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Evaluation of Sea-foam Effective Dielectric Constants at Microwave Frequencies using Maxwell Garnett's and Bruggeman's Methods

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Abstract:

This paper focuses on evaluation of sea foam effective dielectric constants at microwave frequencies using Maxwell Garnett's and Bruggeman's methods. Satellite-based geophysical retrievals of environmental variables from radiometric measurements at microwave frequencies require increasing demands for accuracy. Geophysical retrievals such as sea surface emissivity and brightness temperatures of the ocean can be evaluated accurately if the effective complex dielectric constants of sea foams are well evaluated. An overview of the classical mixing rule and evaluation of complex effective dielectric constant of seawater at various microwave frequencies were reported. Results of the complex effective dielectric constant of sea foam using Maxwell Garnett's and Bruggeman's methods were also reported.

Keywords — **Sea foam, effective dielectric constant, Maxwell Garnett, Bruggeman, Microwave frequency.**

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I. INTRODUCTION

Foam formation is enhanced by the presence of impurities in water. [1],[2], asserted that a foam is a dispersion of a gas in a liquid or solid separated by thin films or lamellae. It has been observed that a pure liquid cannot foam unless a surface-active material is present. Surface-active forming materials comprise of particles, detergents and soap, polymers, specific absorbed cations,or anions from organic salts etc.

In aquatic habitat, sea foam forms when dissolved organic matter in the ocean is churned up but on a grander scale when the ocean is agitated by wind and waves [2].

The formation of sea foam is governed by different conditions on each coastal region. Sea water contains higher concentration of dissolved organic matter (proteins, salts, lipids and lignins, decaying algae or phytoplankton bloom and decaying fish). These acts as surfactants or foaming agents. As the sea water is agitated by breaking waves in the surf zone next to the shore, the existence of these surfactants under turbulent conditions traps air, forming persistent bubbles which stick to each other through surface tension [3]. Foam on ocean surface consists of densely packed air bubbles coated with thin layer of water.

Due to its low density and persistence, foam can be blown by strong onshore winds from the beach face inlands onto sidewalks and street.

Human waste forms a great contribution to sea form in addition to overflow from plants, factory waste and sewer spills. Sea form produced by non-pollutants nor algae bloom is white. Foams formed by pollutants is often brown in colour. However, sea foam produced by red tide or other organic source also appear brownish.

Fig 1. Sea Foam at Ocean Beach at San Francisco [19].

II. DIELECTRIC CONSTANT OF SEAFOAM AT MICROWAVE FREQUENCY

A systematic insight into the application of various mixing rules (effective medium theories) for evaluating the dielectric constant (permittivity) of sea foam (whitecaps) at microwave frequencies between 1.4 to 37GHz was reported by [4]. It is significant to note that foam scattering is weak at these frequencies which explains the interest of [4] in evaluating the dielectric constant of whitecaps using inexplicit scattering computations such as the Maxwell Garnett, Bruggeman, Coherent potential, Looyenga, and Refractive models.

This approach relies on previous findings on various heterogeneous dielectric mixtures and reported characterization of sea foam to evaluate the availability of various permittivity models for obtaining acceptable predictions of sea foam dielectric constant.

Droppleman [5] presented numerous and field observations which characterized deep bubble plumes well but measurements characterizing the surface foam layers are few and usually simulated artificial sea foam [6] ,[7],[8],[9],[10].

Due to limited knowledge of the microscopic characteristics of sea foam from previously published work and experiments, recent models evaluating the foam emissivity and effective permittivity uses exclusively macroscopic foam characteristics, such as void fraction (whitecap coverage) and foam thickness thereby ignoring scattering losses in sea foam. This could be attributed to the fact that previous foam emissivity models that computed the attenuation and permittivity in foam with several scattering theories using as input the microscopic characteristics of foam such as bubble diameters, bubble wall thicknesses, bubble size distribution, filling factor, and stickiness parameter [11],[12] introduced uncertainties which affected the accuracy of the foam emissivity models.

To restrict these uncertainties and enhance use in retrieval algorithms, [13] suggested the use of exclusively macroscopic quantities instead, namely, void fraction profile and foam layer thickness. Avoiding the use of microscopic quantities implies foregoing modelling of the scattering losses in sea foam [14],[15].

Based on the aforementioned consideration, the foam emissivity was obtained by one of the classical permittivity models (mixing rules) which involve only the sea water permittivity, ϵ, and air permittivity $\epsilon_0 = 1 - j0$, and void fraction f_a.

Zhang et. al [16] model assumed the foam layer to be much thicker than the penetration depth of the radiation, thus ignoring the emissivity of the water below the foam layer [16]. Evaluations of extinction, scattering and absorption coefficients were carried out at 19.35GHz for foam consisting of large bubbles (inner radius of 4.3mm) with relatively thick walls (0.13mm). [16] obtained results which represents a numerical analogue of Williams's experimental observations for foam spread over an aluminium plate. [16] eliminated a major contributor to absorption (the water below the foam) and considered large thick-walled bubbles at relatively high frequency and the model, unsurprisingly, predicts low absorption (about 28% of the total extinction) and significant scattering, which is consistent with the other analytical and experimental findings.

Zhang et. al evaluates the scattering, absorption, and extinction efficiency factors (Q_s, Q_{abs}, Q_e) by Mie theory for spherical water bubbles with different sizes and wall thicknesses [16]. The results obtained depicts that absorption was the main attenuation factor which was further clarified by conclusions from [17] observed small attenuation in dry foam is predominated by absorption within the bubble walls, not scattering. Scattering, however, increases as radiation frequency and bubble dimensions (radius and wall thickness) increases.

Based on Raizer's observations various models can be created with significant scattering by using microscopic characteristics of sea foam such as bubble diameter, bubble wall thickness, bubble size distribution, filling factor and stickiness without the introduction of uncertainties by considering two input parameters in the models at different intervals instead of many parameters when computing the scattering losses [18]. However, existing models of sea water can be used coupled with effective medium theories for evaluating the effective dielectric constant of sea foam. In the next section, some existing models for evaluating the dielectric constant of sea water will be mentioned as well as the various mixing rules for sea foam evaluation. Stogryn's model for sea water at fixed sea surface temperature (SST) at 20 and salinity (34psu) at 1.4 GHz, 6.8 GHz, 10.7 GHz, 18.7 GHz, 23.8 GHz, and 37.0 GHz was used to evaluate the effective dielectric constant of sea foam. The dielectric constants obtained at the aforementioned frequencies were used as the dielectric constants of the of the host medium ϵ_b (base medium) while the dielectric constant of air ϵ_{air}= 1.0006 which is approximately equal to the dielectric constant of vacuum ϵ_0, the dielectric constant of the inclusion. Therefore, $\epsilon_{air} \cong \epsilon_0 = 1$ for sea foam (sea water-air interface). It was also used for sea spray (air-sea water interface) which implies that air represents the base medium with sea water as inclusion. Magdalena's model depends on the void fraction f_a (air or water) inclusions. This method was developed using the famous Maxwell Garnet's approximation, Polder van Santen (Bruggeman), Looyenga (cubic) law, refractive (quadratic rule) and coherent potential. It is worth noting that the void fraction changes abruptly with depth. $f_a \cong 100\%$ at the interface adjacent to the air to $\ll 1\%$ at the interface adjacent to sea water and below. More information on void fraction consideration can be found in [19].

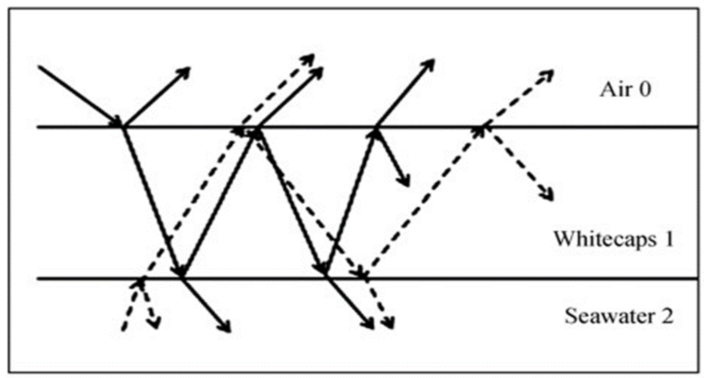

Fig 2. Geometry of whitecaps [20].

III. MODELLING OF SEA FOAM USING EFFECTIVE MEDIUM THEORIES

Sea foam is a heterogeneous mixture composed of air and sea water. Such a mixture could be referred to a diphasic mixture. The dielectric properties of a diphasic mixture can be evaluated using a suitable mixing rule. The mixing rule is an approach of homogenizing an inhomogeneous medium. This is achieved by representing a complex material with a uniform effective permittivity. The mixing rule is also known as effective medium theory (EMT). EMT is a very useful tool for evaluating and analysing the dielectric and radiative properties of composite materials [19]. It matches the effective permittivity ϵ_{eff} of a heterogeneous mixture to the permittivity of its constituents.

To develop a consistent model of sea foam it is necessary to study sea foam properties. The sea foam properties are discussed below.

Sea Foam Properties

Sea foam and whitecap at microwave frequencies are routinely modelled by a poly-disperse system of bubbles. Two layered spherical particles with a thin saltwater shell, with air inclusions. Sea foam and the processes within can be characterize in microscopic and macroscopic form. Microscopic characteristics such as bubbles dimensions (radius r, and wall thickness w) and size distribution or concentration N(r) are necessary. Macroscopic characteristics such as foam layer thickness t and foam void fraction describe the foam layer. The specific mechanical structure of sea foam is represented by a group of medium variables established by micro and macro characteristics of sea foam. [20] gives an overview of sea foam properties in formulating several dielectric models of sea foam.

Classical Mixing Rule

The sea foam modelling based on classical mixing rule assuming explicit macroscopic characteristics of sea foam is a diphasic mixture with constituents described as a host medium with inclusions, each with permittivity ϵ_b and ϵ_i, respectively.

The void fraction f_a (defined as the unit volume of ocean occupied by air) of the total mixture occupied by the inclusions determines the nature and character of the mixture. In this model, sea water is the host medium and air bubbles represent the inclusions thus denoting $\epsilon_{eff}= \epsilon_f$, $\epsilon_e= \epsilon$, $\epsilon_i= 1$, and $f_v= f_a$. Most natural media are material-in-air mixtures with a dielectric constant $\frac{\epsilon_i}{\epsilon_e} < 1(\epsilon_i = \epsilon_0 = 1 - j0)$ and has been more extensively studied than air-in-material mixtures, like the sea foam, with $\frac{\epsilon_i}{\epsilon_e} > 1$.

Effective medium theory has been widely deployed for dense media in which the dipole interactions and resonance in closely packed inclusions need to be evaluated. Examples of these are Maxwell Garnet's (MG) method, the Polder-van Santen (Bruggeman or De Loor formula), Coherent Potential (CP) or Power law formula and Refractive model. There is need to investigate the most appropriate and best suitable mixing rule with the potency to model a consistent foam permittivity to meet the desired remote sensing application. De Loor reported that it is impossible to choose one relation to fully describe the permittivity of a specific mixture.

I. *Maxwell Garnet's Method*

From previous studies [4], the Maxwell Garnet's formula is a very famous mixing rule. It was reported that different mixing rule used to evaluate sea foam permittivity approximates to the expression for Maxwell Garnet's rule with appropriate notations of the variables and some algebraic re-arrangements. For example, Rayleigh mixing formula.

The Maxwell Garnet's method is derived for a diphasic composite, where spherical dielectric inclusions are present in a homogeneous host and could be extended for arbitrary ellipsoid inclusions and for multiphase mixtures. This derivation is based on polarizability of a dielectric sphere. Considering a composite where spherical inclusions with dielectric constant ϵ_i occupy random positions within the host medium ϵ_i and the volume fraction of inclusions to be v_i, and host material $v_b= 1 - v_i$.

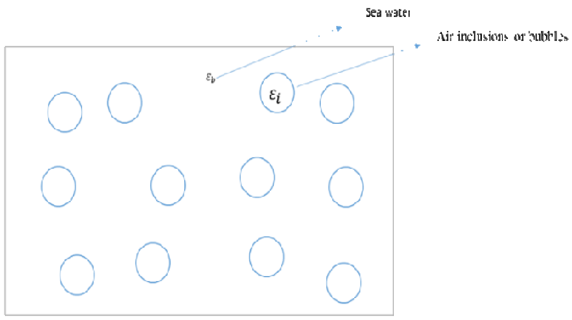

Fig 3. Dispersed dielectric spherical inclusions in a dielectric base material.

Considering an average displacement vector and an average electric field. For a linear isotropic mixture, these parameters are related by

$$\overline{D} = \epsilon_{eff}\overline{E} \qquad (1)$$

where $\epsilon_{eff} = \epsilon_0\epsilon_{effr}$ is the absolute permittivity, complex in general case.

The average field and displacement vector could be written weighted with corresponding volume fractions of phases with absolute complex permittivity $\epsilon_b = \epsilon_0\epsilon_{br}$ for base medium, and $\epsilon_i = \epsilon_0\epsilon_{ir}$ for inclusions. This is usually done for real and frequency-dispersive materials.

$$\overline{D} = v_i\epsilon_i\overline{E} + (1 - v_i)\overline{}_b \ (2)$$

$$\overline{E} = v_i\overline{E}_i + (1 - v_i)\overline{}_b \qquad (3)$$

from (2) and (3) we can obtain

$$\epsilon_{eff} = \frac{v_i\epsilon_i A + (1-v_i)\epsilon_b\ddot{E}_b}{v_i A + (1-v_i)\ddot{E}_b} \qquad (4)$$

where A is proportionality coefficient between the internal field inside the inclusion and external field in the host medium.

$$\overline{E} = A\overline{E_b}$$

For spherical inclusions, by solving a rigorous boundary problem for electrostatic potential, it is possible to express the proportionality coefficient as

$$A = \frac{3\epsilon_b}{2\epsilon_b + \epsilon_i} \qquad (5)$$

By substituting the expression A in (5) into (4) gives

$$\epsilon_{eff} = \frac{v_i\epsilon_i\left(\frac{3\epsilon_b}{2\epsilon_b+\epsilon_i}\right) + (1-v_i)\epsilon_b\overline{E_b}}{v_i\left(\frac{3\epsilon_b}{2\epsilon_b+\epsilon_i}\right) + (1-v_i)\overline{E_b}} \qquad (6)$$

which is further expressed as

$$\epsilon_{eff} = \frac{v_i\epsilon_i 3\epsilon_b + (1-v_i)\epsilon_b(2\epsilon_b + \epsilon_i)}{v_i 3\epsilon_b + (1-v_i)\epsilon_b(2\epsilon_b + \epsilon_i)} \qquad (7)$$

factorizing (7) yields

$$\epsilon_{eff} = \epsilon_b + 3\epsilon_b v_i \frac{(\epsilon_i + \epsilon_b)}{\epsilon_i + 2\epsilon_b - v_i(\epsilon_i + \epsilon_b)} \ (8)$$

This result is the famous Maxwell Garnet's mixing formula for diphasic mixture with randomly dispersed spherical inclusions. For volume fraction $\rightarrow 0, \epsilon_{eff} \rightarrow \epsilon_b$; for volume fraction $v_i \rightarrow 1, \epsilon_{eff} \rightarrow \epsilon_i$.

II. Polder van Santen (Bruggeman or De Loor) Formula

The unified mixing formula can be written as

$$\frac{(\epsilon_{eff} - \epsilon_e)}{\epsilon_{eff} + 2\epsilon_e + v(\epsilon_{eff} - \epsilon_e)} = f_v \frac{(\epsilon_i - \epsilon_e)}{\epsilon_{eff} + 2\epsilon_e + v(\epsilon_{eff} - \epsilon_e)} \ (9)$$

which was published in Table 1. [4], for dimensionless parameter $v = 0$, we obtain the Maxwell Garnet's formula as shown in (8), for $v = 2$, the Polder van Santen formula can be expressed as

$$2\epsilon_{eff}^2 + \epsilon_{eff}[1 - 2\epsilon + 3f_a(\epsilon - 1)] - \epsilon = 0 \quad (10)$$

substituting $v = 2$ in (9) we obtain

$$\frac{(\epsilon_{eff} - \epsilon_e)}{\epsilon_{eff} + 2\epsilon_{eff}} = f_v \frac{(\epsilon_i - \epsilon_e)}{\epsilon_i + 2\epsilon_{eff}} \quad (11)$$

expanding (11) gives

$$\epsilon_{eff} - \epsilon_e\epsilon_i + 2\epsilon_{eff}^2 - 2\epsilon_{eff}\varepsilon_e = 3\epsilon_{eff}f_v\epsilon_i - f_v\epsilon_e\epsilon_{eff} - 2\epsilon_{eff}f_v\epsilon_e \quad (12)$$

This can be further expressed as

$$\epsilon_{eff} - \epsilon_e\epsilon_i + 2\epsilon_{eff}^2 - 2\epsilon_{eff}\varepsilon_e = 3\epsilon_{eff}f_v\epsilon_i - f_v\epsilon_e\epsilon_{eff} - 2\epsilon_{eff}f_v\epsilon_e \quad (13)$$

For sea foam with ϵ_e as base dielectric constant and ϵ_i as dielectric constant of inclusions, when $\epsilon_i = 1$, (13) becomes

$$\epsilon_{eff} - \epsilon_e + 2\epsilon_{eff}^2 - 2\epsilon_{eff}\varepsilon_e = 3\epsilon_{eff}f_v - f_v\epsilon_e\epsilon_{eff} - 2\epsilon_{eff}f_v\epsilon_e \quad (14)$$

which can be written as

$$2\epsilon_{eff} + \epsilon_{eff} - 2\epsilon_{eff}\varepsilon_e - 3\epsilon_{eff}f_v$$

$$- 3\epsilon_{eff}f_v\epsilon_e - \epsilon_e = 0(15)$$

factorizing (15) gives

$$2\epsilon_{eff}{}^2 + [1 - 2\epsilon_e + 3f(\epsilon_e - 1)] - \epsilon_e = 0$$

Other models can be derived from the unified

mixing formula.

At RF and microwave frequencies, inclusions are much smaller in size as compared to the wavelength of electromagnetic waves, which implies that composite materials can be assumed to be in quasi-stable regime from electromagnetic standpoint. Hence, the effects of propagation and multiple reflections within inclusions will be ignored.

IV. CRITICAL REVIEW OF SEA FOAM DIELECTRIC CONSTANT

A simple model for the oceanic foam is presented by considering macroscopic characteristics of sea foam. The effective dielectric constant of sea foam and sea spray was evaluated by deploying Stogryn's model for sea water to calculate the dielectric constant of sea water. Stogryn's model calculated the dielectric constant of sea water at different frequencies with constant sea surface temperature and salinity. The calculated dielectric constants of sea water were used to evaluate the effective dielectric constant of sea foam for sea foam (sea water-air) and sea spray (air-sea water) using exclusively macroscopic characteristics of sea foam which implies the dielectric constant of the impurities were neglected. Previous studies show that the sea water is lossy with high conductivity (salinity) thus most of the electromagnetic radiation from sunlight (passive remote sensing) is absorbed. The air bubbles or foam plumes accounts for scattering which increases with penetration depth but most of the incident radiation is absorbed. Ignoring the impurities or microscopic characteristics is ignoring scattering losses.

The computed dielectric constants of sea water converge with the values in [20].

Table 1. Results for Dielectric Constant of Water evaluated by Guillou's and Wentz model fixed Salinity (34psu) and SST (20°C).

Permittivity of sea water (ϵ_w)	Frequency(GHz)	Permittivity of sea water (ϵ_w)	Frequency(GHz)
70.3719 + j63.8775	1.4	71.8419 + j65.3482	1.4
62.3736 + j33.7977	6.8	63.4152 + j34.7004	6.8
53.3282 + j36.3177	10.7	54.2341 + j37.2669	10.7
36.5362 + j36.5429	18.7	37.1811 + j37.8001	18.7
29.4553 + j35.6596	23.8	29.4553 + j35.6590	23.8
18.1987 + j27.1685	37.0	17.9840 + j28.7506	37.0

at fixed Salinity (34psu) and SST (20°C).

Permittivity of sea water (ϵ_w)	Frequency(GHz)	Permittivity of sea water (ϵ_w)	Frequency (GHz)
70.6301 + j34.0112	1.4	70.9660 + j66.5496	1.4
62.6425 + j27.8729	6.8	63.3405 + j34.1233	6.8
53.5604 + j32.8054	10.7	54.5612 + j36.6399	10.7
36.5500 + j34.9728	18.7	37.8060 + j37.3359	18.7
29.9247 + j33.2233	23.8	30.1423 + j35.2509	23.8
17.7537 + j26.8554	37.0	18.7605 + j28.4104	37.0

Table 3. Results for Dielectric Constant of Sea Water evaluated by Klein and Swift model at fixed Salinity (34psu) and SST (20°C).

Permittivity of sea water (ϵ_w)	Frequency(GHz)
72.2528 + j63.8775	1.4
63.7847 + j35.2256	6.8
54.2260 + j30.0121	10.7
36.5312 + j38.3015	18.7
28.6722 + j35.8699	23.8
17.2817 + j28.4579	37.0

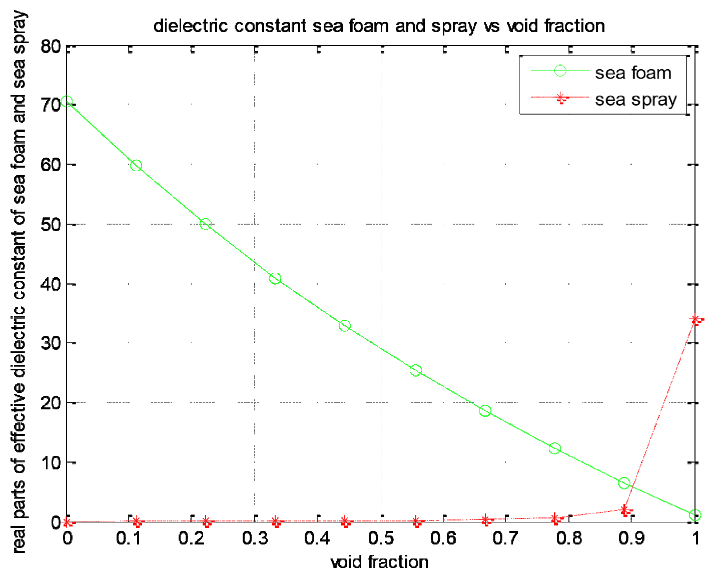

Fig 4. Real dielectric Constant of sea foam and sea spray against volume void fraction using Maxwell Garnet's Method.

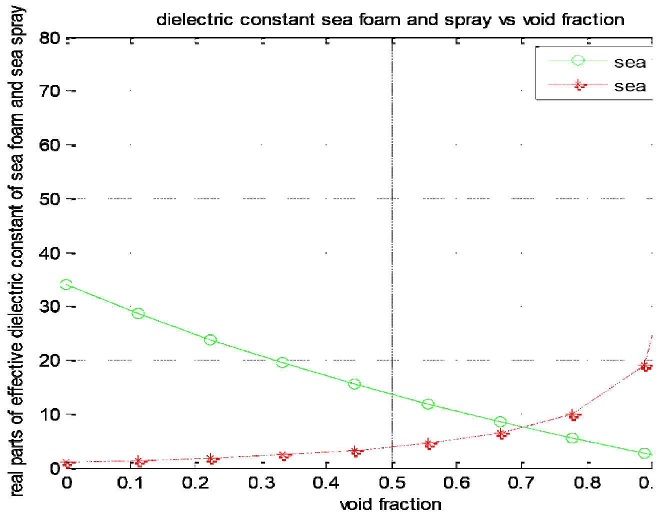

Fig 5. Imaginary dielectric constant of sea foam and sea spray against volume void fraction using Maxwell Garnet's Method.

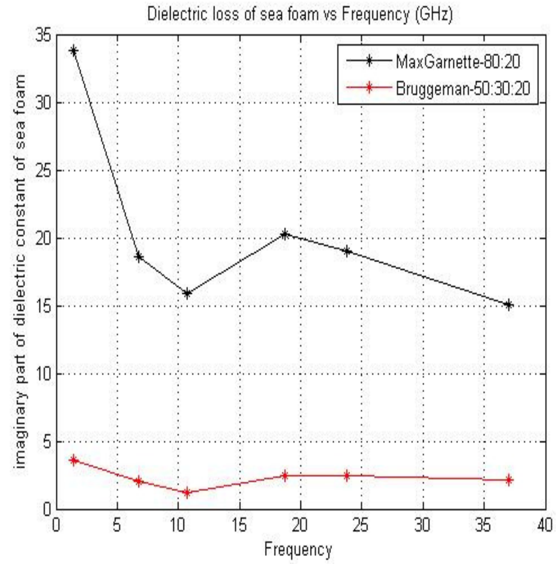

Fig 7. Imaginary Dielectric Constant for Maxwell Garnett and Bruggeman Models

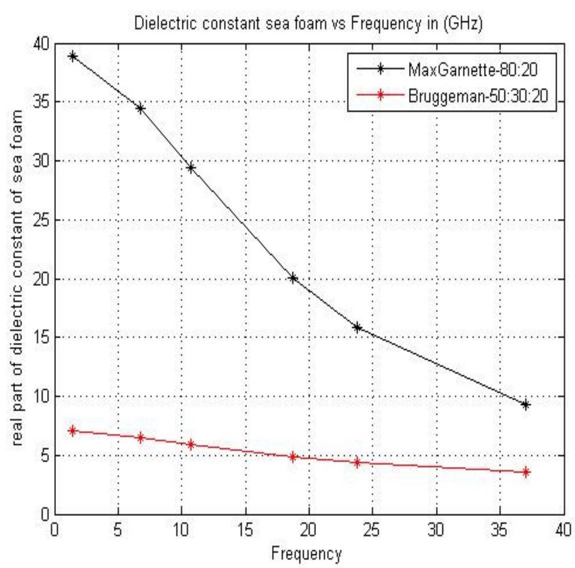

Fig 6. Real Dielectric Constant for Maxwell Garnett and Bruggeman Models.

Fig 6 and 7 gives variation of the effective dielectric constant of wet foam as a function of frequency for real and imaginary part. The dielectric constant and dielectric loss of wet foam follow similar pattern as that shown by Klein and Swift model of seawater. Fig 3 shows that the real part of the effective dielectric constant of wet sea foam decreases with increase in frequency (GHz). The dielectric loss in Fig 7 decreases with increase in frequency up to 10 GHz, then increase gradually to 18.7 GHz and later decreases from 18.7 GHz to 37 GHz.

V. CONCLUSION

This work present estimates of sea foam complex effective dielectric constants using effective medium theories. Maxwell Garnett and Bruggeman models are famous in evaluating the effective dielectric constants of complex mixtures in terms of their volume ratio. Estimates of effective dielectric constants of seawater using existing methods such as Stogryn, English, Wentz, Guillou, and Klein and Swift models at fixed salinity (34psu) and sea surface temperature (20˚C) were reported. With these estimates at various microwave frequencies, Maxwell Garnett and Bruggeman models were used to evaluate complex effective dielectric constants of sea foam as mixture of seawater and air. Further research on evaluation of scattering, emissivity and brightness temperature of ocean surface covered by foam can be achieved if accurate estimates of the effective dielectric constants of sea foams are computed.

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REFERENCES

[1] S. Katerina, Z. Matthias, "Foam in the aquatic environment", Water Research, Vol.45, No.15, 2011.

[2] J. Heard et.al, "The effect of filamentous bacteria on foam production and stability. Colloids and Surfaces B: Biointerfaces", Water research, Vol.65, pp.21-26, 2008.

[3] Holmberg et al, "Forming of surfactant solutions", John Wiley & Sons, Ltd, 2003.

[4] Magdalena D. Anguelova, "Complex Dielectric Constant of Sea Foam at Microwave Frequencies", Journal of Geophysical Research, Vol. 113, C08001, 2008.

[5] Droppleman J., "Apparent Microwave Emissivity of Sea Foam", J. Geophys. Res., 75, pp696-698.1970

[6] Militskii Y. A, V. Y. Raizer, E .A .Sharkov, and V.S. Etkin, " Scattering of Microwave Radiation by Foaming Structures", Radio Engineering, Electron Physics, 22(11), pp4650,1977.

[7] Militskii Y. A, V. Y. Raizer, E .A .Sharkov, and V.S. Etkin, "Thermal Radio Emission from Foam Structures", Sov., Physics Tech.,, Vol.23, pp601-602,1978.

[8] Peltzar R. D, O.M. Griffin, "Stability of a three dimensional foam layer in sea water", J. Geophysics, 93,10,804-10,812, 1998.

[9] Rose L.A. et al, "Radiometric measurements of the emissivity of ocean foam", IEEE Trans. Geosci, Remote Sens., 40, 2619-2625, 2002.

[10] Camps A et al, "The emissivity of foam covered water surface at Lbands: Theoretical Modelling and experimental results from the FROG 2003 field measurement", IEEE Trans. Geosci., Remote Sens., 41, 782-790, 2003.

[11] Raizer V, "Macroscopic foam spray models for ocean microwave radiometry", IEEE Trans, Geosciences, Remote Sensing., 45(10), pp3138-3144, 2007.

[12] Raizer V. Ya., and E.A Sharkov, "Electrodynamic Description of Densely Packed Dispersed Systems", Izv. Radiophysics, Quantum Electron, Vol.17, pp238-241, 1982.

[13] Guo et al, "Applications of Dense Media Radiative Transfer Theory for Passive Microwave Remote Sensing of Foam-Covered Ocean, IEEE Trans. Geosci, Remote Sens., 39,1019-1027, 2001.

[14] Chen et .al, "Microwave emission and scattering of foam based on Monte Carlo Simulations of Dense Media", IEEE Trans, Geosci, Remote Sens., 41, 782-790, 2003.

[15] Bordonskiy. G.S. et al, "Spectral Characteristics of the Emissivity of Foam Formations", Izv. Atmos. Ocean Physics, Vol.15, pp193-198, 1998.

[16] Zhang et al, "A composite model for estimation of polarimetric thermal emission from foam covered wind driven ocean surface", Prog. Electron. Res., PIER 41, 143-190.

[17] Dombrovskiy L.A, "Calculation of thermal radio emission from foam on sea surface", Izv. Atmos. Ocean Physics, Vol.17, pp238-241, 1979

[18] Dombrovskiy L.A, "Absorption and Scattering of Microwave Radiation by Spherical Water Shells", Izv. Atmos. Ocean Physics, Vol.17, pp238-241, 1982.

[19] Choy T.C, "Effective Medium Theory: Principles and Applications", pp193, Oxford University Press, New York, 1999.

[20] Wei EnBo et al, "Application of Effective Medium Approximation Theory to Ocean Remote Sensing under Wave Breaking", Sci China Ser D-Earth, March 2007, Vol.50, no.3, 474-480,2007.

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