Modeling the Observed Angular Anisotropy of Land Surface Temperature in a Savanna

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***Abstract*—Several recent studies have found that retrievals of land surface temperature (LST) from remote sensing measurements depend upon the angle of observation. To understand, predict, and ultimately correct this sensitivity, simple but physically based models of LST angular anisotropy are needed. In this study, we describe and evaluate the modified geometric projection (MGP) model, a highly parameterized model of scene thermal infrared (TIR) radiance applicable to both homogeneous and discontinuous canopy environments. Based on geometric optics modeling, MPG assumes that the angular anisotropy of TIR radiance over discontinuous canopies is due strictly to the different proportions of scene endmembers (e.g., sunlit tree crowns, background shadows) visible to a sensor at different sun-view geometries. We tested MGP against DART, a rigorous three-dimensional radiative transfer model, and against field-measured data from a southern Africa savanna. For a prescribed set of canopy conditions, MGPs estimates of observable endmember fractions and scene temperatures in the solar principal plane compared well with estimates from DART. We also parameterized MGP with field-measured endmember data for an *acacia/combretum* savanna near Skukuza, South Africa. We angularly integrated the MGP-predicted radiances and compared the results with measurements of scene hemispherical exitance from a tower-based pyrgeometer. The modeled exitances exhibited the normal diurnal behavior. Model predictions generally agreed with the pyrgeometer measurements; however, model accuracy decreased as the difference in endmember temperatures increased. These tests suggest that the assumptions inherent in the MGP model do not seriously impact the accuracy of the simulated radiances. We conclude that the MGP model accurately captures the predominate thermal emission directionality resulting from discontinuous canopy structure, and could therefore be applied at continental and global scales.**

***Index Terms*—African savanna, angular effects, geometric optics (GO), land surface temperature (LST), thermal infrared (TIR), vegetation structure.**

I. Nomenclature

K_g	Background illuminated fractional cover.
K_z	Background shaded fractional cover.
K_c	Crown illuminated fractional cover.
K_t	Crown shaded fractional cover.
$X_k(\theta, \phi)$	Endmember projected fractional cover.
$\langle \varepsilon \rangle$	Ensemble emissivity.
$\langle T_{sk} \rangle$	Ensemble radiative temperature (Kelvin).
$h2$	Maximum tree crown center height (meters).
$h1$	Minimum tree crown center height (meters)
ϕ_i	Solar azimuth angle.
θ_i	Solar zenith angle.
σ	Stefan–Boltzmann constant; $5.67 \times 10^{-8} (\mathrm{W \cdot m^{-2} \cdot K^{-4}})$.
b	Tree crown average height (meters).
R	Tree crown average width (meters).
d	Tree density (tree stems per square meter).
ϕ_v	View azimuth angle.
θ_v	View zenith angle.
λ	Wavelength (micrometers).

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II. Introduction

LAND surface temperature (LST) is strongly related to the energy and hydrological state of the Earth's surface. Thus, LST data sets can be used to infer information about the surface-atmosphere heat exchange, soil moisture and vegetation hydric stress. The value in assessing these characteristics over long time periods in part led NASA's Earth Observing System (EOS) to include global LST record in its "24 EOS Measurements" [1].

Most satellite LST algorithms estimate the surface "skin" kinetic temperature based on measurements of top-of-atmosphere brightness (apparent) temperature in two thermal infrared (TIR) spectral bands [2], [3]. The algorithms typically require three key assumptions: 1) that atmospheric effects can be approximated as a function of the differential absorption in two pseudo-contiguous channels; 2) that surface emissivity can be reasonably estimated *a priori*; and 3) that surface emission is angularly isotropic (equal radiance in all directions).

The present paper concerns the validity of the last assumption: angular isotropy of surface emission. In fact, multiple studies have reported that field measurements of surface TIR radiance vary with sun-target-view geometry [4], [5], [26]. Point-scale models of TIR radiance likewise show an angular dependence [6]–[8]. A recent study [9] revealed that angular artifacts exist in moderate-resolution LST data derived from wide-field-of-view Advanced Very High Resolution Radiometer (AVHRR) observations. Unfortunately, the "noise" introduced by angular effects in satellite LST data can affect derived products and modeling results. For example, a 0.5 K LST error can lead to a 10% error in sensible heat flux [10], and 1–3 K errors can lead to surface flux errors of up to 100 W/m^2

[11]. Clearly, understanding and ultimately correcting the angular effects could significantly improve the accuracy and utility of LST data sets.

The sensitivity of LST measurements to observation angle arises from the combined effects of angularly anisotropic surface emissivity at the microscopic scale, and the different proportions of scene components (hereafter referred to as "endmembers") observed by a sensor under different sun-view geometries at coarser scales. Both effects may be characterized with physically based computer models such as geometric projection models and radiative transfer models. Geometric projection models [6], [12], [13] represent tree crowns as opaque solids (no within crown gap consideration), and do not simulate the radiative transfer within the canopy. If a scene's endmembers include the sunlit and shaded areas of crown and soil or other surface components, these models can estimate the fraction of each surface endmember visible from a given direction. The TIR radiance of the scene can then be estimated as the sum of endmembers radiances multiplied by their respective projected fractions.

Thermal radiative transfer models [4], [7], [8], [26] provide a more rigorous approach to radiance calculations. Specifically, these models simulate the propagation and the interaction of radiation within and between a canopy, soil, and the surrounding atmosphere. The canopy is represented as a set of infinitesimal plane elements (leaves) statistically distributed into homogeneous horizontal layers [14]. The radiances exiting the canopy top are calculated by integrating the radiative contributions of all layers. Multiple scattering within the canopy is included. The realism of these models leads to their need for many input parameters, including temperature distribution, and leaf density and angle distribution within the canopy. Recent TIR models such as the discrete anisotropic radiative transfer (DART) model [14] simulate the radiance field of discontinuous or clumped canopies, and fully account for the three-dimensionality of the vegetation structure.

Our goal in this study was to develop and test a TIR radiance model that could be used to predict, interpret and eventually correct directional effects in satellite LST data sets. For these applications, we sought a model that:

- could accurately simulate directional thermal radiance from discontinuous canopies;
- was based on relatively few input parameters that could be independently estimated;
- was computationally fast such that it could be systematically applied to long time series of global data.

These criteria implied that a model based on geometric projection and the linearly weighted radiance concept [5] would be most satisfactory. We therefore developed the modified geometric projection (MGP) model based on the well-used geometric optics (GO) model [15]. The MGP model predicts the ensemble temperature in a given direction as a function of the input vegetation structure and endmember temperatures. It does not predict endmember temperatures. Endmember emissivities are assumed to be isotropic; however, scene emissivity varies with angle since the endmember composition varies with angle. The MGP model accounts for the three-dimensional scene structure and benefits from some characteristics of the radiative transfer models, such as the consideration for within canopy gaps.

In this paper, we demonstrate the validity and viability of the MGP model through comparisons with both field data and a state-of-the-art radiative transfer model. Specifically, we considered the MGP accuracy over structurally complex African savannas using new data sets collected as part of the SAFARI 2000 initiative [16]. The sparse distribution of leaves in savanna tree crowns, as well as the sparse distribution of tree crowns over savanna landscapes, ensures a challenging environment for model evaluation.

VI. Discussion and Conclusion

In this study, we described and tested the MGP model, a highly parameterized model of scene thermal radiance based on geometric optics. We assumed here that all thermal infrared angular variability in a savanna-like system was due strictly to the different proportions of scene endmembers visible to a sensor from different angles. We term these proportions *projected endmember fractions*. In modeling the thermal radiance, we further assumed that all visible members of a single endmember class are isothermal and fixed to the same temperature.

We studied the behavior of the projected fractions and the resultant scene temperature under different solar geometries and different observation angles, and generally found that for the projected fraction approach, thermal signal saturation (at which point a canopy behaves as a medium of semi-infinite depth) for this particular scenario occurs at a low LAI (<2) compared to some solar reflective wavelengths.

We compared the modeled fractions and scene temperatures to similar parameters estimated with a radiative transfer model (DART), and found very good agreement for different sun-view geometries. This suggests that the various assumptions inherent in the MGP model do not seriously impact the accuracy of the modeled radiances for typical savanna conditions. However, the model is less accurate under low tree LAI conditions.

Finally, we angularly integrated the modeled radiances for the Skukuza field site using field-measured endmember temperatures and canopy structural information. The modeled scene exitances demonstrated the correct behavior over the diurnal cycle, and generally agreed well with scene exitance measurements from a tower-based pyrgeometer. Better agreement was found between modeled and measured data for the dry season than for the wet season. We suggest that high variability in soil moisture conditions over the area in the wet season led to lack of representativeness for our point measurements. In general, the MGP model accuracy decreases as the endmember temperatures differences increase. This occurs predominately for very clear days. The endmember temperatures tend to converge as cloudy conditions increase. This comparison does not validate thermal radiances themselves since the angular integration step may mask radiance errors.