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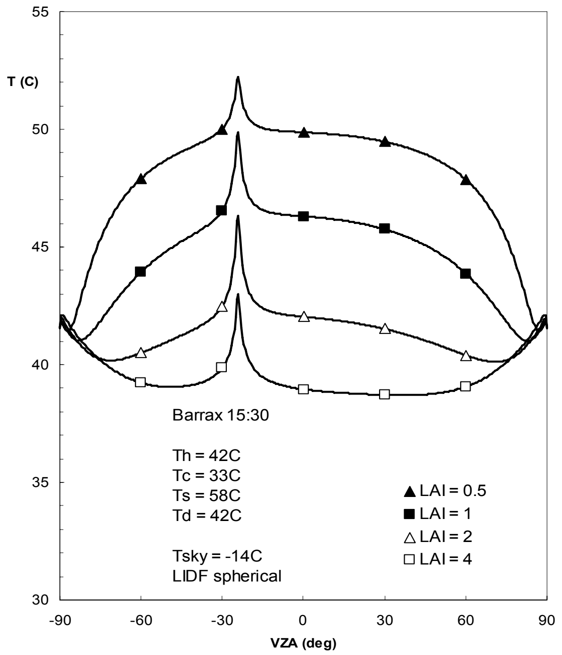
Executive summary

Optical-thermal canopy radiance directionality modelling by unified 4SAIL model



Problem area
Retrieval of canopy and soil temperatures from multidirectional thermal radiance observations is usually based on knowledge of fractional vegetation cover for the given viewing directions. A unified optical-thermal modelling approach facilitates the modelling of co-registered observations in both spectral domains, thus enabling the search for new methods allowing simultaneous retrieval of biophysical variables along with canopy and soil component temperatures.

Description of work
Four-stream radiative transfer theory has been successfully applied in the 4SAIL model to simulate directional reflectances of canopy-soil combinations in the past. Recently it has been found that with small additions this theory can be applied to the thermal spectral region as well, so that for the entire optical-thermal domain one can apply the same unified modelling approach, with a common description of canopy architecture. The extended theory allows to compute effective emissivities for

Report no.
NLR-TP-2007-242

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Report classification
UNCLASSIFIED

Date
April 2007

Knowledge area(s)
Safety & Security

Descriptor(s)
Radiative transfer
Optical
Thermal
Vegetation

This report is based on a presentation to be held on the 2nd International Symposium on Recent Advances in Quantitative Remote Sensing, Valencia, Espagna, September 2006.

soil and canopy as well as directional signatures of top-of-canopy radiance and brightness temperature, if soil and leaf temperatures and emissivities are given as input parameters. Since in reality leaves and soil in the sun and in the shade often have distinct temperatures, the model accommodates temperatures for a maximum of four components: sunlit leaves, shaded leaves, sunlit soil and shaded soil.

Results and conclusions
Simulation results for this case indicate that in the principal plane of the sun one should be able to observe a thermal hot spot of several degrees in magnitude if sunlit and shaded components have clearly different temperatures.

Applicability
The unified model can be applied to retrieve structural and thermal properties of vegetation and soil simultaneously, and thus leads to more accurate retrievals for both types of information.

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Optical-thermal canopy radiance directionality modelling by unified 4SAIL model

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Customer	National Aerospace Laboratory NLR
Contract number	----
Owner	National Aerospace Laboratory NLR
Division	Aerospace Systems & Applications
Distribution	Unlimited
Classification of title	Unclassified

Approved by:

Author	Reviewer	Managing department
	130407	26/4/07

Summary

Four-stream radiative transfer theory has been successfully applied in the 4SAIL model to simulate directional reflectances of canopy-soil combinations in the past. Recently it has been found that with small additions this theory can be applied to the thermal spectral region as well, so that for the entire optical-thermal domain one can apply the same unified modelling approach, with a common description of canopy architecture. The extended theory allows to compute effective emissivities for soil and canopy as well as directional signatures of top-of-canopy radiance and brightness temperature, if soil and leaf temperatures and emissivities are given as input parameters. Since in reality leaves and soil in the sun and in the shade often have distinct temperatures, the model accommodates temperatures for a maximum of four components: sunlit leaves, shaded leaves, sunlit soil and shaded soil. Simulation results for this case indicate that in the principal plane of the sun one should be able to observe a thermal hot spot of several degrees in magnitude if sunlit and shaded components have clearly different temperatures.

Retrieval of canopy and soil temperatures from multidirectional thermal radiance observations is usually based on knowledge of fractional vegetation cover for the given viewing directions. The unified optical-thermal modelling approach facilitates the modelling of co-registered observations in both spectral domains, thus enabling the search for new methods allowing simultaneous retrieval of biophysical variables along with canopy and soil component temperatures.

Contents

1 Introduction

Modelling the interaction of radiation with vegetation canopies can be applied to enhance the insight in remote sensing observations of the earth and to devise advanced methods for the retrieval of biophysical canopy properties from earth observation data by means of model inversion. Radiative transfer models for vegetation canopies (Goel, 1988) in the optical spectral domain (400 – 2500 nm) can be divided into two broad categories of models: ones that are based primarily on geometric optics considerations (GO models, Norman & Welles, 1983; Li & Strahler, 1992) and those that are more based on radiative transfer considerations (RT models, Gobron et al., 1997; Gerstl & Borel, 1992; Chelle, 1997). This distinction is not always very sharp, and in so-called GORT models (Gastellu-Etchegory et al., 1996) both approaches are combined.

More or less independently of these optical models, other models have been developed for application to thermal infrared (TIR) imagery, to simulate the brightness temperature of canopy-soil combinations (Kimes, 1983; Sobrino & Caselles, 1990). These models can be grouped into the same prevailing categories as the optical models. While GO models are suitable to model clumped (forestry) or row-structured canopies, the physical processes included in these models are mostly limited. RT models involve various degrees of detail in physical processes, characterizing the vegetation canopy by a leaf density distribution (or only total leaf area index, LAI), a leaf inclination distribution function (LIDF), etc., and often assuming canopies as homogeneous turbid media composed of layers with different temperatures which are either given as input or that are solved simultaneously in a process modelling approach.

Optical and thermal remote sensing techniques can be applied to assess biophysical parameters of vegetation canopies. In the optical domain, variables like the leaf area index, fractional cover and leaf chlorophyll and water contents can be retrieved by applying model inversion to hyperspectral and – possibly – multiangular observations. The thermal domain offers the possibility of retrieving foliage as well as soil temperature, important quantities for assessment of the exchange of turbulent heat flux between vegetated land and the atmosphere.

Combined simultaneous and spatially co-registered observations in both domains would offer unprecedented opportunities for the accurate retrieval of canopy structure, leaf biochemistry, as well as leaf and soil temperature. Since leaf and soil temperature retrieval requires some variation of vegetation fractional cover, multi-angular (or at least dual-looking) observations are necessary in this case. However, one may expect that optical observations under the same geometries can provide important complementary information, for instance about fractional cover, or about directional emissivity, which both are essential factors for the accurate retrieval of leaf and soil temperatures.

In order to investigate the potential of this unified optical-thermal approach to biophysical variable retrieval, the widely used SAIL (Verhoef, 1984) canopy reflectance model, and in particular the four-stream radiative transfer modelling concept applied in it (Verhoef, 1985), has been extended to the thermal infrared spectral domain. It has turned out that for the case of homogeneous foliage and soil temperatures one can still apply the optical output parameters provided already for long by the SAIL subroutine. These parameters describe the optical properties of the isolated canopy layer (the so-called black soil problem), and these can be used to predict directional and hemispherical emissivities and the top-of-canopy (TOC) brightness temperature after taking account of the soil background by means of the adding algorithm. However, sunlit and shaded leaves may have different temperatures, since sunlit leaves receive more radiation and therefore are probably warmer. This problem requires a special treatment, and in a more recent version of SAIL (called 4SAIL), which is also more robust against numerical problems, some extra quantities are provided on output which can be used to take account of this kind of foliage temperature heterogeneity. In this paper first some theoretical considerations are presented in section 2. Section 3 presents some results with regard to the functioning of the model in the thermal infrared, as well as some comparisons with in-situ measurements on wheat.

2 Theory

The four-stream radiative transfer concept is based on two diffuse hemispherical fluxes and two specular flux types (direct solar flux and the radiance in the observer's direction). The corresponding radiative transfer equation including thermal emission can be described in matrix-vector notation by

$$\frac{\mathrm{d}}{L\,\mathrm{d}x}\begin{pmatrix}E_s\\E^-\\E^+\\E_o\end{pmatrix}=\begin{pmatrix}k&&&\\&\kappa&&\\&&-\kappa&\\&&&-K\end{pmatrix}\begin{pmatrix}E_s\\E^-\\E^+\\E_o\end{pmatrix}+\begin{pmatrix}&&&\\-s'&-\sigma'&-\sigma&\\s&\sigma&\sigma'&\\w&v&v'&\end{pmatrix}\begin{pmatrix}E_s\\E^-\\E^+\\E_o\end{pmatrix}+\begin{pmatrix}\\-\kappa\\\kappa\\K\end{pmatrix}\varepsilon_v H_v \qquad (1)$$

in which the first (diagonal) matrix on the right-hand side describes the interception of radiation by leaves, and the second the scattering. Thermal emission by leaves is included in the rightmost vector. Vacancies in the above matrices and vectors indicate zeros. These occur because 1) intercepted radiation only applies to incident fluxes, 2) the solar flux is assumed to remain unaffected by scattering and emission, and 3) the observed radiance is the end product of all interactions, which means that it can have no influence on fluxes that are placed on a hierarchically higher level. Not all extinction and scattering coefficients will be explained here, but the unprimed scattering coefficients indicate backscattering (transfer from one hemisphere back into the same one), and the primed ones forward scattering (transfer from one hemisphere to the other). Explicit expressions for all coefficients are given in (Verhoef, 1984). Important quantities are further the leaf area index, here symbolized as *L*, and the leaf emissivity ε_v, which is assumed to be equal on both sides of the leaf, and equal to one minus the single leaf reflectance. Leaf transmittance is assumed to be zero in the thermal infrared. The thermal hemispherical flux emitted by leaves is given by

$$H_v = \pi B(T_v) ,$$

where $B(T_v)$ is Planck's radiance function. Finally, the quantity *x* is called the relative optical height. By convention, it runs from –1 at the canopy bottom to 0 at the top.

The analytical solution of the radiative transfer equation (1) can be expressed by the following set of four equations:

$$\begin{aligned} E_s(-1) &= \tau_{ss} E_s(0) \\ E^-(-1) &= \tau_{sd} E_s(0) + \tau_{dd} E^-(0) + \rho_{dd} E^+(-1) + \gamma_d H_v \\ E^+(0) &= \rho_{sd} E_s(0) + \rho_{dd} E^-(0) + \tau_{dd} E^+(-1) + \gamma_d H_v \\ E_o(0) &= \rho_{so} E_s(0) + \rho_{do} E^-(0) + \tau_{do} E^+(-1) + \tau_{oo} E_o(-1) + \gamma_o H_v \end{aligned} \qquad (2)$$

These equations describe the relations between all fluxes incident to the isolated canopy layer and the fluxes exiting from that layer. All ρ and τ quantities are output quantities of the SAIL models, and indicate the reflectances and transmittances of the isolated canopy layer, respectively. The two γ quantities are new and they are related to thermal emission. It can be shown that these are given by

$$\begin{aligned} \gamma_d &= 1 - \rho_{dd} - \tau_{dd} \\ \gamma_o &= 1 - \rho_{do} - \tau_{do} - \tau_{oo} \end{aligned}$$

which means that they can be interpreted as absorptances and, through application of Kirchhoff's Law, also as emissivities. They can be directly obtained from the reflectance and transmittance quantities, and this is precisely the reason why SAIL can be immediately applied in the thermal domain without any extra efforts, provided that the canopy layer is thermally homogeneous.

If sunlit and shaded soil parts have different temperatures, incorporation of the bi-directional gap fraction as obtained from modelling the optical hot spot effect (Kuusk, 1985) is still sufficient to take this into account for the thermal domain. However, if also leaves have different temperatures in the sun and in the shade, then this approach is no longer adequate. This situation, which might occur for stressed vegetation that is not able to sufficiently cool itself, or which may be expected to occur in healthy but sparse vegetation canopies, has been analysed in detail, and the result is formed by three additional output quantities of the modernised canopy reflectance model 4SAIL. These new output quantities appear in the following set of equations, which is similar to Eqs. (2), but now includes extra terms related to the temperature difference between sunlit and shaded leaves:

$$\begin{aligned}
E_s(-1) &= \tau_{ss} E_s(0) \\
E^-(-1) &= \tau_{sd} E_s(0) + \tau_{dd} E^-(0) + \rho_{dd} E^+(-1) \\
&\quad + \gamma_d H_c + \gamma'_{sd}\, \varepsilon_v (H_h - H_c) \\
E^+(0) &= \rho_{sd} E_s(0) + \rho_{dd} E^-(0) + \tau_{dd} E^+(-1) \\
&\quad + \gamma_d H_c + \gamma_{sd} \varepsilon_v (H_h - H_c) \\
E_o(0) &= \rho_{so} E_s(0) + \rho_{do} E^-(0) + \tau_{do} E^+(-1) + \tau_{oo} E_o(-1) \\
&\quad + \gamma_o H_c + \gamma_{so} \varepsilon_v (H_h - H_c)
\end{aligned} \qquad (3)$$

Here, H_h and H_c are the hemispherical thermal radiation fluxes emitted by blackbody leaves in the sun (hot) and in the shade (cold) with radiative temperatures T_h and T_c, respectively, and as computed by means of Planck's function. The new coefficients obtained are γ_{so}, γ_{sd} and γ'_{sd}, of which the first has a bi-directional nature and is responsible for the thermal hot spot effect due to the foliage, and the other two describe the influence of the temperature difference between sunlit and shaded leaves on the diffuse hemispherical fluxes. By the way, this illustrates that longwave top-of-canopy upward flux is also influenced by this phenomenon. Note that, if foliage temperature is uniform, we obtain Eqs. (2) again. Eqs. (3) can be combined with the reflectance and emissivity properties of the soil background by means of the four-stream adding algorithm, and the final result can be expressed by

$$\begin{aligned}
E_o(0) = \pi L_o(0) &= r^*_{so} E_s(0) + r^*_{do} E^-(0) \\
&\quad + \varepsilon_v^{AEE} H_c \\
&\quad + \varepsilon_s^{AEE} H_d \\
&\quad + \gamma^*_{so} (H_h - H_c) \\
&\quad + \varepsilon^*_s (H_s - H_d)
\end{aligned} \qquad (4)$$

where the first two terms on the right describe surface reflectance of solar and sky irradiance, the next two terms the effective thermal emission from foliage and soil, and the last two terms are the ones that take account of temperature differences between 1) sunlit and shaded leaves and 2) sunlit and shaded soil, respectively. It has been verified for this model that the hemispherical-directional top-of-canopy reflectance and the two effective emissivities for vegetation and soil are related by the equation

$$r_{do}^{*} + \varepsilon_{v}^{AEE} + \varepsilon_{s}^{AEE} = 1 \;, \tag{5}$$

which confirms Kirchhoff's Law, and the fact that the sum of the effective emissivities for foliage and soil is equal to the total emissivity of the ensemble.
When this model is applied in the thermal infrared domain, five different radiative temperatures are to be supplied on input:

- T_{sky} = narrow-band sky temperature
- T_h = temperature of sunlit (hot) leaves
- T_c = temperature of shaded (cold) leaves
- T_s = temperature of sunlit soil
- T_d = temperature of shaded (dark) soil

In addition, the emissivities of leaves and soil have to be supplied, as well as the canopy structure parameters LAI, LIDF (two parameters), and the hot spot size parameter.

3 Results

The functional behaviour of the model has first been tested by investigating the predicted thermal hot spot effect. This was done by taking rather extreme variations of component temperatures that had been measured in a vineyard canopy at the Barrax site on a hot and nearly windless day in July 2004 during the SPARC campaign (Su et al., 2005). The component temperatures measured on two moments of the day were directly used as inputs for the 4SAIL model, along with the narrowband (at 9.5 µm) sky brightness temperature, which was derived from MODTRAN4 atmospheric RT modelling results. For the 4SAIL simulations a spherical leaf inclination distribution was assumed, and the LAI was varied in four steps: 0.5, 1, 2, and 4.
Some results are presented as a plot of the brightness temperature as a function of the viewing zenith angle in the principal plane in figure 1. From these simulation results it becomes clear that hot spot effects of a considerable magnitude can be expected for all common LAI values if component temperature differences are as large as measured during this campaign. Angular signatures of brightness temperature depend on LAI and on time of day. Retrieval of foliage and soil temperatures from these signatures will not be easy, since they are also influenced by the leaf angle distribution (not shown). One may expect that the most accurate retrievals of component temperatures are possible by employing model inversion techniques in which also observations from the optical domain are incorporated, since these can provide information on

LAI and LIDF (Bach et al., 2005), which both are crucial canopy structural parameters that determine the shape of brightness temperature angular signatures.

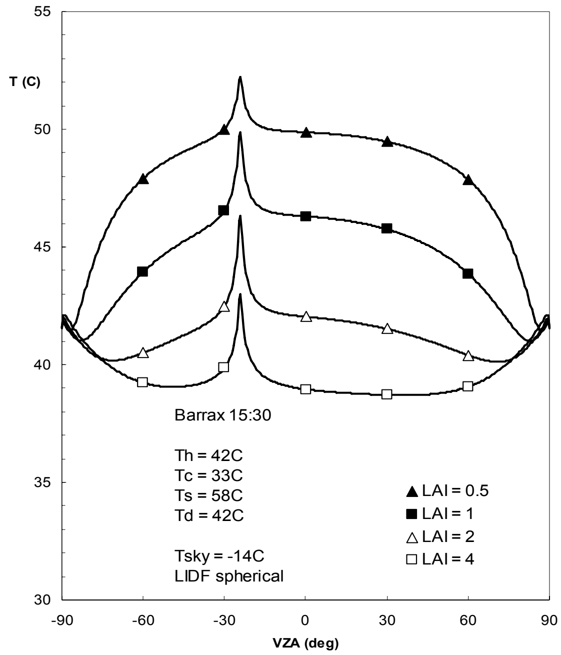

Fig. 1 Simulated TOC brightness temperatures in the principal plane for a spherical LIDF and four LAI values. Component temperatures as indicated, and obtained from measurements at the Barrax site at 15:30 hrs. local time

The influence of component temperatures on angular signatures of the top-of-canopy brightness temperature has further been analysed in Figure 2, which shows the effects of a series of successive temperature changes for a canopy with LAI = 1. The LIDF is spherical. When soil temperature, foliage temperature and narrow-band sky brightness temperature are all equal to 20 degrees C, the simulated angular signature of top-of-canopy brightness temperature is a flat line. This is due to Kirchhoff's Law, as expressed by Eq. (5). Although the effective emissivities of foliage and soil, and the hemispherical-directional reflectance are direction-dependent, their sum equals unity for all angles, and if also the hemi-spherical fluxes from soil, foliage and sky are equal, the resulting top-of-canopy radiance becomes constant (Lambertian). If the sky brightness temperature is decreased, this is no longer the case, and a weak angular effect becomes visible. A five degree increase of soil temperatures, and an equal decrease of foliage temperature gives a strong angular dependence, but no hot spot effect. If only the sunlit soil fraction is increased in temperature, a hot spot emerges of about two degrees magnitude, which is about 40% of the actual temperature difference.

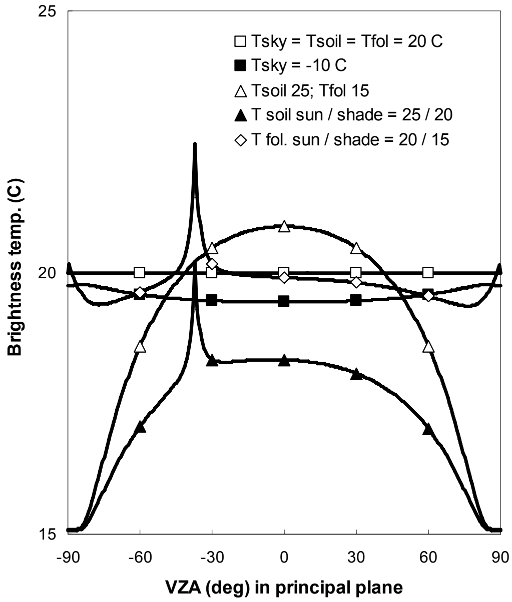

Fig. 2 Changes of angular brightness temperature signatures as a function of four component temperatures and narrow-band sky brightness temperature

Note, that, in the case of a temperature difference between sunlit and shaded soil, only for shallow observations approaching the horizon and for the exact hot spot condition there is little difference between both cases (with and without a soil temperature difference). This can be explained by the fact that under both conditions no shadowed soil can be observed, so also its lower temperature is not noticed. If finally the temperature of sunlit foliage is increased from 15 to 20 degrees, the hot spot effect is further increased to a magnitude of about three degrees and especially for observations near the horizon the observed brightness temperature rises by about five degrees.

For validation, goniometer brightness temperature measurements of wheat from the Shunyi field campaign (Liu et al., 2002) in China have been provided. Figure 3 shows a comparison between measurements close to the principal plane and corresponding model outputs for the 3-component case and the 4-component case. In this case the temperature differences are not as extreme as in Barrax, but a weak hot spot effect is still noticeable in the measurements. The 4-component simulation clearly gives the best fit to the measured signature.

An example of model results from both the optical and the thermal domain is presented in Figure 4. It shows the relationship between emissivity and NDVI for nadir viewing if the LAI is varied by steps of 0.25 from zero until six, for three common leaf angle distributions, planophile, spherical and erectophile. For a spherical LIDF, the results more or less confirm the well-known empirical logarithmic relationship of Van de Griend & Owe (1993), but for other leaf angle distributions correspondence is less good. If for known NDVI the emissivity is estimated when the LIDF is unknown, considerable errors of about 0.01 in the emissivity may well occur.

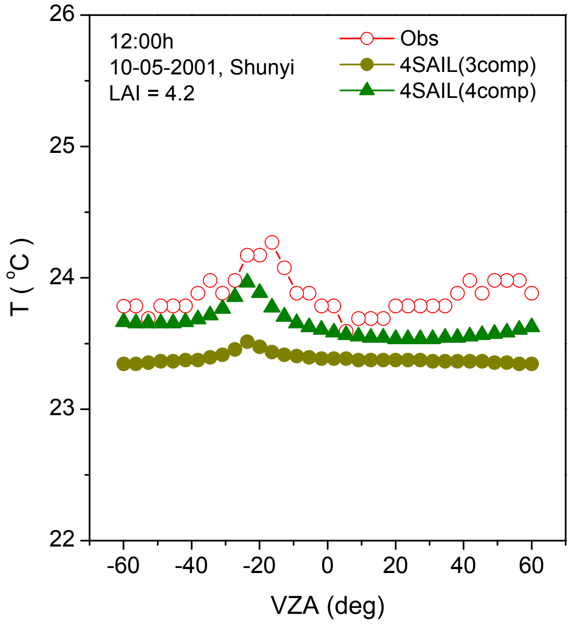

Fig. 3 Directional signatures of brightness temperature (°C) computed by 4SAIL model compared with measurements on 10 May from Shunyi campaign, China. In the 3-component model sunlit and shaded soil have distinct temperatures, in the 4-component model also the foliage has distinct temperatures in the sun and in the shade

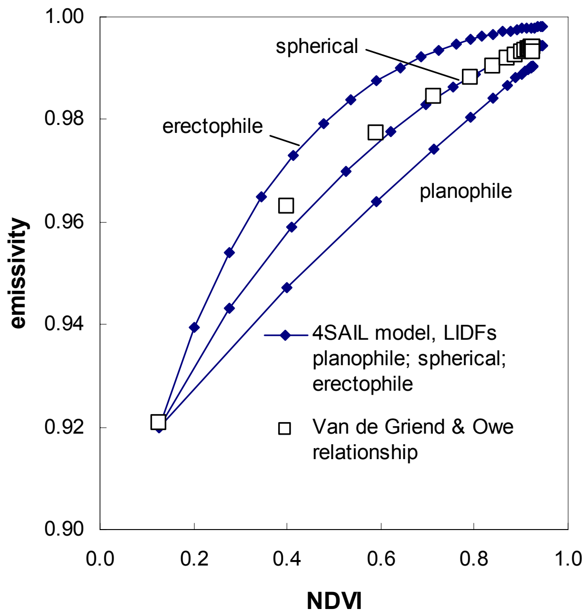

Fig. 4 Relationships between emissivity and NDVI as modelled with 4SAIL compared to empirical relationship of Van de Griend & Owe (1993)

Acknowledgment

The work reported here was partly supported by NLR's own research programme, as well as by an IAC fellowship from the Netherlands Ministry of Agriculture, Nature Management and Fisheries, the Netherlands Users Support Program (SRON GO) under grant no. EO-049 (with Dr. R. de Groot as the SRON GO programme manager), and the EC FP6 GMES EAGLE project (Contract no. 502057, led by Prof. J.A. Sobrino, with Dr. P. Breger as the EC project officer). The Shunyi field campaign was part of the 'Quantitative of Remote Sensing theory and application for Land Surface Parameters (QRSLSP)' project funded by China's Special Funds for Major State Basic Research (project No. G2000077900, led by Prof. X. Li).

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