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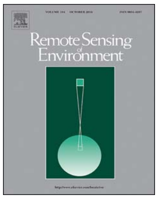

An analytical four-component directional brightness temperature model for crop and forest canopies

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ABSTRACT

Measurements of surface thermal infrared (TIR) radiance that are made to extract temperatures display strong directional anisotropy effects. Directional brightness temperature (BT) models that describe this anisotropic behavior of TIR emissions can be applied to separate component temperatures using multi-angle observations. The surface temperature differences that occur between sunlit and shaded areas and the leaf clumping phenomenon jointly affect the directional signatures of out-of-canopy directional BTs. However, these factors are not fully considered in existing directional BT models. This paper therefore extends the FR97 analytical model to 1) a four-component scene containing sunlit and shaded soil and leaves by incorporating the effective emissivity values of the sunlit and shaded parts and 2) row-planted crop and forest canopies by introducing a leaf clumping index. The proposed model was assessed using a synthetic dataset that was generated by the Thermal Radiosity-Graphics Combined Model (TRGM) under various conditions. The evaluation results indicated that the proposed model performed as well as the Scattering by Arbitrarily Inclined Leaves (4SAIL) model over continuous canopies with root mean squared errors (RMSEs) lower than 0.3 °C. Over non-continuous crops and forests, the behavior of the proposed model displayed improved agreement with the TRGM with RMSEs lower than 0.65 °C. The proposed model also displayed a robust performance over both the maize and pine canopies, which was evaluated against the directional anisotropy of measured datasets that were collected at the Huailai remote sensing test site and the Institut National de la Recherche Agronomique (INRA), respectively. From these points, the proposed model has potential for component temperature inversion and rapid assessment of TIR angular effects.

1. Introduction

Land surface temperature (LST) is a vital physical parameter of the surface-atmosphere interface that is a key input in studies of the surface energy budget and the hydrological cycle. Examples include mapping evapotranspiration and estimating longwave upwelling radiation (Bastiaanssen et al., 2000; Kustas and Norman, 1997; Norman et al., 1995). Using remote sensing techniques, LSTs can be retrieved over a range of spatial and temporal scales. A review can be found in (Li et al., 2013). However, measurements of thermal infrared (TIR) radiance that are acquired from both aircraft and satellite platforms for LST retrievals are prone to strong view-angle dependence, and this discrepancy can even reach up to 15 °C, according to many authors (Kimes, 1983; Lagouarde et al., 1995; Ren et al., 2011; Sobrino and Cuenca, 1999).

To address the angular anisotropy of these measurements, efforts are typically made to 1) improve the retrieval accuracy of LSTs and 2) separate the component temperatures. In meeting these two goals, forward models of directional brightness temperature (BT) are a vital tool for explaining the angular behaviors of surface TIR emissions. To date, many directional BT models have been proposed. These models include radiative transfer models (Francois et al., 1997; Verhoef et al., 2007), geometrical models (Kimes, 1981; Sobrino and Caselles, 1990), hybrid models (Ni et al., 1999), and computer simulation models (Gastellu-Etchegorry et al., 1996; Liu et al., 2007; Qin and Gerstl, 2000). By simplifying or improving these directional BT models, Duffour et al. (2016), Vinnikov et al. (2012) and Ren et al. (2014) proposed several simple parametric models, which seem promising for applications that involve the angular normalization of large swaths of

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satellite data. These directional BT models are likewise needed in order to better characterize and record the surface temperature state. In particular, Jia et al. (2003), Menenti et al. (2001) and Li et al. (2001) proposed practical inversion procedures for separating component temperatures using multi-angle satellite data. These component temperatures are considered essential for assessing the energy budget and particularly for determining evapotranspiration (Kustas and Norman, 2000; Norman et al., 1995). In any case, a suitable directional BT model is a prerequisite for these practical applications.

In the content of component temperature inversion, robustness is a real concern because of the various landscapes that may appear in satellite pixels. Since efforts have been concentrated on dual-angle observations from the Along Track Scanning Radiometer (ATSR) series, most previous inversion algorithms are intended to separate two components, leaves and soil (Jia et al., 2003; Li et al., 2001; Menenti et al., 2001). However, large temperature differences between the sunlit and shaded portions of a scene may exist. Four components (sunlit and shaded leaves and sunlit and shaded soil) are usually assumed to exist over vegetation canopies. A four-component directional BT model is therefore required to address the link between these components and directional BTs. In addition, producing a four-component BT model also results from the hot spot effect that occurs in satellite TIR images. Verhoef et al. (2007) extended the Scattering by Arbitrarily Inclined Leaves (SAIL) model to the thermal domain by considering the temperature difference between sunlit and shaded areas. According to (Timmermans et al., 2009), this proposed version of SAIL is a suitable tool that can be used to extract four-component temperatures. However, the 4SAIL inversion algorithm may not be suitable for forest canopies. This issue arises from the contrast between the strong leaf clumping effect that occurs within areas of sparse forest and the homogeneous canopy that is assumed by the 4SAIL model. In practical applications of satellite data, an understanding of the surface leaf clumping effect is also required. Such work has been performed in the visible and near-infrared domains (Chen, 1996; Chen et al., 2005; Fan et al., 2013; Huemmrich, 2001; Ni-Meister et al., 2010; Verhoef and Bach, 2007; Yan et al., 2012), and the effect of the vegetation clumping index on evapotranspiration has been analyzed (Anderson et al., 2005); however, few studies have assessed directional BT models. Summarizing the above discussion, the four-component assumption and the leaf clumping effect should be incorporated into a robust directional BT model for use in both forward modeling and practical inversion.

The simplicity of the FR97 model, an analytical model proposed by Francois et al. (1997), makes it very attractive for use in studies that involve component temperature inversion and rapid assessment of the impact of angular sampling. In addition, the FR97 model has proven to be reliable and to have explicit physical meaning, based on comparisons between models provided by Francois (2002) and Sobrino et al. (2005). However, the original FR97 model assumes two components. Effective emissivity values of sunlit and shaded soil have been provided by Bian et al. (2016) to enable the application of the FR97 model to a three-component (leaves and sunlit and shaded soil) temperature inversion task. Therefore, further exploring the potential application of this model to four-component scenes is well motivated. This work represents the next step in the development of the three-component FR97 model. Recently, Chen (1996) and He et al. (2012) have succeed in retrieving the leaf clumping index from satellite data. Therefore, at the same time, we aim to explore the performance of the model over row-planted crops and forest canopies after introducing the leaf clumping index.

To test the performance of the new version of the FR97 model, both synthetic and measured datasets are used. The Thermal Radiosity-Graphics Combined Model (TRGM) model was selected as a benchmark for use in data simulation. In addition, datasets collected from maize and pine canopies at the Huailai remote sensing test site and the Institut National de la Recherche Agronomique (INRA) were used to test the proposed model. The outline of this paper is as follows. In Section 2, we describe the new version of the FR97 model. We evaluate the performance of the proposed model against a reference model of TRGM under different conditions in Section 3. The proposed model is then tested using measured directional anisotropies (DA) in Section 4. The limitations of the evaluation and the new model are discussed in Section 5, and Section 6 provides a short summary of this paper.

2. The analytical FR97 model

2.1. Four-component FR97 model

The FR97 model was originally proposed based on a two-component assumption involving leaves and soil. Because the emissivity that is calculated by the FR97 model can be identified as the “R-emissivity” (Becker and Li, 1995), the three-component FR97 (TFR97) model, which includes average leaves and sunlit and shaded soil, can be expressed by directly introducing the visible proportions of sunlit and shaded soil (Bian et al., 2016). A simple description of the original and three-component FR97 models can be found in Appendix I.

In the FR97 framework, the radiance from leaves can be divided into the following subparts: 1) radiance traveling directly to the sensor, 2) radiance reflected by the soil to the sensor, and 3) radiance reflected by other leaves to the sensor. At this point, the separation coefficients between sunlit and shaded leaves cannot be calculated simply using their visible proportions. To retain a similar pattern to the original FR97 model, which displays the component effective emissivity

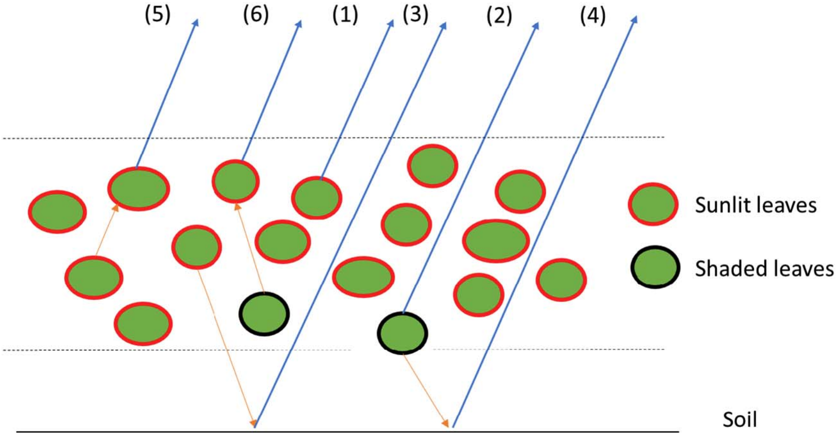

Fig. 1. Composition of leaf emissions: the radiance emitted from sunlit (1) and shaded (2) leaves travels directly to the sensor; the radiance emitted by sunlit (3) and shaded (4) leaves is reflected by the soil; the radiance emitted from sunlit (5) and shaded (6) leaves is reflected by other leaves.