually decreases to about 0.0421 when the thickness of the foam layer increases to 5cm. The oscillations in its descending process are because the electromagnetic wave is absorbed by the foam layer. These foams can cause the sea surface backscattering coefficient \( \sigma^0 \) to decrease about 11.5dB, resulting in blind spots for a radar. When the thickness of the foam layer is 5mm, the reflectivity of the sea surface will rapidly decay to 0.2 or so, and the sea surface backscattering coefficient \( \sigma^0 \) will decrease about 4.7dB.

Therefore, the presence of foams greatly attenuates the electromagnetic pulse emitted by the altimeter and causes the backscattering from the sea surface to decrease. Thus when the sea surface wind speed is retrieved by the backscattering coefficient of the sea surface, it will be overestimated, resulting in a larger error of the sea surface wind speed. This effect has been studied by some scholars.

When the wind speed is greater than 7m/s, the thickness of the droplet layer will reach 0.37m according to empirical formula (1). At this time, the electromagnetic reflectivity of the sea surface will start decreasing and situate stably at 0.236 or so in the end, as shown in Figure 4 and 5. From figure 3 and 4, it is obvious that the droplet layer has a stronger reflection effect on the altimeter electromagnetic pulse (Ku band) than the foam layer, which has larger attenuation and absorption characteristics.

Since the droplets and foams have attenuation effect on the electromagnetic pulse of the altimeter, the measurements of the backscattering coefficient of the sea surface by altimeter will be affected by them. The reflectivity of the sea surface decreases from 0.607 to 0.236, or even 0.0421 or zero, which can cause blind spots for the radar.

![Figure 3. The attenuation of wave by foams(Reflectivity).](image)

![Figure 4. The reflectivith of the droplet layer.](image)
The Effect of Foams and Droplets on SSH and SWH

The reflectivity of the sea surface is 0.0421 or even 0 at ku band when foams cover the sea surface, while the reflectivity is 0.236 when foams and droplets cover the sea surface. This calculated result indicates that droplets not only have a larger effect of reflecting the electromagnetic pulses emitted by the satellite radar altimeter and but also reflect back the electromagnetic pulses early before they arrive at the sea surface or the foam layer due to the larger reflection effect. And thus the measured range from the satellite to the sea surface is the range from the satellite to the droplets. The sea surface height (SSH) will be overestimated because of the range. The measured SSH is in fact the height of the interface between the droplet layer, the foam layer and the sea water mixture. The order of the bias will be the same as the thickness of the droplet layer.

The foams cause the electromagnetic pulse of satellite radar altimeter attenuated to a great extent, especially the reflectivity of the sea surface to zero, and thus blind spots for the radar generate. When blind spots appear, the probability density function (pdf) of sea surface height appears zero, and the distribution characteristics of pdf are shown in figure 6. Therefore, the coverage of foams changes the probability density function of sea surface height, which distorts the echo waveform and thus affects the inversion value of significant wave height (SWH).

In order to study the effect of foams on SWH, some calculations and simulations are planned as follows:

1) Given the coverage of foams $W_s$, the PDF of Gaussian height distribution is modified according to the coverage as the same method as figure 6.
Table 1. The comparison of several SWH inversion values with true values.

<table>
<thead>
<tr>
<th>Coverage of whitecaps/ Ws %</th>
<th>SWH(true) /m</th>
<th>SWH(retrieved) /m</th>
<th>Bias: the retrieved - the true</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>4</td>
<td>3.9643</td>
<td>-0.0357</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>3.9616</td>
<td>-0.0384</td>
</tr>
<tr>
<td>11</td>
<td>8</td>
<td>7.1170</td>
<td>-0.8830</td>
</tr>
<tr>
<td>21</td>
<td>4</td>
<td>3.6450</td>
<td>-0.3550</td>
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<tr>
<td>21</td>
<td>8</td>
<td>6.6493</td>
<td>-1.3507</td>
</tr>
<tr>
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<td>4</td>
<td>3.4651</td>
<td>-0.5349</td>
</tr>
<tr>
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<td>8</td>
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<td>-2.6313</td>
</tr>
<tr>
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</tr>
<tr>
<td>61</td>
<td>12</td>
<td>6.4799</td>
<td>-5.5201</td>
</tr>
</tbody>
</table>

(2) Given the significant wave height (SWH) $H_s$ which is considered to be the true (real) value, the simulated echo waveform is calculated by using three terms’ convolution: the flat sea surface response, the point target response and the modified probability density function of sea height distribution.

(3) The simulation echo is fitted and calculated using the ocean echo waveform model [14], and the SWH $H_s'$ is retrieved. We can study the influence of foams on SWH inversion by obtaining the difference between $H_s$ and $H_s'$. The results of calculations and simulations are shown in figure 7. Obviously, the coverage $W_s$ of foams and SWH vary with the sea surface wind. When the wind speed is large, the foam coverage $W_s$ and SWH are larger. The difference between the inversion value and the true value becomes very large when SWH and wind speed are getting larger. Moreover, the inversion value is smaller than the true value, and the error is related to SWH, as shown in table 1. Table 1 is a comparison of several typical values at several sea states.

Summary

In this paper, the effects of foams and droplets on sea surface parameters measured by satellite altimeter are studied.

(1) Under the impact of the coastal rocks, or under the high wind speed and high sea conditions, the air is involved in the sea water, and the sea water is thrown into the air to form the foam and droplet layer.

(2) The foam layer has a great attenuation effect on the electromagnetic pulse emitted by the altimeter, which makes the electromagnetic wave (Ku band) reflectivity rapidly decay from 0.6 to 0.2, even to 0.0421 or nearly 0, resulting in blind spots of the radar, which affects the measurement of the backscatter coefficient of the sea surface. The occurrence of the blind spot distorts the probability density function (pdf) of the sea surface height, and thus the probability density function distorts the echo of the sea surface, which results in a smaller value of the measurements of SWH.

(3) The droplet layer attenuates the electromagnetic pulse emitted by the altimeter. The reflectivity of the sea surface for Ku band decays from 0.607 to 0.236 and rests on 0.236. Compared with the foam layer the droplet layer plays a role of reflecting electromagnetic wave because the reflectivity of the model of the air, droplet, foam and sea water layer is 0.236 while the reflectivity of the model of the air, foam and sea water layer is 0.0241. Before the wave reaches the sea surface, the droplets reflect back to the altimeter in advance, which shortens the distance between the satellite and the sea surface and affects the altimeter’s altitude measurement.
(4) The effect of foams on SWH is simulated and calculated. The inversion value and the error are given at several different sea states. These data and corrections will give a help for the measurements by the radar altimeter.

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References