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► **To cite this version:**

Huimin Li, Danièle Hauser, Bertrand Chapron, Frédéric Nougulier, Patricia Schippers, et al.. Up-to-downwave asymmetry of the CFOSAT SWIM fluctuation spectrum for wave direction ambiguity removal. IEEE Transactions on Geoscience and Remote Sensing, In press. hal-03084669v1

**HAL Id: hal-03084669**

**<https://hal.science/hal-03084669v1>**

Submitted on 21 Dec 2020 (v1), last revised 15 Jun 2021 (v2)

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# Up-to-downwave asymmetry of the CFOSAT SWIM fluctuation spectrum for wave direction ambiguity removal

Huimin Li, Danièle Hauser, Bertrand Chapron, Frédéric Nougquier, Patricia Schippers, Biao Zhang, Jingsong Yang and Yijun He

**Abstract**—The surface waves investigation and monitoring (SWIM) aboard the China-France Oceanography Satellite (CFOSAT), a pioneer conically scanning wave spectrometer, was successfully launched on October 29, 2018. Its innovative configuration composed of one nadir and 5 rotating near-nadir beams is designed to simultaneously observe the significant wave height as well as the directional wave spectrum at global scale. In this study, we examine the two-dimensional fluctuation spectrum of the three spectral beams ( $\theta = 6^\circ, 8^\circ, 10^\circ$ ) by combining all the azimuth directions within one entire rotation of  $360^\circ$ . Spectral analysis of the radar backscattering profile along each azimuth is systematically carried out using the periodogram technique. The obtained fluctuation spectrum is consistent with the collocated wave slope spectra in terms of the qualitative wave features. Moreover, a quantitative up-to-downwave asymmetry of the fluctuation spectrum is documented with larger spectral level in the upwave direction for all the three spectral beams. Magnitude of the defined up-to-downwave spectral ratio are mostly greater than 1 with the down-to-upwave ratio smaller than 1. This asymmetry characteristics can be readily utilized to remove the  $180^\circ$  wave direction ambiguity from a practical point of view. The preliminary results demonstrate that the  $10^\circ$  beam shows better performance in comparison to the other two beams. This shall lay strong basis for the operational implementation of such algorithm to resolve the direction ambiguity.

**Index Terms**—CFOSAT SWIM; Up-to-downwave asymmetry of fluctuation spectrum; Wave direction ambiguity removal

## I. INTRODUCTION

OCEAN waves are important upper ocean processes to regulate the heat, momentum exchange of the air-sea interaction. Since the directional wave spectrum is able to fully characterize the sea state, its observations are essential for wave related studies. Until recently, *in-situ* buoys and spaceborne synthetic aperture radar (SAR) have been the chief source of wave spectra measurements [1]. Yet, limitations of these techniques are also evident due to either the restricted spatial coverage of buoys or the nonlinear loss of wave information of SAR imaging [2]. An innovative technique is necessary to complement the existing manners for accurate and comprehensive observations of directional wave spectrum at the global scale.

Radars operating at near-nadir incidence angles rely on the wave slope induced variations in the returned signal to measure the ocean waves. A conically scanning antenna receives backscatter at various azimuth angles to resolve the two-dimensional wave field. Such concept of a wave spectrometer has been proposed for over 30 years [3]. Its capability to observe the directional wave spectrum was then evidenced by multiple airborne experiments [4], [5]. One of the two payloads aboard the China-France Oceanography Satellite (CFOSAT), surface wave investigation and monitoring (SWIM) is such a wave spectrometer. The instrument characteristics as well as the forward simulation of SWIM backscattering have been detailed to support the mission design [6], [7]. The successful launch of CFOSAT marks the first ever deployment of a conically scanning real aperture radar (RAR) in the space [8], [9]. This shall facilitate the investigation of global ocean waves, not only regarding the wave height, but also the wave directional spectra to characterize the complex sea state [9]. It is expected to help advance our understanding of wind-wave interactions at global scale [10] as well as to refine the accuracy of numerical modeling [11], [12].

SWIM operates at Ku-band with the center radar frequency at 13.575 GHz [7]. It has six beams with 1 nadir and 5 near-nadir incidence angles ( $0^\circ, 2^\circ, 4^\circ, 6^\circ, 8^\circ, 10^\circ$ ). The nadir beam is similar to a state-of-the-art altimeter in purpose to measure both the significant wave height and the wind speed. The five near-nadir beams sequentially illuminates the sea

This work is supported in part by the National Key Research and Development Program of China (under Grant 2016YFC1401002 and 2016YFC1401005), by Centre National d'études Spatiales (CNES) under the TOSCA program, by the Startup Foundation for Introducing Talent of NUIST, by the National Natural Science Foundation (under Grant 42006163 and 41620104003), by the European Space Agency and Ministry of Science and Technology Dragon 5 Cooperation Programme (ID. 58009).

Huimin Li is with School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China and State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou 310012, China. (E-mail: huimin.li@nuist.edu.cn).

Danièle Hauser is with Laboratoire Atmosphère, Milieux, Observations Spatiales (LATMOS), Université Paris-Saclay, UVSQ, Centre National de la Recherche Scientifique (CNRS), Sorbonne Université, 78280 Guyancourt, France (e-mail: danièle.hauser@latmos.ipsl.fr).

Bertrand Chapron and Frédéric Nougquier are with IFREMER, Univ. Brest, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), Plouzane 29280, France (E-mail: bertrand.chapron@ifremer.fr; frederic.nougquier@ifremer.fr).

Biao Zhang and Yijun He are with School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China. (E-mail: zhangbiao@nuist.edu.cn; yjhe@nuist.edu.cn).

Patricia Schippers is with the ACRI-ST company, Guyancourt, France (Email: patricia.schippers@latmos.ipsl.fr).

Jingsong Yang is with the State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou 310012, China (Email: jsyang@sio.org.cn).

Manuscript received xx xx, 2020; revised xx xx, 2020.

surface at different azimuth angles. Each beam employs a chirp signal of 320 MHz for range detection along given azimuth. Spectral analysis of the backscattering profile along the range is conducted to obtain the modulation spectrum in that azimuth. Inversion of the wave height spectrum in this azimuth direction follows. The two-dimensional wave spectra is then accordingly constructed by combining all azimuth directions within one rotation across the entire  $360^\circ$ .

At such low incidence angle as SWIM does, radar backscattering of the sea surface is dominated by the quasi-specular reflection from the wave slope satisfying the specular condition [13]. The geometrical modulation is the dominant mechanism for the signal contrast modulation. It is due to the change of local incidence angle provoked by the tilt of the long wave slopes. Assuming that the mechanism is linear (true for small slopes) and the hydrodynamic modulation is negligible, the measured modulation spectrum is linearly related to the waves slope spectrum via the tilt modulation transfer function (MTF). Under the approximation of small curvature effects, the backscattering at near-nadir incidence is proportional to the wave slope probability density function (PDF), the tilt MTF, the derivative of backscattering, is then related to the wave slope PDF. Most of the simulation studies presumed the wave slope spectrum to be Gaussian and isotropic, producing the simulated polar-symmetric modulation spectrum [6]. However, it has been reported that the modulation spectrum derived from the airborne observations was actually not symmetric [3]. They speculated that this is possibly due to the non-isotropic nature of wave slopes PDF and/or the second-order hydrodynamic modulation. However, no statistical analysis was presented due to the limited number of aircraft measurements in that paper [3]. In the meanwhile, many studies have disclosed that the up-downwave wave slope follows a non-Gaussian shape based on both the sun glitter and the near-nadir microwave radar measurements [14], [15], [16], [17]. In other words, the derivative of wave slope PDF differs from upwave (or upwind) to downwave (or downwind) direction. The MTF variation relative to the wave directions might contradict with previous results of polar-symmetric modulation spectrum. In fact, the tilt MTF estimated based on the Global Precipitation Mission data has demonstrated the azimuthal dependence of MTF with larger values in the upwave (or upwind) [18].

As a matter of fact, it is the fluctuation spectrum that is directly calculated from the backscattering profile rather than the modulation spectrum. These two spectra are related through the radar impulse response spectrum as well as the speckle noise spectrum [3], [4]. In contrast to a fixed antenna configuration, the rotating beams of SWIM allow to observe the sea surface at various azimuth directions. The direct comparison of fluctuation spectrum between the upwave and downwave direction becomes therefore feasible. In this study, SWIM observations are collocated with the directional wave spectra from WaveWatch III (WW3), and the dominant direction of the WW3 spectra are used as reference in the following analysis. Up-to-downwave asymmetry of the fluctuation spectrum is documented through comparison of the values at peak pairs with  $180^\circ$  ambiguity. Note that one of the unsolved issue in the present SWIM data processing chain is the removal of the

wave direction ambiguity [9]. We then present the preliminary results for removing the wave direction ambiguity by taking advantage of this up-to-downwave asymmetry.

The rest of this paper is organized as follows. Section II details the SWIM data included in this study as well as the spectral analysis to obtain the fluctuation spectrum. The up-to-downwave asymmetry of fluctuation spectrum is presented in Section III and the preliminary results for direction ambiguity removal is given in Section IV. Discussion and conclusion then follow in Section IV.

## II. DATA AND METHOD

In this section, we first present the SWIM observations used in this paper as well as the collocated ancillary data, including ocean wave spectra and wind field. The spectral analysis method of periodogram to calculate the fluctuation spectrum for each azimuth direction then follows.

### A. SWIM observations and ancillary data

SWIM is a pioneer Ku-band RAR developed based on the concept detailed in [19]. It measures the radar backscattering with 6 beams at incidence angle from  $0^\circ$  to  $10^\circ$  with the increment of  $2^\circ$ . It is deployed in the orbit at an altitude about 500 km. The observation swaths in radius rely on the incidence angle, for example, the  $10^\circ$  beam has a swath in radius of 90 km. Radar footprint of the near-nadir beams is about 18 km by 18 km on the ground with the original slant range resolution of 0.47 m. Since a certain number of range bins and azimuth samples needs to be averaged on board to reduce the downlink rate, the slant range resolution decreases to 0.9 m or 1.5 m depending on the number of averaged bins. More details of SWIM instrument parameters can be referred to [7].

Each of the near-nadir beams rotates at a speed of 5.6 rpm to cover all azimuth angles with a directional sampling about  $7.5^\circ$ . It should be noted that at any given moment, the 5 near-nadir beams are not contiguous in azimuth angles due to the mechanical constraints in the rotating plate (see Figure 2 in [7]). The near-nadir beams of  $6^\circ, 8^\circ, 10^\circ$  are dedicated to the measurements of directional wave spectra, which are often termed as spectral beams. The other two near-nadir beams of  $2^\circ$  and  $4^\circ$  are mainly kept to provide the backscattering profile relative to the incidence angle. Fig. 1 presents an example of the acquisition pattern of the nadir and  $6^\circ, 8^\circ, 10^\circ$  beams within two entire rotations. In this study, we define one rotation covering the entire  $360^\circ$  to start from the azimuth direction closest to  $270^\circ$  clockwise from the true North. Over one beam rotation about 10.8 s, the characteristics of ocean waves being measured could be reasonably assumed to remain unchanged under low to moderate wind/wave conditions. Therefore, all the azimuth directions within one rotation can then be combined to construct the two-dimensional fluctuation spectrum.

Numerous studies have demonstrated that at small incidence angle as SWIM operates, the radar backscattering is dominated by the quasi-specular reflection from the wave facets perpendicular to the radar line-of sight [13], [20]. According to [7],

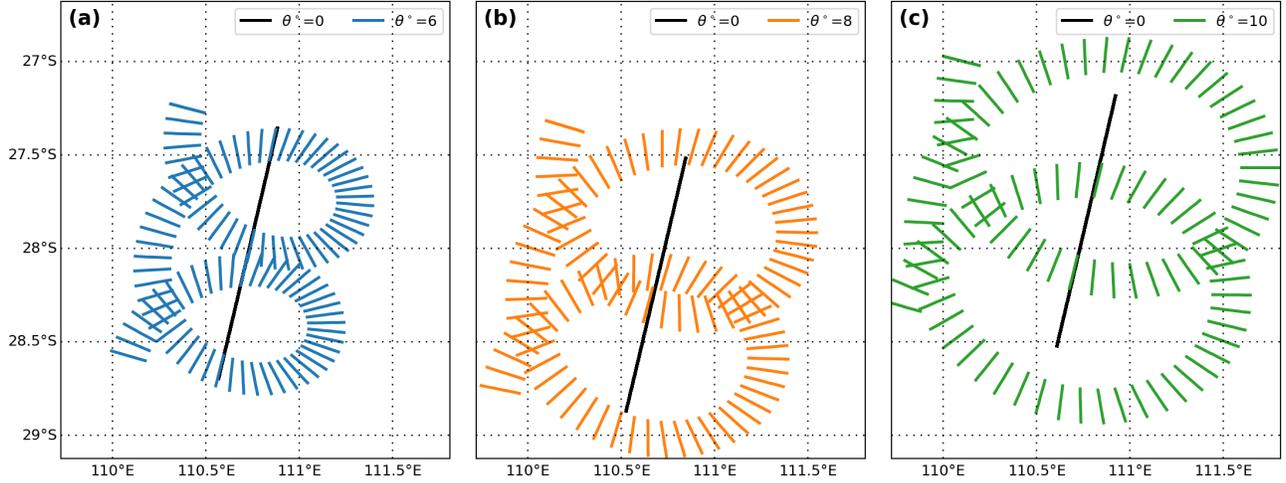


Fig. 1. An example for acquisition pattern of (a) 6°, (b) 8° and (c) 10° beams within two rotations of 360°. Black curve denotes footprint of the nadir beam. Note that the slightly varying coverage of these three incidence angles is due to their incontinuous azimuth directions at given moment.

[13], the modulation spectrum of the radar backscatter can then be written as

$$P_M(k, \phi) = \frac{2\pi}{L_y} \left( \cot\theta - \frac{\partial \ln \sigma_0}{\partial \theta} \right)^2 k^2 F(k, \phi) \quad (1)$$

where  $L_y$  is a length related to the azimuthal width of the beam footprint referred to Eq.(9) in [7].  $F(k, \phi)$  is the two-dimensional wave height spectrum and  $\sigma^0$  is the SWIM-received normalized radar cross-section (NRCS) and  $\sigma^0$  used interchangeably in this paper). As concluded in [3], the hydrodynamic modulation and nonlinear wave-wave interactions are solely of second-order effect and can be neglected at such near-nadir incidence angles. The modulation spectrum is associated with the fluctuation spectrum directly estimated from the backscattering signal by

$$P_F(k, \phi) = P_{IR}(k) P_M(k, \phi) + P_{sp}(k) \quad (2)$$

where  $P_{IR}(k)$  is the impulse response spectrum and  $P_{sp}(k)$  denotes the speckle spectrum. As annotated, these two spectra are usually assumed to be centro-symmetric across one rotation of 360° [9]. This makes the up-to-downwave contrast of the fluctuation spectrum comparable to that of  $P_M(k, \phi)$ . Since this paper does not focus on inversion of the wave spectrum, up-to-downwave asymmetry of only the fluctuation spectrum is investigated unless otherwise stated.

In this study, we utilized the SWIM observations acquired on 21 October, 2019, which are processed with the updated on-board migration compensation algorithm [9]. The ocean wave spectra output from the WaveWath III (WW3) forecast is collocated to be the reference wave direction. The WW3 directional wave spectra are available at the spatial resolution of 0.5° every 30 minutes. The WW3 wave spectrum is composed of 24 directions and 32 frequencies in the range of 0.037 Hz to 0.7 Hz, covering the SWIM resolved wavelength range from 70 m to 500 m. Forecast winds from the European Centre for Medium-Range Weather Forecasts (ECMWF) are also included to examine the possible wind speed dependence of the spectral asymmetry, which are available at a spatial

resolution of 0.25° every 3 hours. Both WW3 and ECMWF products are collocated with the center of each SWIM rotation in terms of the nearest spatial and temporal distance.

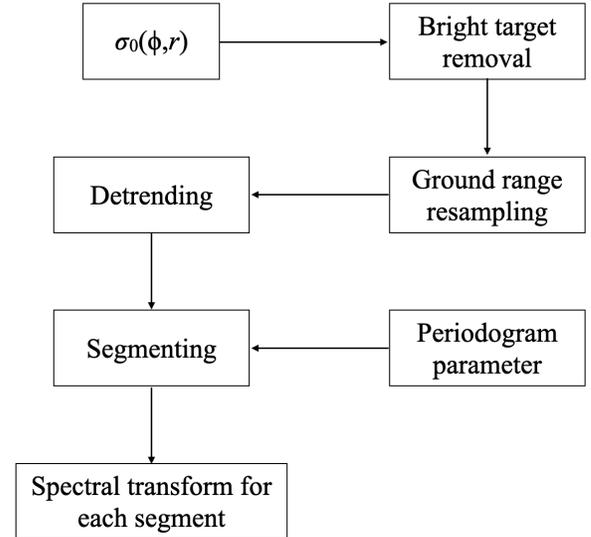


Fig. 2. Flowchart of the fluctuation spectrum estimate along each azimuth direction. The ground range resampling spacing is set to be 5 m and the periodogram window is 512 pixels with 256 pixels overlapping.

### B. Spectral analysis

In this study, the spectral analysis for the three beams of 6°, 8°, 10° is systematically carried out with the algorithm flowchart for the fluctuation spectrum at each azimuth given in Fig. 2. Since targets such as ships or platforms could cause very high backscattering signal, the pixels with NRCS larger than 99% percentile of that azimuth are replaced by the averaged value. The slightly varying incidence angle from the near range to the far range results in an irregular ground range sampling. A preprocessing step is thus performed to resample

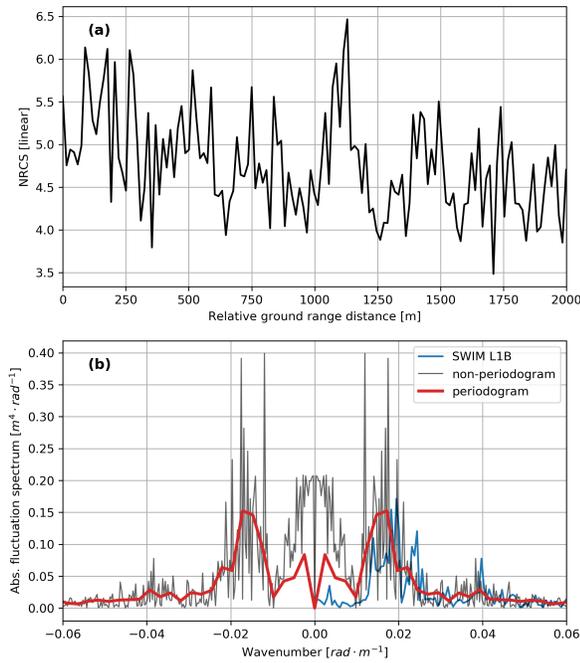


Fig. 3. An example for (a) SWIM measured NRCS profile of  $10^\circ$  beam with respect to the relative ground range distance; (b) Comparison of the obtained fluctuation spectrum using periodogram algorithm in Fig. 2 (red curve) and non-periodogram method (black curve) and the results annotated in SWIM level-1B products (blue curve).

the signal onto a constant ground range grid. Throughout this study, the ground range resampling is set to be 5 m for all three spectral beams. The detrending is conceived with a low-pass Gaussian filtering to estimate the overall trend of backscattering profile along the range. In order to reduce the noise effect, the periodogram technique is employed. The signal fluctuations  $\delta\sigma_0$  profile is divided into segments at lengths of 512 pixels with half overlapping. This leads to 15 segments for each azimuth direction and one averaged spectrum is obtained in the end. Note that this algorithm differs from that used in the level-2 processing chain by two aspects. On one hand, this algorithm takes advantage of the segments and periodogram to reduce speckle noise effect. On the other hand, we use rotations of  $360^\circ$  rather than box in the level-2 products, in order to facilitate the up-to-downwave comparison.

An example of the  $\sigma_0$  profile along the relative ground range distance is given in Fig. 3(a). A decreasing trend of NRCS is evident, which is removed by the detrending step in Fig. 3 prior to the fluctuation spectrum estimate. The fluctuation spectra obtained using different methods are shown in Fig. 3(b). The thin black curve denotes the fluctuation spectrum calculated by the genuine Fourier Transform (FT) of the NRCS profile, which is quite noisy with high spectral signal at the low frequencies. For comparison, the fluctuation spectrum provided in the SWIM level-1b product is plotted as the blue curve. In this latter case, the FT was applied on the full-length segment (limit to the window where the signal-to-noise ratio is higher than 3 dB), and the output spectrum is averaged over two consecutive wavenumbers. With

our periodogram method as well as the averaged spectrum over multiple segments, the spectrum is less noisy and the signature is more clearer. As a result, we choose to compute the fluctuation spectrum along a given azimuth direction using the periodogram method in the rest of this paper unless particularly stated. Note that in calculating the fluctuation spectrum, the resampled ground range spacing is 5 m and the periodogram size of 512 pixel is used, resulting in the wavenumber bin of  $0.00245437 \text{ rad} \cdot \text{m}^{-1}$ .

### III. UP-TO-DOWNWAVE ASYMMETRY OF FLUCTUATION SPECTRUM

In this section, a two-dimensional fluctuation spectrum computed using the periodogram method is first displayed and discussed as a representative example. The up-to-downwave asymmetry of the fluctuation spectrum between the two wave peaks with  $180^\circ$  ambiguity is then presented from a statistical point of view.

#### A. Case study

The two-dimensional fluctuation spectrum is systematically constructed over one beam rotation of  $360^\circ$ . In general, there are approximately 50 azimuth directions within one rotation for each beam. Examples of the obtained directional fluctuation spectrum at positive wavenumbers are shown in Fig. 4 for the three spectral beams of  $6^\circ$ ,  $8^\circ$ ,  $10^\circ$ , respectively. Its counterpart at the negative wavenumber (not shown) is simply a replica of the pattern at the positive wavenumber. Note that the angular sector within  $\pm 15^\circ$  along the track direction is mostly contaminated by high speckle noise, which usually conceals the actual wave signal [9]. As such, this sector is simply masked out in the following analyses. The three beams display quite similar spectral signatures with one dominant wave system at wavelength around 400 m. In the quantitative terms, the  $6^\circ$  beam has the largest spectral magnitude, while the  $10^\circ$  is the smallest. This decreasing spectral level might be partly associated with the impulse response function and the more significant contribution of speckle noise at  $6^\circ$  due to fewer data points for the fluctuation spectrum estimate.

As shown in Fig. 4(a)-(c), the spectral peaks position at  $60^\circ$  and  $240^\circ$  with the  $180^\circ$  ambiguity. By comparison, magnitude of the fluctuation spectrum appears to be smaller at the  $60^\circ$  peak than the  $240^\circ$  peak. Such contrast is more evident for the  $10^\circ$  beam in Fig. 4(c). To determine the relative wave direction, the collocated WW3 wave slope spectra is shown in Fig. 4(d). The dominant wavelength is in good agreement with that of the fluctuation spectra for all three spectral beams. According to the WW3 wave spectra, the peak waves propagate towards the northeast direction. As such, the spectral peak at  $60^\circ$  in Fig. 4(a)-(c) corresponds to the downwave where the radar looking is in alignment with the wave traveling direction. While the peak at  $240^\circ$  correspond to the upwave direction, where the radar line-of-sight direction is opposite to the wave propagation direction. Based on this case study, we found that the fluctuation spectra at downwave exhibits smaller magnitude than that at the upwave direction.

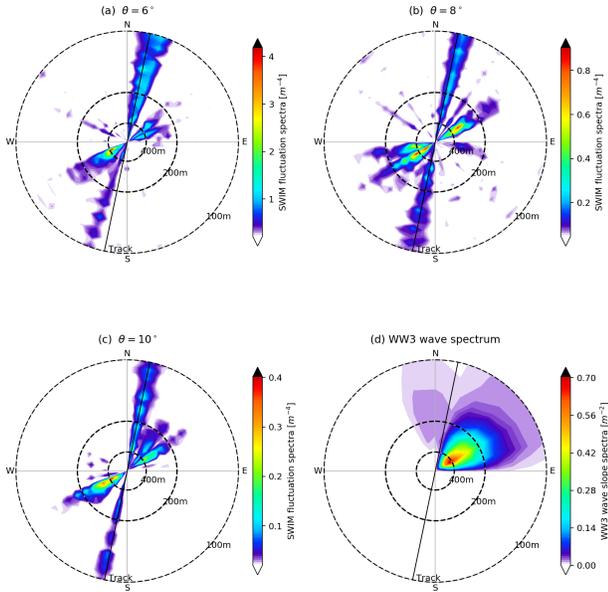


Fig. 4. Two-dimensional fluctuation spectrum constructed from one rotation of  $360^\circ$  for the beam of (a)  $6^\circ$ , (b)  $8^\circ$  and (c)  $10^\circ$ . The collocated WW3 wave slope spectrum is shown in (d) for comparison. The WW3 spectra direction corresponds to the direction that the waves travel to.

As a preparation to further statistics of the up-to-downwave spectrum contrast, the spectral peak pairs with  $180^\circ$  ambiguity are consistently detected. Fig. 6 presents the flowchart to search for the valid peak pairs and to compute the averaged fluctuation spectrum over the detected peaks. Local peaks are identified based on the constructed two-dimensional fluctuation spectrum, among which the peak pairs are determined with their wavelength difference smaller than  $0.0147 \text{ rad}\cdot\text{m}^{-1}$  and their direction difference within  $180 \pm 30^\circ$ . For each pair, the fluctuation spectra profile along the peak direction is extracted relative to the wavenumber. Fig. 5 illustrates such extracted profiles from the fluctuation spectra shown in Fig. 4 for the three incidence angles. It is worth noting that the fluctuation spectral magnitude near the peaks is much higher than the speckle noise level reported in [9], which is reproduced as the green horizontal lines in Fig. 5. The wavenumber range over which to calculate the spectrum average is determined by the 3-dB bandwidth of each profile. This range is marked by the vertical dashed lines in the same color with the corresponding curves. As shown in Fig. 5, the averaged spectral signal around the direction of  $60^\circ$  (blue curve) is smaller than that around  $240^\circ$ . In other words, the averaged spectrum at the downwave peak is lower in comparison to its ambiguous counterpart. In this case, the difference of averaged profile around the peaks within  $[0^\circ, 180^\circ]$  and within  $[180^\circ, 360^\circ]$  is negative as it represents the difference of downwave part relative to the upwave. Considering the magnitude of this difference relying on the absolute value of the fluctuation spectrum, it is not straightforward to reflect their statistical relativity. As an alternative, we define the ratio of spectral average over the peak  $\phi_1$  in  $[0^\circ, 180^\circ]$  to  $\phi_2$  in  $[180^\circ, 360^\circ]$ ,

expressed as

$$RT_P = \frac{P_m(\phi_1)}{P_m(\phi_2)}, \phi_1 \in [0^\circ, 180^\circ], \phi_2 \in [180^\circ, 360^\circ] \quad (3)$$

$RT_P$  is so defined that it is independent of the absolute spectral level. Here it is assumed that the peak spectral level is much higher than the speckle noise, which holds true for wave directions away from the track angle.  $RT_P$  represents the down-to-upwave ratio of averaged fluctuation spectrum when the true wave direction (traveling to) is within  $[0^\circ, 180^\circ]$ . While it is the up-to-downwave ratio if the true wave direction falls within  $[180^\circ, 360^\circ]$ . The wave direction shown in Fig. 4 is about  $60^\circ$  so that the  $RT_P$  denotes the down-to-upwave ratio for this case. As demonstrated in Fig. 5,  $RT_P$  varies relative to the SWIM incidence angles, with values of 0.51 for  $6^\circ$  beam, 0.93 for  $8^\circ$  beam and 0.61 for  $10^\circ$  beam. The fact that  $RT_P$  is smaller than one illustrates that for this selected case, the fluctuation spectrum is smaller in the downwave direction than in the upwave direction.

### B. Statistics of fluctuation spectrum $RT_P$

Though the case in Fig. 4 has manifested the up-to-downwave asymmetry of the fluctuation spectrum, it is not yet plausible to conclude its generality. In order to examine this asymmetry from a statistical point of view, the two ambiguous directions of fluctuation spectrum need to be categorized into the relative wave directions. In this study, we associated the identified spectral peak pairs with the WW3 wave peaks in terms of the spectral distance, which is defined as [21]

$$SD = \frac{1}{60} \left( |D_1 - D_2| + 2 \times \frac{|T_1 - T_2|}{T_1 + T_2} \times 250 \right) \quad (4)$$

where  $D_1, D_2$  are the detected SWIM and the WW3 peak direction, respectively.  $T_1$  and  $T_2$  are the peak wave period in the unit of  $s$ . By definition,  $SD$  takes the impact of both wave period and the propagation direction into account to assess the similarity of two peaks. Factors of 60 and 250 are chosen to describe that  $20^\circ$  errors in direction are equivalent to 8% errors in the wave period. The peak pair is kept if either of the ambiguous peaks obtains the spectral distance smaller than 3 relative to its WW3 counterpart. There are initially 867, 1194, 1443 peak pairs identified based on the directional fluctuation spectrum. The criteria of spectral distance smaller than 3 leads to 647, 855, 975 pairs of  $6^\circ$ ,  $8^\circ$  and  $10^\circ$  beams for the statistical analyses, respectively. Most of the eliminated spectral peaks locate at wavelengths longer than 600 m (not shown), which is beyond the detection range of SWIM.

To examine the asymmetry from a statistical point of view, the box plot of  $RT_P$  as defined by Eq. (3) is shown in Fig. 7 regarding the collocated WW3 peak wave direction. Note that the speckle noise spectrum constant is subtracted from the fluctuation spectrum to compute  $RT_P$ . As annotated in Fig. 5, the constants are  $0.0105 \text{ m}^{-4}$ ,  $0.007 \text{ m}^{-4}$ ,  $0.0055 \text{ m}^{-4}$  for the  $6^\circ$ ,  $8^\circ$  and  $10^\circ$ , respectively. The up-to-downwave asymmetry is prominent for all three beams, featured by the  $RT_P$  either smaller or higher than 1. When  $\phi$  lies in  $[0^\circ, 180^\circ]$ ,  $RT_P$  corresponding to the down-to-upwave ratio is smaller than 1,

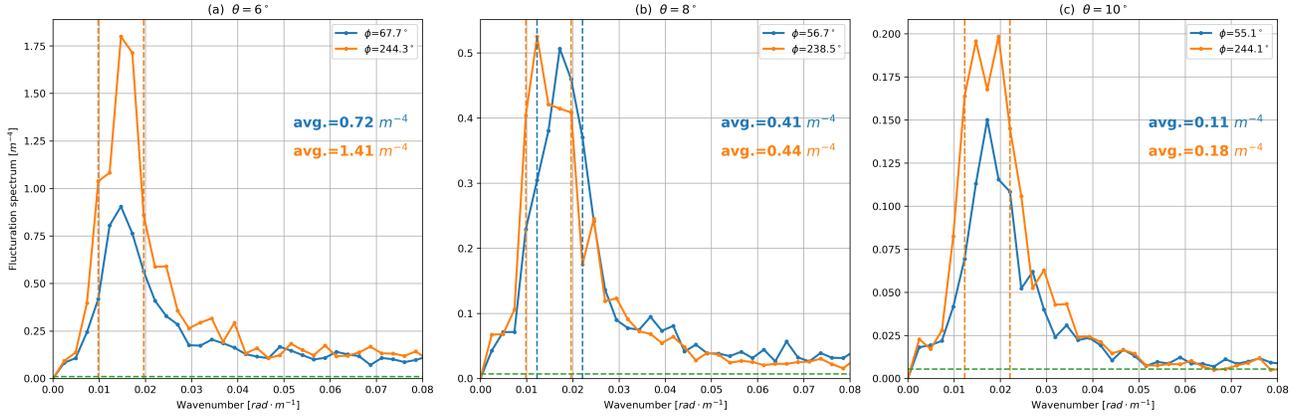


Fig. 5. Demonstration of the fluctuation spectral profile at the ambiguous peaks from the case shown in Fig. 4 for (a)  $6^\circ$ , (b)  $8^\circ$  and (c)  $10^\circ$  beams. The vertical dashed lines indicate the wavenumber range over which to calculate the averaged values. The averaged spectral magnitude is annotated in the same color with the curves. A constant for the speckle noise spectrum is reproduced based on [9] and plotted as the horizontal line in green, which is sufficiently small in comparison to the peak spectrum.

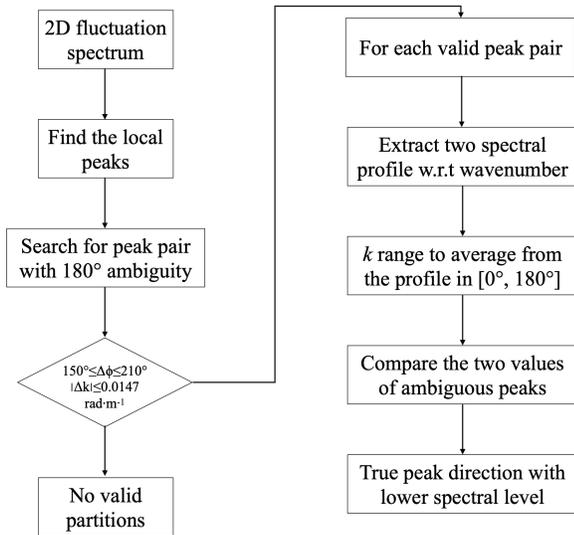


Fig. 6. Flowchart to search for the valid ambiguous peak pairs and to calculate the average of fluctuation spectrum around the identified peaks.

392 which confirms the lower fluctuation spectra at downwave direction.  
 393 In the case of wave direction belonging to  $[180^\circ, 360^\circ]$ ,  
 394  $RT_P$  representing the up-to-downwave ratio is well above the  
 395 horizontal line of 1. In consequence, it is rational to conclude  
 396 that the fluctuation spectrum indeed exhibits notable up-to-  
 397 downwave asymmetry with higher spectral levels at upwave  
 398 direction.

399 Note that the distribution of  $RT_P$  slightly differs among the  
 400 three spectral beams. Within the wave direction range of  $[0^\circ,$   
 401  $180^\circ]$ , the  $10^\circ$  beam shows tighter distribution with its upper  
 402 interquartile (75% of the points) well below 1. While for both  
 403  $6^\circ$  and  $8^\circ$ , the  $RT_P$  spans across the horizontal line of one at  
 404 several wave directions. By contrast, within the wave direction  
 405 of  $[180^\circ, 360^\circ]$ , the lower interquartile (25%) of all three  
 406 spectral beams is mostly above the one line. The behavior that  
 407 the  $RT_P$  spanning on both sides of the one line is expected to  
 408 introduce biases in applications based on this up-to-downwave

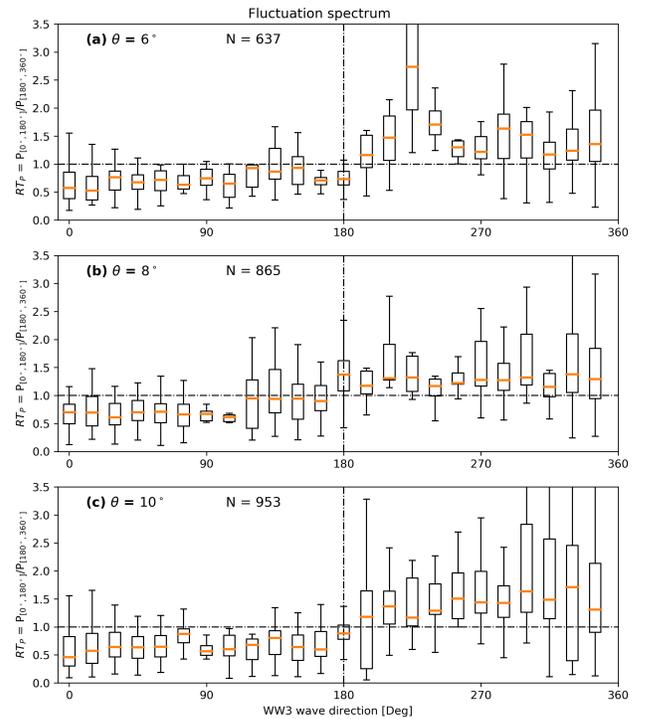


Fig. 7. Box plot of  $RT_P$  as defined by Eq. 3 is given regarding the identified WW3 wave peak direction for (a)  $6^\circ$ , (b)  $8^\circ$  and (c)  $10^\circ$  beams. 'N' annotated in each plot denotes the number of valid peak pairs. The lower and higher end of the box are the first (25%) and the third quartile (75%), respectively. The horizontal line within the box represents the median value. Wave direction is relative to the true north ( $0^\circ$ ) in clockwise rotation. The wave direction bin is  $15^\circ$ .

409 asymmetry. In addition, numbers of the identified peak pairs  
 410 are not the same for the three spectral beams. This is due to  
 411 the fact that one peak pair is not consistently present in the  
 412 fluctuation spectrum of the three beams.

413 We also looked into the  $RT_P$  dependence on the relative  
 414 wave direction in terms of the wind speeds or different  
 415 peak wavelengths as shown in the APPENDIX. The up-  
 416 to-downwave asymmetry considering all conditions is also

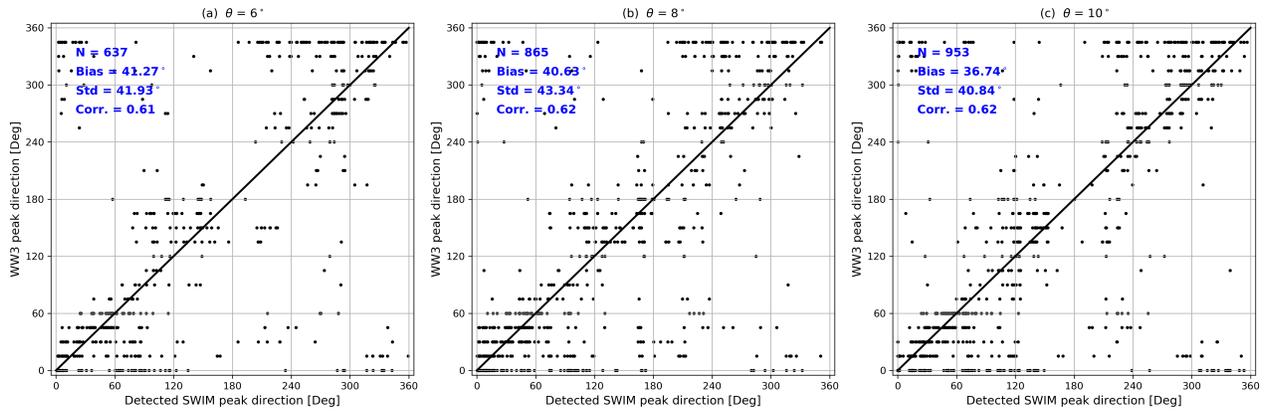


Fig. 8. Comparison of SWIM resolved wave peak direction with respect to the collocated WW3 wave peak direction for (a)  $6^\circ$ , (b)  $8^\circ$  and (c)  $10^\circ$  beams. 'N' annotated in each plot denotes the number of valid peak pairs. Result metrics are given on the upper left corner of each plot.

417 examined for each category of wind speed ( $0 < u_{10} < 5m/s$ ,  
 418  $5 < u_{10} < 10m/s$ ,  $10 < u_{10} < 15m/s$ ) and peak wavelengths  
 419 ( $\lambda_p < 200m, \lambda_p > 200m$ ). There is no clear variation between  
 420 different wind speeds and the peak wavelengths. Similar trend  
 421 is observed that  $RT_P$  is smaller than 1 for the relative wave  
 422 direction in the range of  $[0^\circ, 180^\circ]$ . In summary, it can  
 423 be concluded that the up-to-downwave asymmetry of the  
 424 fluctuation spectrum is solely associated with the relative wave  
 425 direction. This lays strong basis for the following attempt to  
 426 remove the wave direction ambiguity by taking advantage of  
 427 this up-to-downwave asymmetry.

#### 428 IV. PRELIMINARY RESULTS OF WAVE DIRECTION 429 AMBIGUITY REMOVAL

430 The  $RT_P$  in Fig. 7 illustrates that the fluctuation spectrum  
 431 at upwave is indeed larger than its counterpart at downwave  
 432 direction. This characteristics agrees well with the trend of  
 433 tilt MTF as reported in [18] that it has larger value in  
 434 the upwave configuration. From the practical point of view,  
 435 the observed fluctuation spectrum up-to-downwave asymmetry  
 436 can be readily utilized to help resolve the  $180^\circ$  wave direction  
 437 ambiguity. As presented in Fig. 7, the downwave direction  
 438 generally has lower spectral values, which will be taken as the  
 439 true wave direction. This notation is consistent with the wave  
 440 direction definition of traveling to in the WW3 products.

441 In this section, we focus on the wave direction ambiguity  
 442 removal based on the up-to-downwave asymmetry of the  
 443 fluctuation spectra. Fig. 8 displays the direction comparison  
 444 between the SWIM detection results and the collocated WW3  
 445 wave spectra for the three spectral beams. It should be noted  
 446 that the wave slope spectrum is utilized to extract the reference  
 447 wave peaks. Yet since we use the fluctuation spectrum to  
 448 identify the spectral peaks, the spectral peak wavelengths  
 449 might slightly differ with the reference wave peaks derived  
 450 from the WW3 wave slope spectrum due to the impact of  
 451 impulse response function and speckle noise spectrum.

452 As shown in Fig. 8, the extracted SWIM peak directions  
 453 are in good alignment with the reference WW3 peak direction  
 454 for all three spectral beams. Acquisitions from both ascending  
 455 pass and descending pass are included in the analyses, so that

the detected SWIM wave directions span in the entire range  
 of  $[0^\circ, 360^\circ]$ . It should be reminded that direction comparison  
 demonstrated here are based on the spectral distance criteria  
 of 3 for the peak-to-peak association. The  $10^\circ$  beams in  
 Fig. 8(c) shows the relatively better performance with the  
 smallest direction bias of  $36.55^\circ$  and the standard deviation  
 of  $40.61^\circ$ . By comparison, the  $6^\circ$  beam shows comparable  
 biases and standard deviation with the  $8^\circ$  beam. The better  
 performance of  $10^\circ$  for ambiguity removal is expected based  
 on the tight distribution of the  $RT_P$  in Fig. 7. This is consistent  
 with the previously reported results that the  $10^\circ$  is mostly  
 suitable for wave detection [9], [7]. While the correlation  
 coefficient is sort of low, being 0.59, 0.58 and 0.61 for  $6^\circ$ ,  
 $8^\circ$  and  $10^\circ$ , respectively. Combination of the three spectral  
 beams is promising to improve the wave spectral inversion.

Some outliers are still evident, which reduces the quality  
 of direction ambiguity removal. For the  $6^\circ$  beam in Fig. 8(a),  
 a cluster of outliers appears at the position corresponding to  
 the detected SWIM wave direction of  $210^\circ$  and the WW3  
 wave direction of  $150^\circ/60^\circ$ . The misjudgment of SWIM results  
 can be traced back to the wider spread of  $RT_P$  across the  
 horizontal curve of one around the true wave direction of  $60^\circ$   
 in Fig. 7. Note that the up- and downwave observations are  
 usually 100 km apart, which also might result in errors in the  
 ambiguity removal. In addition, the large scatter around  $0^\circ$  and  
 $360^\circ$  wave direction is because of the mask close to the track  
 direction. The other wave directions are much cleaner owing  
 to the tight distribution of  $RT_P$ . Similar cluster of outliers is  
 observed for the other two beams of  $8^\circ$  and  $10^\circ$  in Fig. 7(b)  
 and (c) as well.

#### V. DISCUSSION AND CONCLUSION

The concept of a conical scanning real aperture radar  
 operating at near-nadir incidence angles has been proposed  
 and validated using the airborne instruments for decades. With  
 the successful launch of COFSAT, such observations of ocean  
 waves at the global scale are available for the first time ever.  
 Despite the constant effort to update the operational data pro-  
 cessing algorithms, the inherent  $180^\circ$  wave direction ambigu-  
 ity yet hinders some geophysical applications using the SWIM

measurements. In this paper, the up-to-downwave asymmetry of the estimated fluctuation spectrum is first documented. It is worth noting that the fluctuation spectrum over the angular sector of  $\pm 15^\circ$  relative to the track direction has been excluded in this analysis due to the high level of speckle noise in this direction. Outside this sector, the mean speckle noise spectrum is subtracted for each incidence beam. The ratio of fluctuation spectrum peaks within  $[0^\circ, 180^\circ]$  to its ambiguous counterpart within  $[180^\circ, 360^\circ]$  shows distinct behavior relative to the true wave direction. It can be summarized that the fluctuation spectrum is significantly larger in the upwave than in the downwave direction as shown in Fig. 7. The preliminary results to resolve the wave direction ambiguity in terms of this up-to-downwave asymmetry are promising with relatively better performance of the  $10^\circ$  beam.

This documented asymmetry is consistent with the simulation based on the tilt MTF. At the near-nadir incidence angles, the linear approximation theory relates the modulation spectrum to the wave spectrum via the so-called tilt MTF, which is defined by the change rate of backscattering relative to the incidence angles. Since the wave spectrum can be considered unchanged within the footprint on each side of the SWIM track, under the linear theory, a larger spectrum in the upwave with respect to the downwave can only be explained by a larger MTF in that direction. In [18], the authors analyzed the tilt MTF from an analysis of the backscattering coefficients provided by the Global Precipitation Mission (GPM). They found that the MTF in Ku-Band and at  $10^\circ$  incidence is indeed 5 to 10% larger in upwind than in downwind direction for winds between 10 and 15 m/s. Hence, according to the results of [18], the modulation spectrum in downwave should be smaller than that in upwave. This agrees well with the analyses results presented in Fig. 7. The quantitative comparison of such asymmetry yet requires further efforts. For example, the nonlinear range bunching is usually neglected in the state-of-the-art SWIM simulators, which might modify the up-to-downwave asymmetry of the simulated fluctuation spectrum. Other factors including the high-order hydrodynamic modulation and the instrumental performance needs more investigations as well. In any case, this consistent asymmetry shall provide valuable data reference to complete our understanding on SWIM measurement principles.

In addition to the application for direction ambiguity removal, the skewed fluctuation spectrum between upwave and downwave shall be further employed to refine the wave inversion. With the ambiguity resolved and the along-track noise issue corrected, the derived two-dimensional wave spectra shall help to fully characterize the sea state conditions across the globe. More oceanographic studies will benefit from the simultaneous measurements of ocean waves by SWIM and wind field by the scatterometer aboard CFOSAT. For example, the wind-wave interaction can be possibly quantified as well as the local air-sea interaction. Wave in the sea ice is also an promising aspect to investigate, just to name a few.

The preliminary results of ambiguity removal by utilizing the up-to-downwave asymmetry demonstrated in this study are affirmative for the future operational implementation. Though, a more thorough algorithm needs to be devised for quanti-

cation of up-to-downwave asymmetry of wave partitions in addition to the local peaks. This algorithm shall greatly help refine the wave inversion scheme as well as enhance the usage of SWIM observations in oceanographic related studies.

## APPENDIX

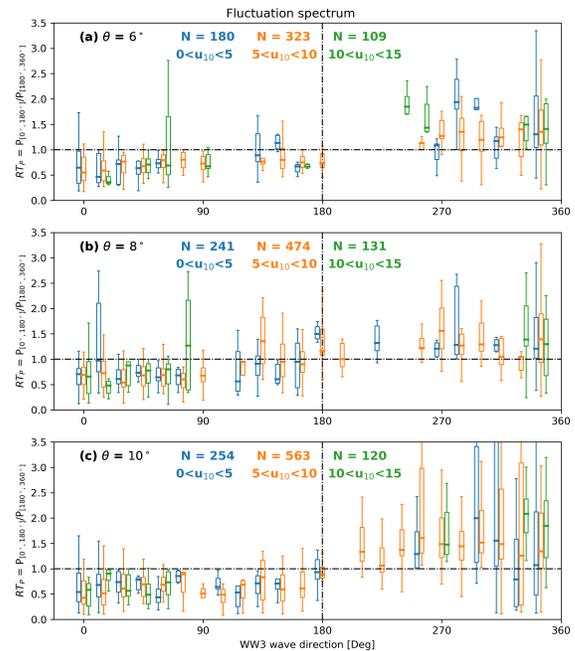


Fig. A1. Box plot of  $RT_P$  as defined by Eq. 3 is plotted as a function of the WW3 wave peak direction for three wind speed ranges for (a)  $6^\circ$ , (b)  $8^\circ$  and (c)  $10^\circ$  beams, respectively. 'N' annotated in each plot denotes the number of valid peak pairs.

## ACKNOWLEDGMENT

We would like to acknowledge the CNSA and CNES for providing the CFOSAT/SWIM Level-1A and Level-1B products. The ECMWF forecast winds are obtained in the framework of Sentinel-1 Mission Performance and are publicly available (ecmwf.int). WaveWatch III wave spectra are produced at Ifremer/LOPS within the framework of CFOSAT mission. All CFOSAT products are provided by the courtesy of CNSA and CNES.

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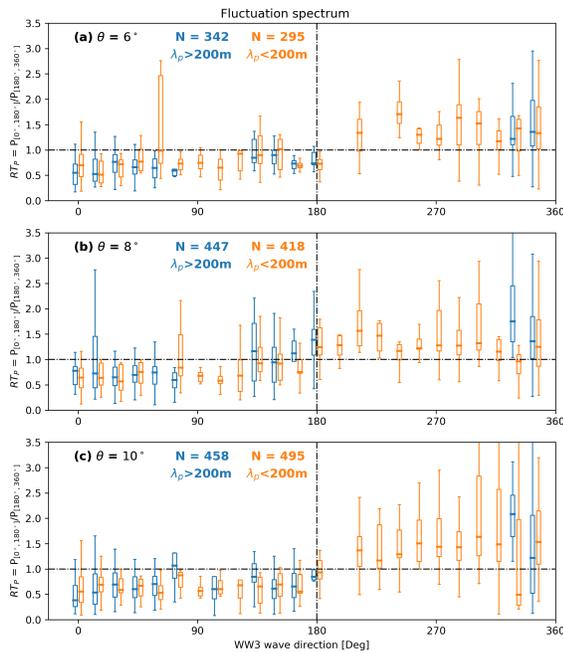


Fig. A2. Box plot of  $RT_P$  as defined by Eq. 3 is plotted as a function of the WW3 wave peak direction for two classes of peak wavelength ranges for (a)  $6^\circ$ , (b)  $8^\circ$  and (c)  $10^\circ$  beams, respectively. 'N' annotated in each plot denotes the number of valid peak pairs.

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