Directional Radiance and Emissivity Measurement Models for Remote Sensing of the Surface Energy Balance[1]

David L B Jupp
CSIRO Earth Observation Centre

Abstract

Interactions between remotely sensed data and Soil Vegetation Atmosphere Transport (SVAT) models have included inputs in the form of parameters such as albedo and Leaf Area Index as well as validation of outputs such as actual Evapotranspiration (ET) and net radiation. Visible, near infrared and thermal region data can be effectively combined and used in these ways. However, the radiative transfer models involved in the production of these inputs from remotely sensed data or the derivation of outputs are often at least as complex as the SVAT. In many cases, the parameters input to the SVAT represent only a fraction of the information content of the remotely sensed data. In attempts to bring these systems together, a number of people are studying how remotely sensed data and SVAT models can be integrated directly to provide calibration of the models and validation of their performance. The validation is to the level of information the remote sensing can provide which in the case of regional fluxes may be all that can be provided. The key to this development is having a remote sensing "measurement model" that is consistent with the level of aggregation and scale of the SVAT. This paper describes the directional radiance and emissivity effects which must be modelled to interpret regional remotely sensed data and the effect they have on the derivation of consistent information from SVATs.

1. SCENE BRIGHTNESS VARIATIONS & ENERGY BALANCE PARAMETERS

Optical, shortwave and thermal image data from airborne and satellite platforms have varying degrees of angle dependent brightness variation which change with the sun position, atmospheric conditions, land surface type and sensor characteristics. This brightness variation must be taken into account when processing and interpreting remotely sensed data. However, it is also an observable indicator of a wider need to take angular effects into account in all energy balance modelling. The surface effects will be referred to here as the "BRDF" or Bi-directional Reflectance Distribution Function. The BRDF is strictly a surface property which underlies the variation being described (Nicodemus *et al.*, 1977) but we will use the term loosely to describe variations that occur with varying sun and view geometries.

In the shortwave region the atmosphere contributes to the total effect observed in remotely sensed data partly due to the varying path length at different parts of the scan and partly to the atmospheric scattering described by the composite phase function of the atmospheric constituents. The land surface contributes to the broad level brightness variations common to all remotely sensed images. The base 'colour' and brightness is a function of the spectral properties of the material types making up the scene (e.g. leaf reflectances and transmittances or soil grain mineralogy) plus structural effects which give rise to the angular variations. The angular effects can be ascribed to three main factors - the volume effect, the occlusion (or hotspot) effect, and the specular or glint effect:

- **Volume Effect**: Because of the changes in path lengths and extinction in complex surfaces as the relative incidence (sun) and exitence (look) angles change, there is a volume BRDF which has some similarity to the atmospheric phase function induced variations. It will depend on surface structure and in vegetation it depends on factors like leaf density variations and angle distributions as well as total leaf area.
- **Occlusion Effect**: The occlusion effect is a more specific effect induced by the fact that the shadows cast by the sun represent parts of the surface that are not 'seen' by the sun. The areas that are not 'seen' by the sensor which are also not 'seen' by the sun are the common areas between shadow cast by the sun if it were in the two positions.
- **Specular (or Glint) Effect**: The specular or glint effect is most pronounced on water surfaces. It refers to the surface 'mirror' (or Fresnel) reflectance in which the radiation is usually unaltered by the surface material from which it is reflected. On land surfaces it is a composite of reflections diffused from facets of varying angular positions and specularity. In Australia, eucalypt leaves are especially specularly reflective due to their waxy coating. On water, glint is probably the major component of the BRDF and the hotspot effect does not occur.

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[1] Presented at MODSIM 97, Hobart Tasmania, 8-11 December 1997

The sum of these effects in remotely sensed data is an image brightness variation that is a sum of the atmospheric brightness and the scene brightness variations. The atmospheric and surface effects also interact to provide a composite effect that varies with sun, target and sensor geometry. The effects are more obvious in aerial photography and video images where the central perspective means that at high sun angles, the hotspot and specular points are within the angular radius of the frame. For airborne scanners and satellite borne scanners it is possible to avoid the brightest hotspot and glint points by careful consideration of the scan geometry. However, the angular variations also affect the net radiation in both short and long wave regions in a way that cannot be avoided in modelling as will be described below.

2. MODELLING BRIGHTNESS VARIATIONS

2.1 Measurement Model Approach

2.1.1 Atmospheric Correction of remotely sensed data

Assuming the data are accurately calibrated to radiances, there are different ways to describe the process of correction. An equation relating the recorded radiance sensed at altitude h above the target to the target reflectance factor is:

$$L_t(\mu_v,\mu_s,h,\lambda)=\frac{1}{\pi}E_T^*(\lambda)\,t(\mu_v,h,\lambda)\,(\rho_t+\rho_{env})+L_p(\mu_v,\mu_s,h,\lambda)$$
$$\left[+L_g(\mu_v,\mu_s,h,\lambda)\right]$$

where:

$L_t(\mu_v,\mu_s,h,\lambda)$ is the radiance observed by the instrument from altitude h, with look (or view) direction μ_v and sun direction μ_s at wavelength λ;
E_T^* is the effective irradiance at the target, or
$t(\mu_v,h,\lambda)$ is the beam transmittance through the layer between the surface and altitude h in direction μ_v;
ρ_t is the target directional reflectance factor;
ρ_{env} is the environmental reflectance due to the background albedo ρ^*,
$T(\mu_v,h,\lambda)$ is the diffuse transmittance for a layer of thickness h and for initial beam direction μ_v.
$L_p(\mu_v,\mu_s,h,\lambda)$ is the path radiance of light which did not interact with the surface; and
$L_g(\mu_v,\mu_s,h,\lambda)$ is the glint term that is most significantly present over water covered targets and is sometimes present over land targets.

If the atmosphere is well characterised it is possible to retrieve the directional reflectance factor (ρ_t) for each pixel. This term needs careful definition as there are many different types of 'reflectance' used. The directional reflectance factor (ρ_t) as used here is defined as:

$$\rho_t(\mu_s,\mu_v,f_d,\lambda)=\frac{\pi\,L(\mu_v,\lambda)}{E_T^*(\mu_s,f_d,\lambda)}$$

in which the irradiance (E_T^*) is the sum of diffuse and direct terms and the fraction of diffuse (f_d) is included as a parameter. The value of using this form of reflectance is that it corresponds to what is measured in the field using an irradiance radiometer or a reference standard.

This reflectance factor, or equivalent factors, are the properties underlying the term in the short wave net radiation expression called the "albedo". The Albedo (α) is the ratio of all wave solar generated outward radiation to incoming. It defines the net amount of shortwave radiation available at the surface for the energy balance:

$$\alpha=\frac{E_u}{E_d}$$

$$E_d=\int_0^\infty E_T^*(\mu_s,f_d,\lambda)\,d\lambda$$

$$E_u=\int_0^\infty \overline{\alpha}(\mu_s,f_d,\lambda)\,E_T^*(\mu_s,f_d,\lambda)\,d\lambda$$

$$\overline{\alpha}(\mu_s,f_d,\lambda)=\frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2}\rho_t(\mu_s,\mu_v,f_d,\lambda)\cos\theta_v\sin\theta_v\,d\theta_v d\varphi$$

The term $\overline{\alpha}(\mu_s,f_d,\lambda)$ is called the "spectral albedo" and it and the all-band albedo (α) depend on both the sun angle and the level of diffuse radiation as well as the properties of the surface. To interpret remotely sensed data and also to use the information in an energy balance model it seems necessary to model the BRDF effect.

2.1.2 Analytic BRDF Models

Assuming the atmospheric correction can be made, the surface BRDF can sometimes be defined by an analytic model. Among the many models for the volume effect are the Suits and Sail models as well as many more sophisticated ones such as the hotspot based model described (as an example) in Qin and Jupp (1993). The literature is vast and Myneni and Ross, (1990) provides a good review.

The hotspot effect is a geometric or occlusion effect. There are many models for this effect now available. A simple model for the remote sensing of a canopy is the Geometric Optical (GO) model summarised recently in Jupp and Walker (1996) as follows.

The simple GO (or hotspot) model for scenes which describe open forest or woodland areas is based on the one described in Jupp *et al.* (1986), Li and Strahler (1986), Strahler and Jupp (1991) and Li and Strahler (1992). In this model, there are four kinds of ground cover 'visible' from a given direction. These are referred to as scene components and consist of sunlit canopy (symbol *sc*), shaded canopy (*shc*), sunlit background (*sb*), and shaded background (*shb*). Each component is assumed to have a characteristic radiance and the radiance of a pixel is modelled as the area weighted combination (or linear mixture) of the characteristic component radiances. That is, the observed radiance of a single pixel (r_S) is modelled as:

$$r_S = k_{sc}R_{sc} + k_{shc}R_{shc} + k_{sb}R_{sb} + k_{shb}R_{shb}$$

where the subscripts *sc*, *shc*, *sb*, and *shb* indicate the radiances of the four components as named above, R_j represents the (mean) radiance of component 'j' and k indicates the sensed proportion of each component within the pixel from the given view direction.

The mean radiance over the scene (R_S), assuming the view and sun directions are constant, can be written as:

$$R_s = K_{sc}R_{sc} + K_{shc}R_{shc} + K_{sb}R_{sb} + K_{shb}R_{shb}$$

where, capital K_j represents the mean or expected value of the varying proportions k_j over the scene for j as the components *sc*, *shc*, *sb* or *shb*. The mean value (R_s), as a function of sun and observer position, defines the BRDF of the scene.

In order for the scene BRDF model to be computed, a description of the size and shapes of the objects, their density and how they are distributed over the background is needed and the geometrical relationships between the objects and the expected values of the four components must be established. Jupp *et al.* (1986), Strahler and Jupp (1991) and Li and Strahler (1992) describe such a model for spheroidal crown (not necessarily opaque) volumes which is valid for any view or illumination angles using the 'Boolean' model of Serra (1982). These basic scene BRDF models are quite simple and are easily implemented in various forms such as mathematical packages or spreadsheets.

2.2 Semi-empirical or "Kernel" Methods

Semi-empirical models have also been developed (Roujean *et al.*, 1992; Wanner and Strahler, 1995) which are empirical but are based on physical models and often contain parameters that relate to surface parameters. They offer the means of using the mosaic approach and 'empirical' model fitting but also enable surface parameters to be extracted. The methods are called 'semi-empirical' because they generally assume atmospheric correction can be done and also often have forms that involve earth surface parameters. The main class of these models is that of the 'kernel' models.

A complete kernel-driven semiempirical model is formulated as a linear combination of kernels. Most suitably it has the form

$$R = f_{iso} + f_{geo}k_{geo} + f_{vol}k_{vol}$$

which is derived from adding appropriate choices of geometric-optical surface-scattering and radiative-transfer volume-scattering kernels, each multiplied by a proportion that weights the contribution of each model. These proportions may be regarded as the areal proportions of land cover types exhibiting each type of scattering (neglecting multiple scattering between the two components), or as mixing proportions for land cover types that display both a volume-scattering and a geometric-optical contribution to the BRDF. The quantities k_{geo} and k_{vol} are the respective kernels; the factors f_{geo} and f_{vol} are their respective weights; and the term f_{iso} is the isotropic contribution

In the inversion and fitting of a semiempirical model to data, estimates of the weights f are retrieved from bidirectional reflectances and specification of viewing and illumination positions. Although this objective satisfies many of the goals of a BRDF/Albedo product (Strahler *et al.*, 1995), the existence of formulae for the weights f in terms of physical parameters could provide for direct inference of physical parameters from the weight values fitted. This possibility is being explored by a number of researchers at the present time. Kernel models provide a means to parameterise the albedo in a way which, until recently, has been neglected as too hard.

2.3 Estimation of surface albedo

Estimates of spectral albedo (and consequently total albedo) are conveniently made by considering two special cases of irradiance. One is for pure beam irradiance and the other is for uniformly diffuse irradiance. Without going into detail of the derivation from the BRDF, the approximation to the directional reflectance factor will have the form:

$$\rho_t = (1 - f_d)\,\overline{\rho}(\mu_r, \mu_s) + f_d\,\overline{\rho}(\mu_r, 2\pi)$$

from which the albedo can be derived as above if the functional forms can be integrated or by numerical integration if not. The term $\overline{\rho}(\mu_r, \mu_s)$ is called the "black sky albedo" and the term $\overline{\rho}(\mu_r, 2\pi)$ is called the "white sky albedo" and both can be estimated if the underlying BRDF has been modelled or approximated by a semi-empirical kernel function.

The introduction of the spectral albedo also allows the traditional shortwave radiation to be broken down into more wavebands - such as visible and near infra-red. There are significant advantages in doing this for the estimation of radiative transfer in canopies.

3. DIRECTIONAL EFFECTS IN TEMPERATURE

3.1 Directional effective Emissivity

The radiance (L) observed in any of the thermal channels of a thermal sensor on (for example) a Daedalus Scanner, TIMS, Landsat TM, AVHRR or [A]ATSR has a directional component which is a function of μ_v. It is possible to invert the Planck function $B_\lambda[T]$ and represent this radiance as an equivalent brightness temperature (T_b) which is the temperature of a black body radiator that would produce the observed radiance:

$$T_b(\mu_v) = B_\lambda^{-1}[L(\mu_v)]$$

In general, this brightness temperature will be a directional function due in part to the directional nature of the atmospheric transmittance and airmass temperature effects and in part to the directional effects introduced by the land surface. It is these second group that are of primary concern here. One primary purpose of such estimation is to compute the net longwave radiation at the surface. This can be written:

$$S_{L,net} = -\varepsilon_s \sigma T_s^4 + (1-\varepsilon_s)\varepsilon_a \sigma T_a^4$$

Suppose the data can be accurately atmospherically corrected so that the radiance observed is the surface leaving radiance distribution. A significant issue is what degree of directionality exists and what is the source of it and how this affects the definitions of the surface temperature and emissivity? Observed directionality has been ascribed to a directional emissivity (or reflectance) but below we will see that this is only one source of the directionality.

3.2 The Volume Effects

The volume effect is due to the interactions between materials and radiation in the complex land surface. If the surface is covered by vegetation this can be discussed and illustrated in terms of the well known SAIL model (Verhoef, 1984). There, the upwelling and downwelling thermal radiation are modelled with a 'Kubelka-Munk' approximate two-flow model as described in Dong and Li (1992). The equations will nor be repeated here but generally model the upwelling (E_u) and down welling (E_d) irradiances in the thermal region.

The leaves are assumed to have a temperature T_v and emissivity ε_v and the soil background to have a temperature T_g and emissivity ε_g. The Kirchhoff Law is used to relate reflectance (ρ) and emissivity.

$$\varepsilon = 1 - \rho$$

The radiation leaving the top of the canopy (in Dong & Li notation $E_u(h)$) arises from two sources:

1. the thermal emission from soil and leaves ($E_u^{(1)}$) and
2. the reflection of incident sky radiation ($E_u^{(2)}$)

Assuming the sky to be radiating as a black body they show how there is an effective canopy emissivity and reflectance such that:

$$E_u^{(2)} = \rho_c\ E_{sky} = \rho_c\ B_\lambda[T_{sky}] = (1-\varepsilon_c)\ B_\lambda[T_{sky}]$$

The emission term comprises two components. One is a 'line of sight' term which effectively depends on the visible fractions of the different components from the surface and the other arises when the emissivities are less than 1.0 due to multiple reflections in the canopy volume.

When the emissivities of the soil and vegetation are 1.0 the effective canopy reflectance will be zero, the effective canopy emissivity will be 1.0 and the only term leaving the canopy is the emission term which is:

$$E_u^{(1)} = f_v\ B_\lambda[T_v] + (1-f_v)\ B_\lambda[T_g]$$

where $f_v = f_v(2\pi)$ is a 'hemispherical' vegetation fraction.

When the emissivities of the vegetation and soil are not 1.0 but are still large (as they are in practice in the thermal region) it is clear that the radiation leaving the canopy will have a dominant 'line of sight' emission term and smaller volume reflectances of emitted radiation and reflected sky radiation terms. For the canopy source generated by the emission, the multiple reflectances can be taken into account by replacing the leaf emissivity (ε_v) by the infinite depth canopy emissivity as defined in Dong and Li which will be denoted ε_v^*.

That is:

$$\begin{aligned} E_u(h) &= E_u^{(1)} + E_u^{(2)} \\ &\approx f_v\ \varepsilon_v^*\ B_\lambda[T_v] + (1-f_v)\ \varepsilon_g\ B_\lambda[T_g] + (1-\varepsilon_c)\ B_\lambda[T_{sky}] \\ &= \varepsilon_c\ B_\lambda[T_c] + (1-\varepsilon_c)\ B_\lambda[T_{sky}] \end{aligned}$$

In this expression, the emission term *defines* the effective canopy temperature T_c once the emissivity is defined. There are many ways to define such a temperature but this one is consistent with radiative transfer.

3.3 Directional Effects

There is a directional effect in the effective reflectance (and hence emissivity) which may not be very strong as the incident sky radiation is generally quite diffuse. It will depend on the leaf angle distribution of the canopy. There will be a similar angular variation in the volume multiple reflectances of the canopy radiation. The line of sight variation, however, will have an especially clearly defined angular variation of the approximate form:

$$L_u^{(1)}(\mu_v) = f_v(\mu_v)\,\varepsilon_v^*\,B_\lambda[T_v] + (1 - f_v(\mu_v))\,\varepsilon_g\,B_\lambda[T_g]$$

where the fraction of vegetation generally increases with oblique views and the general behaviour depends on the leaf angle distribution as well as (obviously) the temperature difference between the components.

By analogy with the hemispherical case, an effective angular canopy temperature could be defined by using the effective angular reflectance to fix the effective emissivity. The most significant aspect at this point, however, is that the angular effect in the emissivity (ie reflectance) is only one component of the directional variation in the brightness temperature. There is both an angular emissivity and an angular temperature which between them explain the data as:

$$\begin{aligned} L_u(\mu_v) &= L_u^{(1)} + L_u^{(2)} \\ &\approx \varepsilon_c(\mu_v)\,B_\lambda[T_c(\mu_v)] + (1 - \varepsilon_c(\mu_v))\,B_\lambda[T_{sky}] \end{aligned}$$

where it is assumed the sky radiation is uniformly diffuse. If the Planck functions are expanded about (say) air temperature to a first order and emissivities are high then to a reasonable approximation:

$$\begin{aligned} T_c(\mu_v) &\approx f_v(\mu_v)\,T_v + (1 - f_v(\mu_v))\,T_g \\ \varepsilon_c(\mu_v) &\approx f_v(\mu_v)\,\varepsilon_v^* + (1 - f_v(\mu_v))\,\varepsilon_g \end{aligned}$$

However, if the emissivities drop significantly below 1.0 these simple expressions will be in error.

The simple volume effect described above does lead to directional effects. These will be greatest when the vegetation and soil temperatures are different and the cover not too sparse and not too dense. However, they will not depend on the sun position at the time of the overpass - only on the view angle. A hotspot effect will, however, be present in the line of sight component since the field of view of an instrument will 'see' both sunlit and shaded vegetation and soil components. The proportions of each will change as the relative sun and observer positions change. If the temperatures of the sunlit and shaded components are markedly different then there will be a strong hotspot component.

The visible region hotspot effect is only one component of the BRDF in that case. In the thermal it is more a component of the volume effect than the emissivity (ie reflectance). That is, the hotspot and volume emission effect (the BEDF) are due to the temperature generated emission of radiation from different components in a structured surface and the canopy reflectance (ie emissivity) will not show a hotspot effect. It will, however, have a DRDF depending on the view angle.

4. CONCLUSIONS

In both the short and long wave regions, remote sensing has to take full account of the directional surface properties. These have significant impact on the sun-angle dependent albedo and longwave energy balance components. It seems that in order to bring remote sensing and energy balance modelling together there must be changes in the way the radiation balance is handled in current models.

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