

Directional Effect on Change of Spatial Scale Over Heterogeneous Surface in Thermal Infrared Remote Sensing

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ABSTRACT

The issue of deriving cross-scale aggregation rules has been heavily investigated during the past two decades. The widely used approach consists of formulating grid-scale surface fluxes using the same equations that govern the patch-scale behavior but whose arguments are the aggregate expressions of those at the patch-scale (Becker,¹ Chehbouni²). Such approach has been used in the past derive area-averaged or effective radiative surface temperature as it might be observed using low spatial resolution satellite data. The problem however is such satellite data exhibits large directional effect and none the past studies have addressed this issue.

The present work tackles this issue of the combined effects of surface heterogeneity and view angle variations on surface temperature measurements. The directional effects are modeled on surfaces having a known heterogeneity. Then, the angular properties of local surfaces, assumed homogeneous, are calculated according a multiple scattering model. By applying the principle of aggregation, the equivalent angular radiance of the whole heterogeneous scene is then defined. This made it possible to show that this radiance is particularly sensitive to the directional effects, in particular when the spatial variation of surface temperature is significant and when there is a vegetation component in the heterogeneous land surface. The structure of the vegetation component is also a significant factor of directional effect on equivalent angular radiance.

Keywords: Directional effect, Change of Scale, Heterogeneity, Directional Surface Temperature, Infrared Radiometry

1. INTRODUCTION

Land surface temperature is a key variable since it results from the equilibrium of the surface energy balance. As a result, remote sensing of surface temperature has been largely used to monitor temporal variability of surface fluxes across a wide range of spatial scales. However, most of the previous investigations - if not all - ignored directional effects on surface temperature measurements despite experimental and theoretical evidences of the importance of such effects (Chehbouni³). Additionally, the magnitude of the directional effect is also affected by the nature and the spatial structure of the observed surface.

The objective of this study is to investigate the combined effects of surface heterogeneity and view angle variations on surface temperature measurements.

2. MODELING OF DIRECTIONAL RADIANCE OF A HETEROGENEOUS SURFACE

2.1. Principle

Becker *and al*¹ proposed an aggregation approach to obtain the equivalent expressions of thermo-optical data for a heterogeneous surface. Let us consider a large area and assume that it contains N different homogeneous

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elements, each element (i) being characterized by its surface thermo-optical parameter (i.e. temperature and emissivity). This parameter is defined from the radiance L_i , the spectral radiance observed at ground level with appropriate approximations (Becker⁴):

$$L_i(\theta; \lambda) = \varepsilon_i(\theta; \lambda) L^{CN}(T_{s_i}; \lambda) + (1 - \varepsilon_i(\theta; \lambda)) L^{atm\downarrow}(\lambda) \quad (1)$$

$\varepsilon_i(\theta; \lambda)$ is the directional spectral emissivity of the i element, T_{s_i} is the surface radiometric temperature of this element, $L^{CN}(T_s; \lambda)$ is the radiance Planck function and $L^{atm\downarrow}(\lambda)$ is the downwelling hemispheric spectral atmospheric radiance (which is supposed to be the same for each element). For the whole area, the overall quantity $\langle L \rangle$ may be described as a function of the N quantities L_i . Let $d\omega_i$ be a small solid angle from which a homogeneous area within the surface is observed at ground level by a radiometer having a field of view Ω ($\Omega = \sum_{i=1}^N d\omega_i$). The incident $\langle L(\theta; \lambda) \rangle$ radiance at radiometer level can be written as:

$$\langle L(\theta; \lambda) \rangle = \sum_{i=1}^N L_i(\theta; \lambda) \frac{d\omega_i}{\Omega} = \sum_{i=1}^N L_i(\theta; \lambda) S_i(\theta) \quad (2)$$

where S_i is the normalized fractional area of the homogeneous sub-surface i . N is the number of homogeneous areas that compose the heterogeneous surface. In the case of a viewing angle variation, it is necessary to introduce an angular variation of the solid angle. When the observation angle varies, the solid angle, under which heterogeneous surface as well as the homogeneous areas are seen, is modified. From (2), it is possible to determine the equivalent thermo-optical data of the heterogeneous surface. While constraining the radiance models so that measurement are identical for any given spatial scale, one obtains the following expression:

$$\langle L(\theta; \lambda) \rangle = \langle \varepsilon(\theta; \lambda) \rangle L^{CN}(\langle T_s(\theta; \lambda) \rangle, \lambda) + (1 - \langle \varepsilon(\theta; \lambda) \rangle) L^{atm\downarrow}(\lambda) \quad (3)$$

where $\langle \varepsilon(\theta; \lambda) \rangle$ and $\langle T_s(\theta; \lambda) \rangle$ is the equivalent thermo-optical parameters of the heterogeneous surface. By identification, one obtains the thermo-optical parameters of heterogeneous surface:

$$\langle \varepsilon(\theta; \lambda) \rangle = \sum_i S_i(\theta) \varepsilon(\theta; \lambda)_i \quad (4)$$

$$\langle T_s(\theta; \lambda) \rangle = L^{CN-1} \left[\frac{\sum_i S_i(\theta) \varepsilon_i(\theta; \lambda) L^{CN}(T_{s_i}, \lambda)}{\langle \varepsilon(\theta; \lambda) \rangle} \right] \quad (5)$$

In this study, the surface temperature will not be obtained with this last expression, but directly by inverting (3), using (4) for the expression of equivalent emissivity:

$$\langle T_s(\theta; \lambda) \rangle = L^{CN-1} \left[\frac{\langle L(\theta; \lambda) \rangle - (1 - \langle \varepsilon(\theta; \lambda) \rangle) L^{atm\downarrow}(\lambda)}{\langle \varepsilon(\theta; \lambda) \rangle} \right] \quad (6)$$

The objective of the study presented here consists of analyzing the surface heterogeneity effects (related on T_{s_i} and $\varepsilon_i(\theta; \lambda)$) on the directional radiance of heterogeneous surface. For that, we will place ourselves in simple cases of surface heterogeneities. Here, heterogeneous surface will be made of two homogeneous areas. Using (2), it is possible to calculate directional radiance if the $L_i(\theta; \lambda)$ radiances of homogeneous areas are known. The equivalent surface temperature is then obtained using (6).

To compute the radiances of an homogeneous zone, one seeks to use a generic model of surface radiometric budget equation, which takes into account vegetation effects.

2.2. Modeling of Homogeneous Surface

An analytical model made up of two parts is used (François⁵) : a statistical characterization of vegetation and its components and a model of radiative transfer in canopy.

- The vegetation part is characterized by its thermo-optical properties: the spectral angular emissivity $\varepsilon_v(\theta; \lambda)$ of leaves and its surface temperature T_v , then by a statistical distribution of vegetal elements in the cover. The vegetation fraction cover is modeled using the contribution coefficient p_v .

- The bare soil part is characterized by its thermo-optical properties: the spectral angular emissivity $\varepsilon_s(\theta; \lambda)$ of ground and its surface temperature T_s . The contribution coefficient corresponding to the ground is the soil fraction cover $p_s = 1 - p_v$.

For a given vegetated homogeneous unit area, the measured radiance at sensor level (the sensor is supposed to be immediately above the target, i.e. pure upwelling atmospheric effects are neglected) is expressed as:

$$L(\theta; \lambda) = \underbrace{\tau_c(\theta; \lambda) \varepsilon_s(\theta; \lambda) L^{CN}(T_s; \lambda)}_{\text{bare soil part}} + \underbrace{\omega_c(\theta; \lambda) L^{CN}(T_v; \lambda)}_{\text{vegetation part}} + \underbrace{(1 - \varepsilon_c(\theta; \lambda)) L^{atm\downarrow}(\lambda)}_{\text{atmospheric part}} \quad (7)$$

Here, $\tau_c(\theta; \lambda)$ is the upward directional canopy transmittance, $\omega_c(\theta; \lambda)$ is the fraction of radiation that is emitted upward by the vegetation in the direction θ , and $\varepsilon_c(\theta; \lambda)$ is the directional canopy emissivity. The coefficient $\tau_c(\theta; \lambda)$, $\omega_c(\theta; \lambda)$ and $\varepsilon_c(\theta; \lambda)$ have a different expression, according to the complexity of the approach that has been chosen. To be more accurate, these coefficients should include the multiple scattering between soil and vegetation. Without vegetation, this model allows to compute the case of bare soil. These computed radiances from each homogeneous zone are aggregated to obtain the equivalent radiance of the whole surface landscape at a lower spatial resolution.

The directional canopy radiance is obtained by summing the relative contributions of vegetation, ground and atmosphere layers. These contributions are calculated using the directional gap frequency through the vegetation. The latter depends on the canopy structure and foliage amount (Plant Area Index (PAI), the sum of leaf and stem area index) in each vegetation layer, and can be expressed as Beer law (Chehbouni³):

$$b(\theta) = \exp \left[-\Lambda(\theta) \frac{G(\theta)}{\cos\theta} PAI \right] \quad (8)$$

where the ration $G(\theta) / \cos\theta$ represents the directional extinction coefficient for a canopy with a random leaf dispersion, and $\Lambda(\theta)$ is the directional leaf dispersion parameter which accounts for the departure from a canopy with a random leaf distribution (e.g. canopy clumping). For a given θ direction, $b(\theta)$ is the amount of incoming radiation that goes through the canopy (either from the sky to the ground, or from the ground to the sky) in the θ direction, and $1 - b(\theta)$ is the proportion of the radiation that is intercepted by the leaves. $G(\theta)$ is the fraction of foliage projected in the θ direction (Nouvellon⁶).

To obtain a correct and effective model, a new factor of canopy characterization was introduced (François⁷): the hemispherical shielding factor σ_f (linked to the hemispherical transmittance):

$$\sigma_f = 1 - \frac{1}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} b(\theta) d\theta \quad (9)$$

σ_f represents the mean hemispheric amount of leaves seen from the sky.

Then, using the above characterization of the canopy, the 3 coefficients $\tau_c(\theta; \lambda)$, $\omega_c(\theta; \lambda)$ and $\varepsilon_c(\theta; \lambda)$ are expressed using the multiple scattering model developed by François⁷:

$$\tau_c(\theta; \lambda) = \frac{b(\theta)}{1 - \sigma_f (1 - \varepsilon_s(\theta; \lambda)) (1 - \varepsilon_v(\theta; \lambda))} \quad (10)$$

$$\omega_c(\theta; \lambda) = 1 - (1 - b(\theta))(1 - \varepsilon_v(\theta; \lambda)) - b(\theta) \frac{(1 - \sigma_f)(1 - \varepsilon_s(\theta; \lambda)) + \varepsilon_s(\theta; \lambda)}{1 - \sigma_f(1 - \varepsilon_s(\theta; \lambda))(1 - \varepsilon_v(\theta; \lambda))} \quad (11)$$

$$\varepsilon_c(\theta; \lambda) = 1 - (1 - b(\theta))(1 - \varepsilon_v(\theta; \lambda)) - b(\theta) \frac{(1 - \sigma_f)(1 - \varepsilon_s(\theta; \lambda))}{1 - \sigma_f(1 - \varepsilon_s(\theta; \lambda))(1 - \varepsilon_v(\theta; \lambda))} \quad (12)$$

Bare soil case When there is no vegetation, the transmission to the top of ground must be equal to 1, the reflection must be 0 and finally, the emissivity $\varepsilon_c(\theta; \lambda)$ must be reduced to that of bare soil. For a bare soil, $PAI = 0$, $b(\theta) = 1$ and $\sigma_f = 0$, thus:

$$\tau_c(\theta; \lambda) = 1 \quad \omega_c(\theta; \lambda) = 0 \quad \varepsilon_c(\theta; \lambda) = \varepsilon_s(\theta; \lambda) \quad (13)$$

and the radiance (7) for a bare soil is:

$$L(\theta; \lambda) = \varepsilon_s(\theta; \lambda) L^{CN}(T_s; \lambda) + (1 - \varepsilon_s(\theta; \lambda)) L_\lambda^{atm\downarrow}(\theta; \lambda) \quad (14)$$

The classical expression for bare soil is thus recovered.

2.3. Modeling of viewing geometry

In the case of view angle variation over a heterogeneous land surface, it is necessary to introduce an angular variation on the solid angle. Actually, as illustrated on figure 1, when the observation angle varies, the solid angle, under which heterogeneous surface as well as the homogeneous areas are seen, is modified. In this study, we will suppose that the size of the viewing area do not depend on the viewing geometry. In other world, the viewing area size always remains constant whatever the observation angle, which imposes an angular variation of the solid angle ratio (see figure 1).

To model the directional effects, it is thus necessary to define an observation geometry of the scene. Here, one observes a same heterogeneous surface made up of two homogeneous elements (area 1 and 2) of identical S surface. The observation is done on constant surface. The angular variation is done along a circle of radius d and for different zenith angle θ . The data d , θ and S are considered known and characterize completely the geometric observation condition. The values of d and S will be respectively fixed to 10 m and 2 m.

As shown in figure 1, the θ_1 and θ_2 angles are expressed as:

$$\begin{aligned} \theta_1 &= \arctan\left(\tan\theta + \frac{S}{2d \cos\theta}\right) \\ \theta_2 &= \arctan\left(\tan\theta - \frac{S}{2d \cos\theta}\right) \end{aligned} \quad (15)$$

The solid angles under which are seen each homogeneous surface can be written:

$$d\omega_i = \frac{dS_i \cos\theta_i}{d_i^2} = \frac{dS \cos\theta_i}{d_i^2} \quad i = 1, 2 \quad (16)$$

The sum of the solid angle ratios must fulfil $\sum \frac{d\omega_i}{\Omega} = \sum S(\theta_i) = \sum S_i(\theta) = 1$. Which leads to:

$$S_i(\theta) = \frac{d\omega_i}{\Omega} = \frac{\cos^3\theta_i}{\cos^3\theta_1 + \cos^3\theta_2} \quad i = 1, 2 \quad (17)$$

The heterogeneity of an observed surface varies thus with the solid angle ratio and this variation must be well taken into account. In this case, the equivalent angular radiance of heterogeneous surface is obtained by:

$$\langle L(\theta, \lambda) \rangle = \sum_{i=1}^2 L_i(\theta, \lambda) S_i(\theta) \quad (18)$$

where $L_i(\theta, \lambda)$ is computed with (7) for each homogeneous area.

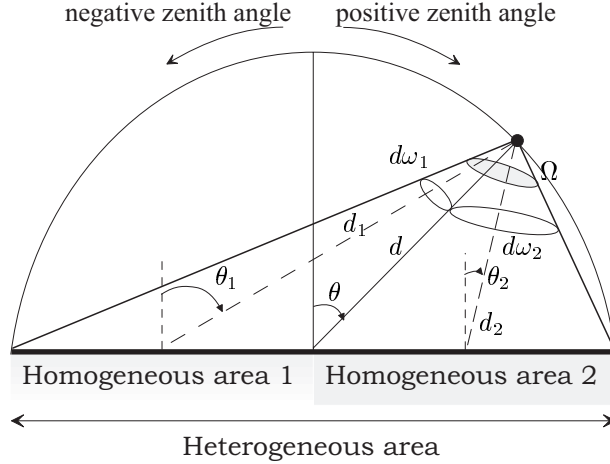


Figure 1. Angular variation of solid angle over a heterogeneous surface

3. EFFECT OF SURFACE HETEROGENEITY ON DIRECTIONAL RADIANCE

The objective of this study is primarily to identify and quantify the effects of surface heterogeneities on the directional radiance. To simplify this study and also for a practical reason, calculated radiances will be integrated on the 8-12 μm thermal infrared band. There is a practical reason to that: the majority of the ground infrared sensors operate in this band and the measurements of these sensors are also integrated. Moreover, a measurement campaign is currently underway and uses infrared cameras whose spectral band is 8-12 μm .

In the following, all the results are plotted with the same layout. The X-axis represents the view angle (relative to nadir, see figure 1). The sign convention of zenith angle is defined on figure 1. The Y-axis is the difference between inclined and vertical measurements, respectively in equivalent radiance or equivalent surface temperature. For each simulation, the value of $L^{atm\downarrow}(8-12\ \mu\text{m})$ will be taken with $3.10^{-4}\ \text{W.m}^{-2}.\text{sr}^{-1}$. It corresponds to an average value measured in summer on the ONERA PIRRENE* site near Toulouse(France).

In thermal infrared remote sensing, there are three types of effects on the equivalent signal of a heterogeneous surface: (i) effects due to the spatial variability of the surface temperature, (ii) effects due to the spatial and angular variation of the surface emissivity and, (iii) effects due to solid angle variation. In the case of a vegetated surface, the first two effects are more difficult to analyze. Actually, it will be necessary to add the effects of the spatial distribution of leaves, related in particular to the *PAI*. In this study, we will only take into account three effects previously described and we will consider vegetation as an additional effect. So for each simulation, the value of *PAI* will be 2.5.

3.1. Effect of vegetation

In a first step, two heterogeneous scenes are simulated. The first one will consist of two different bare soils, the second one will be made of the same soils but one is covered with a vegetation layer. The simulated bare soil is considered as opaque and lambertian, therefore $\varepsilon_i(\theta) = \varepsilon_i$.

The simulated cases are given in table 1. It should be noted that here, in the case of the two bare soils, only the surface temperature variability induces heterogeneity. It is the simplest case of heterogeneous surface. The presence of vegetation involves a more complex heterogeneity, with the introduction of the directional canopy emissivity $\varepsilon_c(\theta)$, which is different from that of the bare soil. Moreover, the canopy temperature also has an angular variation due to the distribution of the leaves in the canopy. Figure 2 shows equivalent directional radiances for two heterogeneous surfaces, as well as the equivalent surface temperatures.

*<http://www.onecert.fr/pirrene>

Table 1. Thermo-optical characteristics of the two heterogeneous surfaces

heterogeneous surface cases	part 1 (bare soil or vegetation)				part 2 : bare soil	
	T_{ground} °C	$T_{vegetation}$ °C	ε_{ground}	$\varepsilon_{vegetation}$	T_s °C	ε_s
1 (bare soil/bare soil)	35	-	0.94	-	40	0.94
2 (vegetation/bare soil)	35	25	0.94	0.98	35	0.94

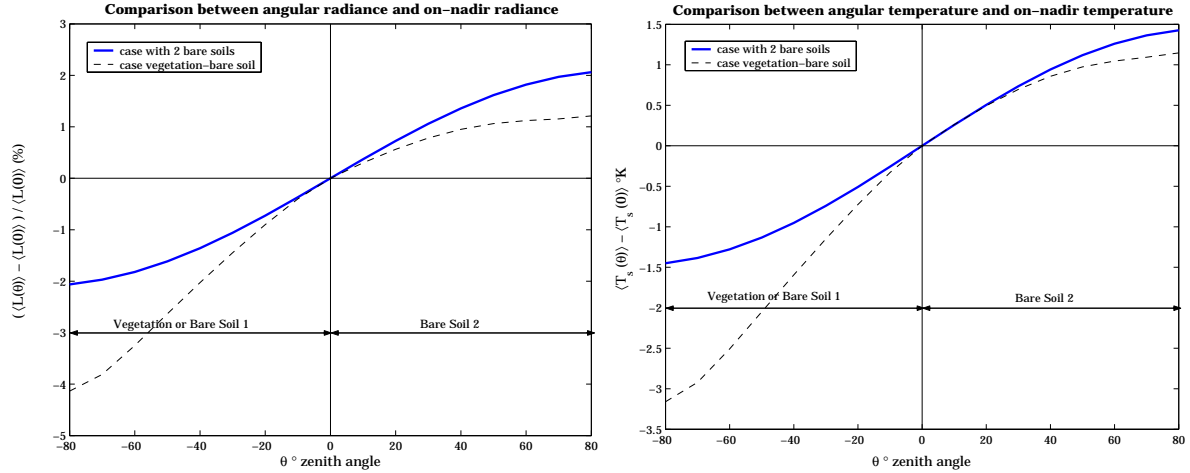


Figure 2. Comparison between heterogeneous surface with and without vegetation.

In the case of two bare soils, the angular variation is only due to $S_i(\theta)$ and to the amount of signal from each homogeneous surface on whole surface. It is only a weighting effect related to the scene geometry. The obtained variations (2% in radiance and 1.5 K in temperature at the maximum for $\theta = 80^\circ$) remain weak and correspond well to the values expected in the case of two bare soils (Lagouarde⁸).

The effects are much more significant in the presence of vegetation. A significant asymmetry appears. Along the observation axis, the value of the difference between angular and nadir measurements can be very different. For example, for a 60° zenith angle, on the vegetation side (towards the negative angles), the variation is of 3% (2.5 K) whereas it is 1% (1K) on the bare soil side (positive angle). The presence of vegetation in the heterogeneous surface thus introduces an asymmetry in the angular variation of equivalent radiance. This is due to the effect of the weighting by $S_i(\theta)$ but also by the angular variation of the radiance of the homogeneous vegetated surface. It is thus important to consider the presence of vegetation in the heterogeneous surface. According to the observation axis, a significant difference is observed which increases with the zenith angle.

In the case presented here, the ground temperature under the vegetation (homogeneous area 1) is the same one that of the bare soil (homogeneous area 2). This case is not very realistic and it can easily be assumed that, in the real world, bare soil temperature will be higher than that of the ground under the vegetation. Moreover, here, the surface heterogeneity effect acts only on the surface temperature. It is interesting to see the influence of the temperature spatial variability on equivalent directional radiance.

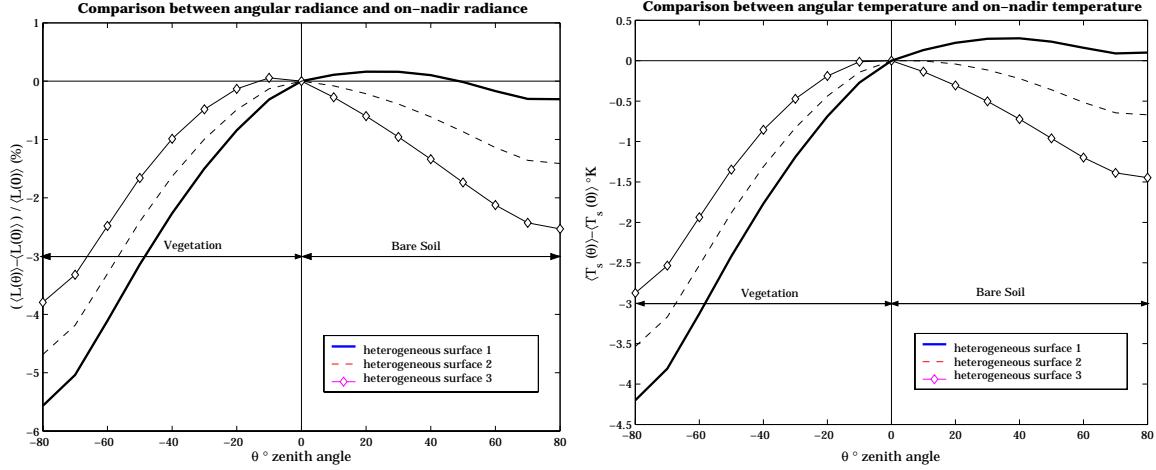
3.2. Effect of temperature heterogeneity

To estimate the effects of temperature spatial variability on the signal, three heterogeneous surfaces (bare soil) will be modeled with three different surface temperature (table 2). Here also, simulated bare soil will be considered opaque and lambertian. Equivalent directional radiances for three heterogeneous surfaces are plotted on Figure 3, as well as the equivalent surface temperatures.

For the first case, surface heterogeneity is less significant than that of case 3. Identically, the asymmetry is weaker for case 1 than for case 3. For example, the asymmetry, expressed $\delta T = |\langle T(\theta) \rangle - \langle T(-\theta) \rangle|$ is of 0.7K for surface 1, 2K for surface 2 and 3.3K for surface 3 for a 60° zenith angle. This is due to the effect of weighting

Table 2. Thermo-optical characteristics of the three heterogeneous surfaces

heterogeneous surface cases	part 1 : vegetation				part 2 : bare soil	
	T_{ground} °C	$T_{vegetation}$ °C	ε_{ground}	$\varepsilon_{vegetation}$	T_s °C	ε_s
1	35	25	0.94	0.98	40	0.94
2	35	25	0.94	0.98	35	0.94
3	35	25	0.94	0.98	30	0.94

**Figure 3.** Effect of surface temperature heterogeneities on directional surface parameters.

by $S_i(\theta)$. For positive zenith angle, the sensor views mainly vegetation, whereas for the positive zenith angles, it mainly views bare soil. The share of each type of surface in the total signal varies with view angle and involves this asymmetrical behavior. We can conclude that temperature heterogeneity plays a significant role in the angular variation of equivalent radiance. It increases the asymmetrical character of the latter.

For case 1, the maximum bias between on-nadir measurement and angular measurement are less than 4% (less than 3K) for a viewing angle of -80° . With a 60° angle, this variation is range form 1.5 to 2K. These results are in agreement with those obtained by Lagouarde⁸ and Kimes⁹ in the case of corn, case approaching well the simulation of row crop canopies presented here. For surface 2, the maximum bias between on-nadir measurement and angular measurement are less than 5% (3.5K) for an angle of -80° . With 60° , this variation is of 0.5K to 2.5K. For surface 3, the maximum bias between on-nadir measurement and angular measurement are less than 6% (more than with 4K) for an angle of -80° . With a 60° angle, this variation is range form 0.5K to 4.5K. Temperature heterogeneity clearly increases the variations obtained on the equivalent data.

In conclusion, the spatial variability of surface temperature plays a significant role on the directional radiance. It introduces an asymmetrical behavior that increases with heterogeneity. Moreover, the resulting variations increase with this variability. This is a source of significant directional effects. The knowledge of the spatial variability of surface temperature seems thus essential for apprehending well the directional effects on heterogeneous surfaces.

3.3. Effect of emissivity heterogeneities

Up to now, emissivities ε_i were identical for all simulations. It was set to 0.94 and 0.98 for respectively bare soil and vegetation. To evaluate the effect of ε_i on the equivalent radiance, four heterogeneous surfaces will be simulated, each having a lambertian behavior. Only bare soil emissivity will vary.

3.3.1. Lambertian bare soil assumption

The thermo-optical parameters of the four soils simulated here are given in table 3. The bare soil emissivity varies from 0.85 to 0.99. This range of values corresponds to that of terrestrial materials (Salisbury¹⁰) in the

8-12 μm atmospheric window. It should be noted that in the four cases presented, the ε_c emissivity of vegetated part, is close to 0.98. Surface 4 is thus the least heterogeneous in terms of emissivity but the most emissive (emissivity close to 1). The equivalent directional radiances for four heterogeneous surfaces are plotted on Figure 4, as well as the equivalent surface temperatures.

Table 3. Thermo-optical characteristics of the four heterogeneous surfaces

heterogeneous surface cases	part 1 : vegetation				part 2 : bare soil	
	$T_{ground} \text{ } ^\circ C$	$T_{vegetation} \text{ } ^\circ C$	ε_{ground}	$\varepsilon_{vegetation}$	$T_s \text{ } ^\circ C$	ε_s
1	30	25	0.94	0.98	35	0.85
2	30	25	0.94	0.98	35	0.90
3	30	25	0.94	0.98	35	0.94
4	30	25	0.94	0.98	35	0.99

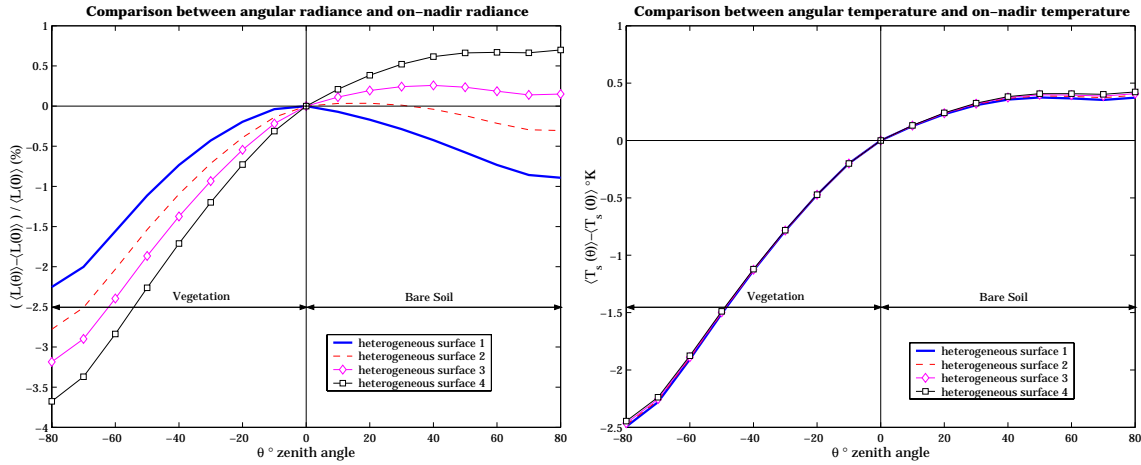


Figure 4. Effect of surface emissivity heterogeneities on directional surface parameters.

First, it is clear that emissivity heterogeneity plays a significant role on the radiance level. It is not the case for the level of the equivalent surface temperature where no effect between the different simulated cases is visible. This is due to the fact that the various emissivity variations are neglected when the radiative budget equation is reversed. Case 1 seems to be the one giving the weakest asymmetry. However, this surface is the most heterogeneous. Similarly, the variations obtained for surface 1 are the weakest. Conversely, surface 4, the most homogeneous, gives the most significant asymmetry. This feature can be explained simply. In the case of surface 1, the bare soil is much less emissive than the vegetation part. Thus, in the total signal of heterogeneous surface, it is the radiation emanating from the vegetation which plays the major role. In the case of surface 4, the bare soil is very emissive (0.99). As the surface temperature of bare soil is much higher than that of vegetation (here $35^\circ C$), the bare soil impacts more on the equivalent radiance. Once again, this is due to the weighting of $S_i(\theta)$. Here, the observed variations are primarily due to the difference in temperature between the two homogeneous zones and, the heterogeneity in emissivity thus acts on the difference in radiance between the two areas. In fact, heterogeneity in emissivity acts on the emissive character of the homogeneous components of the global surface, and thus, on the spatial variability of radiances $L_i(\theta, \lambda)$.

Up to now, the bare soils were considered lambertian. This assumption is not valid in the case of terrestrial materials (Lagouarde⁸). The following paragraph will investigate the impact of the directional emissivity.

3.3.2. No lambertian bare soil assumption

Only two cases will be modeled here: one with a lambertian bare soil part and the second with an angular emissivity. For each heterogeneous surface, the vegetation part will be the same. The thermo-optical parameters

of the two simulated surfaces are described in table 4 and the angular emissivity data is represented on figure 5 (Labeled¹¹). In fact, these data correspond to measurement of relative emissivity, i.e. $\frac{\varepsilon_s(\theta)}{\varepsilon_s(0)}$. It will be considered as representative of natural terrestrial materials. Figure 6 shows equivalent directional radiances for two heterogeneous surfaces, as well as the equivalent surface temperatures.

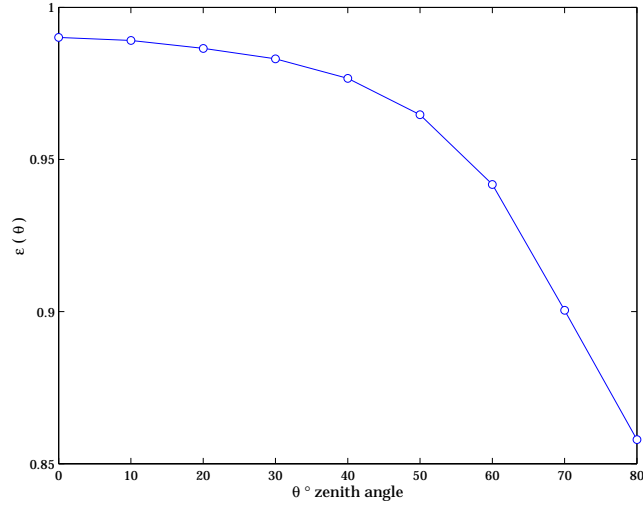


Figure 5. $\varepsilon_s(\theta)$ angular emissivity for LEHM bare soil (Labeled¹¹).

Table 4. Thermo-optical characteristics of the two heterogeneous surfaces

heterogeneous surface cases	part 1 : vegetation				part 2 : bare soil	
	$T_{ground} \text{ } ^\circ C$	$T_{vegetation} \text{ } ^\circ C$	ε_{ground}	$\varepsilon_{vegetation}$	$T_s \text{ } ^\circ C$	ε_s
1	30	25	0.94	0.98	35	0.95
2	30	25	0.94	0.98	35	$\varepsilon_s(\theta)$

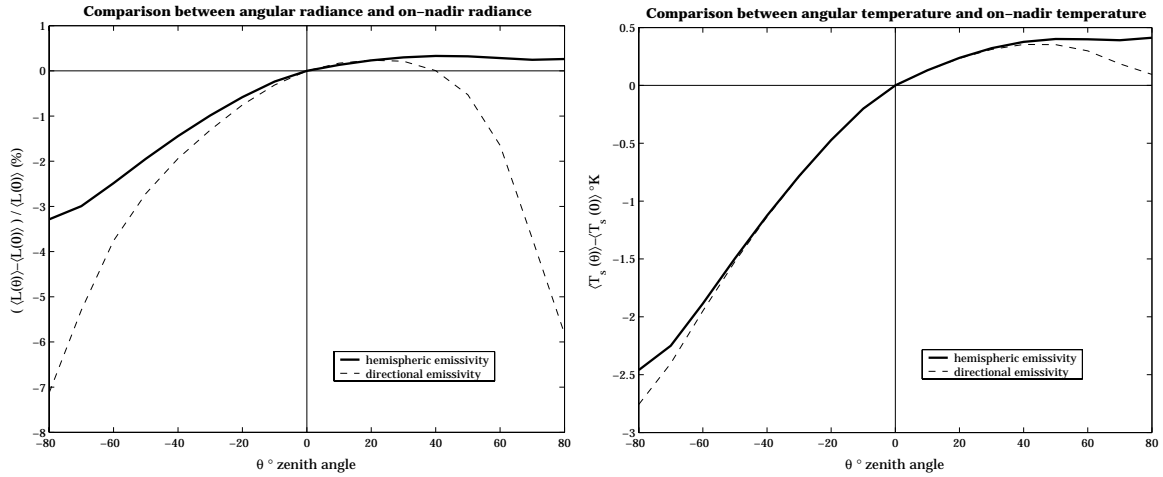


Figure 6. Effect of angular variation of bare soil emissivity on directional surface parameters.

It is clear that an angular variation of emissivity causes a significant impact on equivalent radiance. Up to approximately 50°, this impact remains weak (lower than 0.5%). For higher angles, the difference becomes

significant. Moreover, the values of obtained variations are significant and can reach 7% in radiance. Also, the impact on the equivalent surface temperature is very weak and only significant for zenith angles higher than 60° . If the parameter of interest is angular radiance it is consequently very important to take into account directional emissivity. Conversely, if one is interested in temperature the emissivity directional effects can probably be neglected.

4. CONCLUSION

Directional effects on thermal infrared observations have not received as much attention as in short wave region, despite experimental and theoretical evidence showing the importance of such effects. In this study, we investigated the effect of surface heterogeneities on directional radiance and directional radiative surface temperature. For this purpose, heterogeneous surfaces were simulated using several elementary homogeneous surfaces of known characteristics. The simulations relied on a generic model of surface radiometric budget equation, which takes into account vegetation effects.

To illustrate the influence of vegetation on angular radiance, a bare soil (lambertian) and vegetation covered surface were compared. The bare soil made it possible to show the effect of the viewing geometry and weighting by the solid angles ratio. The comparison between vegetation covered and bare soil surfaces showed the importance of the role of vegetation in the heterogeneous pixel and, thus, the importance of taking it into account. This result concurs with results of previous studies about the directional effects on canopy (Chehbouni,³ François⁷). The presence of vegetation introduces an asymmetrical behavior into the radiance angular variation. Moreover, it increases the variations between nadir and off-nadir values.

Another significant factor of directional effect is the spatial variability of surface temperature. It introduces an asymmetrical behavior that increases with heterogeneity. Moreover, the variations obtained increases with this variability. This is a source of significant directional effects. The knowledge of the spatial variability of surface temperature seems thus essential for well apprehending the directional effects on heterogeneous surfaces.

The last effect studied here is the impact the surface emissivities and their non-lambertian character. Emissivity heterogeneity plays a significant role on the level of radiance that it is not the case for the equivalent surface temperature. In fact, heterogeneity in emissivity acts on the emissive character of homogeneous zones, and thus, on the spatial variability of local radiances. Furthermore, considering directional emissivity it was shown that angular variation of emissivity has a significant impact on the equivalent radiance. For example, a bias of 7% in reference of nadir in the equivalent radiance is obtained for a 80° angle. In this case, it is of primary importance to characterize the directional emissivity of the soils composing the scene. The impact remains weak in the case of directional radiative surface temperature and can be neglected for viewing angle less than 60° .

This study had for main objective the characterization of the significant factors of directional effect on heterogeneous surfaces. Some of these aspects have to be further analyzed: spatial variability of temperature, angular emissivity. Currently, a field campaign is carried out to progress in understanding the effect of surface heterogeneity on observed directional radiative temperature measurement.

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