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The effect of E-M wave's attenuation on sea surface reflectivity, emissivity and estimation of sea surface temperature

Qing Xu [a,b,*], Yuguang Liu [a], Yongcun Cheng [a,c]

[a] *Physical Oceanography Laboratory, Ocean University of China, Qingdao, 266003, PR China*
[b] *Department of Atmospheric and Oceanic Science, University of Maryland, College Park, 20742, Maryland, USA*
[c] *Institute of Meteorology, PLA University of Science and Technology, Nanjing, 211101, PR China*

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Abstract

The imaginary component of the complex index of refraction denotes the attenuation of E-M waves in amplitude within the procedure of propagation in a medium. The attenuation of E-M waves in sea water is of great importance in microwave remote sensing, because the Snell's law of refraction in air–sea interface, sea surface reflectivity, sea surface emissivity and the estimation of sea surface temperature (SST) from microwave radiometer detections are all related to it. The well-known expressions of the reflectivity were derived in optics, but they cannot be applied directly to microwave remote sensing, since the E-M waves of microwave bands propagating in the sea water are greatly attenuated. In this study, a more appropriate formula of the reflectivity is proposed for the full range of E-M waves with considering the attenuation of E-M waves in the sea water. The proposed formula can be used to obtain the emissivity of sea surface, which is useful to estimate SST in microwave remote sensing. The error analysis indicates further that the proposed formula of the reflectivity is significant for improving ocean microwave remote sensing and increasing the retrieval accuracy of SST.

Keywords: Ocean remote sensing; Microwave; Reflectivity; Emissivity; Sea surface temperature

1. Introduction

As an important physical parameter in the electromagnetic (E-M) theory, the reflectivity is an indispensable variable in oceanic remote sensing. It can be used to calculate sea surface emissivity, which is useful to estimate sea surface temperature (SST) and sea surface salinity (SSS). The microwave theory of active remote sensing of sea surface wind speed is also related to the reflectivity.

The reflectivity ρ of a surface is defined by the ratio of the irradiance I_r reflected from the surface to the irradiance I_i incident on the surface (Stewart, 1985)

$$\rho = \frac{I_r}{I_i} \tag{1.1}$$

The Fresnel reflection coefficient $\boldsymbol{R}$ is defined as

$$\boldsymbol{R} = \frac{\boldsymbol{E}_{0r}}{\boldsymbol{E}_{0i}} \tag{1.2}$$

where $\boldsymbol{E}_{0i}$ and $\boldsymbol{E}_{0r}$ denote the amplitude of incident electric field intensity and that of reflected electric field intensity, respectively. A boldfaced variable in this paper

* Corresponding author. Fax: +86 532 82032471.
E-mail address: xuqing215@yahoo.com.cn (Q. Xu).

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denotes that its value is either a real number or a complex number. The arrow above the variable denotes that it is a vector.

The irradiance is proportional to the square of the electric field intensity; thus, the reflectivity ρ should be

$$\rho = |\boldsymbol{R}|^2 = \left|\frac{\boldsymbol{E}_{0\mathrm{r}}}{\boldsymbol{E}_{0\mathrm{i}}}\right|^2 \tag{1.3}$$

For sea water, ρ and $\boldsymbol{R}$ are both functions of SST, SSS, the frequency and the complex index of refraction. However, authors of the previous literature (Lorrain and Corson, 1970; Reeves, 1975; Ulaby et al., 1981; Stewart, 1985) did not pay detailed attention to the imaginary component n'' (which denotes the attenuation of the E-M waves in amplitude) of the complex index of refraction $\boldsymbol{n}$ in the process of derivation. They confused the real component n' with $\boldsymbol{n}$. For visible light and infrared bands, the attenuation is so small that n'' can be neglected compared with the real component n' of $\boldsymbol{n}$. So the expressions of the reflectivity in optics in the previous literature are right. For microwave bands, the attenuation becomes larger and n'' cannot be ignored any more, but authors of previous literature (Lorrain and Corson, 1970; Reeves, 1975; Ulaby et al., 1981; Stewart, 1985) did not take this into account. They just directly applied the expressions in optics to the microwave bands, which seems not so correct to some extent.

In this study, we try to derive the more appropriate expressions of reflectivity for the full range of E-M waves. In order to derive new formulas, we have to know dielectric characteristics of sea water. Based on Maxwell's equations and Debye's equation, the calculation of the complex index of refraction $\boldsymbol{n}$ and the relative complex permittivity $\boldsymbol{\varepsilon}_\mathrm{r}$ of sea water is introduced in Section 2. Snell's law of refraction, Fresnel's equations and the proposed formulas of the reflectivity are presented in Section 3. Comparisons between the proposed and traditional formulas are shown in Section 3.3. Applications of the reflectivity on sea surface emissivity, sea surface brightness temperature and the estimation of SST are introduced in Section 4. Section 5 is the conclusion.

2. The complex index of refraction $\boldsymbol{n}$ and the relative complex permittivity $\boldsymbol{\varepsilon}_\mathrm{r}$

2.1. The relation between $\boldsymbol{n}$ and $\boldsymbol{\varepsilon}_r$

The dynamics of electric and magnetic fields in the presence of matter is described by Maxwell's equations. Of particular importance to our discussions is the solution for a propagating wave, which when propagating in z direction may be written (Ulaby et al., 1981)

$$\boldsymbol{E}_x = \boldsymbol{E}_{x0}\exp[\boldsymbol{j}(\omega t - \boldsymbol{k}z)] \tag{2.1}$$

where subscript x denotes the x component of the electric field, which is perpendicular to the propagating direction. For simplicity, only one component of the electric field, say x component, is considered. The boldface denotes that the physical variable is complex and the same notation is used in the following expressions. The related parameters are

$$\boldsymbol{k} = \omega\sqrt{\boldsymbol{\mu}\boldsymbol{\varepsilon}},\ \ \omega = 2\pi f,\ \ \boldsymbol{\mu} = \mu_0\boldsymbol{\mu}_\mathrm{r},\ \ \boldsymbol{\varepsilon} = \varepsilon_0\boldsymbol{\varepsilon}_\mathrm{r} = \varepsilon_0(\boldsymbol{\varepsilon}_\mathrm{r}{}' - \boldsymbol{j}\boldsymbol{\varepsilon}_\mathrm{r}'') \tag{2.2}$$

where the notation used in this section is given in Table 1. For most materials of interest to remote sensing, the relative permeability is unity, i.e. $\boldsymbol{\mu}_\mathrm{r}=1.0$. In free space, $\boldsymbol{\varepsilon}_\mathrm{r}=1.0$ and the waves propagate at a velocity

$$c^2 = 1/(\mu_0\varepsilon_0) \tag{2.3}$$

where c is the phase velocity of light in free space. In a medium, the complex velocity of electromagnetic waves is

$$\boldsymbol{v} = \frac{\omega}{\boldsymbol{k}} = \frac{c}{\sqrt{\boldsymbol{\varepsilon}_\mathrm{r}\mu_\mathrm{r}}} \approx \frac{c}{\sqrt{\boldsymbol{\varepsilon}_\mathrm{r}}} \tag{2.4}$$

Table 1
Notation for describing electromagnetic radiation

c	Velocity of light in free space [3.0×10^8 m·s^{-1}]
$\vec{\boldsymbol{E}}$	Electric-field intensity [V·m^{-1}]
$\boldsymbol{E}_x$, $\boldsymbol{E}_y$	Components of the electric-field intensity [V·m^{-1}]
f	Frequency [Hz]
$\boldsymbol{j}$	$\sqrt{-1}$
$\boldsymbol{k}$	Complex wavenumber [rad·m^{-1}]
$\boldsymbol{n}$	Complex index of refraction [dimensionless]
n', n''	Components of the complex index of refraction [dimensionless]
t	Time [s]
$\boldsymbol{v}$	Phase velocity of electromagnetic waves in a medium [m·s^{-1}]
x, y, z	Components of a Cartesian coordinate system [m]
$\boldsymbol{\varepsilon}$	Complex permittivity of the medium [F·m^{-1}]
ε_0	Permittivity of free space [8.85×10^{-12} F·m^{-1}]
$\boldsymbol{\varepsilon}_\mathrm{r}$	Relative complex permittivity [dimensionless]
$\boldsymbol{\varepsilon}_\mathrm{r}'$, $\boldsymbol{\varepsilon}_\mathrm{r}''$	Components of the relative complex permittivity [dimensionless]
$\boldsymbol{\mu}$	Permeability of the medium [H·m^{-1}]
μ_0	Permeability of free space [$4\pi\times10^{-7}$ H·m^{-1}]
$\boldsymbol{\mu}_\mathrm{r}$	Relative permeability, which equals 1.0 for most material [dimensionless]
σ	Conductivity of the medium [S·m^{-1}]
ω	Angular frequency [rad·s^{-1}]
k_a	Attenuation coefficient [m^{-1}] for electric-field intensity
d	Skin depth [m]