SPECTRAL EMISSIVITY MEASUREMENTS OF LAND-SURFACE MATERIALS AND RELATED RADIATIVE TRANSFER SIMULATIONS

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ABSTRACT
Spectral radiance measurements have been made in the laboratory and in the field for deriving spectral emissivities of some land cover samples with a spectroradiometer and an auxiliary radiation source in the wavelength range 2.5-14.5 μm. An easy and quick four-step method (four steps to measure the sample and a diffuse reflecting plate surface under sunshine and shadowing conditions, respectively) has been used for simultaneous determination of surface temperature and emissivity. We emphasized in-situ measurements in combination with radiative transfer simulations, and an error analysis for basic assumptions in deriving spectral emissivity of land-surface samples from thermal infrared measurements.

INTRODUCTION
As is well known, remote sensing of land surface temperature (LST) usually requires certain assumptions about, and knowledge of, spectral reflectivity and emissivity of natural terrestrial surfaces. Also, the surface emissivity over the whole thermal infrared (TIR) wavelength range is needed for accurate calculation of long wave radiation from a surface after its temperature has been estimated. Recently, Salisbury et al. have published quantitative directional hemispherical infrared spectra for mineral samples in the 2.1-25 μm spectral range /1/, and for terrestrial material samples in the 8-14 μm atmospheric window /2/. Nerry et al. /3/ used a large "double-box" to cover an area of 1 m² in flat uniform fields to measure spectral averaged emissivities in the 10.5-12.5 μm band. Becker et al. /4/ used an active method to measure TIR bidirectional reflectivity and effective emissivity of heterogeneous surfaces (a grass-land sample, for example) in the atmospheric window 8-14 μm.

The Moderate Resolution Imaging Spectroradiometer (MODIS), being developed for flight on the first EOS platforms scheduled for operation in the late 1990's, is a keystone instrument for global studies of atmosphere, land, and ocean processes /5/. It has a total of 36 bands: bands 1-19 in the visible and near infrared range, and bands 20-36 in the thermal range from 3 to 15 μm. It uses 12 bits for quantization and the TIR bands have an IFOV of about 1000 m at nadir. The calibration accuracy specification is better than 1% absolute in the emitted thermal infrared. Seven thermal bands shown in Table 1 could be used for better estimations of SST and LST. Band 21, with a large dynamic range, is designed for forest-fire detection and volcano monitoring. MODIS is a unique spaceborne instrument which has three bands in the medium wavelength infrared range from 3.5 to 4.1 μm so that it may be possible to make a multiband correction of solar radiation effects on these bands for development of accurate daytime SST and LST algorithms or to estimate medium wavelength infrared emissivity of various land covers from space after the surface temperature is estimated from the other three bands in the atmospheric window 8-14 μm. As shown in Table 1, the band widths are much narrower than AVHRR bands. Ground-based measurements of spectral reflectivity and emissivity of land cover at a high spectral resolution are necessary in order to develop and to validate EOS/MODIS LST algorithms /6, 7/. The main purpose of this paper is to describe a method for ground-based TIR measurements which is essentially comparable to satellite measurements.

TABLE 1. Specifications of MODIS Bands for Surface Temperature Measurements

<table>
<thead>
<tr>
<th>Band no.</th>
<th>Center (μm)</th>
<th>Width (μm)</th>
<th>NEAT (°K)</th>
<th>F_max (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.75</td>
<td>0.18</td>
<td>0.05</td>
<td>335</td>
</tr>
<tr>
<td>21</td>
<td>3.75</td>
<td>0.05</td>
<td>5</td>
<td>700</td>
</tr>
<tr>
<td>22</td>
<td>3.98</td>
<td>0.06</td>
<td>0.07</td>
<td>324</td>
</tr>
<tr>
<td>23</td>
<td>4.06</td>
<td>0.06</td>
<td>0.07</td>
<td>324</td>
</tr>
</tbody>
</table>

BASIC ASSUMPTIONS IN EMISSIVITY MEASUREMENTS
Most laboratory and field emissivity measurements of terrestrial materials depend on the following basic assumptions: 1) The surface temperature does not change during the TIR measurement or the correlation between the surface temperature and variations in the external radiation source is negligible; 2) The surface emissivity does not change during the TIR measurement; 3) The surface is a Lambertian surface or a specular reflecting surface unless a complete set of bidirectional reflectance is also measured.

Regarding the first assumption, emitted spectral radiance L into direction μ = cosθ at wavelength λ from a surface at thermodynamic temperature T_s is

(391)
Then the averaged TLR data should be used to derive the surface spectral emissivity. However, we can easily check this measurement at $T_s = 300°K$ than at $T_s = 1000°K$. Usually, it is difficult to check the surface temperature change during real measurements. So we have to pay great attention to the first assumption in measurements made at a relative low surface temperature.

Regarding the second assumption, although the surface emissivity usually does not change during measurements for inorganic samples, it may be a problem for measurements of terrestrial organic samples such as soils, vegetation and tree leaves, because their moisture conditions may change during measurements, especially if measurements are made at high temperature conditions or if a powerful external radiance source is used in order to obtain a high signal-to-noise ratio. However, we can easily check this assumption by repeated measurements. In order to avoid emissivity variations, it is better to use a low-power external radiance source and to make many infrared measurements under natural conditions in the field. Then the averaged TIR data should be used to derive the surface spectral emissivity.

Regarding the third assumption, the best way is to make bidirectional reflectance measurements for a given land cover with an infrared goniometer at the wavelengths of interest in order to check whether the surface can be approximated by a Lambertian surface. In most cases, we use this assumption first, and then check its suitability by changing the incident direction of the external radiation source.

LABORATORY MEASUREMENTS

A multiwavelength pyrometer has been used at the NASA Lewis Research Center to measure the emissivity and temperature of a non-grey silicon carbide ceramic surface $B/$. The surface of a silicon carbide wafer sample is polished to a $10\mu m$ finish so that it behaves well as a specular reflecting surface. The sample surface is heated by allowing it to equilibrate in front of a black body furnace. Therefore, the above three basic assumptions are well satisfied for TIR measurements. The pyrometer consists of a spectral radiometer at wavelength range from 2.5 to $14.5\mu m$, an auxiliary radiation source which can be turned on and off (either manually or by mechanical chopping), and a computer for data acquisition and data processing. The auxiliary radiation source is a $20$ Watt infrared lamp regulated by a constant current power supply such that its typical light output rms ripple is $0.05\%$. It is also used as a black body for calibrating the TIR system. Spectral radiance measurements have been made in the laboratory for soil and sand samples. The soil and sand samples are initially at room temperature. Because surfaces of soil and sand samples are more like a Lambertian surface than the silicon carbide sample plate, the output of the auxiliary radiation source is too weak. A commercial radiative heater ($300$ Watt) of unknown temporal stability was used as an auxiliary radiation source. A diffuse reflecting gold plate was used to measure the spectra of the environmental radiation and the radiative heater. It was found to be difficult to obtain accurate spectra with the gold plate because its reflectivity pattern is no more Lambertian at large viewing angles. Since liquid nitrogen was used for cooling the HgCdTe detector, we tilted the forward looking spectral radiometer downward only by $30^°$ in order to prevent the liquid nitrogen from spilling out. This means that the viewing angle used in our measurements is about $60^°$ from the normal of the gold plate surface. One more difficulty was that the temperature was observed to change during measurements over a water surface even if the radiative heater was quickly turned on and off (or blocked manually). A thermocouple just beneath the water surface indicated the temperature change but there was no good way to measure the actual temperature change of the water surface and sand samples. Therefore, the first basic assumption is a serious problem in TIR measurements of these samples.

Atmospheric transmission measurements were made by locating a black body at temperature $764.4°K$ at different distances between $3$ m and $15$ m along a laboratory hall. According to atmospheric radiative transfer simulations using the LOWTRAN7/9, the transmission functions at wavelength $4$ m and $10$ m are larger than $0.995$ for this distance range. We can assume that there is no transmission change at these wavelengths over this distance range so that the geometric factor in the TIR measurement could be corrected. Measurement results from LOWTRAN7 are shown in Figure 1. It indicates clearly that the atmospheric effect for an optical path of $3-12$ m near the ground in the range $2.5-14.5\mu m$ except in the atmospheric windows $3.4-4.1\mu m$ and $8.5-10.5\mu m$ should be corrected in order to derive accurate surface emissivity in the whole spectral range from TIR measurements. Two different methods could be used for making atmospheric correction. In the first method, a black body at the same temperature as the target surface temperature and located at the same distance is measured at nearly the same time to find an optimum response function so that the atmospheric effect is correctly included in the response function. This is the best way, but it makes measurements very time-consuming. Another method is to measure surface air temperature and humidity simultaneously and then use these data in radiative transfer simulations to make the necessary adjustment of the response function. The second method makes field TIR measurements not so restricted as in the first method. However it will be more dependent on the accuracy of atmospheric radiative transfer simulations.

FIELD MEASUREMENTS

The same spectral radiometer system was used in TIR measurements at a grass land by the Lewis Research Center baseball field under clear-sky conditions in early Spring of 1992. Measurements were also made over...
a concrete surface. In order to reduce the radiation contributions from the spectroradiometer, computer system and the tripod which supports the instrument to the TIR measurements, the radiometer was located above the ground surface by 102 cm and was tilted down by only about 15-18°. The distance between the instrument and target surfaces was 3.65 m. We used the solar beam as an external radiation source in the following four-step method: step 1, measure the sample surface under sunshine; step 2, measure the sample surface under a shadow by blocking the solar beam; step 3, measure the diffuse gold plate surface under sunshine; step 4, measure the diffuse gold plate surface under a shadow by blocking the solar beam.

Use of the solar beam as an external radiation source has the following advantages: 1) It is natural and makes measurements easy; 2) The solar beam is a major part (>96%) of the total solar radiative flux to the Earth surface in the wavelength range 2.5-14.5 μm under clear-sky conditions; 3) The surface emissivity of the land cover usually does not change when it is moved from sunshine to shadow or the reverse; 4) The solar beam at the surface is only effective for wavelengths shorter than 4.2 μm and it is negligible for 8-14.5 μm. Therefore, the environmental radiation (including solar and sky radiations) in 8-14 μm exposed on the sample surface does not change after the solar beam is blocked. So the radiance from the surface only changes with the surface temperature. As a result, the change of surface temperature may be well estimated from the radiance change.

The measured radiance from land surfaces changes with time due to the random noise of the measurement system, surface temperature change, and stochastical changes in the atmospheric state. In the atmospheric windows 3.4-4.1 and 8-13 μm, the first two reasons are the dominant factors. A temporal analysis of the concrete surface TIR data at wavelengths 3.75 and 12 μm shows radiance standard deviations, dL(λ)/L(λ), of 2.3% and 0.2% respectively under sunshine, or 5.8% and 0.3% under shadowing. According to Eq. (2), \( \eta(3.75 \mu m)/\eta(12 \mu m) \approx 2.5 \), but the ratio between the measured dL/L at 3.75 μm and the measured dL/L at 12 μm is larger than 19 in the shadowing condition. It is estimated that the TIR instrument has a lower signal-to-noise ratio, about 20, at the shorter wavelength, 3.75 μm. A higher signal-to-noise ratio could be achieved by averaging many spectra, or equivalently, by using a slower scan speed. During TIR spectral measurements, the incident radiative flux onto the target surface can be monitored to estimate the external radiative flux and the accuracy of estimated surface temperature change on a display rate of 2 per second. We found that the mean radiance of the field measurements was 800 W/m² and the estimated standard deviation was 1-2 m/s during our measurements. This also suggests the necessity of averaging measurement data. At least 16 spectra were averaged before deriving surface temperature and emissivity values from TIR measurement data.

Now we consider how to estimate a change of the average surface temperature that occurs when a land surface is moved from sunshine to shadowing, or the reverse. We can estimate the surface temperature change by using its brightness temperature as follows. According to the definition, brightness temperature \( T_b \) is related to the surface emissivity and temperature by

\[
B(\lambda, T_b) = \frac{2hc^2}{\lambda^5} \left( e^{hc/kT_b} - 1 \right)
\]

It is easy to find the relation between the change in \( T_b \) and the change in \( T_s \),

\[
dT_b = \frac{T_b}{T_s} \frac{e^{hc/kT_s} - 1 + \varepsilon(\lambda)}{e^{hc/kT_s} - 1} dT_s
\]

And similarly, the relation between the change in \( T_b \) and the emissivity change is

\[
dT_b = \frac{\varepsilon(\lambda)}{1 + \varepsilon(\lambda)} d\varepsilon(\lambda)
\]

Numerical results of \( (T_b - T_s)/T_s \) at wavelengths 3.75, 8.55 and 11 μm for \( T_s = 283, 303 \) and 303 K are listed in Table 2. Because the atmospheric transmission function at 11 μm for a path of several meters is very close to 1 and the emissivity of most land covers at this wavelength is larger than 0.95, the error in estimations of the surface temperature change by using the brightness temperature is less than 3%. Thus, the estimated surface temperature change is 3.3 °K for the grass field, or 0.5 °K for the concrete surface if they are good Lambertian surfaces. We expect that the error associated with the Lambertian assumption will be equal to or larger than the others, so a complete set of bidirectional reflectance measurements is needed for accurate estimation of surface emissivity in the field. After the surface reflectivity and emissivity in 3.4-4.1 μm are estimated by using the above method, an external radiation source effective in 2.5-14.3 μm can be used in field measurements to determine by direct measurements with a TIR spectral radiometer and a reflecting mirror, or a calibrated standard reference surface (for example, a diffuse reflecting gold plate). The TIR measurement data in 3.4-4.1 μm from the target surface should be used to estimate the surface temperature change \( \Delta T_s \), then the estimated \( \Delta T_s \) can be used for deriving surface albedo (reflectivity, in general sense) and emissivity at other wavelengths with the same method.
TABLE 2. Numerical Results \((T_b - T_s)/T_s\) for Different \(T_s\) and \(\varepsilon(\lambda)\) Values

<table>
<thead>
<tr>
<th>(T_s) (K)</th>
<th>1 - (\varepsilon(3.75 \mu m))</th>
<th>0.01</th>
<th>0.02</th>
<th>0.04</th>
<th>0.10</th>
<th>1 - (\varepsilon(8.55 \mu m))</th>
<th>0.01</th>
<th>0.02</th>
<th>0.04</th>
<th>0.10</th>
<th>1 - (\varepsilon(11 \mu m))</th>
<th>0.01</th>
<th>0.02</th>
<th>0.04</th>
<th>0.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>283</td>
<td>0.0015</td>
<td>0.0030</td>
<td>0.0060</td>
<td>0.0164</td>
<td>0.0033</td>
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</tr>
<tr>
<td>303</td>
<td>0.0016</td>
<td>0.0032</td>
<td>0.0064</td>
<td>0.0164</td>
<td>0.0036</td>
<td>0.0071</td>
<td>0.0143</td>
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<td>0.0047</td>
<td>0.0094</td>
<td>0.0188</td>
<td>0.0476</td>
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</tbody>
</table>

CONCLUSIONS

Use of the solar beam as an external radiation source and the four-step method in field TIR measurements has given some encouraging but preliminary results. This procedure may be used to investigate the effects of surface structure and shadowing. More work has to be done to develop an appropriate procedure for the TIR spectral radiometric system used in field measurements of surface bidirectional reflectivity, emissivity and temperature. Radiative transfer simulations should be made for correcting atmospheric effects on ground-based measurements.

ACKNOWLEDGEMENTS

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REFERENCES


![Fig. 1. The spectral atmospheric transmittance.](image1)

![Fig. 2. Estimated surface reflectivity in 3.3-4.1 \(\mu m\).](image2)