

Article

On Sea Ice Measurement by a C-Band Scatterometer at VV Polarization: Methodology Optimization Based on Computer Simulations

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Abstract: We consider sea ice and water microwave backscatter features at the C-band with vertical transmit and receive polarization and present a method for sea ice/water discrimination using a multiple fixed fan-beam satellite scatterometer. The method is based on the criterion of the minimum statistical distance of measured backscatter values to the sea ice and water (CMOD7) geophysical model functions. Implementation of the method is considered both for a typical three fan-beam geometry as well as for a potential five fan-beam geometry of a satellite scatterometer. By using computer simulations, we show explicitly that the number of looks at the same cell from different azimuthal directions needs to be increased to provide better (unambiguous) retrieval of the wind vector and sea ice/water discrimination. The algorithms for sea ice/water discrimination are described, and the results obtained are also discussed along with recommendations for the number of different azimuthal looks (beams) at the same cell from the point of view of sea ice/water discrimination as well as unambiguous wind direction retrieval during the satellite's single pass.

Keywords: spaceborne scatterometer; C-band; fan-beam; radar backscatter; sea ice; water surface; sea ice/water discrimination

1. Introduction

Global warming and reduction of areas covered by sea ice have motivated great interest in the development of polar regions. Sea ice covers about 12% of the oceans (approximately from 7% to 15% depending on the seasons) and interacts with the atmosphere and the ocean itself [1,2]. Although most sea ice is located in the Arctic and Antarctic regions, variations in sea ice coverage significantly affect climate conditions not only in the Earth's polar regions but also over the entire planet. In addition, melting ice imposes threats for economic activities such as offshore oil and gas production, fishing and sea freight, with the Northern Sea Route which is the shortest sea route between northwest Asia and Europe being a prominent example [1]. In a changing climate, rapid variations of temperature, currents, and winds make sea ice very dynamic, which leads to a wide variation in its types and characteristics.

The first systematic, but mostly local, observations of sea ice (from ships and coastal stations) are dated from around 1900. Later, development and application of aviation has extended and improved monitoring of sea ice, thus considerably improving the safety of sea navigation [1]. The era of satellite observations of sea ice started in the 1970s leading to the availability of long-term measurements.

Since that time, a significant number of spaceborne instruments, implementing both active and passive measurement technologies, have been used for sea ice monitoring. These instruments mostly operate in the optical, thermal infrared, or microwave parts of the spectrum [2]. Optical instruments are commonly used for sea ice observations, although they can only operate in the presence of sunlight and under relatively cloudless sky conditions. Thermal infrared instruments operate independently of daylight, while also requiring cloudless sky conditions. Microwave instruments commonly used for sea ice observations remain operational irrespective of the presence of daylight and mostly independent of atmospheric conditions, both being crucial for remote sensing applications in polar areas, as these areas stay in darkness during long periods of the polar night and exhibit common persistent cloud coverage. Thus, sea ice measurements in the polar regions are usually performed by using microwave instruments, either passive or active, represented by radiometers and scatterometers, respectively [3].

A microwave radiometer is a passive measurement instrument (calibrated receiver) designed to measure the properties of natural emissions from the environment [4]. In the case of ocean ice observation, it provides indirect information about the ice's concentration and thickness [5].

By contrast, a microwave scatterometer is an active instrument (carefully calibrated radar) designed for measurement of the backscatter power from the underlying surface that in turn is proportional to the normalized radar cross section (NRCS) and is useful for the retrieval of the wind speed and direction over the ocean/sea [4]. Moreover, scatterometer measurements can be used for sea ice detection and characterization [6]. Other instruments which can operate in scatterometer mode can also be used for such measurements [7–9].

As scatterometers have proved their suitability for monitoring the extent, thickness, and motion of sea ice, here we focus on ice and water geophysical model functions (GMF) analysis and their application to sea ice monitoring and discrimination at the C-band using vertical transmit and receive polarization (VV).

2. Materials and Methods

Spaceborne scatterometers are usually operated by weather satellites. To provide multiple looks at the same cell of the observed surface, two general scatterometer geometry arrangements can be used: three fan-beam geometry or two pencil-beam rotating geometry [4,10–13]. Fan-beam geometries allow for incidence angle diversity, while having variable directional sensitivity perpendicularly to the swath. Pencil-beam geometries allow for wider azimuthal coverage, but they are limited to fixed incidence angles only [14].

A detailed overview of spaceborne scatterometers' geometries and features can be found in the literature describing various scatterometers from the earliest to modern [4,10,11,13,15,16]. Continuous scatterometer monitoring in the Polar areas started in 1991 when the European Remote Sensing (ERS-1) satellite was launched. The development of both satellite and scatterometer technologies allowed for increased power, better signal-to-noise ratios, and improved measurement accuracy of the satellite scatterometers and led to the development of their various configurations, from the earliest fixed two fan-beam geometry to modern multiple-beam fixed or rotating geometries and corresponding measurement algorithms. In this regard, assessment of new scatterometer configuration designs aims at more accurate sea wind retrieval as well as better sea ice/water discrimination and provides the rationale for this study.

Historically, the European Space Agency's (ESA) scatterometers have been designed as C-band instruments while the National Aeronautics and Space Administration's (NASA) scatterometers have been designed to operate in the Ku-band. Moreover, European C-band scatterometers use a vertical transmit and receive polarization (VV) only, while the US Ku-band scatterometers use both VV and horizontal (HH) polarization [13]. The advantage of the C-band is lower sensitivity to atmospheric conditions and better penetration compared to that of the Ku-band. However, the Ku-band provides greater sea ice/water contrast. Using a variety of polarizations allows detection of additional information about the observed surface and provides better discrimination of its characteristics [13].

The most typical three fixed fan-beam scatterometer configuration is exemplified by the Advanced SCATterometer (ASCAT) geometry presented in Figure 1. ASCAT has been installed on board the Metop-A satellite. The scatterometer is represented by a C-band real aperture radar operating at 5.255 GHz with VV polarization only. NRCS measurements are performed at the azimuthal angles of 45° (fore-beam), 90° (mid-beam), and 135° (aft-beam) relative to the satellite's path. The incidence angle for the fore- and aft-beams varies from 37° to 64° and for the fore-beam it ranges from 28° to 53° [17].

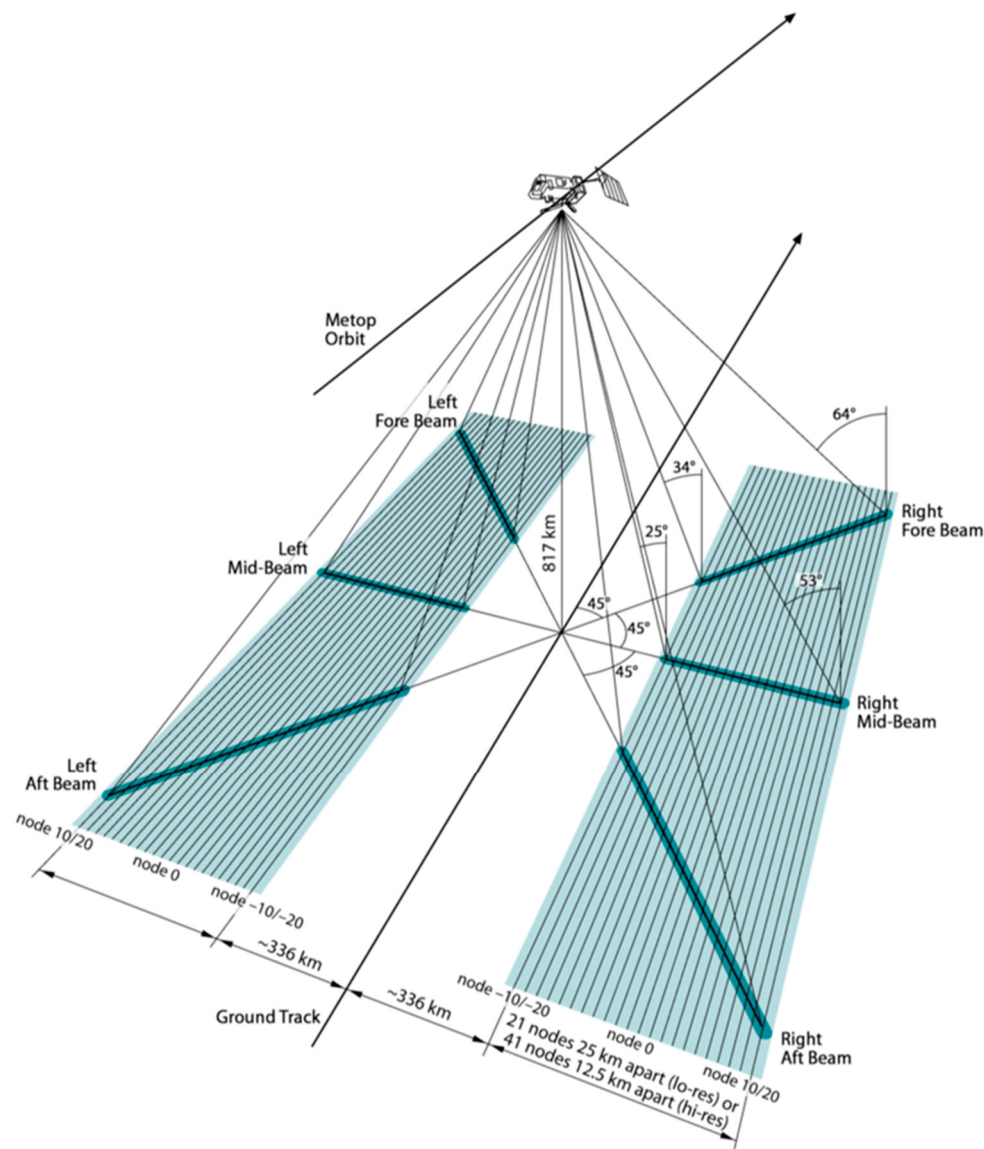


Figure 1. An example of the three fixed fan-beam scatterometer geometry of ASCAT [17].

Operating over the water's surface, a (wind) scatterometer provides information about the wind's speed and direction. Such wind vector measurements are based on a GMF developed for an appropriate band and polarization. Usually, GMF describes the NRCS $\sigma^0(U, \theta, \alpha)$ dependence from the wind speed U , incidence angle θ , and azimuth angle α relative to the up-wind direction [4,18]. GMF can be presented either in an analytical or in a tabulated form. For example, the recent C-band GMF of CMOD7 [19] currently lacks any analytical representation and/or fit. CMOD7 is presented in a tabular form only, as it has been developed by improving CMOD5.n at low wind speeds by using another GMF of C2013 [20].

When a scatterometer operates over the sea ice, it samples information about sea ice backscattering. As backscattering from water and sea ice has different properties, this difference can be used for discrimination of sea ice from the water's surface as well as for evaluation of the sea ice's age (thickness) and extent [11,21].

As sea ice backscatter is relatively isotropic, one of the earlier sea ice/water discrimination criteria was the anisotropy factor k_a introduced in [22]. This coefficient is independent of the incidence angle and can be written as:

$$k_a = \left| \frac{\sigma_f^\circ - \sigma_a^\circ}{\sigma_f^\circ + \sigma_a^\circ} \right|, \quad (1)$$

where σ_f° and σ_a° are the fore- and aft-beam NRCSs (measured at the same incidence angle while differing by 90° in the azimuth). To separate sea ice and water, a threshold for the anisotropy factor value can be proposed. Values below the threshold indicate that sea ice is observed. This criterion appears more efficient at higher incidence angles [23]. Unfortunately, the key disadvantage of this criterion is its potential ambiguity when the sea wind blows along the satellite's ground track (the mid-beam has a cross-wind location), as the measured water NRCSs by the fore- and aft-beams are mostly the same due to the features of the water's GMFs. Thus, small values of the anisotropy factor related to sea backscattering can also take place and so the water could be mistakenly recognized as sea ice in that case.

Another approach used for sea ice/water discrimination is based on the difference between the ice and the water GMF variations as functions of the incidence angle. For that purpose, a backscatter derivative k_d has been applied [24]:

$$k_d = \left| \frac{\sigma_f^\circ - \sigma_m^\circ}{\theta_f - \theta_m} \right|, \quad (2)$$

where σ_m° is the mid-beam NRCS, θ_f and θ_m are the incidence angles corresponding to the fore- and mid-beam NRCSs obtained for the same node. A threshold for the backscatter derivative value is also assumed to separate sea ice and water. In contrast to the anisotropy-based criterion, the latter appears more efficient at lower incidence angles. Nevertheless, this criterion has another disadvantage in sea ice/water discrimination when the wind blows parallel or perpendicular to the satellite's ground track [23]. The backscatter derivative also can be used for sea ice classification as its lower values correspond to multi-year (MY) ice whereas its higher values fit with first-year (FY) ice. The FY ice thickness is typically between 0.3 and 2 m while the MY ice thickness is over 2 m.

Another approach is based on the statistical (Euclidean) distance from the measured NRCSs to the wind GMF and the ice GMF, respectively. The lowest distance value (to the ice or water GMFs) is the criterion to classify the surface area observed within the cell as either ice or water, respectively [14]. Bayesian statistics has been applied, e.g., for the QuikSCAT, ASCAT, and ERS scatterometers, to suggest and implement sea ice detection algorithms based on this approach [3,14,25]. Another Bayesian approach, developed earlier for the SeaWinds instrument, can be found in earlier work [26].

Sea ice backscatter can also be used for discrimination of sea ice types as they have different backscatter properties; MY ice is typically characterized by higher NRCS values than those for FY ice (at the same incidence angles) [11]. The sea ice backscatter dependency from the incidence angle (sea ice GMF) $\sigma_{ice}^\circ(\theta)$ can be presented approximately in a linear form [13]:

$$\sigma_{ice}^\circ(\theta) = A(\theta_{ref}) + B(\theta - \theta_{ref}), \quad (3)$$

where $A(\theta_{ref})$ is the sea ice NRCS at the reference incidence angle θ_{ref} , and $B(\theta - \theta_{ref})$ is the NRCS dependency from the incidence angle relative to the reference incidence angle (in [dB/deg]). Usually, the reference incidence angle is assumed to be 40° , which approximately corresponds to the midswath incidence angle [13].

A more complex form of the sea ice GMF has been presented in [25,27]:

$$\sigma_{ice}^{\circ}(\theta) = \frac{1}{u(\theta)} \left(\sigma_{ice}^{\circ}(\theta_{ref}) + \int_{\theta_{ref}}^{\theta} u(\theta') A(\theta') d(\theta') \right), \quad (4)$$

$$u(\theta') = \exp \left(- \int_{\theta_{ref}}^{\theta'} B(\theta'') d(\theta'') \right), \quad (5)$$

where $A(\theta)$ and $B(\theta)$ are the coefficients obtained for the Northern (NH) and Southern (SH) Hemispheres based on the winter-time ERS and ASCAT sea ice NRCS data (at VV polarization in the C-Band) [25]:

$$A_{NH}(\theta) = 0.257 - 0.00605\theta, \quad (6)$$

$$B_{NH}(\theta) = 0.004 - 0.169 \cdot \exp(-0.075\theta), \quad (7)$$

$$A_{SH}(\theta) = -0.397 + 0.01314\theta - 0.000131\theta^2, \quad (8)$$

$$B_{SH}(\theta) = 0.007 - 0.797 \cdot \exp(-0.206\theta), \quad (9)$$

and the given reference incidence angle is 52.8° .

The sea ice NRCS value at the reference incidence angle is commonly used as a boundary condition to classify the sea ice types at various incidence angles with the help of Equation (4). For example, the recent VV C-band (ASCAT operational frequency of 5.255 GHz) NRCS values of the NH lower boundary conditions are -21 dB, -16 dB, and -12 dB, respectively, for the FY, second-year (SY), and MY ice types at the reference incidence angle of 52.8° [28]. Typical lower boundary condition curves obtained in accordance with [28] and Equation (4) are exemplified in Figure 2.

As uncertainties in sea ice/water discrimination can arise under specific conditions, the NRCS data obtained during several consecutive satellite passes over the same area can be used to improve the discrimination. In the context of operational sea ice/water discrimination and (near) real-time dissemination of the data obtained, such a procedure delays both processing and dissemination for one or several orbits. Moreover, as already mentioned above, for the typical three fan-beam geometry of a satellite scatterometer, the wind vector retrieval can be ambiguous (from two opposite wind directions at similar wind speeds and up to four different directions [11,29,30]). One possible solution is using the wind information from neighboring cells and/or from other sources (e.g., ground-based weather stations) to resolve any ambiguity in the wind direction measurement. Thus, it is desirable to develop the measurement algorithm (and the minimal required geometry) providing for sea ice/water discrimination as well as wind measurement during a single satellite pass [31].

To achieve the above goal, in the following we present a solution based on the criterion of the statistical distance of measured NRCSs to the sea ice GMF and to the water GMF for sea ice/water discrimination. We assume that the sea ice GMF is described by Equation (4) [28], and the water GMF is the VV C-band model function of CMOD7 [19]. By using the system of equations for measured NRCSs, we find the closest water GMF values. To perform sea ice/water discrimination, summation results obtained for the sea ice S_{ice} and water S_{water} by the least square method are compared:

$$\begin{cases} S_{ice} < S_{water} \Rightarrow \text{ice} \\ S_{ice} > S_{water} \Rightarrow \text{water} \\ S_{ice} \approx S_{water} \Rightarrow \text{uncertainty} \end{cases} \quad (10)$$

where

$$S_{ice} = \sum_{i=1}^N (\sigma_i^{\circ*} - \sigma_{ice,i}^{\circ})^2, \quad (11)$$

$$S_{water} = \sum_{i=1}^N (\sigma_i^{\circ*} - \sigma_{water.i}^{\circ})^2, \quad (12)$$

and where $i = \overrightarrow{1, N}$, N is the number of scatterometer looks (from different azimuths) at the same cell (number of beams in the case of multiple fan-beam geometry), $\sigma_i^{\circ*}$ is the i -measured (integrated) NRCS value, and $\sigma_{ice.i}^{\circ}$ and $\sigma_{water.i}^{\circ}$ are the closest sea ice and water GMF values corresponding to the i -measured NRCS value.

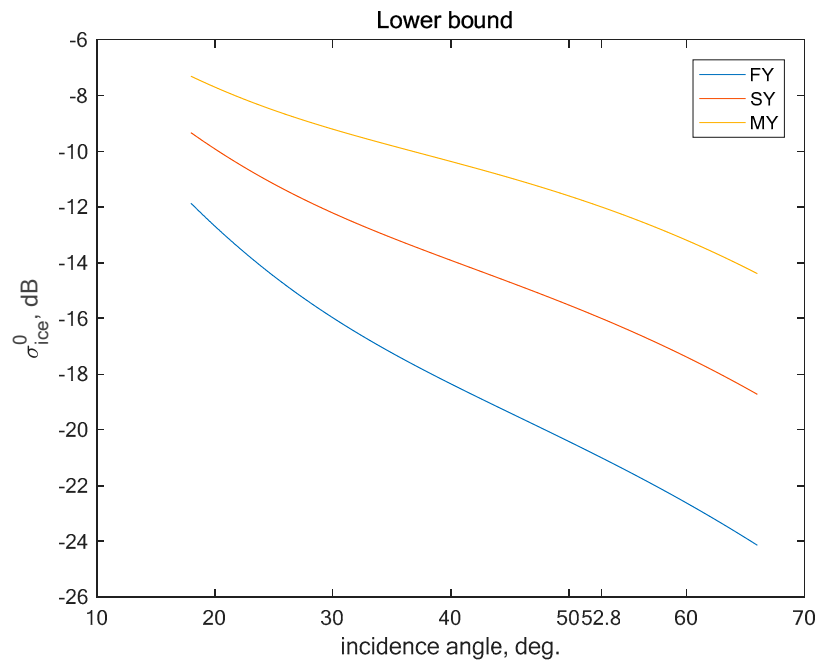


Figure 2. Lower boundary curves for the Arctic sea ice types corresponding to the VV C-band NRCS values of -21 dB, -16 dB, and -12 dB, respectively, for the FY, SY, and MY ice at the reference incidence angle of 52.8° .

First, a typical three fan-beam geometry (Figure 1) case has been considered. In that case, three measured (integrated) NRCSs $\sigma_1^{\circ*}$, $\sigma_2^{\circ*}$, and $\sigma_3^{\circ*}$ (obtained from different azimuthal directions by the fore-, mid-, and aft-beams with the azimuthal angles of 45° , 90° , and 135° relative to the satellite track direction, respectively) are available for the same selected cell.

To obtain the sea ice summation result for the current NRCS triplet, a current sea ice GMF approximation that fits in the best way to the current measured NRCSs is calculated. At the same time, to obtain the water summation result, a system of equations for the current NRCS triplet is solved to find a current water GMF approximation (wind speed and up-wind direction) best fitting the current measured NRCSs:

$$\begin{cases} \sigma_1^{\circ*} = GMF(U, \theta_{\sigma_1^{\circ*}}, \alpha + \psi_{\sigma_1^{\circ*}}) \\ \sigma_2^{\circ*} = GMF(U, \theta_{\sigma_2^{\circ*}}, \alpha + \psi_{\sigma_2^{\circ*}}) \\ \sigma_3^{\circ*} = GMF(U, \theta_{\sigma_3^{\circ*}}, \alpha + \psi_{\sigma_3^{\circ*}}) \end{cases} \quad (13)$$

where $\theta_{\sigma_1^{\circ*}}$, $\theta_{\sigma_2^{\circ*}}$, and $\theta_{\sigma_3^{\circ*}}$ are the incidence angles corresponding to measured NRCSs by the fore-, mid-, and aft-beams from the same selected cell, respectively; and $\psi_{\sigma_1^{\circ*}}$, $\psi_{\sigma_2^{\circ*}}$, and $\psi_{\sigma_3^{\circ*}}$ are the azimuthal angles of the selected cell by the fore-, mid-, and aft-beams relative to the satellite track direction.

Unfortunately, wind vector retrieval with the typical three fan-beam geometry of a satellite scatterometer can be ambiguous [30] especially at the C-band with VV polarization. The wind direction ambiguity mostly arises from two opposite wind directions at similar wind speeds and up to four different directions [11,29,30] due to the water GMF's properties and the three-beam satellite scatterometer configuration. The azimuthal NRCS curve at medium incidence angles is smooth and exhibits its largest maximum in the up-wind direction and the second largest maximum in the down-wind direction, while exhibiting two minima near the crosswind direction shifted slightly to the second largest maximum. A small discrepancy between the NRCS value at the maxima and between the largest maximum and the corresponding minima, along with considerable NRCS spread, can lead to the wind direction ambiguity in the case of three-beam satellite scatterometer [11]. Moreover, VV polarization provides a smaller difference between the largest and second largest maxima compared to the HH polarization scenario at medium incidence angles [32] that is not in favor of the ambiguity's removal. Recently, we have shown that for an accurate and unambiguous estimation of the wind direction (as well as the wind speed) at least four star-configured beams are needed to perform the wind vector retrieval at the same incidence angle [33]. However, satellite scatterometer measurements cannot provide the necessary star geometry observation for the same cell (and at the same incidence angle). Similarly, a multiple fan-beam geometry provides only multiple looks for the same cell at different incidence angles and with a limited azimuthal difference between the beams. At the same time, to provide better discrimination between sea ice and water, revealing the sea ice isotropy (relative to the water anisotropy) also requires a greater number of looks with wider azimuthal cover for the same cell. Thus, the number of looks for the same cell from different azimuthal directions needs to be increased to provide better (unambiguous) retrieval of the wind vector and better sea ice/water discrimination.

In this regard, we have considered a potential (although currently hypothetical) five fan-beam geometry with two extra beams added to the typical three fan-beam geometry. In the considered design, five measured (integrated) NRCSs, $\sigma_1^{\circ*}$, $\sigma_2^{\circ*}$, $\sigma_3^{\circ*}$, $\sigma_4^{\circ*}$, and $\sigma_5^{\circ*}$ (obtained from different azimuthal directions by the “old” fore-, mid-, and aft-beams, and two “additional” fore- and aft-beams with azimuthal angles of 32.5° and 147.5° relative to the satellite track direction), are available for the same selected cell.

The current sea ice GMF approximation that is the best fit to the current measured NRCSs is calculated to get the sea ice summation result for the current NRCS quintet. Moreover, the system of equations for the current NRCS quintet is solved to obtain the current water GMF approximation (wind speed and up-wind direction) that fits in the best way to the current measured NRCSs:

$$\begin{cases} \sigma_1^{\circ*} = GMF(U, \theta_{\sigma_1^{\circ*}}, \alpha + \psi_{\sigma_1^{\circ*}}) \\ \sigma_2^{\circ*} = GMF(U, \theta_{\sigma_2^{\circ*}}, \alpha + \psi_{\sigma_2^{\circ*}}) \\ \sigma_3^{\circ*} = GMF(U, \theta_{\sigma_3^{\circ*}}, \alpha + \psi_{\sigma_3^{\circ*}}) \\ \sigma_4^{\circ*} = GMF(U, \theta_{\sigma_4^{\circ*}}, \alpha + \psi_{\sigma_4^{\circ*}}) \\ \sigma_5^{\circ*} = GMF(U, \theta_{\sigma_5^{\circ*}}, \alpha + \psi_{\sigma_5^{\circ*}}) \end{cases} \quad (14)$$

where $\theta_{\sigma_1^{\circ*}}$, $\theta_{\sigma_2^{\circ*}}$, and $\theta_{\sigma_3^{\circ*}}$ are the incidence angles corresponding to measured NRCSs by the “old” fore-, mid-, and aft-beams from the same selected cell, $\theta_{\sigma_4^{\circ*}}$, and $\theta_{\sigma_5^{\circ*}}$ are the incidence angles corresponding to measured NRCSs by the “additional” fore- and aft-beams from the same selected cell, and $\psi_{\sigma_1^{\circ*}}$, $\psi_{\sigma_2^{\circ*}}$, $\psi_{\sigma_3^{\circ*}}$, $\psi_{\sigma_4^{\circ*}}$, and $\psi_{\sigma_5^{\circ*}}$ are the azimuthal angles of the selected cell by the appropriate beams relative to the satellite track direction.

3. Results and Discussion

First of all, we have analyzed the VV C-band sea ice GMF (Equation (4)) and CMOD7. This was done for a layout of lower boundaries for FY, SY, and MY ice at the NH and the water NRCS upper and lower boundaries corresponding to the maximum (up-wind) and minimum (cross-wind) NRCS values dependent on the incidence angle from 20° to 65° at the wind speeds of 2 and 5 m/s, as represented in Figure 3, while at the wind speed of 10, 15, 20, 25, and 30 m/s as shown in Figure 4.

Figure 3a,b demonstrates clearly that for the VV C-band only, at a wind speed of about 2 m/s and lower, sea ice can be discriminated from water by the NRCS magnitude at incidence angles from 25° to 65° . The same holds for a wind speed of about 5 m/s but only at an incidence angle from 40° to 65° . At higher wind speeds the above sea ice/water discrimination criterion becomes no longer applicable (Figure 4a–e).

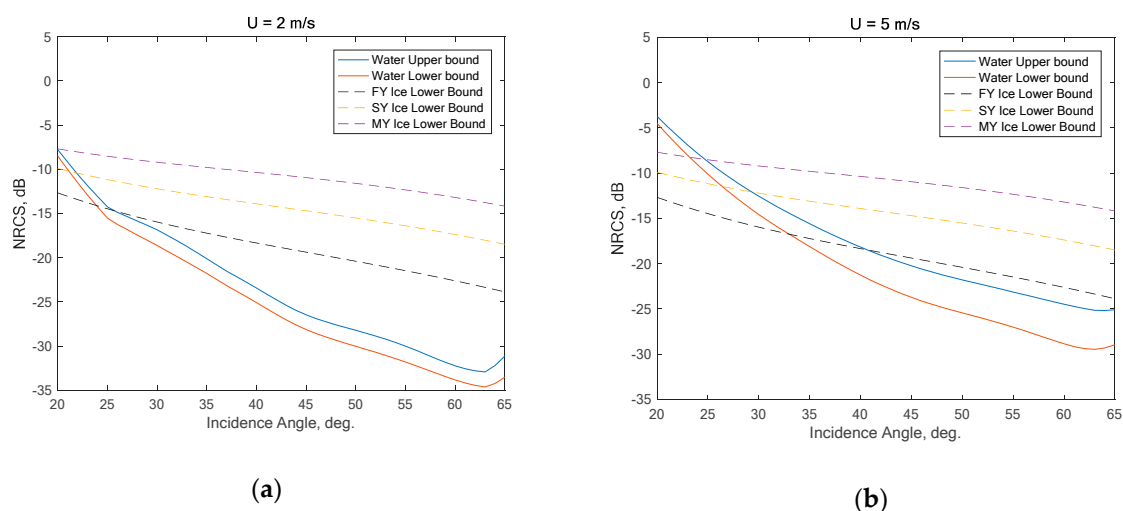


Figure 3. Positional relationship of the sea ice lower boundaries for FY, SY, and MY ice at the NH and water NRCS upper and lower boundaries at low wind speeds depending on an incidence angle from 20° to 65° : (a) wind speed of 2 m/s; (b) wind speed of 5 m/s.

These figures also demonstrate that the tilt of the “water GMF line” becomes similar to that of the “ice GMF line” at incidence angles exceeding approx. 40° to 45° , which makes sea ice/water discrimination more difficult, e.g., by the backscatter derivative criterion (Equation (2)), especially for relatively low (about 2 m/s and lower) or high (over 25 m/s) wind speeds when the water’s azimuthal NRCS curves exhibit only moderate variations at medium wind speeds (between approx. 5 and 25 m/s) (see Figure 5). Moreover, the anisotropy criterion (Equation (1)) also does not perform well when the water NRCSs measured by the fore- and aft-beams are mostly the same due to the water GMF’s azimuthal features.

Following this we considered the proposed sea ice/water discrimination procedure with regard to a three fan-beam geometry (Figure 1). The sea ice GMF approximation using a simulated “measured” NRCS triplet is shown in Figure 6. The figure presents the “measured” NRCS values and the corresponding ice GMFs as well as the resulting sea ice GMF approximations. The incidence angles for the selected cell by the fore-, mid-, and aft-beams are 52.8° , 41.8° , and 52.8° , respectively.

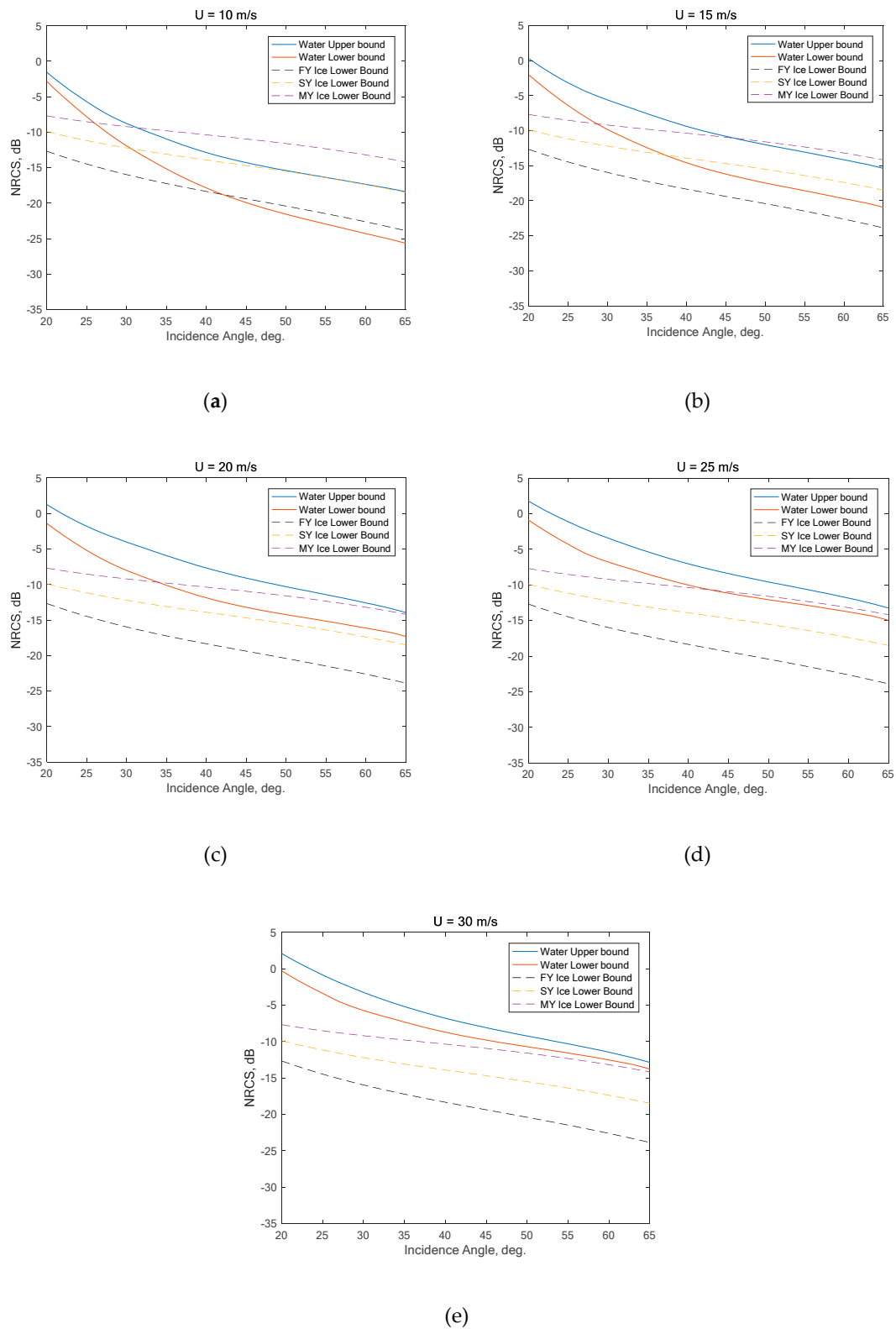


Figure 4. Positional relationship of the sea ice lower boundaries for FY, SY, and MY ice at the NH and the water NRCS upper and lower boundaries at high wind speeds depending on the incidence angle from 20° to 65°: (a) wind speed of 10 m/s; (b) wind speed of 15 m/s; (c) wind speed of 20 m/s; (d) wind speed of 25 m/s; and (e) wind speed of 30 m/s.

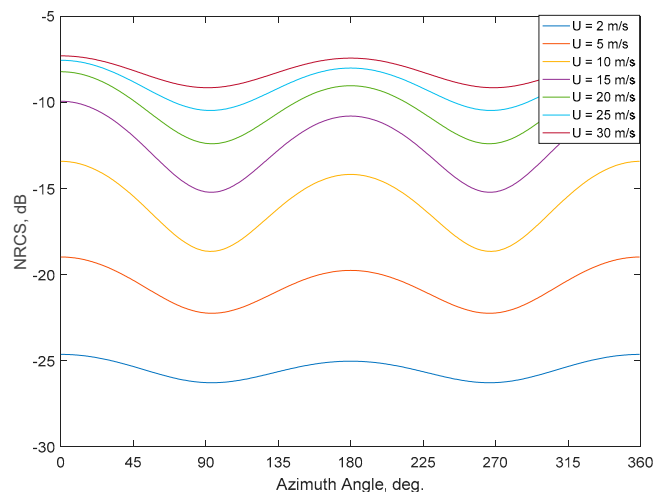


Figure 5. C-band VV polarization azimuthal curves by CMOD7 GMF for wind speeds of 2, 5, 10, 15, 20, 25, and 30 m/s at the incidence angle of 41.8° .

The water GMF approximation is depicted in Figure 7. The figure indicates the simulated “measured” NRCS values (the same values as in Figure 6) and the corresponding resulting water GMF approximations as well as the water GMF curves for incidence angles of 41.8° and 52.8° . The azimuthal angles for the fore-, mid-, and aft-beams are 45° , 90° , and 135° relative to the satellite track direction, respectively. The combination of the water GMF approximations in this example corresponds to the water GMF at a wind speed of 8.1 m/s and up-wind direction of 176° . The sea ice GMF approximations for the “measured” NRCSs are also marked in Figure 7. The figure clearly demonstrates that the sea ice GMF approximations fit much better to the “measured” NRCSs than the water GMF approximations. It means that $S_{ice} < S_{water}$ and the surface observed is thus classified as ice. (The calculated summation results for the sea ice and water are $5.69263 \cdot 10^{-8}$ and $5.35511 \cdot 10^{-6}$, respectively, and the sea ice is classified as FY in this example.)

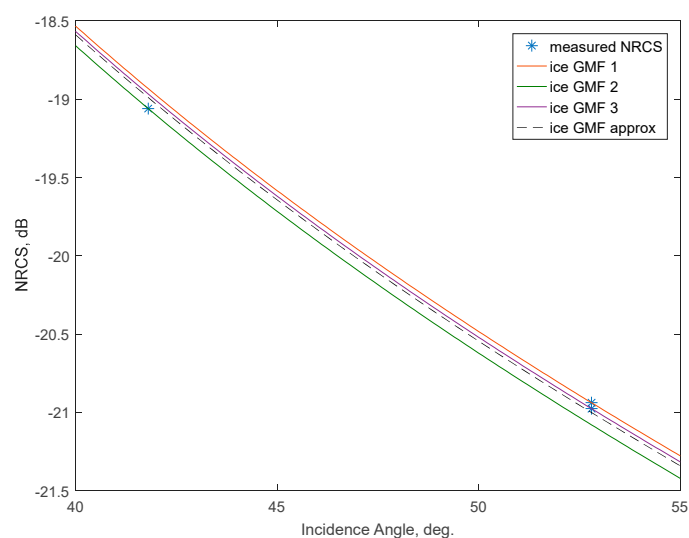


Figure 6. An example of sea ice GMF approximation from the simulated “measured” NRCSs for the selected cell by the fore-, mid-, and aft-beams at incidence angles of 52.8° , 41.8° , and 52.8° , respectively.

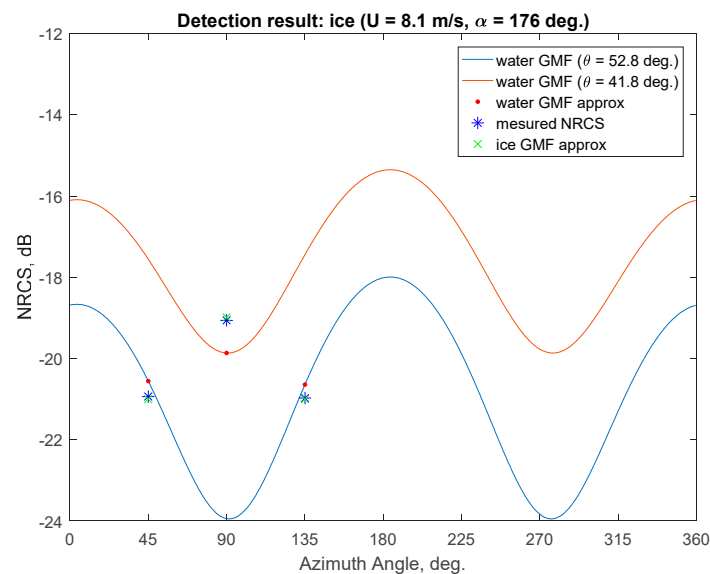


Figure 7. An example of water GMF approximations from the simulated “measured” NRCSs, with water GMF curves for incidence angles of 41.8° and 52.8° , and the sea ice GMF approximations.

Further, we also considered the proposed sea ice/water discrimination procedure with regard to a hypothetical five fan-beam geometry that has two extra beams added to the typical three fan-beam geometry considered earlier.

An example of plotting the sea ice GMF approximation for a simulated measured NRCS quintet is presented in Figure 8. The figure depicts the “measured” NRCSs and the ice GMFs corresponding to those NRCSs, as well as the derived sea ice GMF approximation. The incidence angles for the selected cell by the “old” fore-, mid-, and aft-beams are 52.8° , 41.8° , and 52.8° , respectively, and the incidence angle for the selected cell by the “additional” fore- and aft-beams is 63.6° .

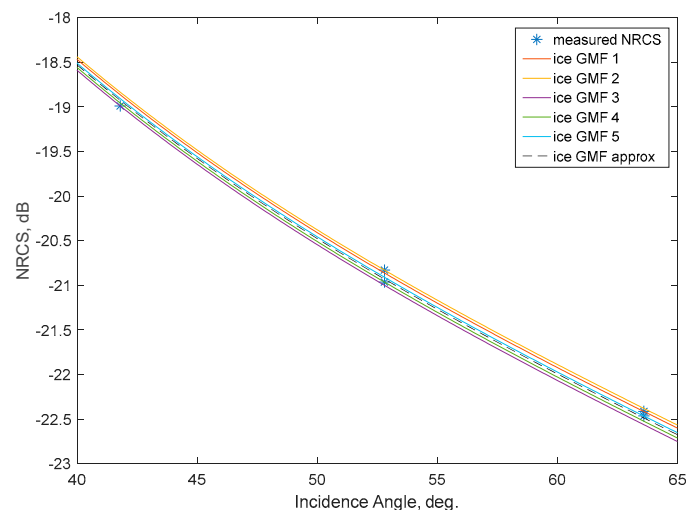


Figure 8. An example sea ice GMF approximation plot from the measured NRCSs for a selected cell by the “old” fore-, mid-, and aft-beams at 52.8° , 41.8° , and 52.8° , respectively, and with the incidence angle for the selected cell by the “additional” fore- and aft-beams of 63.6° .

An example of the water GMF plot is shown in Figure 9. The figure represents the simulated “measured” NRCS values (the same values as in Figure 8) and the corresponding resulting water GMF approximation as well as the water GMF curves for incidence angles of 41.8° , 52.8° , and 63.6° . The azimuthal angles for the “old” fore-, mid-, and aft-beams are 45° , 90° , and 135° and for

the “additional” fore- and aft-beams” are 32.5° and 147.5° relative to the satellite track direction. The combination of the water GMF approximation in this example conforms to the water GMF at a wind speed of 8 m/s and up-wind direction of 175.5° . The sea ice GMF approximations for the measured NRCSs are also shown in Figure 9. The figure indicates clearly that the sea ice GMF approximations fit to the measured NRCSs much better than the water GMF approximations indicating that $S_{ice} < S_{water}$ and thus classifying the observed surface as ice. (The summation results calculated for the sea ice and for the water are 8.39745×10^{-8} and 7.49849×10^{-6} , respectively, and the sea ice is classified as FY in this example.)

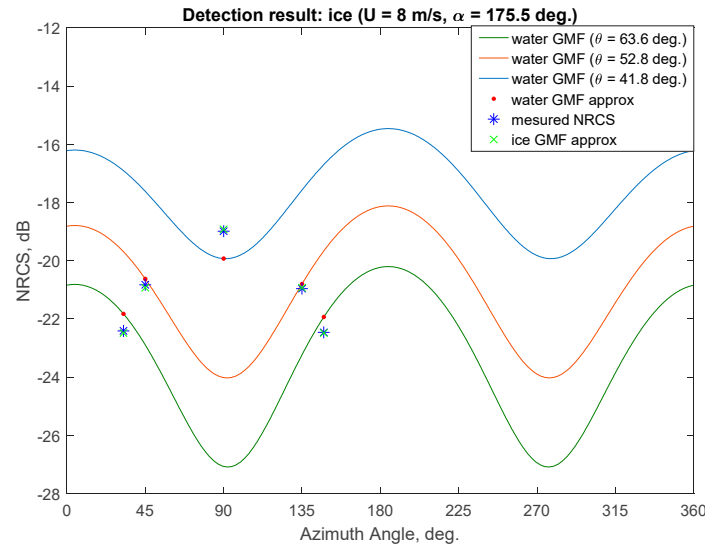


Figure 9. An example of the water GMF approximation from the measured NRCSs, water GMF curves for the incidence angles of 41.8° , 52.8° , and 63.6° and the sea ice GMF approximations.

To compare the summation results obtained for the different numbers of beams (looks), they can be normalized to the number of those beams (looks):

$$S_{n.ice} = \frac{S_{ice}}{N}, \quad (15)$$

$$S_{n.water} = \frac{S_{water}}{N}, \quad (16)$$

where $S_{n.ice}$ and $S_{n.water}$ are the ice and water summation results, respectively, normalized to the number of beams (looks). Accordingly, the normalized sea ice and water summation results for the three-beam geometry are 1.89754×10^{-8} and 1.78504×10^{-6} , respectively, and 1.67949×10^{-8} and 1.4997×10^{-6} , respectively, for the five-beam geometry. The lower normalized sea ice and water summation results for the five-beam geometry indicate that more accurate sea ice/water discrimination can be achieved compared to the three-beam geometry.

To summarize, our results indicate the suitability of the presented methodology for sea ice/water discrimination during a single pass, in this way allowing for near real-time measurement and data acquisition. The results show that, for better disambiguation of the wind vector retrieval and more accurate sea ice/water discrimination, increasing the number of looks at the same cell from different azimuthal directions can be beneficial.

4. Conclusions

Based on our analysis of the VV C-band’s sea ice and water backscatter features, we have presented a sea ice/water discrimination method for multiple fixed fan-beam satellite scatterometers. The method

allows for sea ice/water discrimination during a single satellite pass without any need for additional information from neighboring cells, subsequent passes, or other (e.g., ground-based) data sources.

As a perspective, we have also shown that a five fan-beams (looks) scatterometer configuration seems to be advantageous for unambiguous sea wind retrieval and for sea ice/water discrimination as it allows getting the backscatter information from the wider azimuthal directions. Obtaining the NRCS information from a wider range of azimuthal directions leads to higher contrast between the sea ice isotropy and water anisotropy, thus allowing for their more accurate discrimination as well as for unambiguous sea wind vector retrieval. However, it should be noted that application of additional beams (looks) having wider azimuthal location in comparison with a typical three fan-beams (looks) scatterometer configuration narrows the swath as the farther nodes could not be observed by the additional fore-and aft-beams due to the incidence angle limitation.

Application of C-band microwaves with VV polarization for this purpose is considered to be the less reliable scenario as the alternative horizontal transmitter and receiver (HH) polarization provides better anisotropy use of the water's backscatter (characterized by a more pronounced discrepancy between the up-wind and the down-wind NRCSs as well as between the up-wind and the cross-wind NRCSs) altogether, when compared against the VV polarization scenario [32]. Moreover, from that point of view, the Ku-band is more prospective as it provides better water anisotropy use, greater sea ice/water contrast and greater contrast between FY and MY ice [13], and the Ku-band HH polarization also provides better water anisotropy use than VV polarization. Accordingly, satisfactory performance in the worst possible scenario indicates that alternative scenarios lead to at least similar, or more likely better, performance of our algorithm.

Finally, the method could also be effective for prospective fan-beam rotating (scanning) satellite scatterometers for their application to sea ice monitoring and discrimination.

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References

1. Johannessen, O.M.; Alexandrov, V.; Frolov, I.Y.; Sandven, S.; Pettersson, L.H.; Bobylev, L.P.; Kloster, K.; Smirnov, V.G.; Mironov, Y.U.; Babich, N.G. *Remote Sensing of Sea Ice in the Northern Sea Route: Studies and Applications*; Springer: Berlin/Heidelberg, Germany, 2007; p. 563. ISBN 978-3-540-48840-8. [\[CrossRef\]](#)
2. Shokr, M.; Sinha, N. *Sea Ice: Physics and Remote Sensing*; John Wiley & Sons: Hoboken, NJ, USA, 2015; p. 600. ISBN 978-1-119-02789-8. [\[CrossRef\]](#)
3. Rivas, M.B.; Stoffelen, A. New Bayesian algorithm for sea ice detection with QuikSCAT. *IEEE Trans. Geosci. Remote Sens.* **2011**, *49*, 1894–1901. [\[CrossRef\]](#)
4. Njoku, E.G. *Encyclopedia of Remote Sensing*; Springer: New York, NY, USA, 2014; p. 939. ISBN 978-0-387-36700-2.
5. Cavalieri, D.J.; Parkinson, C.L.; Gloersen, P.; Comiso, J.C.; Zwally, H.J. Deriving long term time series of sea ice cover from satellite passive microwave multisensor datasets. *J. Geophys. Res.* **1999**, *104*, 15803–15814. [\[CrossRef\]](#)

6. Haarpaintner, J.; Spreen, G. Use of enhanced-resolution QuikSCAT/seawinds data for operational ice services and climate research: Sea ice edge, type, concentration, and drift. *IEEE Trans. Geosci. Remote Sens.* **2007**, *45*, 3131–3137. [\[CrossRef\]](#)
7. Bao, Q.; Zhang, Y.; Lang, S.; Lin, M.; Gong, P. Sea surface wind speed inversion using the low incident NRCS measured by TRMM precipitation radar. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2016**, *8*, 5262–5271. [\[CrossRef\]](#)
8. Karaev, V.; Panfilova, M.; Titchenko, Y.; Meshkov, E.; Balandina, G.; Andreeva, Z. Monitoring of inland waters by dual-frequency precipitation radar: First results. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2018**, *11*, 4364–4372. [\[CrossRef\]](#)
9. Panfilova, M.; Shikov, A.; Andreeva, Z.; Volgutov, R.; Karaev, V.; Ryabkova, M. Sea ice detection using near-nadir incidence GPM Ku-band radar data. *IEEE Trans. Geosci. Remote Sens. Lett.* **2019**.
10. Kramer, H.J. *Observation of the Earth and Its Environment: Survey of Missions and Sensors*, 4th ed.; Springer: Berlin, Germany, 2002; p. LVIII. Available online: <http://extras.springer.com/Zip/2002/978-3-642-62688-3.zip> (accessed on 13 September 2019). [\[CrossRef\]](#)
11. Ulaby, F.T.; Long, D.G. *Microwave Radar and Radiometric Remote Sensing*; University of Michigan Press: Ann Arbor, MI, USA, 2014; p. 1116. ISBN 978-0-472-11935-6.
12. Nekrasov, A.; Dell’Acqua, F. Airborne Weather Radar: A theoretical approach for water-surface backscattering and wind measurements. *IEEE Geosci. Remote Sens. Mag.* **2016**, *16*, 38–50. [\[CrossRef\]](#)
13. Long, D.G. Polar applications of spaceborne scatterometers. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2017**, *10*, 2307–2320. [\[CrossRef\]](#)
14. Rivas, M.B.; Verspeek, J.; Verhoef, A.; Stoffelen, A. Bayesian sea ice detection with the advanced acatterometer ASCAT. *IEEE Trans. Geosci. Remote Sens.* **2012**, *50*, 2649–2657. [\[CrossRef\]](#)
15. Jones, W.L. Early days of microwave scatterometry: RADSCAT to SASS. In Proceedings of the IGARSS 2015, Milan, Italy, 26–31 July 2015; pp. 4208–4211. [\[CrossRef\]](#)
16. Li, Z.; Stoffelen, A.; Verhoef, A. A generalized simulation capability for rotating-beam scatterometers. *Atmos. Meas. Tech.* **2019**, *12*, 3573–3594. [\[CrossRef\]](#)
17. Wagner, W.; Hahn, S.; Kidd, R.; Melzer, T.; Bartalis, Z.; Hasenauer, S.; Figa-Saldaña, J.; de Rosnay, P.; Jann, A.; Schneider, S.; et al. The ASCAT Soil Moisture Product: A Review of Its Specifications, Validation Results, and Emerging Applications. *Meteorol. Z.* **2013**, *22*, 5–33. Available online: https://www.schweizerbart.de/papers/metz/detail/22/79822/The_ASCAT_Soil_Moisture_Product_A_Review_of_its_Specifications_Validation_Results_and_Emerging_Applications (accessed on 13 September 2019). [\[CrossRef\]](#)
18. Karaev, V.Yu.; Panfilova, M.A.; Titchenko, Yu.A.; Meshkov, E.M.; Balandina, G.N.; Kuznetsov, Yu.V.; Shlaferov, A.L. Retrieval of the near-surface wind velocity and direction: SCAT-3 orbit-borne scatterometer. *Radiophys. Quantum Electron.* **2016**, *59*, 259–269. [\[CrossRef\]](#)
19. CMOD7. Available online: <http://projects.knmi.nl/scatterometer/cmod7> (accessed on 13 September 2019).
20. Stoffelen, A.; Verspeek, J.; Vogelzang, J.; Verhoef, A. The CMOD7 geophysical model function for ASCAT and ERS wind retrievals. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2017**, *10*, 2123–2134. [\[CrossRef\]](#)
21. Rivas, M.B.; Otosaka, I.; Stoffelen, A.; Verhoef, A. A scatterometer record of sea ice extents and backscatter: 1992–2016. *Cryosphere* **2018**, *12*, 2941–2953. [\[CrossRef\]](#)
22. Cavenié, A.; Gohin, F.; Quilfen, Y.; Lecomte, P. Identification of sea ice zones using AMI wind: Physical bases and applications to the FDP and CERSAT processing chains. In Proceedings of the Second ERS-1 Symposium, Hamburg, Germany, 11–14 October 1993; ESA SP-361. Volume 2, pp. 1009–1012.
23. De Haan, S.; Stoffelen, A. *Ice Discrimination Using ERS Scatterometer*; Technical Report; KNMI: De Bilt, The Netherlands, 2001; p. 38. Available online: http://projects.knmi.nl/publications/fulltexts/safosi_w_icescrknmi.pdf (accessed on 13 September 2019).
24. Gohin, F. Some active and passive microwave signatures of Antarctic sea ice from mid-winter to spring 1991. *Int. J. Remote Sens.* **1995**, *16*, 2031–2054. [\[CrossRef\]](#)
25. Otosaka, I.; Rivas, M.B.; Stoffelen, A. Bayesian sea ice detection with the ERS scatterometer and sea ice backscatter model at C-band. *IEEE Trans. Geosci. Remote Sens.* **2018**, *56*, 2248–2254. [\[CrossRef\]](#)
26. Anderson, H.S.; Long, D.G. Sea ice mapping method for SeaWinds. *IEEE Trans. Geosci. Remote Sens.* **2005**, *43*, 647–657. [\[CrossRef\]](#)

27. Otsuka, I.; Rivas, M.B.; Stoffelen, A. Errata for “Bayesian sea ice detection with the ERS scatterometer and sea ice backscatter model at C-band”. *IEEE Trans. Geosci. Remote Sens.* **2019**, *1*. [[CrossRef](#)]
28. Rivas, M.B. Personal communication, 2019.
29. Liu, Y.; Pierson, W.J. Comparisons of scatterometer models from the AMI on ERS-1: The possibility of systematic azimuth angle biases of wind speed and direction. *IEEE Trans. Geosci. Remote Sens.* **1994**, *32*, 626–635. [[CrossRef](#)]
30. Lin, W.; Portabella, M.; Stoffelen, A.; Verhoef, A. On the characteristics of ASCAT wind direction ambiguities. *Atmos. Meas. Tech.* **2013**, *6*, 1053–1060. [[CrossRef](#)]
31. Neyt, X.; Pettiaux, P.; Manise, N.; Acheroy, M. Single-pass sea/ice discrimination using ERS-2 scatterometer data. *Gayana* **2004**, *68*, 432–438. [[CrossRef](#)]
32. Ulaby, F.T.; Moore, R.K.; Fung, A.K. *Microwave Remote Sensing: Active and Passive, Volume II: Radar Remote Sensing and Surface Scattering and Emission Theory*; Addison-Wesley: London, UK, 1982; p. 1064. ISBN 0-89006-191-2.
33. Nekrasov, A.; Khachaturian, A.; Abramov, E.; Popov, D.; Markelov, O.; Obukhovets, V.; Veremyev, V.; Bogachev, M. Optimization of Airborne Antenna Geometry for Ocean Surface Scatterometric Measurements. *Remote Sens.* **2018**, *10*, 1501. [[CrossRef](#)]



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