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Modeling Directional Thermal Radiance Anisotropy for Urban Canopy

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Abstract**—**one of the significant factors for improving the accuracy of Land Surface Temperature (LST) retrieval is the correct understanding of the directional anisotropy for thermal radiance. In this paper, the multiple scattering effect between heterogeneous non-isothermal surfaces is described rigorously according to the concept of configuration factor, based on which a directional thermal radiance model is built, and the directional radiant character for urban canopy is analyzed. The model is applied to a simple urban canopy with row structure to simulate the change of Directional Brightness Temperature (DBT). The results show that the DBT is aggrandized because of the multiple scattering effects, whereas the change range of DBT is smoothed. The temperature difference, spatial distribution, emissivity of the components can all lead to the change of DBT. The "hot spot" phenomenon occurs when the proportion of high temperature component in the vision field came to a head. On the other hand, the "cool spot" phenomena occur when low temperature proportion came to the head. The "spot" effect disappears only when the proportion of every component keeps invariability. The model built in this paper can be used for the study of directional effect on emissivity, the LST retrieval over urban areas and the adjacency effect of thermal remote sensing pixels.

Keywords**—**Directional thermal radiance, multiple scattering, configuration factor, urban canopy, hot spot effect

I. Introduction

THE surface temperature plays an important role in the studies of urban environment. It is a key parameter for the estimation of heat fluxes, helps to determine the thermal behavior of buildings and monitor the energy exchanges that affect the comfort of city inhabitants. In order to obtain accurate urban canopy temperature from measured thermal radiance, atmospheric and emissivity effects should be corrected. These effects have been carried with several techniques since the 1970s, which were reviewed by Becker and Li[1], Qin and Karnieli[2], Dash et al.[3] and many others. However, the radiance of urban canopy also appears significant directional anisotropy. It is reported that brightness temperature differences between off-nadir and nadir could be up to 10°C[4],[5], with important hot spot effects. This phenomenon may due to the complex geometrical structure and heterogeneity of urban buildings. Hence the correct understanding of the directional anisotropy for urban canopy thermal radiance becomes one of the significant factors for improving the accuracy of surface temperature retrieval. Some of vegetation canopy directional radiance models that have been developed based on gap fractions [6]-[11], which are not directly suited to the urban area because the surface of buildings are usually solid and the gap probability is negligible . In the recent years many 3D models are developed to simulate the urban three-dimensional heterogeneity of the thermal radiance, such as SUM[12], DARTEB[13],TUF-3D[14] and OSIrIS[15], et al., and temperature distribution over urban canopies are simulated use these models[16]-[18] .

A limitation of most directional thermal radiance models is that the contributions of the multi-reflection and scattering in canopy components cannot be accounted for or analytically expressed[19], [20]. The thermal reflectance for most manmade materials is not negligible, and the temperatures of urban components are at the same levels, thermal radiance is emitted and reflected synchronously at each component, this course should be attached more importance during the modeling. We define the concept of configuration factor, and the multiple scattering effect between heterogeneous non-isothermal surfaces of urban buildings is described rigorously, based on which a directional thermal radiance model is built, and the directional radiant character for urban canopy is analyzed.

II. Definition of the Model

For a non-isothermal target, the effective radiance in a view direction could be expressed as

$$M = \sum_{i=1}^{m} Me_i a_i / \sum_{i=1}^{m} a_i, \qquad (1)$$

where M is the directional thermal radiance; Me_i and a_i is the effective radiance and projective area for component i, respectively. The component in the model for an urban target is defined as a sub-area that the surface is isothermal and Lambertian. Suppose that the atmosphere among surfaces is homogenous and without turbulence, under the condition of local energy balance, the effective radiance Me_k of unit area for component k is the sum of its own thermal radiance and the incident radiation for reflectance. The effective radiance Me_k of component k can be expressed as

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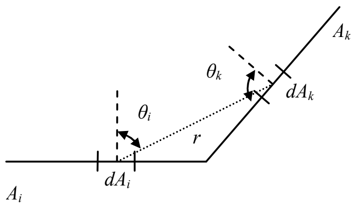

Fig. 1 Illustration of the three dimensional iso-thermal heterogeneous surfaces

$$Me_k a_k = \left[\varepsilon_k B_k + (1-\varepsilon_k) E_k\right] A_k f(\alpha_v, \varphi_v, \beta_k, \varphi_k), \quad (2)$$

where ε is the emissivity, B is the blackbody' energy flux density in W m^{-2}, A is the area of surface and $f(\alpha_v,\varphi_v,\beta_k,\varphi_k)$ is the projection function, where α_v, φ_v, β_k, φ_k is the view zenith and azimuth, and the surface gradient and direction, respectively. If $|\alpha_v - \beta_k| \geq \pi/2$, then component k is invisible, and $a_k = 0$.

E_k is the incident radiant flux (unit: W/m^2), which can be into two parts: E_k^{air} and E_k^{envi}

$$E_k = E_k^{air} + E_k^{envi}, \quad (3)$$

where E_k^{air} is the sky irradiance(normally including clouds and atmosphere radiant), which can be calculated using the empirical models which were built according to the near-surface temperature, humidity and cloud cover etc[21]-[23], it can also be calculated using simulation tools such as MODTRAN. Therefore, the method for calculating E_k^{envi} is mainly discussed in this paper.

E_k^{envi} is the radiant flux emitted and scattered from other components when going through the medium(generally is the atmosphere). Some energy is absorbed when getting across the medium and this part will increase the radiance of the medium. We define a finite micro-area dA_i on component i and a finite micro-area dA_k on component k. Suppose the length of the line-of-centers between dA_i and dA_k is r, and the included angle between r and the normal line of dA_i, dA_k, is θ_i, θ_k, respectively. The description of θ_i, θ_k and r can be shown in Fig.1. We define a configuration factor $dF_{di\text{-}dk}$, which means the proportion that energy flux project from micro-area dA_i to dA_k with respect to the total radiant emitted from dA_i, hence $dF_{di-dk} = \cos\theta_i \cos\theta_k dA_k / \pi r^2$. The irradiance from dA_i to dA_k can be computed as

$$E_{di-dk}^{envi} = \frac{[Me_i \tau(\lambda,r) + B_{air}\alpha(\lambda,r)] dF_{di-dk} dA_i}{dA_k}, \quad (4)$$

where $\tau(\lambda,r)$ is the transmisivity of the medium with wavelength λ and optical path length r, and $\alpha(\lambda,r)$ is its absorptivity; B_{air} is the near-surface atmospheric radiant flux. Hence the radiant flux from i to k can be computed as

$$\begin{aligned} A_k E_{i-k}^{envi} &= \int_{A_i}\int_{A_k} [Me_i \tau(\lambda,r) + B_{air}\alpha(\lambda,r)] dF_{di-dk} dA_i dA_k \\ &= Me_i \int_{A_i}\int_{A_k} \tau(\lambda,r) \frac{\cos\theta_i \cos\theta_k}{\pi r^2} dA_i dA_k + \\ & B_{air} \int_{A_i}\int_{A_k} \alpha(\lambda,r) \frac{\cos\theta_i \cos\theta_k}{\pi r^2} dA_i dA_k, \end{aligned} \quad (5)$$

If the absorption and radiance of the medium among components are ignored, (5) can be simplified as

$$\begin{aligned} A_k E_{i-k}^{envi} &= Me_i \int_{A_i}\int_{A_k} \frac{\cos\theta_i \cos\theta_k}{\pi r^2} dA_i dA_k \\ &= Me_i A_i F_{i-k}, \end{aligned} \quad (6)$$

where $F_{i-k} = \frac{1}{A_i}\int_{A_i}\int_{A_k} \frac{\cos\theta_i \cos\theta_k}{\pi r^2} dA_i dA_k$ is defined as the configuration factor from component i to k.

$A_k E_k^{envi}$ is the total of the radiant flux from all other components, that is

$$A_k E_k^{envi} = \sum_{i=1}^{m} A_k E_{i-k}^{envi}. \quad (7)$$

Hence the incident radiant E_k of the component k is

$$E_k = E_k^{air} + \sum_{i=1}^{m} E_{i-k}^{envi}, \quad (8)$$

The configuration factor $F_{i\text{-}k}$ has the following three characteristics: <1> symmetrical, $A_i F_{i-k} = A_k F_{k-i}$; <2> complete, to a closed space composed by s components, $\sum_{i=1}^{s} F_{k-i} = 1$; <3> additive. If i is divided into n parts, then $F_{k-i} = \sum_{j=1}^{n} F_{k-j}$. According to <1> and (5), E_k can be defined as

$$E_k = E_k^{air} + \sum_{i=1}^{m} Me_i F_{k-i}. \quad (9)$$

When (9) is substituted into (2), the effective radiance Me_k of component k can be computed as

$$Me_k = \varepsilon_k B_k + (1-\varepsilon_k)\left(E_k^{air} + \sum_{i=1}^{m} Me_i F_{k-i}\right). \quad (10)$$

The configuration factor is merely related to the shape of the component and the spatial relationship between components. For simple targets such as row structures, the configuration factor can be calculated using algebraic method, integral

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method and graphical method, etc., while for complex conditions, finite element method can be applied.

On the conditions that the shape and distribution of each components, the emissivity, geometry of solar-target-sensor, and atmospheric parameters are acquirable, (10) is a m dimensional equation set with m unknown number, which is resolvable.

III. Main Results

The model is applied to a typical urban canopy structure as shown in Fig.2. The surface is classified to 2 kinds of components: the sunlit areas and the shaded areas. Each area may be constituted with the roof, the wall or the street; hence the urban canopy components can be divided into 6 main kinds. Assuming that thermal difference between the sunlit and shaded wall is ΔT_w, and difference between the sunlit and shaded street is ΔT_s, the angle between the roof and the wall is 90°, and the solar azimuth is similar with the direction of the street and the solar zenith is α_s. The values of input coefficients are shown in Table I. The sunlit proportions are calculated from the solar position and the geometric positions of every component. The effective thermal radiance of urban canopy from the model is shown in Fig.3. It can be concluded that the component temperature is the most significant factor to directional brightness temperature (DBT) for urban canopy. The DBT changing curves is smoothed by the multi-scattering effect while be enhanced in magnitude, and the magnification extent correlates highly with the temperature differences, emissivity and the spatial structure. The "hot spot" phenomena occur when the proportion of high temperature component in the vision field came to a head. On the other hand, the "cool spot" phenomena occur when low temperature proportion came to the head. The "spot" effects disappear only when the proportion of every component keeps invariability.

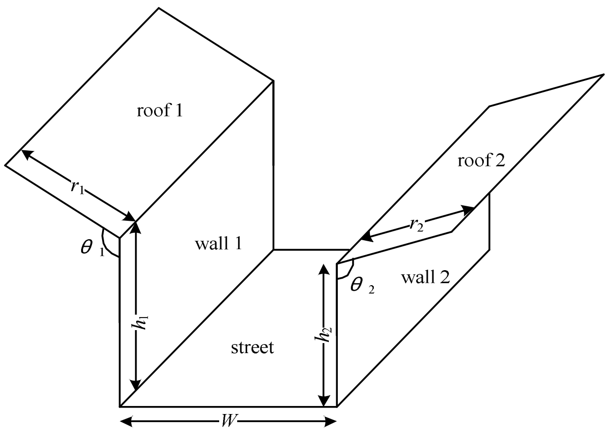

Fig. 2 The 3D structure of typical urban buildings

TABLE I
Input Parameter Values for the Model

Symbol	Description	Initial value
α_s	solar zenith	15.0 °
r	width of the roof	0.3 m
h	height of the wall	0.5 m
W	width of the street	0.7 m
ε_{roof}	roof emissivity	0.975
ε_{wall}	wall emissivity	0.96
ε_{street}	street emissivity	0.95
T_{roof_sun}	temperature of sunlit roof	310.0 K
$T_{wall\ sun}$	temperature of sunlit wall	308.0 K
T_{street_sun}	temperature of sunlit street	320.0 K
ΔT_w	temperature difference between the sunlit and shaded wall	6.0 K
ΔT_s	temperature difference between the sunlit and shaded street	15.0 K

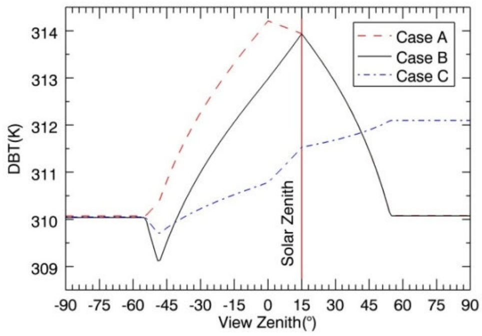

Fig. 3 The canopy directional brightness temperature in different case Case A: T_{wall_sun}=315K, ΔT_w=0K, ΔT_s=3K; Case B: T_{wall_sun} =315K, ΔT_w =7K, ΔT_s =3K; Case C: T_{wall_sun} =320K, T_{street_sun}=315K, ΔT_w =5K, ΔT_s =0K.

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