Estimation of soil and vegetation temperatures with multiangular thermal infrared observations: IMGRASS, HEIFE, and SGP 1997 experiments

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Abstract. The potential of directional observations in the thermal infrared region for land surface studies is a largely uncharted area of research. The availability of the dual-view Along Track Scanning Radiometer (ATSR) observations led to explore new opportunities in this direction. In the context of studies on heat transfer at heterogeneous land surfaces, multiangular thermal infrared (TIR) observations offer the opportunity of overcoming fundamental difficulties in modeling sparse canopies. Three case studies were performed on the estimation of the component temperatures of foliage and soil. The first one included the use of multi-temporal field measurements at view angles of 0°, 23° and 52°. The second and third one were done with directional ATSR observations at view angles of 0° and 53° only. The first one was a contribution to the Inner-Mongolia Grassland Atmosphere Surface Study (IMGRASS) experiment in China, the second to the Hei He International Field Experiment (HEIFE) in China and the third one to the Southern Great Plains 1997 (SGP 1997) experiment in Oklahoma, United States. The IMGRASS experiment provided useful insights on the applicability of a simple linear mixture model to the analysis of observed radiance. The HEIFE case study was focused on the large oasis of Zhang-Ye and led to useful estimates of soil and vegetation temperatures. The SGP 1997 contributed a better understanding of the impact of spatial heterogeneity on the accuracy of retrieved foliage and soil temperatures. Limitations in the approach due to varying radiative and boundary layer forcing and to the difference in spatial resolution between the forward and the nadir view are evaluated through a combination of modeling studies and analysis of field data.

1. Introduction

Thermal Infrared (TIR) radiance, as a rule, is "directional" (or anisotropic, or angle dependent). The TIR radiance from a smooth surface is directional because of the angular variation of the emissivity according to the laws of electromagnetism. This is not specific to emitted radiance and the reflectivity (either TIR or solar) would also be angle dependent for the same reason. However, since the TIR emitted radiance depends on both the emissivity and the temperature, retrieval of the surface temperature would require correcting the radiometric measurements for "angular emissivity" effects.

Alternatively, for any observed real system, but in particular for three dimensional (3D) systems, directionality of TIR radiance will appear because of the radiometric heterogeneity and structure of the system. Hence directionality of TIR radiance may be seen as a manifestation of the complexity of the medium. Inverting TIR directional radiance may thus provide information on biophysical system's variables. Because of different heat capacities and the temperature regulation mechanism of vegetation, it is common to have large (up to 20K or more) differences between sun-lit soil and shadowed leaf surfaces [Nielsen et al., 1984], particularly when the top soil is dry.

Estimates of the component temperatures of foliage and soil within a heterogeneous target can be used to improve the parameterization of heat transfer at heterogeneous land surfaces. A mixture of foliage and soil is characterized by large temperature differences within the canopy space. Under these conditions heat transfer between foliage and air and between soil and air should be described separately (so-called dual-source model). We have shown elsewhere [Jia et al., 2000] that estimates of foliage and soil temperatures obtained with the method described here can be used to model heat transfer in this way.

Different models have been proposed in literature to interpret observations of directional exitance: (1) simple geometric (deterministic) models of the system, (2) radiative transfer within a complete canopy, and (3) radiative transfer in an inhomogeneous thick layer of vegetation. These modeling concepts are described in more detail in the section 2. Our approach is based on the third modeling concept. A target comprising a mixture of foliage and soil is characterized by the gap fraction, and observed radiance is...
described as a weighted sum of foliage radiance and soil radiance, with the weights being the gap fraction and its complement, respectively.

This paper describes a simple approach to estimate foliage and soil temperatures from measurements of directional exitance at two view angles. Three case studies are presented to document the feasibility of the method proposed and the challenges involved. The latter relate to the weakness of the angular effect, the coupling with the atmosphere and the necessity to perform accurate atmospheric corrections over a large range of view angles. The case studies were based on both field and satellite observations, the latter obtained with the Along Track Scanning Radiometer (ATSR) instruments onboard ERS-1 and ERS-2.

The choice of the simple model was a consequence of the limited number of directional observations provided by ATSR: with just two view angles and two wavelengths, the model used should not have more than four parameters. Moreover, the information provided by the two wavelengths is limited because it depends on the spectral emissivities of foliage and soil which have to be known a priori. More realistic models and algorithms require a better directional sampling, such as proposed for the ESA Land Surface Processes and Interactions Mission which would provide observations at seven view angles.

2. Background

2.1. Origin of TIR Radiance Anisotropy

Anisotropy is observed, for example, when sea surface wind produces wavelets leading to a variation of surface emissivity with direction [Masuda et al., 1988; François and Otière, 1994]. Here a clear distinction can be made between emissivity and surface temperature, which is very uniform. Something similar would be found with, for instance, ice surface [Rees and James, 1992].

A second example is the situation with coarse resolution instruments, such as NOAA/AVHRR, over land. In this case the bidirectional reflectivity in the midinfrared (3-5 μm) window can be determined using the methods described by Li and Becker [1993]. An angular variation of the “effective” emissivity has been observed and can be accounted for using simple phenomenological models [Nerry et al., 1998]. With a few parameters it is possible to represent the angular variation of a macroscopic surface property, for example reflectance or emissivity, although its precise physical interpretation may be difficult. As a third example, the TIR exitance from a canopy may exhibit anisotropy as is shown below. Hence multangular measurements are needed to document this variation and incorporate it into the retrieval of the hemispheric longwave flux. In the context of Earth observation from space, where geophysical variables are determined from the top of atmosphere (TOA) radiance, the observed directional TOA TIR radiance results from a combination of surface directional TIR exitance and atmospheric absorption effects.

The directionality of TIR radiance is due to the following: (1) Radiance exiting in different directions has followed different paths (i.e., sums up different contributions); (2) Different proportions of elements fill the instantaneous field of view (IFOV) of the sensor for different view directions.

Several studies provide evidence of large angular variations of the brightness temperature of a vegetated surface at small (local) scale. The difference between foliage and soil temperature depends on the structure of the canopy, soil moisture, and the solar elevation. Jackson and Idso [1975] found differences between bare soil and air temperature as large as 27°C. For a soybean canopy with 35% ground cover, the soil temperature exceeded the canopy temperature by 11°C and was 15°C higher than air temperature [Kimes, 1980]. Kimes and Kirchner [1983] observed in a cotton field that the difference in radiative temperature between the 0° (mixture of vegetation and soil) and the 80° (vegetation only) zenith view angles was 16.2°C around noon. In the early morning, the difference between the 0° and the 80° zenith view angles was only 0.9°C.

Such measurements have been tentatively used to help model the energy fluxes in the soil–vegetation–atmosphere system [Kimes, 1980; Kimes et al., 1980; Kimes and Kirchner, 1983; Paw U, 1991; Logouarde et al., 1995; Smith et al., 1996]. However, at point scale, direct or inverse detailed deterministic modeling is virtually impossible, since the system must be characterized in an extremely detailed manner. Some degree of spatial integration is needed, in which case exploiting (inverting) TIR directional radiance relies on simpler models of the system.

In radiometrically heterogeneous systems, effective emissivity and effective temperature at a given scale may be defined in different ways, and values obtained vary with the definition [Becker and Li, 1995; Norman and Becker, 1995] due to the nonlinearity of the Planck’s law. Moreover, effective emissivity and effective temperature are to some extent wavelength dependent.

The determination of component temperatures, i.e. foliage and soil, would contribute significantly to improve current models of heat exchange at heterogeneous land surfaces in the context of atmospheric modeling [Dolman, 1993]. Inverting directional TIR radiance aims at retrieving the two variables separately [Norman et al., 1995; Menenti et al., 1999; Jia et al., 2000].

2.2. Modeling of TIR Directional Radiance From Vegetation-Covered Surfaces

Several models have been proposed and developed to describe and handle this angular effect. They can be loosely grouped in three categories.

2.2.1. Simple geometric (deterministic) model of the system. This approach applies to structured vegetation such as row crops, tree lines, and patches. Inasmuch as geometry is known, the system can be simplified and described with a small number of known parameters, for example, height, width and spacing of elements, soil emissivity, and vegetation emissivity [Sutherland and Bartholic, 1977; Kimes et al., 1981; Kimes, 1983; Sobrino et al., 1990; Sobrino and Caselles, 1990; Caselles et al., 1992]. Attempts to incorporate a coupling with the down-welling atmospheric radiation have been scarce [Colton, 1996].

This modeling approach is quite useful for sensitivity studies or to assess the feasibility of the retrieval coupled to the atmospheric correction requirements. Except when the geometry is accurately known or can be inferred from other measurements (also from satellite), usefulness of this type of model is, however, limited since it cannot deal with the physical processes within the system, and model inversion is very sensitive to uncertainties in system properties.
2.2.2. Radiative transfer within the canopy. This approach applies to systems that can be described statistically and using biome characteristics. Models in this domain try to solve radiative transfer in the canopy with atmospheric and soil as boundary conditions, assuming plant type and distribution, plant architecture, LAI (total, horizontally / vertically projected), Leaf Inclination Distribution Function (LIDF), etc.). Examples of this approach were presented by Kimes [1981], Balick et al. [1987], McGuire et al. [1989], Norman and Chen [1990], Ottermann et al. [1992, 1995], Smith and Goltz [1995], Smith et al. [1996], and Ottermann et al. [1999]. Soil temperature, leaf temperature, and temperature gradient within the canopy may either be assumed or be solved for simultaneously. Observed TIR anisotropy may reveal whether there exists a temperature gradient within the canopy. However, interpretation of directional radiance implies that all parameters of the system are known or can be accurately retrieved from other measurements, for example, from satellite in the visible, near infrared (NIR) and shortwave infrared (SWIR) domains.

Since the fluxes within the canopy are coupled to the flux above the canopy, the micrometeorological parameters have to be known. It turns out that the surface TIR directional effect is quite sensitive to ambient conditions [Stoll et al., 1998]. Thus for a given biome, the TIR-emitted radiance may reverse the sign of its angular variation with zenith angle (i.e. decrease or increase with increasing zenith angle), or even show no variation at all.

This category of models may not lead to efficient algorithms to retrieve land surface properties. Nevertheless, radiative transfer models are extremely useful for (1) evaluating the order of magnitude of the angular effect that can be expected and (2) comparing what is observed with outputs of models. It is worth noting that the modeled anisotropy is in case large, no more than a few Kelvins only if radiances is observed at large (> 60°) zenith angles in addition to nadir viewing.

2.2.3. Radiative transfer in an inhomogeneous thick vegetation layer. This can be statistically described by an angle-dependent “gap fraction” or “gap frequency” $P(\theta)$ [Nilson, 1971]. This approach represents an intermediate situation between the two categories mentioned above. It allows the directional TIR radiance to be described as a weighted (by $P(\theta)$) contribution of vegetation radiance (foliage radiance) and soil radiance. Inverting directional TIR radiance may be used to retrieve vegetation temperature and soil temperature, assuming, for instance, an angle dependent canopy emissivity. A detailed and comprehensive discussion of direct and inverse modeling is found in the work of François and Ottlé [1997].

The advantage is that the gap fraction can be correlated with measurements of directional spectral radiance in the visible-NIR domain [Baret et al., 1993, 1995]. Hence a combination of measurements in the solar-reflected domain and in the thermal infrared domain may be of great value to retrieve soil and foliage temperatures. More accurate estimates of the gap fraction may be obtained with a more precise sampling of the bidirectional reflectance distribution function (BRDF), which is useful to determine the leaf inclination distribution function (LIDF).

3. Theory

Neglecting the cavity effect in the canopy, the radiometric surface temperature $T_{\text{rad}}$ can be related to component temperatures by a simple linear mixture model [Norman et al., 1995] as

$$e(\lambda)T_{\text{rad}}(\theta, \lambda) = f_v(\theta)e_v(\lambda)T_v^\theta + f_s(\theta)e_s(\lambda)T_s^\theta,$$

where $\theta$ and $\lambda$ are the zenith angle and the waveband, respectively; $\theta$ is the zenith view angle of the sensor, $f_v(\theta)$ and $f_s(\theta)$ are the fraction of vegetation, respectively, of soil in the field of view of the radiometer when looking at the surface at zenith view angle $\theta$, $f_v(\theta)$ depends on the type of vegetation and the architecture of the canopy. Assuming a random canopy with a spherical leaf angle distribution [Norman et al., 1995]:

$$f_v(\theta) = 1 - \exp \left[ -0.5 \frac{LAI}{\cos(\theta)} \right],$$

where $LAI$ is leaf area index. For nadir view, $f_v(\theta)$ is the fractional vegetation cover $f_v$. A radiometer placed at the surface measures the surface brightness temperature $T_{B0}(\lambda, \theta)$, and equation (1) can be rewritten as:

$$T_{B0}^\theta(\lambda, \theta) = f_v(\theta)e_v(\lambda)T_v^\theta + f_s(\theta)e_s(\lambda)T_s^\theta.$$
downwelling atmospheric emitted radiance to the surface reflected by the surface toward the sensor, and (3) the upwelling atmospheric emitted radiance. The radiative transfer equation in thermal bands can be written as

\[ B\left[T_{\lambda}(\lambda, \theta)\right] = \varepsilon(\lambda, \theta) B\left[T_{\text{at}}(\lambda, \theta)\right] r(\lambda, \theta) + R_{\text{atm}}(\lambda, \theta) + R_{\text{ref}}(\lambda, \theta), \]

where \( B \) is Planck function, \( \varepsilon(\lambda, \theta) \) is the surface emissivity, \( r(\lambda, \theta) \) is the total atmospheric path transmittance, \( R_{\text{atm}}(\lambda, \theta) \) is the upwelling atmospheric exitance, and \( R_{\text{ref}}(\lambda) \) is downwelling atmospheric exitance reflected by the surface. If expressing equation (4) in terms of surface brightness temperature, equation (4) becomes

\[ B\left[T_{\lambda}(\lambda, \theta)\right] = \varepsilon(\lambda, \theta) B\left[T_{\text{at}}(\lambda, \theta)\right] r(\lambda, \theta) + R_{\text{atm}}(\lambda, \theta) + R_{\text{ref}}(\lambda, \theta). \]

One can obtain the corrected brightness temperature at surface \( T_{\text{at}}(\lambda, \theta) \) by inverting the Planck’s function \( B\left[T_{\text{at}}(\lambda, \theta)\right] \) in equation (5) after determining total atmospheric path transmittance and atmospheric emitted radiance at different wavelengths and zenith view angles. The atmospheric radiance can be computed using radiative transfer models such as MODTRAN.

### 4. Data

#### 4.1. Field Measurements

Field data used in this study are from three experiments on land surface processes: two carried in China, the Hei He International Field Experiment (HEIFE) [Mitsuta, 1993] and the Inner-Mongolia Grassland-Atmosphere Surface Study (IMGRASS) [Su et al., 1999], while the third one is the Southern Great Plains 1997 experiment (SGP 1997).

**4.1.1. IMGRASS.** The IMGRASS field experiment was carried out in Inner Mongolia between May and August 1998. This grassland area is located in the northeast of China; several species are present, and there is a significant variability in fractional vegetation cover. The overall objective of the experiment was to improve current understanding of the effects of changing vegetation on the hydrologic and heat cycle of the land surface and of surface-cloud interactions. More specific observational objectives were to provide flux measurements of water, heat, and trace gases over various scales and to develop validated remote sensing algorithms (Table 1). The sites of the present study were Baiyinsunmu (site 4) with sparse vegetated cover, a so-called degraded prairie, and site 6 with a short-grass cover.

During the period of July 26-31, 1998, radiative surface temperature was measured at site 4 using an IR-AH portable digital radiation thermometer operating in the spectral window 8-13 μm, temperature range [-50, +100°C], accuracy ± 2 K with \( T < 20^\circ\text{C} \), footprint diameter equal to [distance/50] (m), and an emissivity of 1. Observations at nadir, 23° and 52° zenith view angle were designed to obtain directional surface brightness temperature. The measurement height at nadir is 1.5 m, corresponding to a footprint diameter of about 3 cm. Because of this small field of view the sensor was mounted to observe bare soil only when at nadir. A leaf area index (LAI) of 0.5 was determined by counting grass leaf area in a meter square [Su et al., 1999].

**4.1.2. HEIFE.** The large-scale field experiment HEIFE was carried out in the arid zone of northwest China during several years (1989-1995). In the area, long-term measurements (Table 1) were done by means of towers, radiometers, automatic weather stations, and by means of additional eddy correlation and Bowen ratio devices during several short-term intensive observation periods. For this study we selected one of the main HEIFE sites, named Zhang-Ye located in the central part of a large oasis with crops such as beans, corn with orchards covering a more limited area, and windbreaks distributed around it. At the 1 km spatial resolution of ATSR this area is relatively homogeneous. Low-level radio-sounding measurements were carried out to obtain more detailed information on the atmospheric boundary layer than the one provided by standard radiosoundings.

At HEIFE and IMGRASS sites, meteorological standard radiosoundings closest to the satellite passing time were collected to determine atmospheric correction. Surface brightness temperatures were also measured using a radiometer (EKO Thermo-Hunter) operating in the spectral
range 7-20 μm with a radiometric resolution 0.1 °C and mounted at a 1.5 m height with a zenith view angle 2° both at HEIFE site and IMGRASS site 6. At IMGRASS site 4 an Eppley pyrgeometer (spectral range 4 μm to 50 μm) was used.

4.1.3. SGP 1997. The SGP 1997 specific radiosonde data (atmospheric pressure, temperature, and relative humidity profiles) collected at different locations named a, c, e located in the south-eastern part of the study area (around the "Central Facility" site of the SGP 1997 experiment) have been provided by T.J. Jackson at USDA ARS Hydrology Laboratory. One standard meteorological sounding has also been obtained from the SGP website at http://www.joss.ucar.edu/cgi-in/codiac/fr_form/id = 25.001, although the location of this sounding is located some 250 km out of the SGP study area.

4.2. Remote Sensing Data

ATSR-1 observations on August 19, 1991 were collected for the HEIFE area, ATSR-2 on June 14, 1998, for the IMGRASS area, and on July 1, 1997, for the SGP 1997 area. All ATSR sensors acquire dual-view angle data (approximately 0° and 53° at surface) in four channels for ATSR-1 and seven channels for ATSR-2. The two thermal bands in ATSR-1/2, with central wavelengths at 11 μm (10.8 μm for ATSR-1) and 12 μm, are employed in our study. The nominal noise equivalent temperature difference (NETD) of ATSR-2 for IRT channels is 0.04 K. The standard ATSR-1/-2 nominal accuracy of surface temperature estimates based on ATSR radiances. This criterion implies that directional effects smaller than the accuracy of observations are neglected.

5.2. Data Screening

The inversion of \( T_s \) and \( T_v \) is based on the assumption that the change of surface radiometric temperature with view angle is only caused by the changing fraction of vegetation cover in the field of view of the radiometer. Therefore a preanalysis is made to evaluate the quality of ATSR directional brightness temperature prior to retrieving \( T_v \) and \( T_s \) from the brightness measurements. Three cases can be distinguished which cannot be used in the inversion of \( T_v \) and \( T_s \), namely,

5.2.1. \( T_{no}(\lambda, \text{nadir}) - T_{no}(\lambda, \text{forward}) < 0 \). In the case that clouds fall in the field of view of the radiometer with the sensor looking at the surface at nadir view angle, while fewer or no clouds exist in the forward view, \([T_{no}(\lambda, \text{nadir}) - T_{no}(\lambda, \text{forward})] < 0 \) may be observed (see Figure 1a). This situation may also be observed because of heterogeneity, that is, a large fraction of vegetation is observed at nadir, while it is mixed with a large fraction of bare soil in the forward view. Observations meeting this criterion, i.e., \([T_{no}(\lambda, \text{nadir}) - T_{no}(\lambda, \text{forward})] < 0 \), are not considered in our study.

5.2.2. \( 0 < T_{no}(\lambda, \text{nadir}) - T_{no}(\lambda, \text{forward}) < 0.5 \) K. This happens when the surface is rather homogeneous with either bare soil or complete canopies. In this case, directional effects in the surface temperature are not significant. Full canopies exist most probably in the HEIFE area, and bare soil surface exists in the IMGRASS area. The threshold \( T = 0.5 \) K is the nominal accuracy of surface temperature estimates based on ATSR radiances. This criterion implies that directional changes smaller than the accuracy of observations are neglected.

5.2.3. \( T_{no}(\lambda, \text{nadir}) - T_{no}(\lambda, \text{forward}) >> 0 \). Field measurements of directional radiometric temperature done during IMGRASS show that the mean difference in \( T_{no} \)
between nadir and forward (52° for the field measurements) views was 2.6 K. *Kimes and Kirchner [1983]* found a 16.2°C difference between the 0° and 80° zenith view angles at noon and a 0.9°C difference in the early morning over a cotton canopy 44 cm high with a mean row spacing of 1 m. In their case the large difference at low solar zenith angle is due to the fact that the fractions of sunlit soil or shaded vegetation change significantly with a large view angle for a row canopy. *Lagouarde et al. [1995]* observed a difference of up to 3.5 K for a corn canopy and 1.5 K for grass (20 cm high) with a view zenith angle between 0° and 60° and around solar noon.

For an oasis in the HEIFE area, where the dominant crops are corns and beans and the IMGRASS area with sparse short grass, the difference in $T_\alpha$ between nadir and forward view should not be larger than 10 K, for instance. Much larger differences in $T_\alpha$ between nadir and forward view are probably caused by the fact that there are clouds in the forward view but none or fewer in the nadir observations (see Figure 1b). The pixels in the three categories described above were not considered when retrieving $T_v$ and $T_s$ from ATSR directional brightness temperature measurements in our study.

### 5.3. Retrieval of Vegetation and Soil Temperature

With measurements of brightness surface temperature at two view angles, $T_\theta (\lambda, \theta)$, we can rewrite equation (3) as

$$T_\theta (\lambda, \theta_1) = \left[ f_\theta (\theta_1) e_v T_v n(\lambda) + f_\theta (\theta_1) e_s T_s n(\lambda) \right] \langle \alpha \rangle,$$

$$T_\theta (\lambda, \theta_2) = \left[ f_\theta (\theta_2) e_v T_v n(\lambda) + f_\theta (\theta_2) e_s T_s n(\lambda) \right] \langle \alpha \rangle,$$  

where $n(11)$=4.5, $n(12)$=4.2. At wavelengths in the range 1.1 µm to 12 µm the spectral emissivity of foliage is rather high and constant. Reliable estimates of $e_v$ can be found in, for example, *Rubio et al. [1997]*.

After obtaining the atmospherically corrected surface brightness temperature at two angles and two channels, $T_\theta (\lambda, \theta_0)$, from an ATSR image, we can derive $T_v$, $T_s$, LAI, and $e_s$ by rewriting equations (6) and (7) as four equations with four unknowns $T_v$, $T_s$, LAI (or $f_v$), and $e_s$ ($=e_v-e_s$):

$$T_\theta (1, 0) = \left[ f_\theta (0) e_v T_v n(1) + f_\theta (0) e_s T_s n(1) \right] \langle \alpha \rangle$$

$$T_\theta (1, 53) = \left[ f_\theta (53) e_v T_v n(1) + f_\theta (53) e_s T_s n(1) \right] \langle \alpha \rangle$$

$$T_\theta (2, 0) = \left[ f_\theta (0) e_v T_v n(2) + f_\theta (0) e_s T_s n(2) \right] \langle \alpha \rangle$$

$$T_\theta (2, 53) = \left[ f_\theta (53) e_v T_v n(2) + f_\theta (53) e_s T_s n(2) \right] \langle \alpha \rangle.$$

In this study we have used the same $e_v$ at both 1.1 µm and 12 µm, although different values might have been used. We have also neglected directional changes in $e_v$ and $e_s$, although this may be easily taken into account if the explicit dependence of $e_v$ and $e_s$ is known. The forward view angle, i.e., 53°, applies to the ATSR sensors. The solution of equation (8) is determined using a standard minimization algorithm to minimize the root-mean-square (rms) difference between estimated and observed brightness temperatures in the two channels and at the two view angles.
5.4. Validation

Validation of estimates of land surface variables based on radiometric observations from space at low spatial resolution is challenging for several reasons. (1) Most land targets comprise a mixture of different land surface types at a spatial resolutions of 1 km or lower; (2) the heterogeneity of the target requires the definition, estimation, and observation of effective values of required variables. These values apply to the entire target, and the relationship with a sample of local observations within the heterogeneous target is not very precise. The latter adds to the complexity of a validation experiment; (3) when using multi directional observations such as ATSR, a significantly larger target is observed in the forward than in the nadir view; (4) validation of estimates of foliage and soil temperature is even more challenging due to the rapid changes in time. In principle, one should measure leaf and soil temperatures of a rather large number of objects simultaneously to obtain the frequency distribution of both temperatures at the time of satellite overpass.

We did not consider it feasible to set up a proper validation experiment and followed a simpler approach. (1) The method to estimate foliage and soil temperature from measurements of directional brightness temperature was validated with local field measurements; (2) surface brightness temperatures inferred from ATSR observations were compared with all available field measurements; (3) the impact of errors in the atmospheric correction was evaluated by assessing how the frequency distribution of the difference between the forward and the nadir brightness temperature changed when using different procedures and assumptions to retrieve the bottom of atmosphere (BOA) brightness temperature; (4) the algorithm described above retrieves estimates of the leaf area index (LAI) besides foliage and soil temperature. This provides another opportunity to assess the consistency of our results by comparing the observed relationship between normalized difference of vegetation index (NDVI) (from ATSR red and near-infrared reflectance) and LAI (from directional brightness temperature) with similar relationships found in literature.

6. Results

6.1. Retrieval of $T_v$ and $T_s$, Case Study Based on Field Measurements (IMGRASS)

With the measurements of directional brightness surface temperature at three view angles, for example, 0°, 23° and 52°, $T_v$ and $T_s$ are retrieved using equations (6) and (7). The LAI of the observed target was measured, and it was 0.5 corresponding to $f_c=30\%$. This reduced the number of unknowns to 2, and a reduced system of two equations for each pair of view angles was used. The radiometer used for these measurements has only one band from 8 µm to 13 µm. Mean spectral emissivities were taken as 0.98 for vegetation and 0.95 for soil.

Theoretically, $T_v$ and $T_s$ can be derived using measurements of brightness temperature at any pair of view angles, i.e., $T_{bo}(0)$ and $T_{bo}(23)$, $T_{bo}(0)$ and $T_{bo}(52)$, and $T_{bo}(23)$ and $T_{bo}(52)$. In our study, the radiometer used had a small field of view and the footprint was 3 cm in diameter. The radiometer was placed so that only bare soil was seen in the field of view when measurements were made at nadir. $T_{bo}(0)$ is therefore the soil brightness temperature. To obtain $T_v$ from $T_{bo}(0)$, $e_v = 0.95$ was used. This value of emissivity was also used to retrieve $T_v$ and $T_s$, from $T_{bo}(23)$ and $T_{bo}(52)$ with equations (6) and (7). The agreement between retrieved and observed $T_s$ was good, with a rmsd (root mean square difference) of 0.8 K (Figure 2).

6.2. Impact of Errors in the Atmospheric Correction

The proposed approach to estimate foliage and soil temperatures requires the determination of bottom of atmosphere (BOA) spectral directional radiance. Uncertainty in the knowledge of the atmospheric state affects the accuracy of the retrieved radiance. On the other hand, there is a simple relation between the impact of atmospheric state and the observations at two view angles, when the atmospheric state is known. We have analyzed the impact of uncertainty on the knowledge of the atmospheric state by comparing the frequency distribution of $[T_{bo}(\lambda, 0) - T_{bo}(\lambda, 53)]$ as obtained past the data-screening procedure described above in the following three different cases (Figure 3): (1) atmospheric transmittance and path radiance calculated (MODTRAN [Kneizys et al., 1996]) with actual radio soundings; (2) same as case 1, but atmospheric profile modified to give a 20% increase in the column water content; and (3) same as case 2, but for a 20% decrease.

The range of the $T_{bo}$ difference (nadir minus forward) is limited by the data screening bounds described above. The data screening does not modify significantly the distributions for the 11 µm case, while it has a clear impact on the 12 µm case, where it cuts out part of the lower-end tail. On the other hand, the impact of errors in the atmospheric correction appears limited, since the distributions are similar in the three cases. We note that the distributions relate to all valid (i.e., past the screening) observations used to retrieve soil and vegetation temperatures.

The effect of aerosols has been calculated using MODTRAN version 3.5 for a rural aerosol type and a visibility of 23 km. We have analyzed the impact of errors in the selection of the type of aerosol and in the estimation of visibility.

We have taken as a reference the atmospheric sounding
used in the analysis of the SGP 1997 ATSR data set. We have then computed at-satellite brightness temperatures at both view angles and wavelengths for a given set of arbitrary at-surface brightness temperatures. These at-satellite "observations" have been then used to determine at-surface brightness temperatures for the following situations: (1) aerosol type: rural, urban, and maritime; (2) visibility: 5, 15, and 23 km; (3) initial at-surface brightness temperatures: 301.2, 306.2, 311.2, and 316.2 K.

We have finally computed (Table 3) the standard deviation of at-surface brightness temperature for each ATSR channel and each view angle. The results show that the selection of aerosol type is not very critical, except for the lowest visibility. Under these conditions, however, observations from space are not usable for land surface studies.

6.3. Impact of Spatial Heterogeneity on the Retrieved Soil and Foliage Temperatures

The difference in the ATSR footprint at the ground in the nadir and forward views is significant: 1 km × 1 km at nadir; 1.5 km × 2.0 km in the forward view. When observing heterogeneous land surfaces, a significantly different target may be observed in the forward view only. To estimate soil and foliage temperatures, we have to assume that the target is statistically homogeneous in both view directions and that anisotropy in observed radiance is due to the varying fractions of soil and foliage in the IFOV.

We have done a simple evaluation of this effect for two situations: (1) full canopy in the nadir view surrounded by bare soil viewed in the forward direction only; (2) partial
Table 3. Effects of Aerosol on the Ground Brightness Temperature Retrieval

<table>
<thead>
<tr>
<th>$T_v$</th>
<th>$\sigma T_{B1}(n)$</th>
<th>$\sigma T_{G1}(f)$</th>
<th>$\sigma T_{G2}(n)$</th>
<th>$\sigma T_{G2}(f)$</th>
<th>$\sigma T_{B1}(n)$</th>
<th>$\sigma T_{B1}(f)$</th>
<th>$\sigma T_{G1}(n)$</th>
<th>$\sigma T_{G1}(f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>301.2</td>
<td>0.065</td>
<td>0.278</td>
<td>0.058</td>
<td>0.254</td>
<td>0.019</td>
<td>0.072</td>
<td>0.017</td>
<td>0.066</td>
</tr>
<tr>
<td>306.2</td>
<td>0.219</td>
<td>0.529</td>
<td>0.196</td>
<td>0.481</td>
<td>0.043</td>
<td>0.112</td>
<td>0.042</td>
<td>0.101</td>
</tr>
<tr>
<td>311.2</td>
<td>0.373</td>
<td>0.780</td>
<td>0.335</td>
<td>0.707</td>
<td>0.072</td>
<td>0.158</td>
<td>0.070</td>
<td>0.143</td>
</tr>
<tr>
<td>316.2</td>
<td>0.523</td>
<td>1.025</td>
<td>0.471</td>
<td>0.930</td>
<td>0.101</td>
<td>0.203</td>
<td>0.098</td>
<td>0.186</td>
</tr>
</tbody>
</table>

$\sigma$ (o) denotes the standard deviation of temperature.

canopies in combination with spatial variability of the fractional vegetation cover.

For situation 1, a simple calculation [see Stoll et al., 1998] shows that a 10% bare soil fraction in the forward IFOV (no soil in the nadir IFOV) is sufficient to cancel the anisotropy effect inherent to the target observed in the nadir view. For situation 2, a 10% error on the forward fractional vegetation cover gives an error of 2 K on foliage temperature. This analysis is relevant when sharp boundaries are observed between different land cover types, such as the Gobi desert surrounding the Zhang-Ye oasis in the Hei He basin (HEIFE area).

6.4. Retrieval of $T_v$ and $T_s$, Case Studies Based on ATSR Data

The component temperatures of heterogeneous land targets, $T_v$ and $T_s$, were derived using the inversion method described in section 5. In the HEIFE area (Figure 4) the peak of $T_v$ appears around 36°C, while a larger range is observed for $T_s$ which varies between 35 and 50°C. On the contrary, in the IMGRASS site 4 (Figure 5), $T_s$ has a peak around 46°C, $T_v$ is scattered between 20 and 40°C. This can be explained by the different surface types and fractional vegetation cover in these two areas. The Zhang-Ye oasis in the HEIFE area comprises irrigated crops: sufficient water supply keeps $T_v$ rather low and closer to the air temperature, irrespective of the fractional vegetation cover. The latter determines the variability of $T_v$. This is confirmed by the wider range of $T_v$ values in the IMGRASS, site 4 (Figure 5), where LAI is more variable and lower than in the HEIFE area.

The complex and combined impact of spatial heterogeneity and of LAI is clearer in the observations for the two SGP 1997 subsites (zones A and B). The LAI is lower in zone A (Figure 6), and this appears to correspond with larger differences between $T_v$ and $T_s$. On the other hand higher LAI values are observed in zone B (Figure 7), and this corresponds to lower $T_v$ and higher $T_s$ in comparison with zone A.

The LAI values shown in Figures 4 through 7 were retrieved by solving equation (8). Because of the high sensitivity of our $T_v$ and $T_s$ estimates to the value of LAI, we propose to use LAI to assess the skill of our algorithm. The low spatial resolution of ATSR makes the validation of LAI as challenging as the validation of $T_v$ and $T_s$. In the case of LAI, however, we can take advantage of additional and independent measurements provided by ATSR-2, namely, spectral radiances in the visible and near-infrared region to obtain independent estimates of LAI.

We have performed a simple preliminary evaluation by determining a NDVI versus LAI relationship with our ATSR-2 measurements and comparing it with similar relationships given in the literature (Figure 8). This analysis could only be done for the SGP 1997 data set, since the HEIFE case study was done with ATSR-1 data, which did not have the visible and near-infrared channels, and the IMGRASS data set was affected by major miscalibration errors in these channels. With the exception of four outliers, our data points give a
NDVI versus LAI relationship similar to the ones given in literature [Myneni et al., 1999]. We regard this result as an indication of the satisfactory quality of our LAI estimates based on the directional change in $T_B$ and therefore of our estimates of $T_v$ and $T_s$.

We compared the estimates of $T_v$ and $T_s$ with field measurements of $T_B$ for the HEIFE and IMGRASS case studies (Table 4). No such field measurements were available for the SGP 1997 case. In the HEIFE case, the field measurements were done above a dense, complete canopy in the oasis of Zhang-Ye. The sensor was mounted to measure canopy temperature. As expected, the ATSR forward view (higher foliage fraction in the field of view) was closer to the field measurements and to the estimated foliage temperature. The nadir ATSR $T_B$ was significantly higher than the forward $T_B$ and this gave a $T_s$ value significantly higher than the foliage temperature $T_v$. In the case of IMGRASS the comparison of the ATSR estimates with field measurements is far less straightforward. The measurements shown in Figure 2 cannot be used easily because of the small field of view of the radiometer used, which gives observations at the very local scale of within-canopy spatial variability. The $T_{\text{sky}}$ values in Table 4 were obtained using broadband, large field of view thermal infrared radiometers. The instruments used in the HEIFE experiment and IMGRASS site 6 give total radiant flux density in the 7 $\mu$m to 20 $\mu$m spectral region and the one used in the IMGRASS site 4 experiment in the 4 $\mu$m to 50 $\mu$m. Although the large field of view of these instruments averages exitance over the very local spatial variability, the difference between both the ATSR nadir and the forward $T_B$ remains large. This may be due to differences in emissivity between the narrow band ATSR observations at 11 $\mu$m and 12 $\mu$m and the broadband radiometers.

If we take into account that errors on $T_v$ and $T_s$ (see background) are of the order of 2 K, the distribution (Table 5) of $T_v$ and $T_s$ is near normal in most subareas, as indicated by the relatively small differences among mean, modus, and median (not shown). Air temperature in HEIFE and IMGRASS sites was measured at 2 m height. Spatial variability of estimated $T_v$ and $T_s$ was large in all cases as shown by the large differences between averages and the values observed at the sites (pixels) where the field

**Figure 5.** Vegetation and the soil temperature and leaf area index (LAI) derived for Inner-Mongolia Grassland Atmosphere Surface Study (IMGRASS) site 4.

**Figure 6.** Vegetation and the soil temperature and leaf area index (LAI) derived for Southern Great Plains (SGP) 1997 zone A.
measurements were collected. Estimated foliage temperature was higher than air temperature. In the IMGRASS case, when taking into account the range of estimated $T_v$, the lower observed foliage temperatures (e.g., average minus one standard deviation) are close to air temperature as expected. In the case of HEIFE the difference between foliage and air temperature was larger than expected, given the impact of irrigation on the heat balance of crops in the study area. These results have implications for the modeling of heat transfer at partial canopies and heterogeneous land surface in general. Some of these implications were discussed by Jia et al. [2000] who describe a dual-source model of sensible heat transfer which makes use of estimated soil and vegetation temperatures obtained as described in this paper. Moreover, we are not discriminating (see equation (1)) between warmer sunlit and cooler shadowed leaves. Our estimated foliage temperature may therefore be higher than air temperature because of our simplified model.

7. Discussion

Two general conclusions may be drawn from the results presented above. First, the simple mixture model used in our study to interpret observations of directional exitance appears valid both in the conditions of the IMGRASS field experiment and in the SGP 1997 study. We showed that the simple mixture model gives accurate estimates of soil surface temperature using the field measurements of directional exitance collected during the IMGRASS experiment. With regards to the large area case studies it was not feasible to validate our ATSR estimates of component temperatures. We provided indirect evidence of the applicability of the simple mixture model by showing that estimates of LAI, obtained by inverting this model, are consistent with NDVI versus LAI relationships obtained as described in this paper. Moreover, we are not discriminating (see equation (1)) between warmer sunlit and cooler shadowed leaves. Our estimated foliage temperature may therefore be higher than air temperature because of our simplified model.

Large differences were observed in all cases between foliage and air temperature when comparing air temperature with the ATSR estimates for the pixel collocated with the

![Figure 7](image_url)  
**Figure 7.** Vegetation and the soil temperature and leaf area index (LAI) derived for SGP 1997 zone B.

![Figure 8](image_url)  
**Figure 8.** Leaf area index retrieved from ATSR directional radiometric observations (equation (8)), SGP 1997 zones A (squares) and B (circles); normalized difference of vegetation index (NDVI) versus LAI relationships derived by radiative transfer modeling for different biomes [Myneni et al., 1999].
field measurements. When taking into account the spatial variability of $T_v$, however, estimated foliage temperatures are consistent with observed air temperature. In the IMGRASS case, observed air temperature was close to mean $T_v - \sigma$, with a fraction of estimated foliage temperature, i.e., between $(T_v - \sigma)$ and $(T_v - 2\sigma)$ lower than air temperature.

Smaller differences between foliage and bare soil temperature were observed at higher LAI values (HEIFE, Zhang-Ye oasis) compared with areas having lower LAI (SGP 1997, zone A). Such findings depend strongly on radiative forcing and boundary layer conditions. An in-depth analysis of such interactions is necessary to understand these complex interactions and role of fractional vegetation cover (or LAI) in determining heat exchanges between land and atmosphere by controlling the surface temperature of foliage and soil.

In all cases the frequency distributions of both $T_v$ and $T_s$ were near-normal, taking into account errors on $T_v$ and $T_s$ of the order of 2 K. This indicates statistical homogeneity of the land targets studied. Differences between mean and modus were larger for the distribution of $T_v$. This result indicates that some knowledge of the actual spatial distribution of surface temperature is necessary to determine aggregated values of surface temperature such as needed in the context of weather and climate modeling. Differences between $T_v$ and $T_s$ were comparable with values given in literature (see section 2), independently of the statistics used to measure such difference.

Validation of estimates of $T_v$ and $T_s$ based on low-resolution data such as ATSR, remains challenging. We have compared our estimates with field measurements of brightness temperature done with different instruments and under different conditions. Our results highlighted challenges rather than providing answers. Our study does have a general implication in terms of the observational approach required for a validation approach. The anisotropy of exitance and the difficulty of estimating accurately the composite emissivity of the mixture of soil and foliage suggest to use field measurements of brightness temperature at a view angle selected to observe both soil and foliage. The field measurements should be done with a radiometer, having a large field of view and the same spectral range as the sensor used for the spaceborne observations. This would provide reliable observations to validate BOA estimates of exitance. Estimates of $T_v$ and $T_s$ could then be validated by calculating directional brightness temperature using the retrieved values of $T_v$, $T_s$, and LAI. We could not apply this approach, since our radiometers had the right spectral range but narrow field of view, or the required large field of view but a spectral range very different from the ATSR channels.

### 8. Summary and Conclusions

This study describes the evaluation of a simple mixture model to interpret directional measurements of exitance. Such directional spectral measurements have the potential of leading to fundamentally new insights on heat exchanges at heterogeneous land surfaces. We have applied this simple model to field measurements collected during the IMGRASS field experiment, to one ATSR-1 data set collected during the HEIFE experiment and two ATSR-2 data sets collected during the IMGRASS and SGP 1997 experiments.

The study underscores both the opportunities and the challenges of these novel spectral and directional observations. On the one hand, the analysis of accurate field observations of a well-identified target have shown that the simple mixture model is applicable and that it provides accurate estimates of component temperatures. On the other hand, the analysis of the three ATSR data sets underscored the challenges in this approach. The directional signal is marginally larger than experimental errors. The latter are due to two main sources: insufficient knowledge of atmospheric

### Table 4. Comparison Between Brightness (Nadir and Forward Observations), Vegetation and Soil Temperature From ATSR (11 µm Channel) and the Observed Surface Temperature in the Field

<table>
<thead>
<tr>
<th>Site</th>
<th>$T_v \pm \sigma$</th>
<th>$T_s \pm \sigma$</th>
<th>$T_{BO,N} \pm \sigma$</th>
<th>$T_{BO,P} \pm \sigma$</th>
<th>$T_{BO,obs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEIFE</td>
<td>33.1 ± 1.05</td>
<td>44.1 ± 3.97</td>
<td>34.1 ± 0.33</td>
<td>32.1 ± 0.37</td>
<td>32.6</td>
</tr>
<tr>
<td>IMGRASS, 4</td>
<td>34.1 ± 7.30</td>
<td>48.1 ± 0.44</td>
<td>43.8 ± 0.45</td>
<td>42.0 ± 0.74</td>
<td>38.2</td>
</tr>
<tr>
<td>IMGRASS, 6</td>
<td>30.8 ± 0.62</td>
<td>35.3 ± 2.20</td>
<td>32.3 ± 0.90</td>
<td>31.1 ± 1.10</td>
<td>29.6</td>
</tr>
</tbody>
</table>

The range indicated is ± $\sigma$.

### Table 5. ATSR-1 and ATSR-2 Data Analysis

<table>
<thead>
<tr>
<th>Site</th>
<th>$T_v$</th>
<th>$T_s$</th>
<th>$T_{surf,obs}$</th>
<th>$T_{air}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEIFE</td>
<td>35.56 ± 3.09</td>
<td>44.72 ± 3.87</td>
<td>36.2</td>
<td>48.6</td>
</tr>
<tr>
<td>IMGRASS-4</td>
<td>32.10 ± 5.11</td>
<td>42.90 ± 4.48</td>
<td>33.5</td>
<td>45.5</td>
</tr>
<tr>
<td>IMGRASS-6</td>
<td>28.83 ± 4.49</td>
<td>35.63 ± 2.81</td>
<td>30.3</td>
<td>38.5</td>
</tr>
<tr>
<td>SGP 1997 - A</td>
<td>22.38 ± 5.67</td>
<td>40.22 ± 3.70</td>
<td>20.9</td>
<td>41.3</td>
</tr>
<tr>
<td>SGP 1997 - B</td>
<td>27.96 ± 5.36</td>
<td>37.00 ± 5.97</td>
<td>30.2</td>
<td>33.4</td>
</tr>
</tbody>
</table>

Mean and modus of the vegetation and soil temperature distribution within selected subareas with observed surface temperature and air temperature; the range indicated is ± $\sigma$ (unit, $^\circ$C).
state and spatial heterogeneity in combination with the
different footprint of ATSR in the nadir and forward views.

We were not able to perform a proper validation of our
estimates of foliage and soil temperatures obtained with
ATSR observations. This would require: (1) collection of
field measurements with a radiometer having a large field of
view and spectral channels identical to the spectral channels
of ATSR; (2) a relatively large number of simultaneous field
measurements with a sufficiently large footprint to average
local heterogeneity. Our algorithm was validated with field
measurements of directional exitance. We have also shown
that our algorithm gives estimates of LAI consistent with
independent observations in the visible and near-infrared
spectral range and that field measurements of brightness
temperature are consistent with the estimates of foliage and
soil temperature.

We have focused the evaluation of our results on statistics
of the spatial distribution of foliage and soil surface
temperature. The distribution was near-normal in all cases,
although deviations from a normal distribution were larger for
the soil surface temperature. These results imply that accurate
spatial aggregation of surface temperatures requires some
knowledge of the frequency distribution within the area
selected for aggregation, such as a model grid in the context
of weather and climate modeling.

Estimates of component temperatures within
heterogeneous land targets provide an opportunity to improve
models of heat transfer at heterogeneous land surfaces. The
distribution of heat sources within the canopy must be taken
into account to avoid ad hoc empirical adjustments of
parameters in heat transfer models. Estimates of foliage and
soil temperatures make it possible to model separately the
soil-air and foliage-air heat exchanges using more realistic
parameterizations of heat transfer.

Remote sensing of directional exitance is a new and
emerging area of research. Many of the obstacles met in this
study could be overcome by using observations at higher spatial
resolution and at a larger number of view angles. The
European Space Agency is studying a Land Surface Processes
and Interactions Mission as a possible candidate for an Earth
Explorer Core Mission due to fly in the time frame 2003-
2005. The payload is an imaging spectrometer covering the
region 0.45 to 2.35 μm with two additional channels (8.0-
8.5 μm; 8.6 – 9.1 μm). An agile spacecraft has been designed
to allow for user-selected directional sampling in both along-
and across-track directions. Such a concept would provide
unique multiangular observations of exitance and with that
a fundamentally new understanding of heterogeneous terrestrial
targets.

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