Effects of Ocean Wind, Foam/Spray and Atmosphere on Four Stokes Parameters in Passive Polarimetric Remote Sensing of the Ocean Based on Numerical Simulations and Analytic Theory

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ABSTRACT

The research last year consisted of three parts:

A. Microwave emission and scattering of foam based on Monte Carlo simulations of dense media using the fcc structures and realistic Lord Kelvin's Tetrakaidecahedron Model of minimal contact area;

B. Polarimetric passive microwave remote sensing of wind vectors with foam-covered, rough ocean surfaces;

C. Brightness temperature of ocean with wind based on paralleled code of MoM with RWG basis function in conjunction with SMCG fast method.

A: MICROWAVE EMISSION AND SCATTERING OF FOAM BASED ON MONTE CARLO SIMULATIONS OF DENSE MEDIA

Emissivities of ocean surfaces are affected by the presence of foam. Recently, field experiments have been conducted at the Chesapeake Bay Detachment to study the foam emissivity as a function of polarization, observation angle and frequencies at 10.8 GHz and 36.5 GHz. The measurements exhibit important frequency dependence [1]. The results are not explained by simple mixing formulae nor past empirical models. In particular, the emissivities at 10.8 GHz are observed to be comparable to that of 36.5 GHz. Foam is a mixture of air bubbles and sea water. The bubbles range from sizes of hundreds of microns to millimeters. We conduct theoretical modeling based on modeling the microstructure of foam taking into account bubble size, fractional volume of water to rigorously study the emission, absorption and scattering properties and to account for the observed frequency dependence and polarimetric dependence of emissivities. In a previous paper, wave scattering and emission in a medium consisting of densely packed coated particles are solved by using the quasicrystalline approximation in combination with the dense-media radiative-transfer theory [2] (DMRT). Recently, we applied Monte Carlo simulations of solutions of Maxwell equations of densely packed coated particles to analyze the microwave emission and scattering of foam. The absorption, scattering and extinction coefficients are calculated. These quantities are then used in dense-media radiative-transfer theory to calculate the microwave emissivity**.** In order to have high density packing, we use a face-centered-cubic (fcc) structure to place the air bubbles. Salient features of the numerical results are (1)

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the absorption coefficients at 10.8 GHz are appreciable and (2) the emissivities at 10.8 GHz and 36.8 GHz are comparable. These features are consistent with experimental measurements. Comparisons are made with experimental measurements for vertical and horizontal polarizations, as shown in Fig. 1 and Fig. 2 and good agreement can be seen. Simulation results of emissivity with typical parameters of foam at 10.8 GHz and 36.5 GHz are illustrated in Reference [3]. The further study was conducted by assuming the foam is consisted of different layers with different bubble parameters [4]. Specifically, the foam is divided into two layers with different bubble parameters as shown in Fig. 3. In either layer, the total number of coated air bubbles, which are arranged in a face-centered-cubic structure, is $N = N' + N'' = 500$. Two species of coated air bubbles are used in each layer, as shown in Table I. They have the same outer radii but have different inner radii, b' and b''. We choose N' bubbles randomly of inner radii b', and the rest have inner radii of b''. The thicknesses of Layer 1 and Layer 2 are both 1.5cm. Seven realizations are generated by rotations of the sample. The absorption rate, scattering rate, extinction rate, albedo, and effective permittivity, calculated from Monte Carlo simulations for Layer 1 and Layer 2, are shown in Tables II-III, respectively. As the size of the bubbles in Layer 1 is larger than that of Layer 2, the scattering coefficient and albedo in Layer 1 is larger than in Layer 2. These quantities are used in DMRT theory to calculate the microwave emissivity, as shown in Figs. 4-5. The results indicate that absorption at 10.8GHz is appreciable for both large bubble layer and small bubble layer. In addition, the simulations show that emissivities at 10.8GHz and 36.5GHz are comparable. The absorption coefficient at 36.5GHz is larger than that at 10.8GHz. However, scattering has a significant effect at 36.5GHz.

A more realistic structure, Kelvin's cell, is the bubble model [7]. When spherical bubbles pack together to form a foam, they are forced into polyhedral shapes as gravity extracts most of the liquid from their interstices. This is because surface energy has great effects for liquids, due to their lack of resistance to shear, enabling them to take up shapes which minimize surface energy or its combination with other energy terms such as that due to gravitation. Surface energy may be defined as the energy change of creating a unit area of new surface or interface. So the geometry of interface in the foam is an important characteristic of its microstructure. In the single bubble case, a spherical shape has the minimum surface area with given volume. However, for the congregated bubbles, a conglomeration of spheres does not have the minimum contact area. Lord Kelvin studied the problem in 1887 and developed a structure named tetrakaidecahedron, or Kelvin's cell, as shown in Fig. 6. The Kelvin's cell can be approximated by the truncated octahedron. The surface area and volume of one truncated octahedron is $(6+12\sqrt{3})a^2$, and $8\sqrt{2}a^3$, respectively, where a is the length of edge. The cells are packed in body-centered-cubic structure. We formulate the integral equation for the collection of Kelvin's cells to calculate the absorption, scattering and extinction coefficient. We will compute the solutions to study the microwave emissivity of foam.

B: POLARIMETRIC PASSIVE MICROWAVE REMOTE SENSING OF WIND VECTORS WITH FOAM-COVERED ROUGH OCEAN SURFACES

Polarimetric microwave remote sensing means that all four Stokes parameters are measured. There has been an increasing interest in the applications of polarimetric microwave radiometers for ocean-wind remote sensing. Recently, we developed a physically based approach taking into account the micro-structure of foam, which treats the foam as densely packed air bubbles coated with thin seawater. It was shown that the polarization and frequency of the brightness temperatures depend on the physical microstructure properties of foam and the foam layer thickness. Guo et al. [2] used the Quasi-Crystalline Approximation (QCA) model for foam, while Chen et al. [3] used the Monte Carlo simulations. Controlled experiments of radiometric measurements of foam microwave emissions have also been made [1].

In this work [5], the polarimetric microwave emissions from wind-generated, foam-covered rough ocean surfaces are studied, as indicated in Fig. 7. The dense media model of foam is applied to calculate the values of the complex effective propagation constants, the extinction coefficients and the albedo. These are used to describe the characteristics of the foam layer. The effects of boundary roughness of ocean surface are included in the boundary conditions of DMRT by using the second-order small-perturbation method (SPM) describing the bistatic reflection coefficients between foam and ocean. The small-scale, wind-generated sea surfaces are generated by anisotropic directional spectra. The iterative method is employed to solve dense-media radiative-transfer equations. Theoretical results of four Stokes brightness temperatures with typical parameters of foam based on Monte Carlo simulations in passive remote sensing at 10.8 GHz, 19 GHz and 36.5 GHz are illustrated. The first two Stokes parameters are increased with the presence of foam, and the third and fourth parameters are reduced. The first two Stokes parameters are even functions of ϕ, while the last two parameters are odd functions of ϕ. Emissions with various wind speeds and foam layer thicknesses are also studied. In Fig. 8, we plot the brightness temperature of four Stokes parameters as functions of thickness of foam layer. As the thickness of the foam layer increases, *Tv* and *Th* will increase correspondingly and then saturate at a particular thickness of the foam layer. On the other hand, *U* and *V* components will decrease to zero. The details of results and discussions are described in [5].

C: BRIGHTNESS TEMPERATURE OF OCEAN WITH WIND BASED ON PARALLEL CODE OF MOM WITH RWG BASIS FUNCTION

There is an increasing interest in simulating electromagnetic scattering from rough surfaces in recent years. They have a lot of applications in active and passive remote sensing for soil, ocean and ice, etc. Classical analytic approaches are limited in regimes of validity and do not give the correct frequency and polarimetric dependence of electromagnetic wave scattering. Neither can they be used to make quantitative comparisons with real-life experiments. With the advent of modern computers, fast numerical simulations for rough surface scattering have become attractive. The most common methods are the fast multipole method (FMM) and the sparse-matrix canonical-grid (SMCG) method. The computational complexity and memory requirement are $O(N\log N)$ and $O(N)$, respectively, in these fast algorithms.

Over the last few years, we have made significant progress on the SMCG method for solving large-scale random rough surface scattering problems up to 1.5 million unknowns. This method entails the decomposition of the impedance matrix into strong near-field interaction and weak far-field interaction matrices. The far interactions, which require most of the computation time in matrix-vector multiplication of an iterative solution, can be computed simultaneously through fast Fourier transforms (FFTs), while the Taylor series expansions of the Green's functions are performed about a uniformly spaced canonical grid. The numerical solution in the past has been restricted mostly to Gaussian correlation function. This well-established SMCG method by using pulse basis functions produced very good results of emission for surfaces by Gaussian.

But it is noted that the exponential correlation function, power law spectrum, and ocean spectrum are rather realistic representations of soil and ocean. These kinds of surfaces are featured with fine scale structures. In order to better model rough surfaces, the Rao-Wilton-Glisson (RWG) basis functions are employed, and solve the integral equations by the method of moments (MoM) in conjunction with SMCG. In this work, highly accurate simulations are performed. Exponential correlation function and ocean spectrum are used to generate surfaces of soil and ocean. The energy conservation is obeyed well in all simulations, which is less than a relative error of 0.005 for both TE and TM waves. In ocean spectrum, the upper band limit k_U is related to the high frequency part of spectrum, which corresponds for fine scale structures. In Table IV, the emissivities at the wind speed of 20m/s are listed with various values of k_U. As k_U increases, emissivity increases for both of TE and TM waves. In Table V, the emissivities at the wind speed of 20m/s are listed with observation angles from 30 to 60 degrees and in Table VI, the results are listed for the wind speed of 10m/s. We also compare the brightness temperatures with those calculated SPM for various wind speed. They are in good agreements, as shown in Fig. 9 for the speed of 10m/s. In the case at wind speed 20m/s, the results by SPM are a little over-estimated for TM incident wave, as shown in Fig. 10. Parallel computation is implemented in this work as discussion in [6].

FIGURES

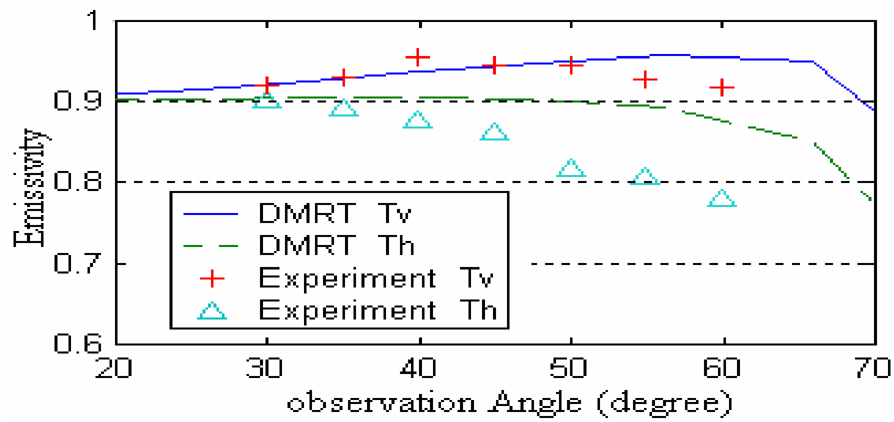

Fig. 1. Comparison between the simulation results and the measurements of the microwave emissivity at 10.8GHz for horizontal polarization and vertical polarization, respectively.

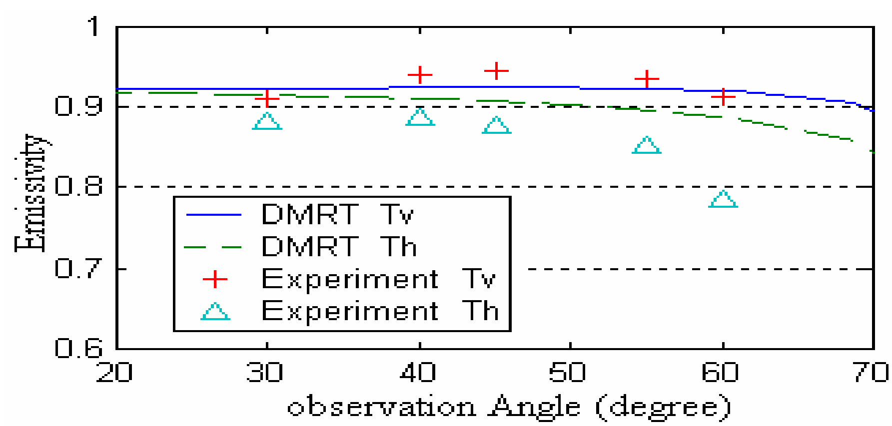

Fig. 2. Comparison between the simulation results and the measurements of the microwave emissivity at 36.5GHz for horizontal polarization and vertical polarization, respectively.

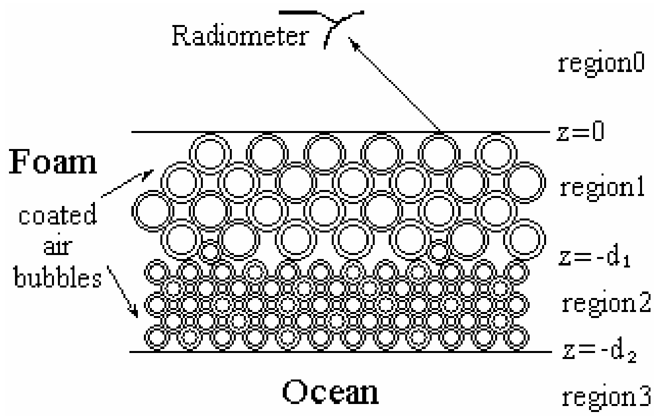

Fig. 3. Geometrical configuration for emission from foam-covered ocean

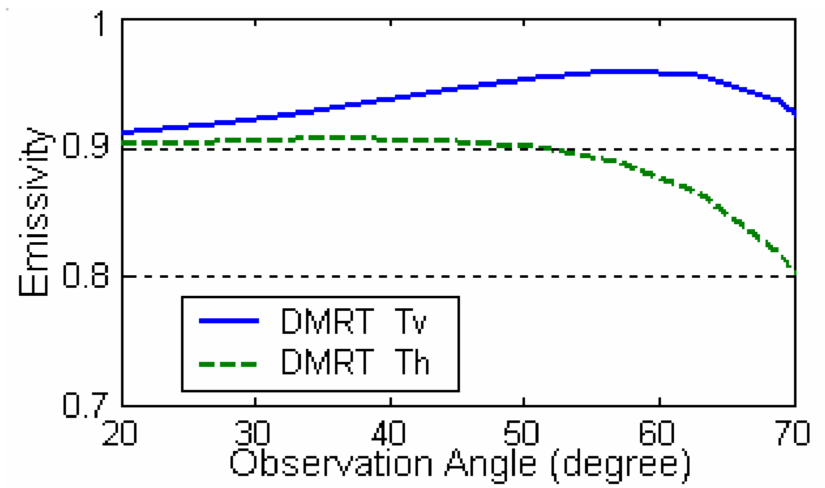

Fig. 4. Microwave emissivity at 10.8 GHz for horizontal and vertical polarization.

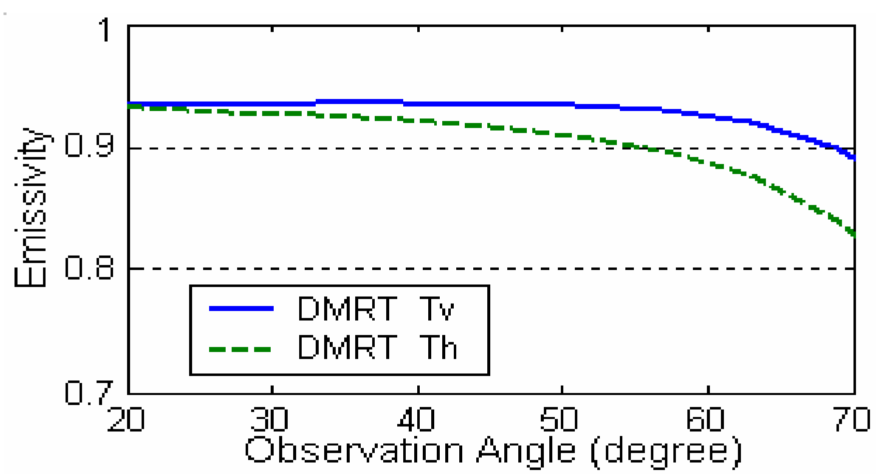

Fig. 5. Microwave emissivity at 36.5 GHz for horizontal and vertical polarization.

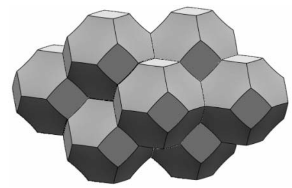

Fig. 6. Realistic bubble model, Kelvin's structure

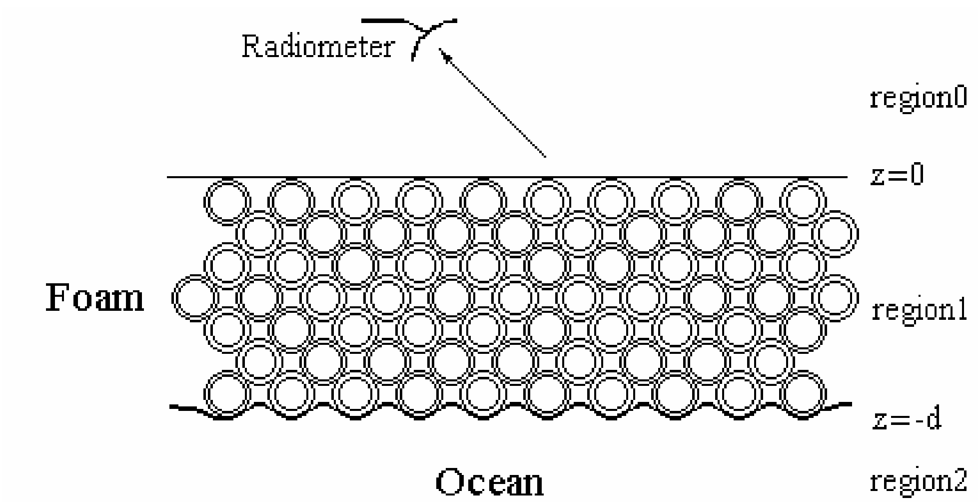

Fig. 7. Geometrical configuration for thermal emission from foam-covered rough ocean surface.

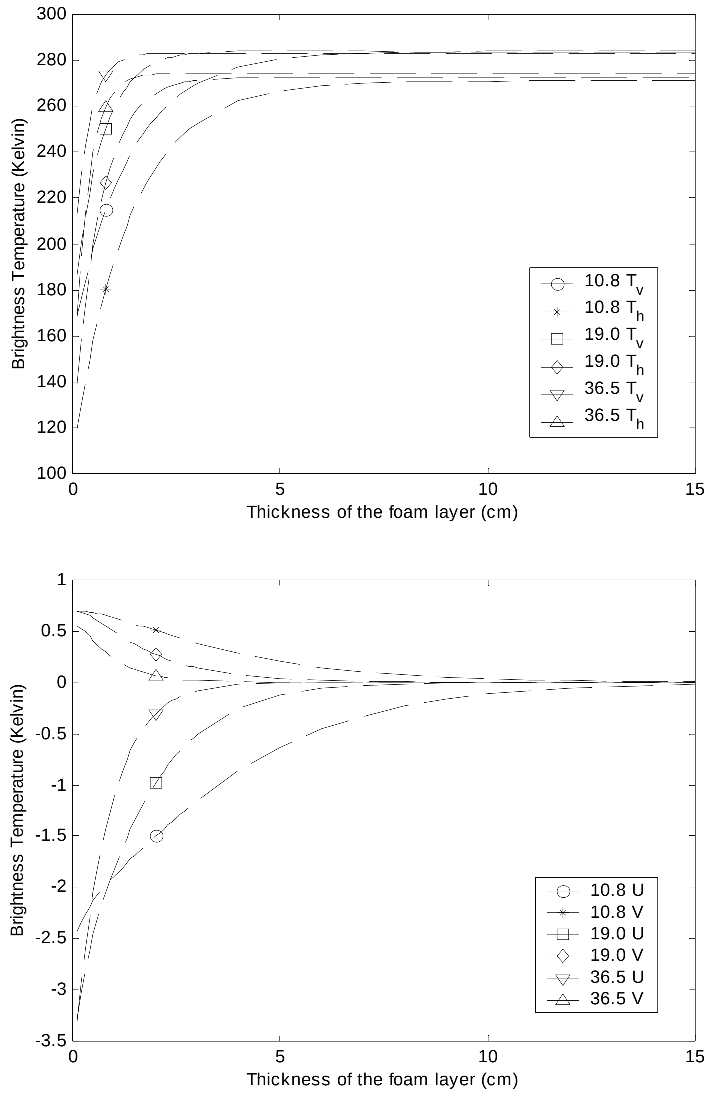

Fig. 8. Brightness temperature as a function of the thickness of the foam layer at aspect angle θ = 53 degree, at 10.8GHz, 19GHz and 36.5GHz.

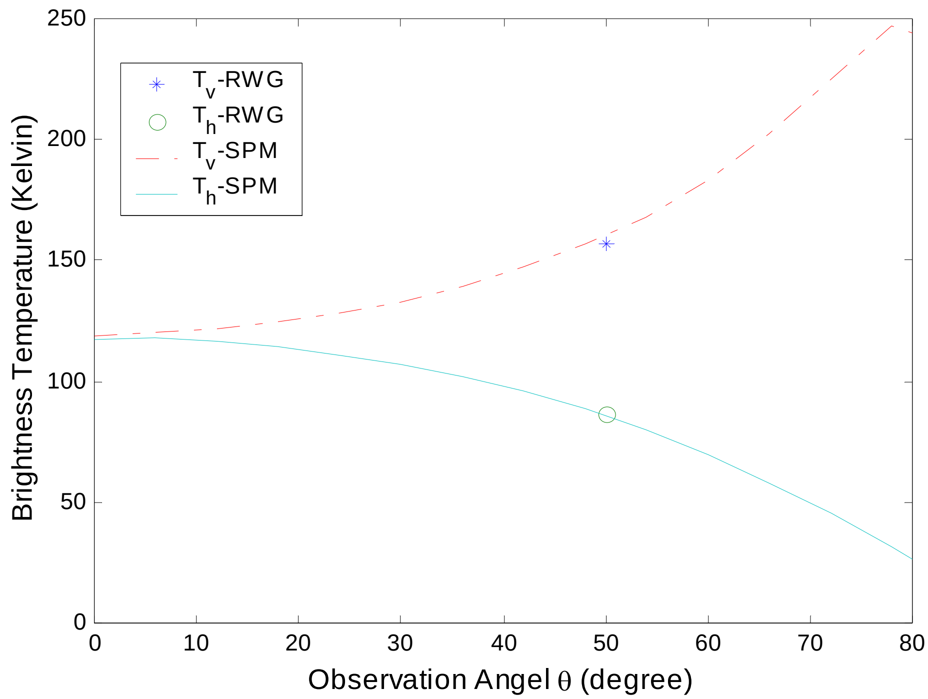

***Fig. 9. Brightness temperature as a function of incident angle θ, at 19GHz, wind speed* 10m/s *and physical temperature* 283 K.**

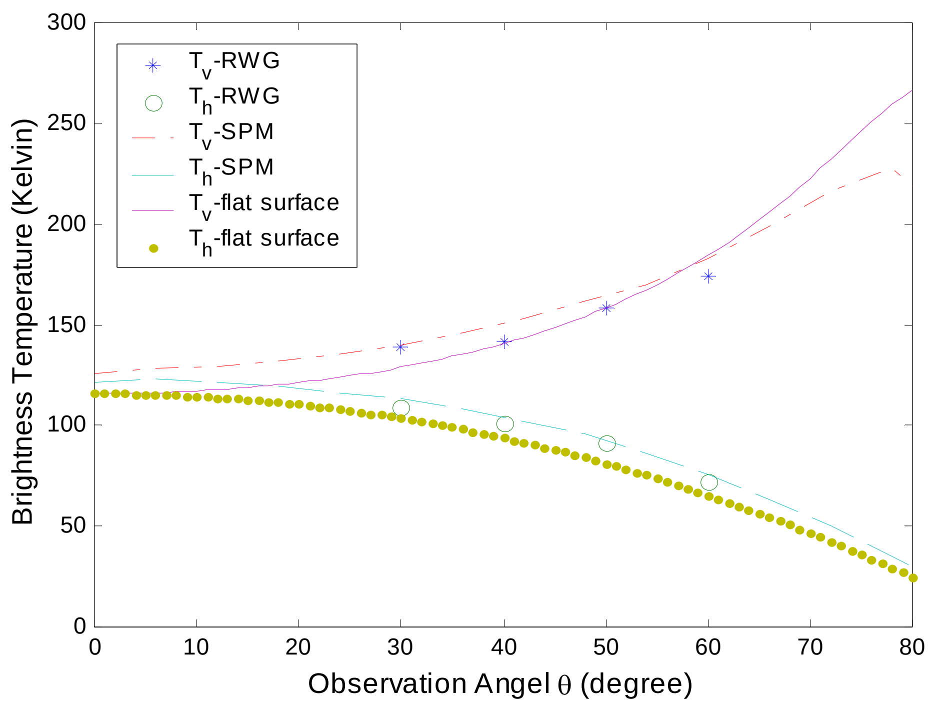

***Fig. 10. Brightness temperature as a function of incident angle θ, at 19GHz, wind speed* 20m/s *and physical temperature* 283 K.**

Table I. Parameters for Monte Carlo simulations in two layers

	a(mm)	b'(mm)	N'	b''(mm)	N''	V(mm^3)	f_w (%)
Layer 1	0.9	0.44	77	0.8978	423	2062	10.5
Layer 2	0.3	0.135	74	0.2993	426	76.37	10.4

Table II. Numerical results of layer 1

Parameter	10.8 GHz	36.5 GHz
Absorption rate	0.3248	0.8756
Scattering rate	0.01383	0.4159
Extinction rate	0.3386	1.2915
Albedo	0.04084	0.3220
Effective permittivity	1.480+*i*0.182	1.173+*i*0.184

Table III. Numerical results of layer 2

Parameter	10.8 GHz	36.5 GHz
Absorption rate	0.2830	0.9189
Scattering rate	3.704×10^{-4}	0.04367
Extinction rate	0.2834	0.9626
Albedo	1.307×10^{-3}	0.04537
Effective permittivity	1.483+*i*0.153	1.343+*i*0.146

Table IV. Emissivity and brightness temperature with various values of k_U, for 3-D ocean scattering problem with wind speed 20m/s. k_L =100rads/m, surface area 64 λ^2, 256 points/λ^2.

Polar.	k_U *(rads/m)*	emission	Energy cons.	Emission of flat surface	T_B(K)	ΔT_B(rough-flat surface)
TE	400	0.3118	0.9921	0.2872	88.2	6.96
TE	1000	0.3207	0.9920	0.2872	90.8	9.48
TE	4000	0.3233	0.9915	0.2872	91.5	10.22
TM	400	0.5477	0.9967	0.5594	155.0	-3.31
TM	1000	0.5550	0.9961	0.5594	157.1	-1.25
TM	4000	0.5604	0.9925	0.5594	158.6	0.30

Table V. Emissivity and brightness temperature at various incident angle θ, with $\phi = 0$, for 3-D ocean scattering problem with wind speed 20m/s, with k_L =100rads/m, k_U =4000rads/m.

Polar.	Incident angle θ	emission	Energy cons.	ΔT_B(rough from numerical -flat surface)	ΔT_B(rough from SPM-flat surface)
TE	30	0.3863	1.0006	5.69	9.3
TE	40	0.3584	0.9986	7.50	10.4
TE	50	0.3233	0.9915	10.2	11.3
TE	60	0.2548	0.9920	6.60	10.5
TM	30	0.4898	0.9980	9.70	11.1
TM	40	0.5015	0.9971	1.25	10.1
TM	50	0.5604	0.9925	0.30	6.1
TM	60	0.6145	0.9921	-10.6	-2.1

Table VI. Emissivity and brightness temperature at various incident angle θ, with $\phi = 0$, for 3-D ocean scattering problem with wind speed 10m/s, with k_L =100rads/m, k_U =4000rads/m.

Polar.	Incident angle θ	Emission	Energy cons.	Emission Of Flat	ΔT_B(rough -flat surface)
TE	30	0.3723	1.0028	0.3662	1.72
TE	40	0.3427	0.9956	0.3319	3.06
TE	50	0.3056	0.9927	0.2872	5.21
TM	30	0.4744	0.9960	0.4555	5.35
TM	40	0.4991	1.0040	0.4971	0.57
TM	50	0.5534	0.9966	0.5594	-1.70

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