Microwave Specular Returns and Ocean Surface Roughness

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Abstract — Remote sensing measurements have been an important data source of ocean surface roughness. Scatterometers operating at moderate and high incidence angles provide information on the Bragg resonance spectral components of the ocean surface waves. Monostatic and bistatic reflectometers provide spectrally integrated information of ocean waves longer than several times the incident electromagnetic (EM) wavelengths. The integrated surface roughness is generally expressed as the lowpass mean square slope (LPMSS). Tilting modification of the local incidence angle for the specular facets located on slanted background surfaces is an important factor in relating the LPMSS and microwave specular returns. For very high wind condition, it is necessary to consider the modification of relative permittivity by air in foam and whitecaps produced by wave breaking. This paper describes the application of these considerations to monostatic and bistatic microwave specular returns from the ocean surface. Measurements from Ku band altimeters and L band reflectometers are used for illustration. It remains a challenge to acquire sufficient number of high wind collocated and simultaneous reference measurements for algorithm development or verification effort. Solutions from accurate forward computation can supplement the sparse high wind databases. Modeled specular normalized radar cross sections (NRCSs) for L, C, X, Ku, and Ka bands with wind speeds up to 99 m/s are provided.

Index Terms— Ocean surface roughness, normalized radar cross section, specular reflection, tilting effect, Bragg resonance, relative permittivity, whitecaps.

I. INTRODUCTION

The range of ocean surface wavelengths important to microwave remote sensing extends several orders of magnitude. Crombie [1] reports the Doppler frequency spectrum of 13.56 MHz radar sea echo at low grazing angle. A distinct spectral peak at 0.38 Hz is illustrated, corresponding to the resonance ocean surface wavelength of about 10 m (wavenumber \(k\) about 0.6 rad/m). He goes on to suggest that variable frequency equipment can be used to measure the ocean surface wave spectrum. Depending on frequency and incidence angle, the range of resonance surface wavenumbers spans from about 500 rad/m (Ku band) to about 20 rad/m (L band) for microwaves sensors operating at moderate and high incidence angles [2, 3].

For altimeters and reflectometers, the specular reflection mechanism dominates. The normalized radar cross section (NRCS) is proportional to the number of specular points and the average radii of curvature of the specular reflection facets [4, 5]. With the Gaussian distribution describing the elevation/slope/velocity of the moving ocean surface [6], a simple inverse relationship between NRCS and surface mean square slope (MSS) is established [4, 5]. Further analysis [7-9] indicates that the responsible MSS is contributed by surface waves longer than the EM wavelengths. The frequently cited ratio between the upper cutoff wavenumber \(k_u\) of lowpass MSS integration and the EM wavenumber \(k\) is between 3 and 6 [8-9]. Thus, for Ku band (~14 GHz) altimeter, \(k_u\) is about 50 to 100 rad/m, and for L band (~1.6 GHz) reflectometer it is about 6 to 11 rad/m.

These theoretical and empirical analyses provide useful guidelines for quantitative investigation of the connection between specular NRCS and ocean surface roughness. Ku-band altimeters have been in operation for many decades and there is a rich trove of well-calibrated Ku band altimeter NRCS data for a close examination of the specular point theory applied to nadir-looking altimeter: \(\sigma_0 = |R(0)|^2 / s_{\tau 0}^2\), where \(\sigma_0\) is NRCS, \(R(0)\) is the Fresnel reflection coefficient for normal incidence, and \(s_{\tau 0}\) is the Ku-band LPMSS [7]. One peculiar outcome is that the resulting \(s_{\tau 0}\) calculated from measured Ku-band NRCS is larger than the optical total MSS [10-11]. The difference is especially obvious in low and moderate wind speeds (\(U_{10}\) less than about 10 m/s). To address this paradox, an effective reflectivity ranging from 0.34 to 0.5 has been suggested [7-9]; those numbers are much smaller than the nominal value of 0.62 computed from the Ku band relative permittivity. An alternative explanation is that the peculiar result can be reconciled if the tilting effect of the reflecting specular facets is considered when applying the specular point theory [12-13]. Therefore, in addition to \(s_{\tau 0}\), it is necessary to address another surface slope quantity: the tilting MSS \(s_{\tau T}\). It has been about two decades since the study of [12-13] and our understanding of the ocean surface wave spectrum has advanced considerably with incorporation of remote sensing data into the relatively sparse databases of short-scale ocean surface waves accumulated from direct observations [14-16]. Here we revisit the Ku-band altimeter NRCS analysis. The results are applied to the bistatic observations of L band LPMSS [17-20] and recent reports of bistatic NRCS results derived from the NASA CYclone

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Global Navigation Satellite System (CYGNSS) mission [21-24].

Sec. II gives a brief review of the specular point theory [4-5, 7]. Sec. III describes its application to monostatic and bistatic observations. Sec. IV discusses issues such as wind speed and wave age relationship on LPMSS, whitecap effects on surface reflectivity in high winds, tilting modification of specular returns, extending the analysis to other frequencies, and the relationship between $k_d$ and $k$. Sec. V is summary.

II. REVIEW OF SPECULAR POINT THEORY

Kodis [4] presents a theoretical analysis of backscattering from a perfectly conducting 1D irregular surface at very short EM wavelengths (the irregular surface extends uniformly in the perpendicular direction of the horizontal plane). The integral formulas are derived directly from the vector field theory. He shows that to the first order of approximation, the backscattering cross section is proportional to the product of the average number of specular points illuminated by the EM waves $n_A$, and the geometric mean of the two principal radii of curvature of those specular points $r_1$ and $r_2$, i.e.,

$$\sigma(k_i, -k_i) = \pi \left\langle n_A r_1 r_2 \right\rangle n_A, \quad (1)$$

where $k_i$ is the incidence EM wavenumber. This analysis elicits the close connection between EM scattering and statistical and geometrical properties of the rough surface. In order to carry out the calculations further, it is necessary to specify the statistics of the rough surface, in particular in regard to the average number of illuminated specular points and their average curvature.

Barrick [5] extends the analysis to 2D horizontal plane, bistatic configuration, and finite surface conductivity. Following his notations as defined by the scattering geometry depicted in his Fig. 1, which is reproduced here as Fig. 1, the NRCS for arbitrary incident and scattered polarization states ($\eta$ and $\zeta$, respectively), incidence angles ($\theta$, $\phi=0$), and scattering angles ($\theta$, $\phi$) is

$$\sigma_{0\eta\eta} (\theta, \phi) = \pi n_A \left\langle |r_1 r_2| \right\rangle |R_{\eta\eta}(i)|^2, \quad (2)$$

where $R_{\eta\eta}(i)$ is the reflection coefficient from infinite plane tangent to the surface at the specular points for incidence and scattered states, and $i$ is the local (effective) incidence angle at the specular points and can be expressed as a function of incidence and scattering angles: (after correcting a couple of typographic errors)

$$\cos i = \left[ 1 - \sin \theta \sin \phi \cos \phi + \cos \theta \cos \phi \right] / 2 \right]^{1/2}. (3)$$

The average number of specular points per unit area for a rough surface is then derived in terms of the surface statistics, leading to

$$\sigma_{0\eta\eta} (\theta, \phi) = \pi \sec^4 \gamma p(\zeta_{sop}, \zeta_{sop}) |R_{\eta\eta}(i)|^2, \quad (4)$$

where $p(\zeta_{s}, \zeta_{s})$ is the joint probability density function (pdf) of the two horizontal orthogonal ocean surface slope components, and the secondary subscript ‘sp’ indicates the specular points.

Two surface slope probability density functions (Gaussian and exponential) are considered in [5]. For the ocean surface the Gaussian function is more suitable [6] and the resulting NRCS is

$$\sigma_{0\eta\eta} (\theta, \phi) = \frac{|R_{\eta\eta}(i)|^2}{s_f^2} \sec^4 \gamma \exp \left( -\tan^2 \gamma / s_f^2 \right), \quad (5)$$

where $s_f^2$ is the ocean surface LPMSS [7], and $\tan \gamma$ is the surface slope at the specular point, which can be expressed as a function of incidence and scattering angles

$$\tan \gamma = \frac{\left( \sin^2 \theta - 2 \sin \theta \sin \phi \cos \phi + \sin^2 \phi \right)^{1/2}}{\cos \theta + \cos \phi}. (6)$$

A case of special interest is backscattering: $\phi=\pi, \theta=\theta_i, \tau=0, \gamma=\theta$, and the NRCS is

$$\sigma_{0\eta\eta} (\theta, \pi) = \frac{|R_{\eta\eta}(0)|^2}{s_f^2} \sec^4 \theta_i \exp \left( -\tan^2 \theta / s_f^2 \right). (7)$$

III. APPLICATION

A. Monostatic Ku band

For a nadir-looking altimeter ($\theta=0$) with linear polarization ($h$ or $v$ for horizontal or vertical), (7) becomes

$$\sigma_0 (0) = \frac{|R(0)|^2}{s_f^2} = \sigma_{0hh} (0) = \sigma_{0vv} (0), \quad (8)$$

where $R(0)$, shorthand for $R_{\eta\eta}(0)$ with $\eta = h$ or $v$, is the Fresnel reflection coefficient for normal incidence, and the NRCS is independent on polarization states. Applying (8) to Ku band altimeter measurements, a rather peculiar result is discovered [7-9, 12-13]: that the computed Ku-band LPMSS is larger than
the total optical MSS in clean water [10-11], the total optical MSS is denoted as $s_0^2$ in this paper. The LPMSS $s_r^2$ is an integrated surface wave property, which is defined as

$$s_r^2 = \int_0^{k_u} k^2 S(k) \, dk,$$  \hspace{1cm} (9)

where $S$ is the surface wave elevation spectrum, and $k_u$ is the upper limit of lowpass filter, which is in turn proportional to the EM wavenumber $k_r$. The ratio $k_u/k_r$ is generally given as between 3 and 6 [8-9]. When distinction of EM frequency is desired, $s_r^2$ is also given as $s_{0h}^2$ in this paper. For example, for Ku band EM frequency $f_r = 14$ GHz and $k_u = k_r/3 = 293/3 = 98$ rad/m, the corresponding $s_r^2$ is $s_{0h}^2$ for clarification. The optical EM frequency is many orders of magnitude higher than those of the microwave sensors used in ocean remote sensing, so $s_0^2$ is expected to be the upper bound of $s_r^2$ observed by microwave equipment.

Fig. 2(a) shows the Ku-band altimeter NRCS collected in the Gulf of Alaska and Bering Sea [13], and the calculated NRCSs based on the optical MSS from sun glitter analyses in clean and slick waters [10-11]. Fig. 2(b) shows the optical MSS and $s_r^2$ derived from the Ku-band altimeter NRCS using (8). Two sets of MSS reported in [10] are obtained from airborne sun glitter analyses in clean water surfaces (wind speed up to 14.5 m/s) and water surfaces covered with artificial slicks created by an oil mixture (wind speed up to 10.2 m/s). The optical MSS reported in [11] is also from sun glitter analysis but from a spaceborne optical sensor (wind speed up to 15 m/s); the results are essentially identical to those of the clean water condition in [10]. For the slick waters, surface waves shorter than about 30 cm are suppressed [10], so the two sets of MSS in [10] are $s_{0h}^2$ and $s_{21h}^2$. The Ku band (14 GHz) EM wavelength is about 2.1 cm, with the factor $k_u/k_r$ = 3 to 6 applied, the observed LPMSS is between $s_{0h}^2$ and $s_{21h}^2$. It is expected that the surface roughness sensed by the Ku band altimeter to be between the optical data in clean and slick waters. This, however, is not the case for the result in low and moderate winds ($U_{10} \leq 10$ m/s) as illustrated in Fig. 2(b).

As mentioned in Introduction, many researchers resort to using an effective reflectivity much smaller than that computed from the relative permittivity [7-9], more discussion on reflectivity is deferred to Sec. IV. An alternative explanation is offered in [12-13]: that (7) carries the physical meaning of an exponentially attenuating contribution (with respect to tilting angle, $\theta = \gamma$) of off-specular returns to the observed altimeter return. The off-specular contribution can also be interpreted as the specular contributions from roughness patches on slanted background surfaces. This is graphically illustrated in [12, Fig. 7], which is reproduced as Fig. 3 here. In the figure, the parallel lines represent the far-field EM wave fronts emitted from zenith and impinge on the ocean surface. Five scattering patterns are illustrated. Patterns 1, 4, and 5 are from three incrementally rougher patches located on background surfaces that are locally parallel to the incoming wave fronts such that the local incidence angle is not changed from the nominal incidence angle (0 in this case). The backscattering returns from the three patches are inversely proportional to the surface roughness as expected from (8). Patterns 2, 3, and 4 are from three statistically identical roughness patches and located on background surfaces with different orientations. The backscattering strengths from the three patches observed by the monostatic antenna are different although the reflecting patches have identical statistical roughness. The difference of the returns toward the nominal incidence direction (from zenith) reflects the tilting effect as described by the exponential term in (7).

To account for the exponentially attenuated specular contribution from patches on slanted surfaces, the two-scale (or tilted Bragg) solution [7] can be adapted to the altimeter problem. The altimeter NRCS (7) becomes

$$\sigma_0(0) = \int \frac{\left| R(0) \right|^2}{s_r^2} \sec^4 \theta \exp \left[ -\frac{\tan^2 \theta}{s_r^2} \right] p(\theta) \, d\theta, \hspace{1cm} (10)$$

where $\theta$ is the local incidence angle at the specular point, and $p(\theta)$ is the pdf of the background surfaces that tilt the specular patches ($\theta = \gamma$). Assuming 1D Gaussian distribution of the
tilting surfaces with variance $\delta_i^2$ and with the assumption of small $\theta$ (thus $\sec^2\theta \approx 1$ and $\tan^2\theta = \theta^2$), (10) becomes [12]

$$
\sigma_{01D}(0) = \frac{1}{2 \pi \sigma_f^2} \exp \left(-\frac{\theta^2}{2 \sigma_f^2} \right) \exp \left(-\frac{\theta^2}{2 \delta_i^2} \right) \, d\theta
$$

which has the following closed-form solution:

$$
\sigma_{01D}(0) = \frac{1}{2 \pi \sigma_f^2} \left( \frac{\sigma_f}{\delta_i} \right)^{1/2}.
$$

For 2D Gaussian pdf with equal upwind and downwind tilting slope components, the solution is [13]

$$
\sigma_{02D}(0) = \frac{1}{2 \pi \sigma_f^2} \left( \frac{\sigma_f}{\delta_i} \right)^{1/2}.
$$

Fig. 4(a) shows the NRCS results computed with (12) and (13), and their comparison with altimeter observations. Fig. 4(b) shows two sets of $s_f^2$ used in the computation. They are based on the H18 spectrum model ($\delta_i^2$) [14-15] integrated to $k_u = k/3$ and $k_u = k/5$. The tilting mean square slope $\delta_i^2$ is composed of a wind-related component $s_f^2$, and an ambient component $S^2$ that exists in the turbulent background and non-wind-related [12-13], i.e.,

$$
\delta^2 = s_f^2 + S^2.
$$

The ambient component $S^2$ is set to be $5 \times 10^{-3}$, which is about the mean value of the residual terms of the linear least-squares fitting functions applied to the optical MSS data in clean and slick waters [10, Eq. 42] with the reference wind speeds at 41° (12.5 m):

$$
\begin{align*}
    s_{c,\text{clean}}^2 &= 5.12 \times 10^{-3} U_{12.5} + (3 \pm 4) \times 10^{-3} \\
    s_{c,\text{slick}}^2 &= 1.56 \times 10^{-3} U_{12.5} + (8 \pm 4) \times 10^{-3}.
\end{align*}
$$

The optical MSS [10-11] are also illustrated in Fig. 4(b). The MSS data have been a significant part of ocean surface wave research. For example, some discussion on the optical MSS observations and several contemporary spectral models are described in [10, Sec. 4]. Updated discussions are presented in [16] on comparing with modern spectral models, especially focusing on the short scale waves, directional distribution, and interaction mechanisms.

The wind-related tilting component $s_f^2$ is assumed to be proportional to $s_f^2$. From experimentation, the following formulas are recommended:

For $s_f^2$ integrated to $k_u = k/3$:

$$
\begin{align*}
    s_f^2 &= s_f^2 / 10 & \text{for 1D solution, and} \\
    s_f^2 &= s_f^2 / 15 & \text{for 2D solution.}
\end{align*}
$$

For $s_f^2$ integrated to $k_u = k/5$:

$$
\begin{align*}
    s_f^2 &= s_f^2 / 3 & \text{for 1D solution, and} \\
    s_f^2 &= s_f^2 / 4 & \text{for 2D solution.}
\end{align*}
$$

More discussion on LPMSS analysis and reflectivity $|R(0)|^2$ is deferred to Sec. IV.

B. Bistatic L band

The wind modification is expected to impact both bistatic and monostatic specular reflections. Applying the same procedure discussed in the monostatic case to the bistatic system, the NRCS for 1D Gaussian pdf of tilting surfaces is:

$$
\sigma_{02\phi\phi}(\theta, \phi) = \frac{R_{\phi\phi}(\theta \phi)}{s_f^2} \left( \frac{s_f^2}{s_f^2 + \delta_i^2} \right)^{1/2}.
$$

For 2D Gaussian pdf of tilting surfaces, it is:

$$
\sigma_{02\phi\phi}(\theta, \phi) = \frac{R_{\phi\phi}(\theta \phi)}{s_f^2} \left( \frac{s_f^2}{s_f^2 + \delta_i^2} \right).$$

Consider the simpler case of scattering in the same transmission plane (Fig. 5), there are three possibilities: (a) $\theta$
The least-squares fitted curve through all the GPSR data is given by the solid black line (labeled KG). The least-squares fitted curve for the two quarters are given by dashed and dashed-dotted curves labeled TCF and TCB. The LPMSS in the TC back quarter (TCB) is slightly higher than that in the front quarter (TCF), and the average GPSR measurements (KG) are generally between TCF and TCB. The three fitting functions are:

\[ s_{\text{GPSR}}^2 = 4.66 \times 10^{-3} + 9.03 \times 10^{-3} \ln U_{10} \]
\[ s_{\text{TCF}}^2 = 0.74 \times 10^{-3} + 9.23 \times 10^{-3} \ln U_{10} \]
\[ s_{\text{TCB}}^2 = -2.38 \times 10^{-3} + 11.17 \times 10^{-3} \ln U_{10} \]

For comparison, the optical data obtained in clean and slick sea surfaces [10-11] are illustrated with black markers in the figure. The GPSR data have expanded the wind speed coverage considerably, and they are critical for refining the ocean surface wind wave spectrum models in high wind conditions [26].
For many decades, the airborne sun glitter analyses in clean and slick waters reported in 1954 [10] have remained the most comprehensive ocean surface MSS dataset, the wind speed range is between 0.7 and 13.5 m/s for the clean water condition, and between 1.6 and 10.6 m/s for the slick water condition. The spaceborne sun glitter analysis reported in 2006 [11] expands slightly the wind speed range of clean water condition to about 15 m/s and the results are essentially identical to those of the clean water condition reported in 1954 [10]. The recent result of $s_{GPSR}^2$ further extends the wind speed coverage to 59 m/s [17-20]. With the EM frequency of 1.575 GHz, the $k_w$ is between about 5 and 11 rad/m and $s_{GPSR}^2$ data are most useful for investigating the wind wave spectrum slope. The study leads to establishing a general wind wave spectrum function G18 [26], the applicable upper limit ($k_{max}$) of the G18 spectrum function is estimated to be about the upper range of L band $k_w$ (11 rad/m). For Ku band application, the hybrid model H18 is more suitable [14-15, 26]. The H18 model uses G18 for long waves and H15 [32] for short waves, with linear matching between $k = 1$ and 4 rad/m; the detail is described in [14].
Wind speed $U_{10}$ and windsed dominant wave period $T_p$ are the only required input for computing the G18 and H18 spectra (and many other spectrum models). The combination of $U_{10}$ and $T_p$ can be expressed as the dimensionless spectral peak frequency $\omega_p = U_{10}/c_p = U_{10}/(gT_p/2\pi)$, where $c_p$ is the wave phase speed of the spectral peak component, and $g$ is gravitational acceleration. The inverse of $\omega_p$ is wave age, which represents the stage of wave development. Determining the wave spectrum requires consideration of both wind speed and wave development stage. With a wave spectrum function, the $s_{21}$ can be pre-calculated for a range of $U_{10}$, $\omega_p$, and $k_u$.

For example, Fig. 9(a) and 9(b) show the contour maps of H18 $s_{21}$ and $s_{11}$, respectively. They are illustrated for $U_{10}$ between 0 and 70 m/s, and $\omega_p$ between 0.8 and 5.2. These pre-calculated results serve as design curves (lookup tables) for quickly obtaining the desired LPMSS through interpolation. Superimposed in the figures are the observed $\omega_p(U_{10})$ in TC and non-TC conditions. The interpolated LPMSS for $k_u = 98$ and 11 rad/m using the observed $\omega_p(U_{10})$ in TC and non-TC conditions. For comparison, illustrated with black markers are the optically sensed MSS in clean and slick waters [10-11]. Also shown in the figure are the interpolated LPMSS assuming constant $\omega_p$ (1 and 2), and $\omega_p$ approximated by (22).

Also shown in Fig. 9(c) are the interpolated $s_{21}$ and $s_{11}$ assuming constant $\omega_p$ (1 and 2 are used for illustration). As wind speed increases, the difference increases between $s_{21}$ computed with constant and observed $\omega_p$. Interestingly, if the approximation

$$\omega_p = \max \left(0.8, 0.065U_{10}\right)$$

is employed, the resulting $s_{21}$ is very close to that obtained with observed $\omega_p$. Adopting (22) simplifies the procedure to obtain $s_{21}$ from a wave spectrum function in practical applications since it requires only the $U_{10}$ input (with $k_u$ specified).

B. Surface reflectivity and tilting factor

The reflectivity $|R_{ztt}(t)|^2$ is a function of relative permittivity and generally treated as a constant for a given EM frequency (with the assumption of some representative sea surface temperature and sea water salinity; 293 K and 35 psu are used throughout this paper). In high winds when air is entrained by wave breaking into the water surface layer and foam covers the water surface, the modification of relative permittivity by the mixed air needs to be considered. Through analyses of multi-frequency, multi-incidence-angle microwave radiometer measurements collected in TCs [33-41], the foam effects are expressed as a function of wind speed, microwave frequency, and incidence angle [42-43]. The effective air fraction $F_a$ is related to the whitecap coverage $W_c$ as described in Appendices A and B in [43].

Fig. 10 shows the reflectivity at 0°, 10°, 30°, and 50° incidence angles for Ku (14 GHz) and L (1.575 GHz) frequencies. The Ku band altimeters discussed in this paper operate with linear polarizations ($h$ and $v$), so $|R_{zh}(\theta)|^2$ and $|R_{vh}(\theta)|^2$ are illustrated. The GPSR signals are right-hand-circular transmit and left-hand-circular receive, so for L band $|R_{v}(\theta)|^2$ is given, its dependence on incidence angle is very weak up to about 60° incidence angle [14]. For specular reflection from the ocean surface, $|R_{ztt}(t)|^2$ is the quantity of interest (Sec. III.B) and it is independent on polarization states ($hh$, $vv$, and $lr$), but can vary considerably with wind speed as a result of air entrainment by wave breaking. The foam modification is more severe toward higher frequency as expected; this can be seen from comparing the black solid line of L band and red/green (overlapped) solid lines of Ku band.

The tilting effect of scattering patches also introduces an attenuation factor. Take the altimeter solutions as an example. Compare the specular only solution (8) and the 2D tilting solution (13), the tilting consideration produces an extra term $s_{21}^+ (s_{21}^++\alpha^2)$ that effectively decreases backscattering and
it is denoted as the tilting factor in this paper. For 1D tilting solution (12), the tilting factor is \( \left[ \frac{s_f^2}{f} + 2s_f^2 \right]^{1/2} \). Fig. 11 shows the tilting factors for Ku and L bands, they are computed with the assumption that \( s_f^2 \) (here \( s_{f,18}^2 \) is used) is integrated to either \( k/3 \) or \( k/5 \), and for 1D or 2D solution. The \( s_{f,18}^2 \) is computed with \( U_{10} \) as the only input and \( \omega_0 \) is approximated by (22).

As discussed in Sec. III.A, when (8) is used for altimeter analysis, it produces unreasonably high LPMSS and an effective reflectivity \( |R(0)|_{\text{eff}}^2 \) is frequently invoked, i.e.,

\[
\sigma_0(0) = \frac{|R(0)|_{\text{eff}}^2}{s_f^2}.
\]

For Ku band (13.755 GHz), instead of the value of about 0.62, numbers between 0.34 and 0.52 have been reported [7-9, 44-45]. Applying the tilting factor to the \( |R(0)|^2 \) computed with foam-modified relative permittivity yields an effective reflectivity for using (23) in the altimeter analysis. The smooth curves in Fig. 12 are the results computed with the assumption that \( s_{f,18}^2 \) is integrated to either \( k/3 \) or \( k/5 \), and for 1D or 2D solution. The black circles are the result based on analyzing the rain-free nadir-looking data measured by the Tropical Rainfall Mapping Mission (TRMM) Ku band (13.8 GHz) precipitation radar (PR) reported in [9]. The TRMM PR (TPR) data and modeled curves are within about the same numerical range in the overlapping wind speed region. The TPR analysis [9] uses the E spectrum model [46], which is known to underestimate LPMSS for \( U_{10} \) greater than about 14 m/s [14, Fig. 4]. This may explain the much sharper dropoff in the higher wind region of the TPR \( |R(0)|_{\text{eff}}^2 \) result. For reference, we also show \( |R(0)|_{\text{eff}}^2 \) for L band 1.575 GHz with magenta curves in Fig. 12. For \( U_{10} \) greater than 5 m/s, the wind dependence is much weaker, mainly because of the decreased foam effects on L band compared to Ku band.

C. Ku band altimeter NRCS revisited

The Ku band altimeter systems have many more well-calibrated NRCS datasets compared to the L band systems due to the long history of using Ku band for ocean wind sensing.

For comparison, the effective reflectivity from analysis of TRMM PR rain-free altimeter data (F03) [9] are shown with black circles. The L band circular polarization effective reflectivities \( |R(0)|_{\text{eff}} \) for 2D solutions are shown with magenta curves.

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The Ku band altimeter systems have many more well-calibrated NRCS datasets compared to the L band systems due to the long history of using Ku band for ocean wind sensing.
systems and missions. Sometimes the systematic difference is a simple offset. Sometimes it is more complex and involves both offset and wind speed trend. These are illustrated in the following two figures: the reference winds in the first figure (Fig. 13) are from buoys or microwave radiometer, whereas ECMWF model wind is used in the second figure (Fig. 14).

Fig. 13 shows the bin-averaged T/P data from the three regions (red pluses) and the TPR data digitized from [9, Fig. 4] (blue diamonds). Compared to the T/P results, there is a 1-dB systematic bias in the TPR data, which is subtracted in the figure. A 1.92 dB bias is reported in [9] from comparing with the modified Chelton and Wentz (MCW) GMF [47, Table 1]. The MCW is designed for the Geosat altimeter. With improved algorithm and including atmospheric correction, the T/P NRCS differs from Geosat NRCS by 0.7 dB [48]. The MCW GMF with 0.7-dB adjustment is shown with the red solid line, which goes through the center of T/P and adjusted TPR data. Superimposed in the background are the NRCS computed by the 2D solution (13) with \( s_{H18}^2 \) calculated with \( U_{10} \) input and \( \omega_s \) approximated by (22); both \( k_u = k_3 \) and \( k_5 \) results are presented. Results based on the 2D solution with \( k_u \) equal either \( k_3 \) or \( k_5 \) yield good agreement with data in the overlapped wind speed region. The computation covers a much wider wind speed range than that can be achieved from collocated measurements. Also plotted in the figure are two GMFs. (a) The MCW GMF (with 0.7 dB adjustment), which modifies the Chelton and Wentz [52] algorithm for Geosat data. The MCW GMF is given in look up table (LUT) and valid for wind speed between 0 and about 20 m/s. It remains robust for application to T/P measurements when the 0.7-dB systematic difference is adjusted (red solid curve). (b) The TPR GMF [9, Eq. 1 and Table 1] is shown with the dashed blue line (with the 1 dB adjustment applied). The TPR dataset has the highest wind speed coverage to our knowledge. The TPR GMF deviates obviously from the data (blue diamonds) for wind speed exceeding about 20 m/s.

Fig. 14 shows sample results of 33-year collocated altimeter NRCS and ECMWF numerical model wind speed given by Ribal and Young [56]. The T/P and it follow-on missions J1, J2, and J3 in the Bering Sea region are extracted for comparison. The maximum wind speed encountered is about 23 m/s. Excluding the low wind portion \((U_{10} < 3 \text{ m/s})\), the results are all within about \( \pm 0.5 \text{ dB} \) up to 20 m/s. There are only a few points in winds greater than 20 m/s and the data scatter is much larger (about \( \pm 1.5 \text{ dB} \)). For its highest wind speed coverage, the TPR data set is also shown in this figure with cyan diamonds and its high wind data go through the middle of the T/P-JASON collection. Also plotted in the figure are the adjusted MCW and TPM GMFs, and the ECMWF altimeter GMF [57]. All three GMFs are in reasonably good agreement with data with \( U_{10} \) up to about 20 m/s. The NRCS computed by the 2D solution (13) with \( k_u = \frac{k_3}{3} \) and \( k_5 \) are also presented with black solid and dashed curves; they lie on the upper edge of the data cloud.

It is a long-standing problem acquiring sufficient number of high wind collocated and simultaneous in-situ and remote sensing data for algorithm development or validation and verification effort. Being able to perform accurate forward computation offers a realistic alternative for using the analytical solutions to supplement the sparse in-situ high wind data. We can compare the forward computation results with the three GMFs developed from collocated datasets (from either in situ observations or numerical models) as illustrated in Fig. 14. All three GMFs appear to deviate from the collective data for wind speed exceeding about 20 m/s. In comparison, the forward computed NRCS using \( s_{H18}^2 \) LPMSS is in excellent agreement with observations for the cases of in situ or microwave radiometer wind speed reference (Fig. 13). For numerical model reference wind, the forward computed NRCS is on the upper edge of the collective data cloud (Fig. 14). The trend of the computed NRCS appears to be in better agreement with the collected NRCS observations over the full overlapped wind speed range. It is recommended that for high
winds ($U_{10} > -20$ m/s) to about 70 m/s and will be further discussed in Sec. IV.D), the NRCS wind dependence uses the black dotted curves:

$$\sigma_0 (dB) = (8 \pm 0.5) - 0.087(U_{10} - 20). \quad (24)$$

D. Frequency variation and lowpass upper bound

Fig. 15 shows the computed NRCSs for L, C, X, Ku, and Ka bands with wind speeds up to 99 m/s. For clarity, only results based on the 2D solution with $s^2_{H18}$ integrated to $k_u = k_u/3$ (black curves) and $k_u = k_u/5$ (red curves) are illustrated. For $U_{10}$ greater than about 20 m/s there is a quasi-linear trend of $\sigma_0$ decreasing with increasing $U_{10}$. For L and C bands, the linear trend persists to about 99 m/s; for X, Ku, and Ka band it continues to about 70 m/s. For wind speed exceeding 70 m/s, the X, Ku, and Ka NRCSs drop at a much steeper rate, mainly due to the foam modification of the reflectivity (Fig. 10).

Fig. 16 shows $s^2_{H18}$ integrated to $k_u = k_u/3$ (black curves) and $k_u = k_u/5$ (red curves) used for the specular NRCS computation displayed in Fig. 14. For comparison, the optical MSS [10, 11] are also illustrated. Interestingly, whereas the difference between integration to $k_u/3$ and $k_u/5$ increases toward higher EM frequency (Fig. 15) its impact on the NRCS computation is rather insignificant for all frequencies examined (Fig. 15).

The attempt to answer the question regarding the proper ratio between $k_u$ and $k_r$ is compounded by the tilting component ($s^2_r$) factor: paring a larger $s^2_i$ with a smaller $s^2_r$ would produce almost identical solution as that derived from paring a smaller $s^2_i$ with a larger $s^2_r$. The NRCSs computed with $s^2_r$ integrated to $k_u = k_u/3$ and $k_u/5$ (black and red curves, respectively in Fig. 15) differ no more than 1dB for any EM frequency examined here. Fig. 17 shows the difference $\delta \sigma_0$ (NRSC computed with $k_u = k_u/3$ minus NRSC computed with $k_u = k_u/5$): for wind speed higher than 5 m/s, the difference is within -0.2 and +0.3 dB. Given the large data scatter in the typical NRCS measurements, it remains a challenge task to determine the optimal ratio between $k_u$ and $k_r$ needed for calculating LPMSS with a wave spectrum function. The results presented in this paper suggest that NRCSs computed with $s^2_r$ integrated to $k_u = k_u/3$ and $k_u/5$, when paired with $s^2_i$ defined by (16) and (17), yield essentially the same degree of agreement with well calibrated datasets such as those shown in Figs. 13 and 14.

V. Summary

The specular point theory [4-5, 7] establishes a firm relationship between specular NRCS and surface wave statistical and geometric properties (5). Specifically, it states that the NRCS is linearly proportional to the reflectivity $|R_{2\theta} (\theta)|^2$, inversely proportional to the LPMSS $s^2_i$, and multiplied with a term dominated by the exponential attenuation with respect to the surface slope at the specular point ($\tan \gamma$). The exponential term in (5) and (7) carries the physical meaning of an off-specular contribution, or specular contribution from roughness patches on slanted background surfaces, to the specular return. It needs to be accounted for when comparing the theoretical solutions to the actual
measurements from the ocean surface where the surface slope at the specular point \((\tan \gamma)\) is not always 0, i.e., flat surface. One way to account for the exponentially attenuating non-spectral contribution (or specular returns from roughness patches on slanted surfaces) is to adopt the two-scale concept of the Bragg resonance scatterometer solution [7] to the specular reflection problem. With 1D and 2D Gaussian distributions of the tilting slopes the result is the closed-form solutions (12) and (13) for monostatic (altimeter) and (18) and (19) for bistatic (reflector) NRCS.

There remains some uncertainty regarding the definition of LPMSS \(s_j^2\) and tilting MSS \(\delta_j^2\). For the former, a range between 3 and 6 has been reported for the \(k_d/k_r\) ratio needed to computing \(s_j^2\) with an ocean wave spectrum [8-9]. In this paper results calculated with \(k_d/k_r = 3\) and 5 are presented. The \(\delta_j^2\) term is composed of an ambient component and a wind-related component [12-13]. The ambient component \(\bar{S}^2\) is set to be \(5 \times 10^{-3}\) based on the sun glitter data [10], the wind-related component \(s_j^2\) is assumed to be proportional to \(s_j^2\). Using the well-calibrated Ku band altimeter NRCS observations, (16) and (17) are recommended for calculating \(s_j^2\) from \(s_j^2\). Computations using (12) and (13) are then in good agreement with Ku band altimeter observations [9, 13, 56] (Figs. 4 and 13). Forward computation can be carried out to much high wind speeds and a wider range of EM frequencies to supplement the lack of in situ data necessary for algorithm development or validation and verification tasks (Figs. 13, 14).

We then proceed to analyze the L band bistatic reflection. There are now several sets of L band \(s_{GPSR}^2\) reported in the literature from delay Doppler analyses [17-20]. They serve as key datasets for addressing a critical parameter in the wind wave spectrum function, i.e., the spectral slope at the high frequency portion of the surface wave frequency spectrum. The improved spectrum function in turn is used to generate \(s_j^2\) with wind speed and dominant wave period available from operational systems such as meteorological buoys and hurricane hunters that carry simultaneous wind and wave sensors [15]. In this paper, a method is developed to reduce the required input to wind speed alone, with the dominant wave period (or equivalently the dimensionless spectral peak frequency) approximated by (22). Solutions (18) and (19) of specular point theory are used to calculate the BNRCs with three different LPMSS sets: \(s_{GPSR}^2\), \(s_{G18}^2\), and \(s_{R18}^2\). The results are in reasonably good agreement with the recent reports of L band CYGNSS BNRCs [23-24] (Figs. 7-8).

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