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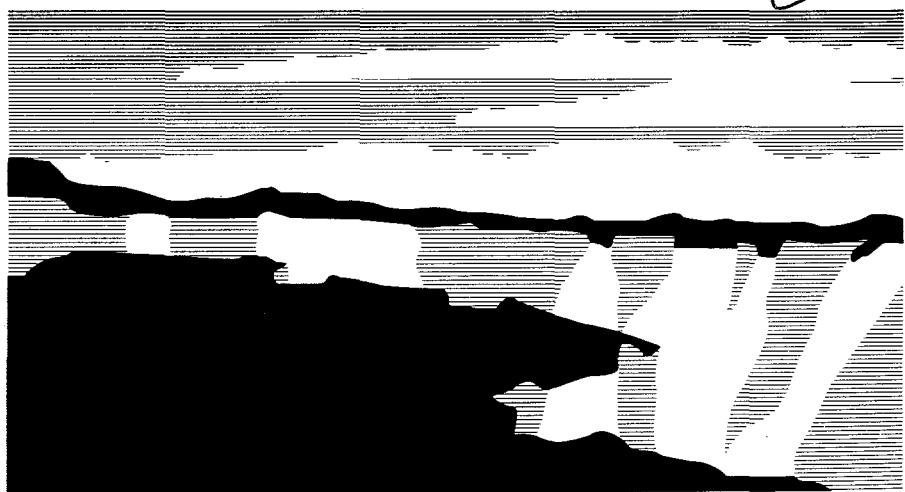
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Iterative Retrieval of Surface Emissivity and Temperature for a Hyperspectral Sensor

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1 Introduction

The central problem of temperature-emissivity separation is as pointed out by Realmuto, 1990, that we obtain N spectral measurements of radiance and need to find $N + 1$ unknowns (N emissivities and one temperature). To solve this problem in the presence of the atmosphere we need to find even more unknowns: N spectral transmissions $\tau_{atmo}(\lambda)$, N up-welling path radiances $L_{path\uparrow}(\lambda)$ and N down-welling path radiances $L_{path\downarrow}(\lambda)$. Fortunately there are radiative transfer codes such as MODTRAN 3 and FASCODE available to get good estimates of $\tau_{atmo}(\lambda)$, $L_{path\uparrow}(\lambda)$ and $L_{path\downarrow}(\lambda)$ in the order of a few percent.

The presently used methods for multispectral sensors such as TIMS, ASTER, etc. are based on assumptions of having a certain emissivity ε_i at a wavelength λ_i (Kahle et al., 1980), fixing the maximum expected emissivity to a certain value (Realmuto, 1990), assuming a linear relationship between mean emissivity and maximum difference for rocks and soils (Matsunaga, 1993) and approximating the Planck function using Wien's law and working with residuals (temperature and alpha) (Hook et al, 1992).

With the growing use of hyperspectral imagers, e.g. AVIRIS in the visible and short-wave infrared there is hope of using such instruments in the mid-wave and thermal IR (TIR) some day. We believe that this will enable us to get around using the present temperature - emissivity separation (TES) algorithms using methods which take advantage of the many channels available in hyperspectral imagers. The first idea we had is to take advantage of the simple fact that a typical surface emissivity spectrum is rather smooth compared to spectral features introduced by the atmosphere.

Thus iterative solution techniques can be devised which retrieve emissivity spectra ε based on spectral smoothness. To make the emissivities realistic, atmospheric parameters are varied using approximations, look-up tables derived from a radiative transfer code and spectral libraries. One such iterative algorithm solves the radiative transfer equation for the radiance at the sensor for the unknown emissivity and uses the blackbody temperature computed in an atmospheric window to get a guess for the unknown surface temperature. By varying the surface temperature over a small range a series of emissivity spectra are calculated. The one with the smoothest characteristic is chosen. The algorithm was tested on synthetic data using MODTRAN and the Salisbury emissivity database.

2 Decorrelation Wavenumbers for Atmosphere and Surface Emissivities

It is a common observation that thermal-infrared spectra of many solids tend to vary more slowly with wavelength λ than thermal-infrared spectra of gases.

To illustrate the spectral differences between atmospheric transmission and emissivities we computed the transmission of the atmosphere using MODTRAN 3 and spectral libraries provided by Salisbury et al (1992). A good measure of spectral smoothness is the autocorrelation function $P_x(L)$ of a sample population x as a function of lag L is defined as (see IDL Online Help, RSI, 1996):

$$P_x(L) = \frac{\sum_{k=0}^{N-L-1} (x_k - \bar{x})(x_{k+L} - \bar{x})}{\sum_{k=0}^{N-1} (x_k - \bar{x})^2}. \quad (1)$$

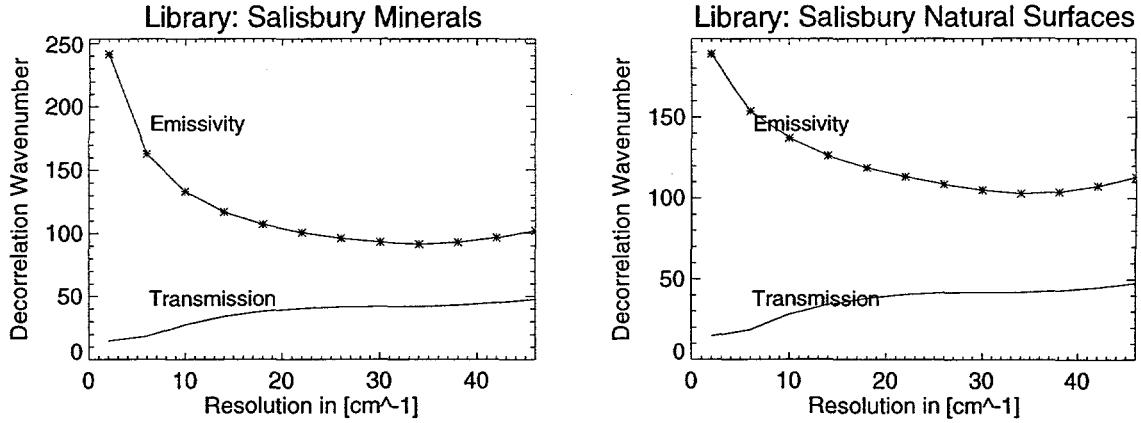


Figure 1: Decorrelation wavelengths for emissivities from Salisburry's minerals (left) and natural surfaces database (right).

The autocorrelation function drops off sharply with lag L for rapidly changing x 's and gradually for smooth functions of x . In our case x is $\varepsilon(\nu)$ or $\tau_{atmo}(\nu)$, where ν is the wavenumber [cm^{-1}]. We chose wavenumbers because the widths of absorption features in gases are relatively constant in terms of wavenumbers in the LWIR. Given the first few samples of $P_x(L)$, $L = 0, 1, \dots, L_{max}$ we calculate the average decorrelation wavenumber D_ν for a range of wavenumbers from L_{min} to L_{max} as:

$$D_\nu = \frac{1}{L_{max} - L_{min} + 1} \sum_{L=L_{min}, \dots, L_{max}} \frac{L}{P_x(0) - P_x(L)}. \quad (2)$$

Note that this is a simple approximation of the decorrelation wavenumber which really is given by finding the lag $L_{decorrelation}$ where $P_x(L_{decorrelation}) = 0$. We can calculate $D_\nu(W)$ as a function of spectral resolution by smoothing x_k with a moving average over W samples:

$$x_{k,W} = \frac{1}{W} \sum_{k=0}^{W-1} x_{k+j-W/2}, k = W/2, \dots, N - W/2. \quad (3)$$

The average decorrelation wavenumbers $D_\nu(W, \tau_{atmo})$ for the atmospheric transmission $\tau_{atmo}(\nu)$ and $D_\nu(W, \varepsilon)$ for the emissivity library spectra are shown in Fig. 1. The parameters for the decorrelation wavenumber calculation are: $L_{min} = W$ and $L_{max} = 2W - 1$. Not surprisingly the decorrelation wavenumber for the atmospheric transmission is roughly twice that of the boxcar filter width. The decorrelation wavenumber for the emissivities is more than $100 cm^{-1}$ and almost constant for resolutions of $10 cm^{-1}$ or greater. From this figure we can determine that we need at least a resolution of $20 cm^{-1}$ or better to distinguish atmospheric spectral features from emissivity features.

3 Iterative Spectrally Smooth Temperature-Emissivity Separation

3.1 Assumptions

For this subsection we assume we have a perfect sensor (no spectral and radiometric errors), a spectral range in the TIR from 7.5 to $13.9 \mu m$ with 100 or more spectral channels. The atmosphere is assumed to have the transmission and path radiances of a US standard atmosphere with a thin cirrus cover. The flight altitude was set to 3.718 km with a surface at 1.31 km above sea level. The MODTRAN 3 calculation was performed in the thermal mode for up-welling and down-welling path radiances and in the transmission mode for the atmospheric transmission between ground and sensor.

3.2 Iterative Algorithm with Variable Surface Temperature

The main idea is that we can solve the equation for the total path radiance for the unknown emissivity ε using an estimate $(T_{est,0})$ of the blackbody ground temperature T_{ground} derived from an average over an atmospheric window assuming a “typical” emissivity of $\varepsilon_0 = 0.95$. Then we vary the blackbody temperature in a range of temperatures near $T_{est,n}, n = 1, 2, \dots, N$ and compute the emissivities ε_n . We compute the smoothness of the spectral emissivity and select the smoothest emissivity as the best estimate $\varepsilon_{opt}(\lambda)$. We found this method to produce very reasonable results under the condition that we also vary the effective atmospheric temperature $T_{atmo,eff}$ and columnar water vapor amount CW to bring the estimated emissivities close to well known emissivities such as water or coniferous forests.

Now a more detailed description of the algorithm includes the following steps:

1. Temperature-Emissivity Separation

The measured radiance (here in wavelengths but could also be in wavenumbers) at the sensor level is:

$$L_{total}(\lambda) = \varepsilon(\lambda)B(\lambda, T_{ground})\tau_{atmo}(\lambda) + L_{path\uparrow}(\lambda) + L_{path\downarrow}(\lambda)[1 - \varepsilon(\lambda)]\tau_{atmo}(\lambda) \quad (4)$$

where $B(\lambda, T)$ is the Planck function for the spectral radiance in $[W/(cm^2 ster\mu m)]$, $\varepsilon(\lambda)$ is the unknown surface emissivity and T_{ground} is the unknown surface temperature. To start a solution we estimate the ground temperature T_{ground} given a fixed emissivity (e.g. $\varepsilon_0 = 0.95$) in an atmospheric window:

$$T_{est,n} = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} B^{-1} \left(\lambda, \frac{L_{total}(\lambda) - L_{path\uparrow}(\lambda) - L_{path\downarrow}(\lambda)(1 - \varepsilon_0)\tau_{atmo}(\lambda)}{\varepsilon_0\tau_{atmo}(\lambda)} \right) d\lambda, \quad (5)$$

where $\lambda_1 = 10.4$ and $\lambda_2 = 11.5\mu m$.

Using this estimated temperature we can solve eq. (4) for $\varepsilon(\lambda)$:

$$\varepsilon(\lambda) = \frac{L_{total}(\lambda) - L_{path\uparrow}(\lambda) - L_{path\downarrow}(\lambda)\tau_{atmo}(\lambda)}{(B(\lambda, T_{est,n}) - L_{path\downarrow}(\lambda))\tau_{atmo}(\lambda)}. \quad (6)$$

Note that we neglected the dependence of $L_{path\downarrow}$ on the water vapor and atmospheric temperature for the sake of simplicity.

2. Atmospheric Parameter Retrieval

For spectral radiances over surfaces such as water where we know the emissivity we can attempt to retrieve atmospheric parameters such as effective atmospheric temperature $T_{atmo,eff}$ and columnar water vapor amounts CW in $[g/cm^2]$.

(a) Approximate the up-welling path radiance by:

$$L_{path\uparrow}(\lambda, T_{atmo,eff}, CW) = B(\lambda, T_{atmo,eff})[1 - \tau_{atmo}(CW)], \quad (7)$$

where the effective atmospheric temperature is $T_{atmo,eff}$ and the water vapor dependent atmospheric transmission is approximated by:

$$\tau_{atmo}(CW) = \tau_{dry} 10^{-\alpha_{wet} CW} \quad (8)$$

where the transmittance of the atmosphere without columnar water vapor τ_{dry} is computed by:

$$\tau_{dry} = \frac{\tau_{atmo}}{\tau_{wet}}, \quad (9)$$

and the water vapor absorbance α_{wet} :

$$\alpha_{wet} = -\frac{1}{CW_0} \log_{10}(\tau_{wet}), \quad (10)$$

where CW_0 is the columnar water vapor amount between the sensor and target using a MODTRAN standard atmosphere and CW is the new relative columnar water vapor amount (e.g. $CW = 0.5, \dots, 2..$

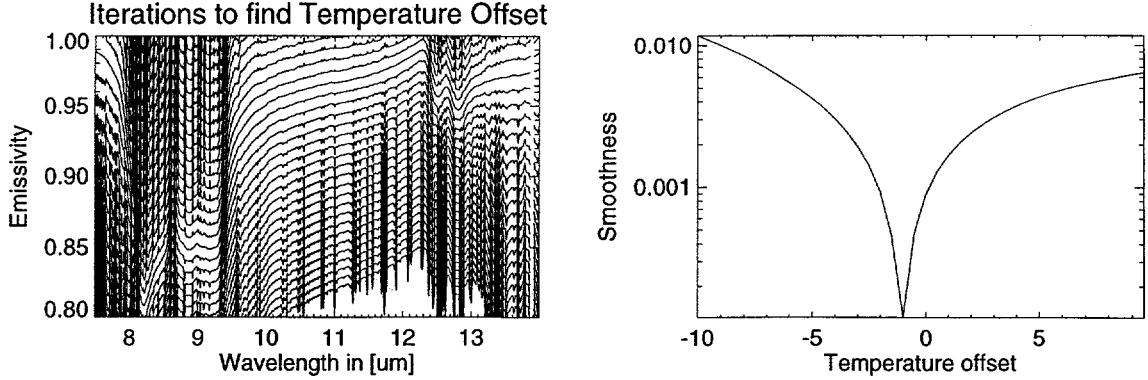


Figure 2: *Left:* Retrieved emissivities for variable surface temperature. The temperature was varied between -10 and +10 K in steps of 0.5 K. The correct emissivity is the third curve from the top at 12 μm . *Right:* Smoothness as a function of temperature offset to $T_{est,0}$.

- (b) We found it is easy to find an appropriate emissivity by repeating the previous step and first step for a number of effective atmospheric temperatures (e.g. 320 K) and columnar water vapor amounts until a reasonable emissivity (e.g. 0.98@10.4 μm) is found.
- (c) The best estimate of water vapor CW_{est} and atmospheric temperature $T_{atmo,est}$ is used to compute new up-welling path radiance and atmospheric transmission terms in eqs. (6) and (5) of step 1.

3. Find Smoothest Emissivity

For all spectral radiances use the optimized up-welling path radiance and atmospheric transmission terms and compute the spectral emissivity $\varepsilon(\lambda)$. The temperature $T_{est,n}$ is varied in eq. (6) using $T_{est,n} = T_{est,0} - T_{range}/2 + n\delta T$, where $T_{est,0}$ is the first temperature estimate from step 1, $\delta T = T_{range}/(N-1)$ and $n = 1, \dots, N$. For the n -th spectral emissivity $\varepsilon_{n,m}$ with M samples the smoothness is computed using:

$$\sigma(\varepsilon_n) = STDEV \left(\varepsilon_{n,m} - \frac{\varepsilon_{n,m-1} + \varepsilon_{n,m} + \varepsilon_{n,m+1}}{3} \right), m = 2, \dots, M-1. \quad (11)$$

The emissivity with the smallest standard deviation $\sigma(\varepsilon_n)$ is chosen as the spectrally smoothest emissivity:

$$\varepsilon_{opt} = \varepsilon_n |_{\sigma(\varepsilon_n) = \min!}. \quad (12)$$

On the left side of Figure 2 we show a series of curves of retrieved emissivities when the temperature is varied. Notice that the atmospheric absorption/emission features seem to disappear when the retrieved emissivity is smooth (third curve from the top). The smoothness as a function of surface temperature offset from the estimated ground temperature $T_{est,0}$ shows a sharp minimum on the linear-logarithmic plot in Figure 2 on the right side. Thus the optimum surface temperature is then given by $T_{opt} = T_{est,0} - T_{range}/2 + n_{opt}\delta T$, where n_{opt} is the iteration which minimizes $\sigma(\varepsilon_n)$. For the emissivity shown in Figure 2 the true surface temperature was 290 K and the estimated temperature was 290.021. The RMS error of the emissivity in the region from 8.2 to 13 μm was 0.082.

Note we found that the method did not require any limiting of the range of the emissivity from 0. to 1. and no negative radiances were produced. Thus this method is easier to implement than a previous algorithm which varied the emissivity in small steps, but has to take care of out-of-range emissivities.

Alternatively we also implemented a gradient search version using the "POWELL.PRO" routine of IDL (RSI, Boulder) which uses the routine *powell* from section 10.5 of *Numerical Recipes in C: The Art of Scientific Computing*, second ed., Cambridge University Press. We simultaneously retrieve surface temperatures and atmospheric temperatures but seems to fail in a few cases if we use an estimated surface temperature

based on the assumption that the surface emissivity is 0.95. The problem can be easily fixed by repeating the optimization using a range of starting values, e.g. $\varepsilon_{0,i} = 0.99 - i \cdot 0.03$, $i = 0, \dots, 10$.

4 Conclusions

We have shown that hyperspectral sensors with 100 or more channels are necessary to accurately retrieve temperature, emissivities and atmospheric parameters. A new method has been developed which uses the smoothness of the spectral emissivity to retrieve temperature and emissivity. A good atmospheric correction is a necessary condition to retrieve accurate surface temperatures and emissivities.

In the future we need to perform a sensitivity study to investigate the effect due to calibration errors (spectral and radiometric) and sensor noise. We need to investigate the problem of mixed pixels and potentially devise nonlinear unmixing methods. We should study the use of low-emissivity surfaces to retrieve down-welling path radiances.

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