ISPRS Journal of Photogrammetry and Remote Sensing 122 (2016) 30–40

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Development of an improved urban emissivity model based on sky view factor for retrieving effective emissivity and surface temperature over urban areas

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ARTICLE INFO

Article history:
Received 2 June 2016
Received in revised form 10 August 2016
Accepted 15 September 2016

Keywords:
Emissivity
Temperature
Geometry
Thermal image

ABSTRACT

This study aims to evaluate the effects of urban geometry on retrieval of emissivity and surface temperature in urban areas. An improved urban emissivity model based on sky view factor (IUEM-SVF) was further enhanced to consider all radiance contributions leaving the urban canopy, including (i) emission by all facets within an instantaneous field of view (IFOV); (ii) reflection by all facets of emission from surrounding facets; and (iii) propagation of emitted and reflected radiation with multiple reflections (scattering) within a complex 3D array of urban objects. The effective emissivity derived from IUEM-SVF was evaluated with a microscale radiative transfer and energy balance model: Temperatures of Urban Facets in 3-D (TUF-3D). IUEM-SVF performs well when urban facets have uniform emissivity and temperature; e.g., root mean square deviations (RMSD) are less than 0.005 when material emissivity is larger than 0.80 ($\varepsilon \geqslant 0.80$). However, when material emissivities are variable within the observed target, differences of effective emissivity between IUEM-SVF and TUF-3D become larger, e.g., RMSD of 0.010. When the effect of geometry is not considered and a mixed pixel emissivity is defined, the difference is even much larger (i.e. 0.02) and this difference increases with the decrease of sky view factor. Thus, the geometry effect should be considered in the determination of effective emissivity. Effective emissivity derived from IUEM-SVF was used to retrieve urban surface temperature from a nighttime ASTER thermal infrared image. Promising results were achieved in comparison with standard LST products retrieved with the Temperature and Emissivity Separation (TES) algorithm. IUEM-SVF shows promise as a means to improve the accuracy of urban surface temperature retrieval. The effect of thermal heterogeneity on the effective emissivity was also evaluated by TUF-3D, and results show that the thermal heterogeneity cannot be neglected since the RMSD between the effective emissivity based on TUF-3D and IUEM-SVF is relatively large.

1. Introduction

Land Surface Temperature (LST) obtained by remotely sensed data provides a synoptic view and an effective measure of the Surface Urban Heat Island (SUHI), by observing the temperature differences between urban surfaces and rural areas (Dousset and Gourmelon, 2003; Voogt and Oke, 2003; Hu and Brunsell, 2013). For a flat and homogenous surface, remote sensors observe surface exitance and emittance, after correction for atmospheric effects and taking into account the reflection of atmospheric emission. Surface temperature can be retrieved from the material emissivity and surface emittance through the Planck function (Sobrino et al., 2004; Sobrino et al., 2012). However, the geometry of urban areas is always complex. This results in anisotropy of satellite-observed

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http://dx.doi.org/10.1016/j.isprsjprs.2016.09.007

surface emittance, due to the complexity of urban geometry and different component temperatures within mixed pixels. The effect of different component temperatures in a mixed pixel over rural areas has been well-studied (Sobrino and Caselles, 1990; Menenti et al., 2001; Jia et al., 2003; Chen et al., 2004; Rasmussen et al., 2011; Ren et al., 2011; Guillevic et al., 2013; Ren et al., 2014; Cao et al., 2015). Other studies of directional anisotropy of surface temperature have shown that geometric effects should be considered in the retrieval of surface temperature over urban areas (Voogt and Oke, 1998; Lagouarde et al., 2004; Soux et al., 2004; Lagouarde and Irvine, 2008; Voogt, 2008; Lagouarde et al., 2010; Lagouarde et al., 2012; Duffour et al., 2016; Krayenhoff and Voogt, 2016). The aforementioned studies have examined different component effects on the radiance measured within the IFOV, but they have not studied the impacts of the complex building geometry and thermal heterogeneity on the retrieval of effective emissivity and land surface temperature in urban environments.

A few terms of thermal infrared radiometry are first defined in this study: (i) emittance, (ii) exitance, and (iii) effective emissivity (Becker and Li, 1995; Norman and Becker, 1995; Norman et al., 1995). The emittance is the radiance emitted by all horizontal surfaces and vertical facets directly. The exitance is the sum of the emittance, the radiance re-emitted after absorption and radiance reflected by the surfaces and building facets. The effective emissivity is defined as the ratio of the total exitance of a pixel to the emittance of a blackbody at the same temperature (Yang et al., 2015a). Due to the multiple scattering and reflection caused by buildings in urban environments, the exitance in built-up areas is different from surface emittance. Multiple scattering and reflection also increase the radiance absorbed and emitted by the 3D-surface within a satellite pixel (Yang et al., 2015a). The total exitance of built-up areas is thus higher than that of a flat surface with the same material and temperature. The term "exitance" is thus more appropriate than emittance and it refers to the radiance leaving the urban canopy. For satellite data with a constant IFOV or footprint, the thermal sensor measures the exitance and not only the emittance. Thus, it is not always accurate to use a material emissivity to retrieve the surface temperature directly from the exitance, and an effective emissivity should be derived. If the surface is flat, the exitance is similar to the surface emittance, which can be derived from material emissivity and the Planck function, with a small contribution owing to reflection of atmospheric emittance. The exitance at the top of the urban canopy includes both the radiance emitted and that reflected by each facet (e.g. horizontal and vertical) of the 3D environment. Thus, the exitance can be determined by the three dimensional urban geometry, component temperatures and material emissivity of surface components. The relationship between effective emissivity and geometry effect has been discussed in several studies (Sutherland and Bartholic, 1977; Harman et al., 2004; Danilina et al., 2012; Yang et al., 2015a).

In order to improve the accuracy of retrieval of urban surface temperature from the mean exitance measured by space- or airborne-sensors over a footprint (i.e., given by the IFOV), Yang et al. (2015a) parameterized the urban effective emissivity using the sky view factor (UEM-SVF). This model considers the additional radiance caused by the cavity effect and the scattered radiance from neighboring pixels and the atmosphere, however it does not include radiance scattered by the surface elements within the pixel directly reflected to the sky. In this study, the UEM-SVF method was further improved by considering all radiance contributions leaving the urban canopy: (a) emission by all facets within an IFOV; (b) reflection by all facets of radiation emitted by the surroundings; and (c) propagation of emitted and reflected radiation with multiple reflections (scattering) within the complex 3D array of urban objects. Thus the improved UEM-SVF, hereafter "IUEM-SVF", was to calculate the cavity effect on emission and reflection separately, while the UEM-SVF in Yang et al. (2015) only accounts for the cavity effect on emission. In addition, the IUEM-SVF was evaluated with a micro-scale three-dimensional (3D) radiation exchange and urban energy balance model, Temperatures of Urban Facets in 3D (TUF-3D) (Krayenhoff and Voogt, 2007). TUF-3D model can be applied to calculate an effective emissivity, which takes all radiative interactions within a scene into account during calculation at a sub-facet resolution specified by the user (Krayenhoff and Voogt, 2007). Subsequently, TUF-3D was used to evaluate the effect of thermal heterogeneity on urban effective emissivity and surface temperature retrieval.

Additionally, the IUEM-SVF was used to retrieve urban surface radiometric temperatures from the ASTER Band 13 data on December 16th, 2015. These temperatures were subsequently compared with the surface temperature product ASTER 2B03 derived from Temperature and Emissivity Separation (TES) algorithm (Gillespie et al., 1998). The ASTER TES algorithm is based on an empirical relationship between the minimum spectral emissivity (ε_{min}) and Minimum-Maximum Difference (*MMD*), established by analyzing 86 laboratory TIR emissivity spectra data (Gillespie et al., 1998). Oltra et al. (2014) analyzed the performance of the ASTER TES algorithm based on simulated data and the ε_{min} -*MMD* relationship derived from material emissivity over urban areas and results showed that the retrieved emissivity was higher than the material emissivity (Oltra et al., 2014). This is because the radiance obtained by remote sensors is affected by multiple reflections caused by geometry effect over urban areas and the actual spectral radiance observed over urban areas does not follow the empirical relationship ε_{min} -*MMD*. The limitation of the application of TES in urban surface temperature was also analyzed in this study.

2. Data

Kowloon Peninsula of Hong Kong was selected as the study area for this research (Fig. 1). A set of airborne high resolution thermal images acquired at 12:57 pm (Hong Kong noon time) on August 6th, 2013 was used to estimate differences in component temperatures. The component temperatures were derived by sampling the image data. The material of buildings was taken as concrete and cement. The mean rooftop temperature (Tr) is 328.56 K, the mean street temperature (Ts) is 316.64 K, and mean wall temperature (Tw) is 304.94 K, respectively, in a built-up area of Kowloon peninsula, at 22.85°N, 114.08°E.

The ASTER thermal radiance data on December 16th, 2015 14:36 (UTC) (Hong Kong local time is 10:36 pm) were used to retrieve urban surface temperature using the single channel method since the urban radiative transfer model can be applied in urban surface temperature retrieval using single channel method, while the ASTER 2B01 LST product was used to evaluate the derived LST from our improved effective emissivity model and single channel method. ASTER Band 13 was selected for LST retrieval since band 10 and 14 which are close to the edge of atmospheric window, are more easily affected by atmospheric effects. In addition, a degradation of sensitivity of band 12 has also been reported (Nichol et al., 2009).

High spatial resolution airborne Lidar data (Lai et al., 2012) and building GIS data covering the entire Hong Kong territories were acquired for calculating SVF. The LiDAR data and 3D building data are provided by the Hong Kong Lands Department and the Hong Kong Civil Engineering and Development Department. The method of calculating SVF on vertical facets is based on the method presented by Kanda et al. (2005); Zakšek et al. (2011) and Yang et al. (2015). Land use and land cover data e.g. woodland, grassland and impervious surface with 6 m resolution were also used. Land use and land cover data are provided by the Hong Kong Planning