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Polarized infrared emissivity of 2D sea surfaces with one surface reflection

Hongkun Li *, Nicolas Pinel, Christophe Bourlier

Lunam Université - Université de Nantes - IETR Laboratory, Polytech Nantes, Rue C. Pauc, La Chantrerie, BP 50609, 44306 Nantes Cedex 3, France

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ABSTRACT

Sea surface infrared emissivity is an important parameter in oceanic remote sensing. This article derives the infrared emissivity of two-dimensional (2D) sea surfaces with an analytical model, where one surface reflection (surface-emitted surface-reflected) is considered. Polarization is studied, and the surface slope probability density function is Gaussian and then non-Gaussian to study the skewness and the kurtosis effects. It is shown that sea surface infrared emissivity is sensitive to the zenith observation angle and the wind direction, and the skewness and the kurtosis effects are significant for grazing directions (with zenith angle > 80°). For Gaussian surfaces, surface emissivity for grazing zenith angles reaches maxima in the up-wind and down-wind directions, whereas minima are found in the cross-wind direction. After taking into account the skewness and the kurtosis effects, the surface emissivity has the largest value in the down-wind direction. The analytical results are then compared with measurements, which shows that considering one surface reflection significantly improves the agreement for large zenith angles.

1. Introduction

Sea surface infrared emissivity in the atmospheric transmission windows is an important parameter in oceanic remote sensing, e.g. for deriving the sea surface temperature. Sea surface infrared emissivity is nearly constant for observation directions near zenith, but it varies significantly with the observation angle measured from zenith (named zenith angle). In these observation directions, shadowing and surface reflections become significant, increasing the difficulty in predicting the sea surface emissivity with accuracy.

Early models of sea surface infrared emissivity derived the emissivity without considering sea surface reflections (named direct emissivity, or zero-order emissivity contribution). By contrast, the shadowing effect was usually considered. Masuda et al. (1988) calculated the unpolarized sea surface infrared emissivity by modeling the sea as a two-dimensional (2D) surface with Gaussian surface slope distribution. A normalization factor was used to estimate the shadowing effect. Instead of using the normalization factor, Yoshimori et al. (1994, 1995) took the shadowing effect into account in their emissivity model by using the Smith illumination function[1] (Smith, 1967). Freund et al. (1997) calculated the sea surface emissivity by an hemispherical ensemble average. Bourlier (2005) took a step forward by considering a non-Gaussian surface slope distribution introduced by Cox and Munk (1954), which takes the skewness and kurtosis effects into account.

However, Smith et al. (1996) reported a difference of about 0.02–0.03 between the measurements and the direct emissivity model of Masuda et al. (1988) for a zenith angle of 73.5°, because surface reflections were ignored. The model of Watts et al. (1996) and that of Wu and Smith (1997) both defined an empirical cutoff angle to calculate the surface-emitted surface-reflected emissivity (SESR, or named first-order emissivity contribution, as one reflection is considered). Because of the difficulty in defining the cutoff angle, the result has a large uncertainty. The model of Henderson et al. (2003) developed a ray-tracing Monte Carlo algorithm to calculate the sea surface emissivity with up to 10 surface reflections. This method may be a valuable reference, but it needs a long computation time. Masuda (2006) took into account the first-order emissivity contribution (SESR) by using a weighting function, which avoided defining an exact cutoff angle. More rigorously, Bourlier (2006) evaluated the first-order emissivity contribution by developing a first-order illumination function (with one reflection), which estimates the probability that a surface-emitted ray is reflected once by another point of the surface into the observation direction. The model of Masuda (2006) and that of Bourlier (2006) are analytical models, but they do not agree well with the results of the ray-tracing Monte Carlo method (Li et al., 2011b). Nalli et al. (2008) shared the idea of Masuda (2006) which used a weighting function to calculate the first-order emissivity contribution, but replaced the shadowing term used in Masuda (2006) by that of Saunders (1968). The most recent model was developed by Li et al. (2011b), in which one surface reflection was considered. They showed that the agreement with measurements is greatly improved by considering one surface reflection.

* Corresponding author. Tel.: +33 240 683 264; fax: +33 240 683 233.
E-mail address: hongkun.li@etu.univ-nantes.fr (H. Li).

[1] The illumination function was originally called “shadowing” function (Smith, 1967; Wagner, 1967). But as the word “shadowing” leads to confusion when surface reflections are considered, more recent models named it “illumination” function (Bourlier, 2006; Li et al., 2011a).

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Most of the above models do not take polarization into account, except for the models of Henderson et al. (2003) and Li et al. (2011b). It is reported that surface emissions are usually partially polarized (Shaw, 1999; Shaw & Marston, 2000) and Shaw and Marston (2000) calculated the degree of polarization (DOP) of the direct infrared emissivity of the sea surface. Li et al. (2011b) calculated the DOP of the sea surface infrared emissivity with one surface reflection, but the sea surface was considered as one-dimensional (1D), making the model less general.

In this paper, the sea surface infrared emissivity is determined, by taking both the zero- (direct) and first-order (SESR) emissivity contributions into account. The zero-order emissivity contribution is calculated following the model of Bourlier (2005), where the Smith illumination function (Smith, 1967) is used. When deriving the first-order contribution, we extend the model of Li et al. (2011b) to a two-dimensional (2D) sea surface. Polarization is taken into account and carefully dealt with, and the DOP is calculated. Moreover, the skewness and kurtosis effects are considered, following the mathematical development of the sea surface slope probability density function (PDF) given by Cox & Munk (1954) and Bourlier (2005). When deriving the sea surface infrared emissivity, the geometric optics approximation is assumed to be valid, as the infrared wavelengths are very small compared with the sea surface roughness (Li et al., 2011b).

This paper is organized as follows: in Section 2, the zero-order infrared emissivity contribution of 2D sea surfaces is calculated, with polarization taken into account, and in Section 3, the first-order emissivity contribution is derived. The numerical calculation results are shown in Section 4 and are compared with measurements.

2. Emissivity without reflection ε_0

The sea surface infrared emissivity without reflection, which is shown in Fig. 1, corresponds to the emission energy propagating directly toward the sensor situated in the observation direction (θ, ϕ), where θ is the zenith angle and ϕ is the azimuth angle measured from the up-wind direction. It is also called the zero-order emissivity contribution, as no surface reflection occurs. Models of zero-order sea surface infrared emissivity are well known (Bourlier, 2005; Freund et al., 1997; Masuda et al., 1988; Yoshimori et al., 1994, 1995). This section follows the work of Bourlier (2005) to derive the zero-order infrared emissivity contribution of 2D sea surfaces. In addition, polarization is taken into account.

2.1. Zero-order illumination function

As pointed out by several authors (Bourlier, 2005; Masuda et al., 1988; Smith, 1967), for large zenith angles θ, not all parts of the sea surface can be “seen” by the sensor, because of the surface roughness. Parts of the surface lie in shadow, as illustrated in dashed line in Fig. 1.

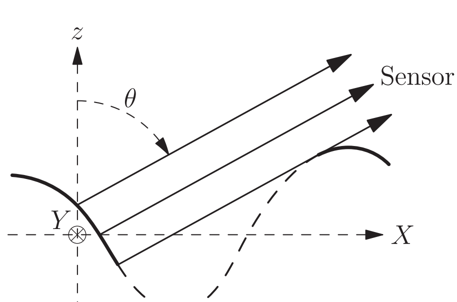

Fig. 1. Shadowing of the sea surface. The dashed part of the surface lies in the shadow for the sensor. The sensor is situated in the (θ, ϕ) direction, where ϕ is not shown. The X direction is the horizontal direction toward the sensor.

Shadowing is too significant to be ignored for large θ. As a result, a zero-order illumination function is used to estimate the probability that an arbitrary point of the sea surface, named M_0, is viewed by the sensor. Following Bourlier (2005), we employ the zero-order illumination function of Smith (1967). For more details, the reader is referred to Smith (1967) and Bourlier (2005). It is given by:

$$S_0(\theta, \gamma_X, \zeta_0) = \Upsilon(\mu - \gamma_X) F(\zeta_0)^{\Lambda(\mu)}, \tag{1}$$

where γ_X is the slope of M_0 with respect to the X direction (X is the horizontal direction toward the sensor, see Fig. 2), and ζ_0 is the height. $F(\zeta)$ is the surface height cumulative density function, given by:

$$F(\zeta) = \int_{-\infty}^{\zeta} p_\zeta(t) \mathrm{d}t, \tag{2}$$

where $p_\zeta(t)$ is the probability density function (PDF) of the surface height. The function $\Lambda(\mu)$ is related to the slope of the emission ray $\mu = cot\theta$ with respect to the X direction, given by (Bourlier, 2005, 2006; Smith, 1967):

$$\Lambda(\mu) = \frac{1}{\mu} \int_{\mu}^{+\infty} (\gamma_X - \mu) p_\gamma(\gamma_X) \mathrm{d}\gamma_X, \tag{3}$$

where $p_\gamma(\gamma_X)$ is the marginal surface slope probability density function (PDF) along the X direction. The function $\Upsilon(\mu - \gamma_X)$ is the unit step function, which equals 1 for $\gamma_X < \mu$ and 0 otherwise, meaning that all surface points with slope γ_X larger than the slope μ of the incidence ray are in shadow.

Averaging Eq. (1) over the heights ζ_0 of M_0 leads to the height-averaged zero-order illumination function, given by (Bourlier, 2005; Yoshimori et al., 1994):

$$\bar{S}_0(\theta, \gamma_X) = \frac{1}{1 + \Lambda(\mu)} \Upsilon(\mu - \gamma_X). \tag{4}$$

Eq. (4) holds for any surface height PDF. As the surface emissivity does not depend on the heights, the height-averaged illumination function is always used.

2.2. Rotation angle introduced by 2D surfaces

Fig. 2 shows the tangent plane of an arbitrary point M_0 of the sea surface with unitary normal vector $\hat{n}_0$.[2] The $\hat{x}$ direction is the up-wind direction, and the $\hat{y}$ direction is the cross-wind direction. The vector $\hat{z}$ points to the zenith. The sensor is located in the direction $\hat{s}(\theta, \phi)$, with θ being the zenith angle and ϕ being the azimuth angle measured from the up-wind direction. For convenience, a new coordinate system XY is defined by rotating anticlockwise the basis xy through an angle ϕ about the z axis, so that the sensor lies in the Xz plane. For short, xyz is the coordinate system related to the wind direction, and XYz is the one associated to the sensor direction.

The local plane of incidence[3] of M_0 is defined by the local normal to the tangent plane $\hat{n}_0$ and the observation direction $\hat{s}$. The angle χ_0 between $\hat{n}_0$ and $\hat{s}$ is the local incidence angle. The local horizontal polarization (denoted h_0, the electric vector is perpendicular to the local plane of incidence) and local vertical polarization (denoted v_0, the electric vector is parallel to the local plane of incidence) are defined. The unitary vector $\hat{u}_{v_0}$ of the v_0 polarization direction belongs to the local plane of incidence and is perpendicular to $\hat{s}$, and points upward of the tangent plane. The unitary vector $\hat{u}_{h_0}$ of the h_0 polarization direction is perpendicular to the local plane of incidence and

[2] In this paper, the symbol ˆ represents unitary vectors.

[3] This paper uses the term “plane of incidence” even though there is no incidence ray. The emission ray is treated as if it were generated by a specular reflection of an incidence ray, where the plane of incidence is defined.