Sea surface wind speed retrieval and validation with future SWOT data

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Abstract. The paper focuses on the sea surface wind speed retrieval and validation using the future SWOT data. Ka band backscatter coefficient and wind speed were simulated by using the theoretical model of Quasi-specular scatter and the simulated position of observation point. The Ka band model function of incident angles from 1° to 4° was proposed based the form of KuLMOD2. Wind speed was retrieved by using Ka band model function, and the results of validation show that the RMSE (Root Mean Squared Error) is 0.35. Therefore, the wind speed retrieval was validated with the ECMWF, which showed good coincidence. Ka band model function was proposed for applicable to the future SWOT data.

1. Introduction
At present, microwave scatterometer, synthetic aperture radar (SAR), radar altimeter and microwave radiometer are the main remote sensors used to observe sea surface wind field. The Tiangong-2 three-dimensional imaging microwave altimeter was launched on September 15, 2016, it has the characteristics of wide swath and high spatial resolution. Ren et al. (2018)[1] established KuLMOD2 for incident angles of 0° to 9°, which is revised version of the former Ku-band low incidence backscatter model (KuLMOD) (Ren et al., 2016)[2]. Gaultier et al. (2016)[3] presents simulator for Surface Water and Ocean Topography (SWOT). Using the simulator tool, synthetic SWOT observations can be generated to explore new techniques of SSH mapping. The simulated SWOT observations have been analyzed.

With the successful launch of Tiangong-2 3D imaging altimeter and the future SWOT mission[4], it is urgent to study the characteristics of sea surface wind speed retrieval of Ka-Band Radar Interferometer (KaRIN) aboard SWOT mission. Based on the KuLMOD2 of Tiangong-2, common model function and the simulated data sets with theoretical model of Quasi-specular scatter and the simulated position of observation point, the Ka model function applicable to SWOT KaRIN was proposed. Wind speed was retrieved by simulated data sets, and the results were validated with ECMWF.

2. Ka band Model function from future SWOT data

2.1. Model function with narrow-swath imaging altimeter
Tiangong-2 three-dimensional microwave imaging altimeter makes interferometric imaging observations of the ocean at an unprecedented incident angles of 1° to 8°, and obtains observed data of backscattering coefficient, which enriches the data sources of wind field.
KuLMOD2, is proposed for retrieving wind speed from the interferometric imaging radar altimeter (InIRA) data aboard the Chinese Tiangong-2 space laboratory by Lin Ren et al., which is a revised version of the former Ku-band low incidence backscatter model (KuLMOD). The incident angles of KuLMOD2 are 0°~9°, whereas the wind speed is 0~20m/s, which is as follows:

\[
\sigma_a(\theta, U_{10}) = a(\theta) + b(\theta) U_{10} + c(\theta) U_{10}^2 \quad 0^\circ < \theta < 9^\circ
\]

\[
\begin{align*}
    a(\theta) &= a_0 + a_1 \theta + a_2 \theta^2 \\
    b(\theta) &= b_0 + b_1 \theta + b_2 \theta^2 \\
    c(\theta) &= c_0 + c_1 \theta + c_2 \theta^2
\end{align*}
\]  

(1)

Where \(a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, \) and \(c_2\) are model coefficients, the model coefficients are estimated by fitting precipitation radar data from the Tropical Rainfall Measuring Mission and collocated wind data from ECMWF, \(a_0\) is 14.429486, \(a_1\) is 0.059035, \(a_2\) is -0.084637, \(b_0\) is -0.351149, \(b_1\) is -0.003623, \(b_2\) is 0.005653, \(c_0\) is 0.003309, \(c_1\) is 0.000121, \(c_2\) is -0.000156.

2.2. Simulated data sets

Backscatter coefficient was simulated based on theoretical model of Quasi-specular scatter (Formula 2) and the simulated position of observation point by the Key Laboratory of Microwave Remote sensing. By calculating the incident angle between the orbit and the observation area, the true value of the theoretical backscattering coefficient is calculated based on the wind speed of the sea surface. Through the probability distribution model of radar backscatter coefficient and the signal-to-noise ratio of the system, the backscatter coefficient is simulated and observed.

\[
\sigma_0 = \frac{|R(0)|^2}{s^2} \sec^4 \theta \exp\left(-\frac{\tan^2 \theta}{s^2}\right)
\]  

(2)

Where \(\sigma_0\) is the backscattering coefficient, \(\theta\) is the incident angle, \(U_{10}\) is the wind speed at 10m above the sea surface, \(R(0)\) is the Fresnel reflection coefficient for the nadir incidence, \(s^2\) is the total variance of the wave slopes.

The measured data cannot be obtained before the launch of the SWOT mission, the data sets can be simulated based on the theoretical model of sea surface backscattering coefficient and the observable conditions of KaRIN. The KaRIN adopts the observable system deviating from the nadir point in order to increase the swath. The imaging altimeter observable conditions are as follows: the observable band is Ka band, the satellite orbit height is 875km, the sea surface observable swath is 120km, the sub-satellite observable gap length is 20km, and the observable incident angles ranged from 0.6° to 3.9°. The schematic is following as follows.

![Figure 1. The schematic of SWOT.](image-url)
The Key Laboratory of Microwave Remote sensing, National Center for space science, Chinese Academy of Sciences provided the simulated position of observation point, such as South China sea region (5°~25°N, 105°~125°E) and kuroshio region (25° to 45°N, 135° to 155°E). Simulated data sets that backscatter coefficient (spatial resolution: 3km) and wind speed in kuroshio region on 20:29:32, January 1,2020 were selected to establish the model function for Ka band, as shown in Figure 2 and Figure 3.

Figure 2. In kuroshio region, on January 1, 2020, (a) Ka band backscatter coefficient, (b) ECMWF scene diagram.

Figure 3. The relationship between Ka band backscatter coefficient and wind speed in kuroshio region on January 1, 2020.

2.3. Ka band model function
The Ka band model function for retrieving wind speed with KaRIN for incident angles from 1° to 4° was proposed based on the form of KuLMOD2 and characteristics of simulated data sets, which is as follows (U10: 3m/s~24m/s):
\[
\sigma_0(\theta, U_{10}) = a(\theta) + b(\theta) U_{10} + c(\theta) U_{10}^2 \quad 1^\circ \leq \theta \leq 4^\circ \\
a(\theta) = a_0 + a_1 \theta + a_2 \theta^2 \\
b(\theta) = b_0 + b_1 \theta + b_2 \theta^2 \\
c(\theta) = c_0 + c_1 \theta + c_2 \theta^2 
\]

Where the model coefficients are estimated by fitting the Ka band data sets, \(a_0\) is 17.0132, \(a_1\) is -0.1182, \(a_2\) is -0.0881, \(b_0\) is -0.6930, \(b_1\) is 0.0218, \(b_2\) is 0.0076, \(c_0\) is 0.0155, \(c_1\) is -9.1215E-4, \(c_2\) is -2.1542E-4.

3. Wind speed retrieval and validation
Simulated data sets that Ka band backscatter coefficient (spatial resolution: 3km) in kuroshio region on 07:50:36, April 1,2020; and simulated data of Ka band backscatter coefficient (spatial resolution: 3km) and wind speed in South China sea region on 09:28:43, April 1,2020 were selected as the wind speed retrieval and validation for Ka band, as shown in Figure 4.

![Figure 4. Ka band backscatter coefficient (a) April 1, 2020, kuroshio region, (b) April 1, 2020, South China sea region.](image)

The stripe wind speed was retrieval by using Ka model function for SWOT simulated data, as shown in Figure 5 (a) and Figure 6 (a). ECMWF scene were shown in Figure 5 (b) and Figure 6 (b). Based on the stripe wind speed retrieval, the regional wind speed retrieval was formed by using linear interpolation, as shown in Figure 5 (c) and Figure 6 (c). The wind speed retrievals were compared with the ECMWF in kuroshio region, as shown in Figure 7.
Figure 5. In kuroshio region (a) The stripe wind speed retrieval, (b) ECMWF scene diagram, (c) the regional wind speed retrieval.
Figure 6. In South China sea region (a) The stripe wind speed retrieval, (b) ECMWF scene diagram, (c) the regional wind speed retrieval.
As shown in Figure 5, Figure 6 and Figure 7, the results of wind speed retrieval, the wind speed retrieval agreed well with the ECMWF.

In the Kuroshio region, four time points are selected to verify the accuracy of wind speed retrieval, 07:35:45, October 1, 2019; 07:50:34, January 1, 2020; 07:50:36, April 1, 2020; and 07:50:38, July 1, 2020. In the South China Sea region, four time points are selected to verify the accuracy of wind speed retrieval, 09:18:15 on October 1, 2019; 09:28:42 on January 1, 2020; 09:28:43 on April 1, 2020; and 09:28:44 on July 1, 2020. The average of RMSE is 0.36 in Kuroshio region, and the average of RMSE is 0.34 in South China sea region, as shown in Figure 8.

4. Conclusion
In this article, future SWOT data were simulated by using theoretical model of Quasi-specular scatter and the simulated position of observation point by the Key Laboratory of Microwave Remote sensing. Based on form of KuLMOD model function, Ka band model function for retrieving wind speed
(incident angles from 1° to 4°) was proposed. The model coefficients were derived by fitting the simulated data sets in kuroshio region, on January 1, 2020. The wind speed was retrieved and validated by Ka band model function and ECMWF. The average of RMSE is 0.36 in Kuroshio region, and the average of RMSE is 0.34 in South China sea region by using Ka band model function. However, the average of RMSE is 0.35, the results show that the wind speed retrieval agreed well with the ECMWF, and the Ka band model function is applied to SWOT KaRIN for retrieving the wind speed.

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