Estimation of Speckle noise spectrum around along-track direction by a theoretical model for SWIM configuration

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1.INTRODUCTION

The ocean scatterometer can obtain the fluctuation spectrum of the sea surface, which is composed of speckle spectrum and wave modulation spectrum. In order to invert the two-dimensional wave height spectrum accurately from the fluctuation spectrum, the influence of speckle spectrum must be effectively eliminated. Recently a theoretical model of speckle spectrum is presented considering the time-varying characteristics of the sea surface within the radar integral time. The parametric model describes how sea surface condition and radar observation geometry influence speckle spectrum. The theoretical model has been validated by the measurements of speckle noise spectrum of the airborne spectrometer KuROS.

In this paper, the theoretical model is applied to the configuration of the space-borne spectrometer SWIM carried by CFOSAT (China France Oceanography Satellite). Considering the range-gate average operation of the received signal power by SWIM, the theoretical model needs to be modified slightly. Then the theoretical model is used to estimate the speckle noise spectrum close to the along track direction. Finally, the wave parameters are inverted and compared with those from MF reanalysis data.

2. MODEL OF SPECKLE SPECTRUM FOR THE AVERAGE OF THE ECHOES THROUGH RANGE GATES

With the consideration of the sea surface time-varying characteristics during the radar integration time, Chen Ping et al. (2020)[1] derived the theoretical speckle spectrum model without the average of the echoes of several range gates:

$$P_{sp}(K,\Phi)=\frac{1}{2\pi K_p N_{tot}(\Phi)}tri\left(\frac{K}{2\pi K_p}\right) \qquad (1)$$

where tri is the triangle function, K is the wavenumber at the surface, Φ is the azimuth angle relative to the flight direction.$K_p=\frac{1}{\delta x}$,δx is effective radar horizontal range resolution, δx is slightly larger than the theoretical resolution $\delta x'=\frac{2B\sin\theta}{c}$, $\delta x = coef * \delta x'$,$coef \geq 1$. θ is incidence angle, B is the bandwidth of the transmitted pulse,c is light speed. $N_{tot}(\Phi)$ is the number of independent samples, it can be calaulated by:

$$\frac{1}{N_{tot}(\Phi)}=\frac{1}{N_{mov}(\Phi)}+\frac{1}{N_{int}(\Phi)}$$

$$N_{mov}(\Phi)=\sqrt{N_a^2(\Phi)+N_{surf}^2}$$

$$N_a(\Phi)=\frac{2kV}{r_0}L_\phi \sin\Phi\cdot\frac{T_{int}}{\sqrt{2\pi}} \qquad (2)$$

$$N_{surf}=2\sqrt{2m_{tt}}\cdot k\cos\theta\frac{T_{int}}{\sqrt{2\pi}}$$

$$\hat{\alpha}=4k^2\cos^2\theta m_{tt}$$

$$\frac{1}{N_{int}(\Phi)}=\frac{1}{T_{int}}\sqrt{\frac{\pi}{\hat{\alpha}}}\int P_{mod}^*(K,\Phi)dK$$

$$P_{mod}^*(K,\Phi)=P_{mod}(K,\Phi)+\frac{\sqrt{2\pi}}{L_\phi}\frac{g}{2m_{tt}}K^2\cdot F(K,\Phi)$$

where k represents the wave number corresponding to the frequency of the radar transmitting pulse, and L_ϕ is ground length of azimuth beam footprint (at 3dB), and r_0 is the distance from the radar to the detected sea surface , and V is the satellite platform speed, and T_{int} is radar integration time, $\hat{\alpha}$ is a factor proportional to the surface vertical velocity variance m_{tt}:

$$m_{tt}=\int_0^{\omega_d}\omega^2F(\omega)d\omega \qquad (3)$$

where $F(\omega)$ is the omni-directional spectrum with the angular frequency ω, $\omega_d$corresponds to the wave scale limit which makes the quasi-specular scattering approximation valid[2].

When the model above is applied to the configuration of SWIM, where the echoes through multiple range gates are averaged on-board , and the model form for the speckle spectrum of the averaged signal need to be modified slightly, which can be expressed as:

$$P_{spN}(K,\phi)=\frac{1}{N^2}\mathrm{P_{sp}(K,\phi)}\left(N+2\sum_{i=1}^{N-1}(N-i)\cos(iK\delta\mathrm{x})\right) \qquad (4)$$

N is number of average of range gates for each beam. It is noted that the above equations are valid when PRF*$T_{int}>N_{tot}$, PRF is the repetition frequency. If PRF*$T_{int}>N_{tot}$, then N_{tot} in (1) should be modified to PRF*T_{int}. According to the CFOSAT flight velocity and PRF of SWIM, the presented model in (1) is used to estimate the speckle noise spectrum for a sector of ±8° from the along-track direction.

3.Validation

In this section, we use the average for speckle spectrum samples measured from SWIM to validate the modified model presented in section 2. First, we select 84 classes of data for each SWIM incidence conditions（6◦, 8◦, 10◦）composed of 7 classes of latitude ([-70◦, -50◦], [-50◦, -30◦], [-30◦, -10◦], [-10◦, 10◦], [10◦, 30◦], [30◦, 50◦], [50◦, 70◦]), and 3 classes of combination of wind speed U and significant wave height (U< 5 m/s and Hs < 2m, 5<U<9 m/s and Hs < 2 m,and U>9 m/s and 2<Hs<4m), and 2 look direction (uptrack or downtrack), and track orientation(ascending or descending). We choosed the data whose wave direction is perpendicular to the observation direction, and the fluctuation spectrum in the observation direction can be considered as the measured speckle spectrum sample. This is because the contribution of the wave is the smallest at this time. We average the speckle spectrum samples and obtain the measured speckle spectrum for each class. Then for each class, We can obtain the collocated wave parameters(significant wave height, dominant wavelength, and dominant wave direction) from MFWAM reanalysis data set, these wave parameters are input to the presented theoretical model to estimate the speckle noise spectrum over a sector of ±8° from the along-track direction. As noted in [3], affected by the rotation of the earth, the direction of the azimuth angle also needs to be corrected:$\phi_{\mathrm{correct}}=\phi-\phi_0$, where ϕ_0 is the the azimuth angle at which speckle spectrum was observed to be maximum. In addition, the value of the parameter $coef$ in (1)is obtained by fitting the model to the mean measured speckle spectrum.

In order to estimate the error between the measurements and model values, an Average Relative Error is defined as:

$$\mathrm{ARE}=\frac{1}{N}\sum_{i=0}^{N-1}\left|\frac{P_{model}(K_i,\phi)-P_{mean}(K_i,\phi)}{\mathrm{P_{mean}}(K_i,\phi)}\right| \qquad (5)$$

where $P_{model}(K_i,\phi)$ is value of modified model, $P_{mean}(K_i,\phi)$ is mean measured value for speckle spectrum. In order to reduce the influence of wave spectrum information on $P_{mean}(K_i,\phi)$, We select the k>0.1 area to calculate ARE.

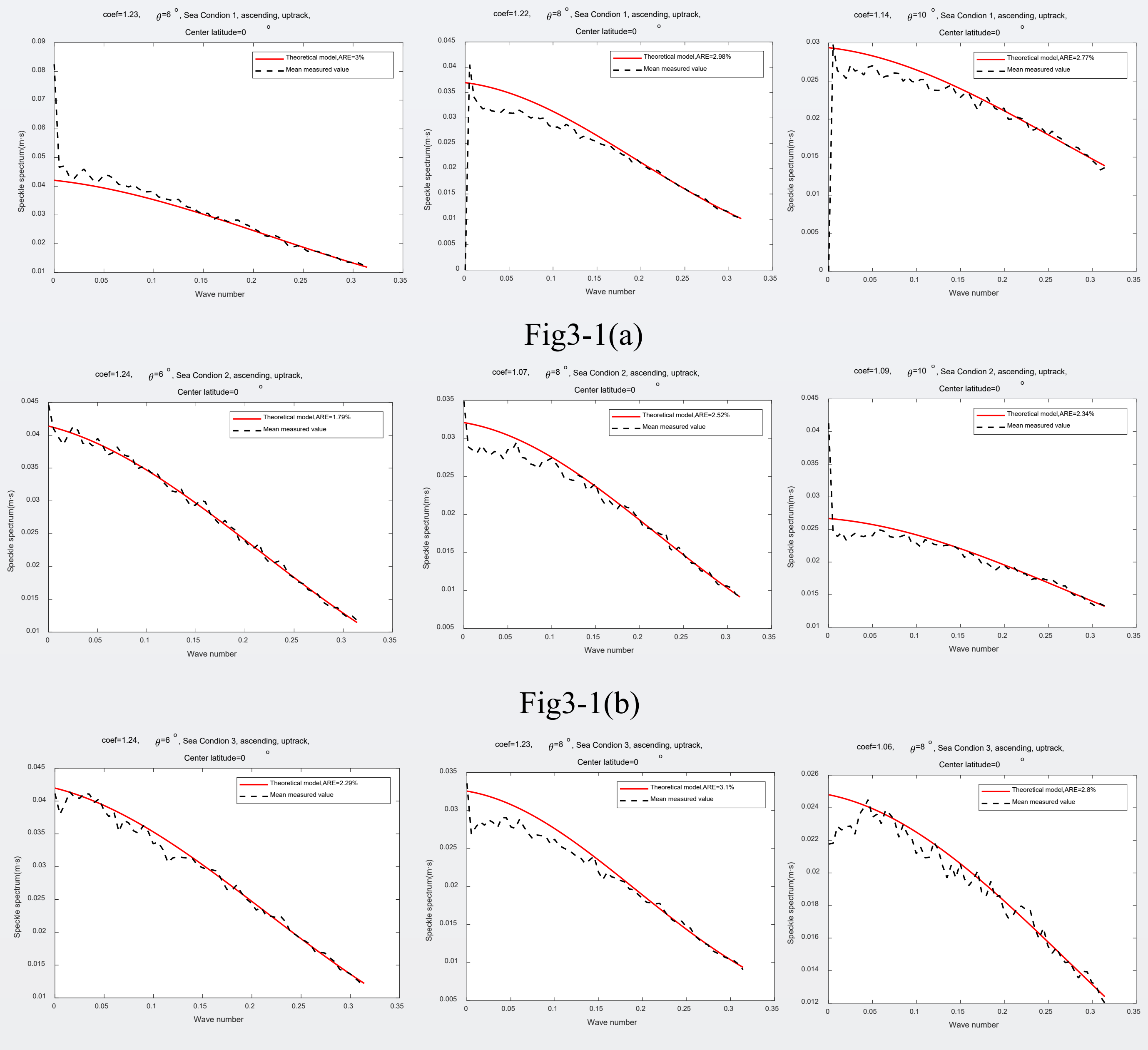

Fig3-1(a)

Fig3-1(b)

Fig3-1(c)

Fig 3-1 Comparison results of two speckle spectra: the red line represent theoretical model, the dash black line represent mean measured value for speckle spectrum. radar Observation geometry:ascending ,uptrack and $\phi=\phi_0$. The figure plot for three sea condition(Sea condition1(Fig 3-1(a)): U< 5 m/s and Hs < 2m, Sea condition2(Fig 3-1(b)): 5<U<9 m/s and Hs < 2 m, Sea condition3(Fig 3-1(c)): 5<U<9 m/s and Hs < 2 m). The data cover 5 days(1st July~5th July 2020).

As shown in Figure 3-1, under this observation, the difference between the two speckle noise spectrum estimates is small. At the same time, we also calculate ARE for all observation, the result show all ARE are less than 5%. These indicate the theoretical model can estimate the speckle spectrum accurately.

In order to evaluate the performance of removing speckle spectrum by the theoretical model, we compare inverted wave parameters with MFWAM wave parameters. For a sector of ±8° from the along-track direction, we estimate speckle spectrum by modified theoretical model. For other sector, the speckle noise spectrum in L1b product is directly used. After removing speckle spectrum from fluctuation spectrum and extracting modulation spectrum, the wave height directional spectrum can be inverted for the waves with wavelength in 50m -500m. Finally, the significant wave heights (Hs) are calculated from the wave directional spectrum.

Figure 3-2 illustrates the scatter plots of Hs by the SWIM-beam 10° versus MFWAM Hs. The Hs by SWIM have good consistency with MFWAM. But it was overestimated in the yield of Hs<3m and underestimated in the yield of Hs>3m. It is because there are still pseudo peaks in the modulation spectrum under small sea conditions, but the modulation signal of waves is over truncated under large sea conditions. In addition, the nonlinear relationship between the modulation spectrum and the wave slope spectrum will also lead to the decline of the accuracy of the retrieved wave spectrum.

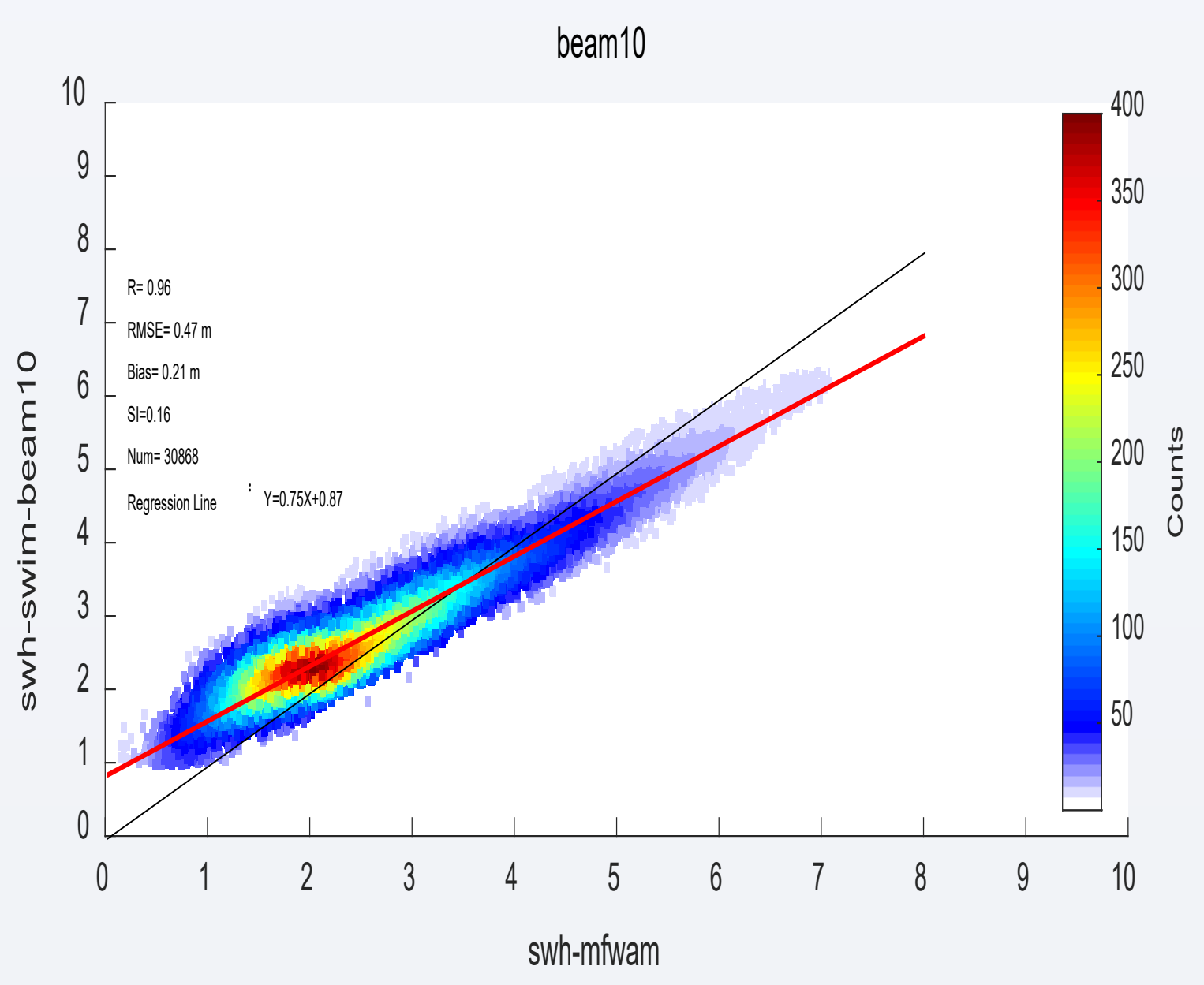

Fig 3-2 Scatter plots of SWIM significant wave height Hs from the 10° beam full spectra as a function of MFWAM Hs, for a 13 days period (1st July~5th July 2020). The color code represents the number of points per bin of values. The red line represents the linear fit.

4. CONCLUSION

In this paper, we presented a theoretical model suitable for the space-borne wave scatterometer to estimate the speckle spectrum close to the along track direction. The presented model is compared with the measured speckle spectrum by SWIM. The result shows theoretical model has good consistency with mean measured value. Then we use theoretical model to remove speckle spectrum over a sector of ±8° from the along-track direction and inverted the wave height directional spectrum. The wave parameters calculated by the directional spectrum are compared with those . provided by MFWAM data.

REFERENCES

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