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Attenuation of Millimeter Wave Propagation by Flat Sea-Surface Covered by Foam using Split-Step Fourier Transform

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Abstract:

In this article, we explore millimeter wave attenuation for discrete random scatterers, with emphasis on the application of microwave remote sensing in sea-foam covered sea surface. Polarimetric microwave emission from a sea-surface covered by foam were investigated. The foam is modelled as densely packed air bubbles coated with thin layer of seawater. Attenuation due to millimeter wave (mmW) propagation through layered sections of sea-foams were computed from split-step Fourier solutions of the parabolic equation method (PEM) derived from Helmholtz equation. The PEM is used to describe wave propagation through the layered medium. Results of attenuation by foam covered sea surface as a function of foam layer thickness and frequency for different polarizations are presented.

Keywords **—Attenuation, Foam, Flat sea-surface, Split-step Fourier Transform.**

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I. INTRODUCTION

Earlier models used empirical microwave emissivity [1-4] to estimate the effect of foam presence at the crest of the ocean surface. This was achieved by passive microwave remote sensing measurements. These measurements were done by assuming physical micro-structure of foam and foam layer thickness. Measurement procedures were empirical fitting and based on experimental data.

Foam dynamics has gained prominence in recent times. Pandey et.al, [5] proposed a composite model of foam scatterers and two scaled driven rough sea surfaces. In [6], controlled field experiments were used to measure foam dynamics and the microwave emissivity of calm water. A fully polarimetric passive model of wind generated and foam-covered rough sea can be represented by empirical Durden-Versecky spectrum [7]. Ding et al, [8] used a face centered cubic (FCC) structure to model high density spheres which represent bubbles placed inside a cube. Ding et al, [8] reported that polarization and frequency of the brightness temperatures are influenced by the physical micro-structural properties of foam and foam layer thickness.

In spite of the fact that foam typically covers only a few percent of sea surfaces, sea surface emissivity can substantially increase with increase in foam coverage area [1,3,6]. However, there is a great concern on the impact of foam on retrieval of the ocean surface wind vector from satellite-mounted microwave instruments, which is due in large part to the difficulty in making measurements at high wind conditions when significant foam coverage is present. In the past, empirical microwave emissivity models [1-5], [9] were used to estimate the effect of foam above the ocean surface on the passive microwave remote sensing instruments. The subject of foam dynamics has also attracted great attention.

More recently, physical based approaches, such as quasi-crystalline approximation (QCA) dense media model and Monte Carlo simulations have been developed to account for the microstructure of foam [10,11]. The model treats the foam as densely packed air bubbles coated with thin seawater coatings. It was shown that polarization and frequency of the foam emissivity depends on the physical microstructure properties of foam and the foam layer thickness [11]. In this paper, we compute millimeter wave attenuation by foam covered flat sea-surface. In section 1, an overview of earlier research on microwave emissivity of sea foam and passive remote sensing measurements are stated. In section 2, an explanation of the computations of sea foam dielectric constants at various microwave frequencies are given. Section 3 explains of the use of the Split-step Fourier transform method in evaluating millimeter wave attenuation as a function of foam layer thickness and frequency. Finally, plots of attenuation in decibel (dB) at 10.7 GHz and 37 GHz as a function of depth in millimeter (mm) of sea foam layers are reported.

II. EFFECTIVE DIELECTRIC CONSTANTS OF SEA-FOAM LAYERS

The sea-foam layer was modelled as randomly distributed air-bubbles coated with thin layer of seawater that are log-normally distributed. These spherical coated-spheres were randomly packed into a cubic domain [12]. Estimate of the effective dielectric constant of sea foams were made by modelling the randomly packed bubbles as concentric circles in 2-D where the outer circle is a mixture of air and seawater while the inner circle contains about $(80 - 95)$ % air.

The dielectric constant of seawater at fixed salinity 34 psu and sea surface temperature $20°C$. The dielectric constant of air is taken as $1.00005 + 0.0000i$. The area of the circles in each slice was calculated using the total number of grid points. The effective dielectric constants of sea foams at frequencies 10.7 GHz and 37.0 GHz were calculated for 5 slices of randomly packed air-bubbles coated with thin layer of seawater as given in table I [12].

TABLE I
Results for Dielectric constant of sea foam at frequencies of 10.7 GHz and 37 GHz for 5 2-D Slices of randomly packed air-bubbles covered with thin-layer of seawater.

FREQUENCY	**10.7 GHz**	**37 GHz**
Slice 1	1.0948-0.1251i	1.0006-0.0332i
Slice 2	1.1248-0.1507i	1.0108-0.0239i
Slice 3	1.1622-0.1810i	1.0225-0.0344i
Slice 4	1.1983-0.2072i	1.0315-0.0569i
Slice 5	1.2271-0.2277i	1.0465-0.0637i

III. SPLIT-STEP FOURIER COMPUTATION FOR INVESTIGATION OF SEA-FOAM LAYER MODEL

The computer routines for the development of the sea-foam layer were written in FORTRAN 95 language with Silverfrost FTN95 compiler using 64-bits machine in double precision. The split-step Fourier method (SSFM) as shown in Fig.1, wasused for observation of mmW attenuation by foam covered flat sea surface, for both horizontal polarized (TE) and vertical polarized (TM) electric fields due to its interaction with five (5) slices of sea foam layers was coded in MATLAB R2018b.

The split-step Fourier transform routine was implemented to propagate the plane wave.

$$E(z_0, x, y) = E(z, x, y) exp\left(ik_x + ik_y + ik_z z\right) \quad (1)$$

with $E(x,y,z) \approx 1$ along the forward positive z direction.

The plane wave was propagated through the slices of sea foam layers, each containing isotropically distributed air-bubbles. The slices are equally dimensioned with area $100\,mm \times 100\,mm$ with layer thickness $\delta_t = 10\,mm$ separating adjacent layers. The foam layer thickness $\delta_t \gg \lambda_0$ is required to account for attenuation and diffuse scattering as the incident E-field travels through slices of sea foam layer.

Attenuation of millimeter wave propagation at $10.7\,GHz$ and $37\,GHz$ were evaluated by propagation of the E-field through slices of sea-foam layer. Given input parameters:

1. Speed of light $v = 2.99\times10^{8}\,ms^{-1}$
2. WindSat frequencies $f_1 = 10.7\,GHz$, and $f_2 = 37\,GHz$
3. Wavenumber $(\lambda_0 = v/f)$
4. k-$vector$ $(k_0) = 2\pi/\lambda_0$
5. Refractive indices of the sea foam layer $n(z,x)$ in each slice of randomly distributed bubbles.
6. Dimension ofslices$100\,mm \times 100\,mm$
7. Foam layer thickness between adjacent slices (δ_t)

The incident wave was propagated at normal incidence and later tilted so that there is an initial gradient along the surface of the sea-foam model. This was achieved by assigning values of zenithangles $0 \ll \theta_i \ll 90^{\circ}$ and fixed azimuthal angle $\phi_i = 45^{\circ}$.

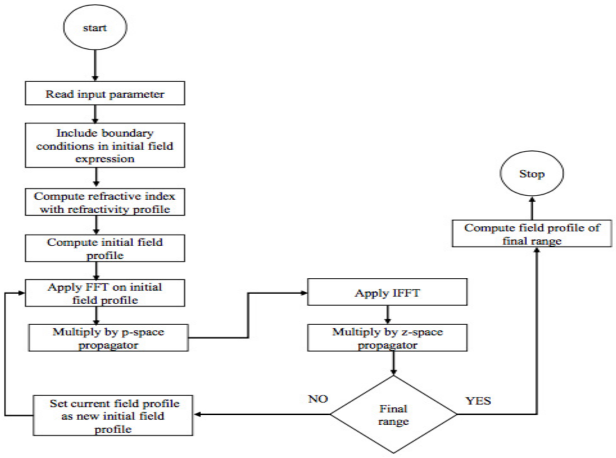

Fig. 1. Flow chart of Split-step Fourier transform algorithm.

For each of the angles θ_i, we compute the E-fields that emerges from the foam layer and calculate the FFT's of the fields.

IV. ATTENUATION OF THE FIELD INTENSITY IN DECIBEL WITH DEPTH OF SEA-FOAM AT WINDSAT FREQUENCIES

The attenuation of the field intensity in decibel (dB) at a low frequency of $10.7\,GHz$ and sea foam slice thickness $\delta_t = 0.1\,mm$ which represents a thin phase scattering screen increases as the depth of sea foam increases. Fig.2 and 3 illustrate the variation of attenuation of the E-field in dB with depth in mm of sea-foam layer. This is due to increase in diffuse reflections or scattering as the EM wave interacts with randomly oriented sea-foams with different refractive indices. This happens for both TE and TM polarized E-fields.

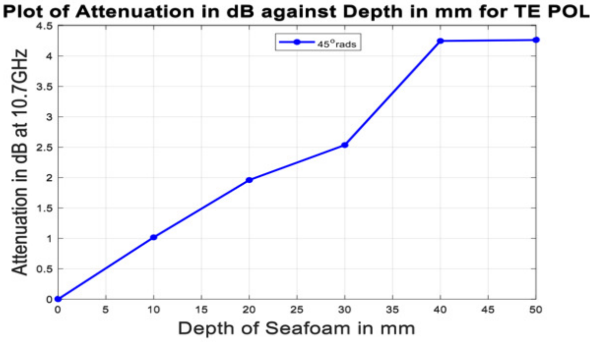

Fig. 2. Attenuation of Field Intensity for horizontal polarization (TE) with zenith $\theta_i = 45°$ and azimuth $\phi = 0°$ with depth of sea-foam at 10.7 GHz and foam layer thickness $\delta_t = 0.1\ mm$.

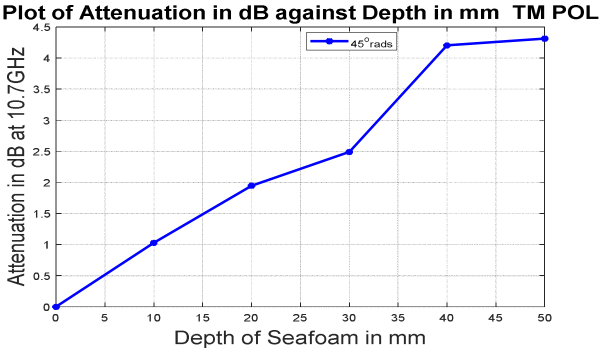

Fig. 3. Attenuation of Field Intensity for vertical polarization (TM) with zenith $\theta_i = 45°$ and azimuth $\phi = 0°$ with depth of sea-foam at 10.7 GHz and foam layer thickness $\delta_t = 0.1\ mm$.

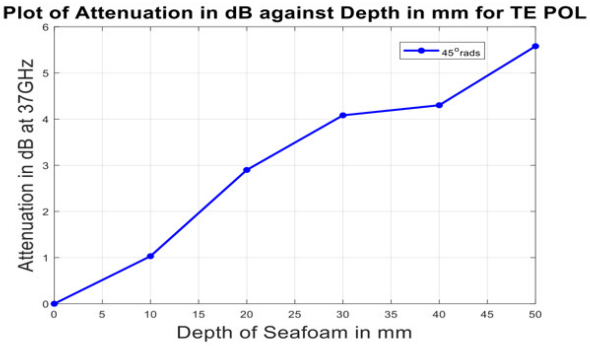

Fig. 4. Attenuation of Field Intensity for horizontal polarization (TE) with zenith $\theta_i = 45°$ and azimuth $\phi = 0°$ with depth of sea-foam at 37 GHz and foam layer thickness $\delta_t = 0.1\ mm$.

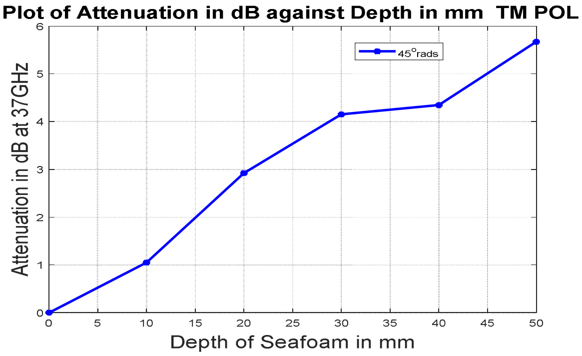

Fig. 5. Attenuation of Field Intensity for vertical polarization (TM) with zenith $\theta_i = 45°$ and azimuth $\phi = 0°$ with depth of sea-foam at 37 GHz and foam layer thickness $\delta_t = 0.1\ mm$.

For thin phase scattering screens $\delta_t = 0.1\ mm$ with a given zenith angle $\theta_i = 45°$ and azimuth $\phi = 0°$, the attenuation $\alpha(dB)$ increases with depth (mm) of sea-foam and frequency at37 GHz. The attenuation at 10.7 GHz is less than that at 37 GHz, which agrees with the fact that there is more interaction of the E-field with the particles at high frequency. In Fig. 4 and 5, attenuation of the E-fields for both TE and TM polarizations are due to phase perturbations due to diffuse scattering of disordered air-bubbles with varying dielectric constants.

V. CONCLUSIONS

We have shown from our results that attenuation of the E-field is due to diffuse scattering when the incident E-field is multiple reflected by sea-foam as it propagates through the various slices of sea-foam layer. The E-field travels through different paths and is scattered due to re-radiation of the dipole moments of the disoriented scatterers which absorbs some of the incident E-field and re-radiates it at various directions. The varying effective dielectric constants of the particles enhances diffuse scattering of the incident and transmitted E-fields within the sea-foam layer. The split-step Fourier transform method is a range marching technique that is suitable for evaluation of the E-field propagation given an initial range, the expected depth of the field can be computed as a function of range and depth. Future works will evaluate variation of the field intensity due to its interaction with rough sea-surface covered by foams.

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