MAPPING HUMAN SETTLEMENTS USING THE MID-IR: ADVANTAGES, PROSPECTS, AND LIMITATIONS

G.M. Henebry

Center for Advanced Land Management Information Technologies (CALMIT)
School of Natural Resources, University of Nebraska – Lincoln, Lincoln, NE, 68588-0517, ghenebry@calmit.unl.edu

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ABSTRACT:

Despite the presence of myriad atmospheric windows between 3-5 μm, relatively little terrestrial remote sensing work has exploited this mid-IR region of the spectrum (the exceptions being fire and volcano monitoring). A principal reason for this under-utilization is the daytime signal mixing of solar reflectance and terrestrial emission. Researchers have focused on this combination of reflectance and emission from dense plant canopies for biomass estimation in tropical forests, especially in situations where atmospheric aerosols degrade conventional vegetation indices like NDVI. However, the utility of the mid-IR for terrestrial remote sensing extends beyond biomass estimation, fire detection, or volcano monitoring. There exist significant spectral contrasts in the 3-5 μm region between the reflectance of active vegetation on the one hand and the reflectance of senesced vegetation, soils, rocks, minerals, and anthropogenic surfaces on the other. This phenomenon enables mapping of human settlements and movement corridors in vegetated landscapes. It also allows for the detection of surface perturbations: devegetation, disturbance of soils and dried plant materials, and the expansion or rearrangement of anthropogenic surfaces, such as paving and roofing materials. A survey the biogeophysics of mid-IR radiation and the phenomenology of spectral contrasts is illustrated with examples from AVHRR as well as the higher spatial and spectral resolution MODIS/ASTER airborne simulator (MASTER).

1. INTRODUCTION

Despite the presence of myriad atmospheric windows between 3-5 μm, relatively little terrestrial remote sensing work has exploited this region of spectrum (other than applications in fire and volcano monitoring). For several years, the principal sensor with middle infrared (mid-IR) imaging capability was the AVHRR (Advanced Very High Resolution Radiometer). Despite its coarse spatial resolution – 1.1 km at nadir – and chronic problems with image noise (cf. Simpson and Yhann 1994), several significant applications for terrestrial remote sensing have emerged. Tucker and coworkers (1984) discovered that AVHRR channel 3 (3.55-3.93 μm) was effective in detecting deforestation in the Brazilian Amazon. Kerber and Schutt (1986) explored the potential of AVHRR channel 3 data for land cover mapping. They noted distinct urban/rural contrasts in analysis of a single summer scene of the Chesapeake Bay region. Channel 3 exhibited greater within scene variability, thus increasing discriminatory power for classification. They concluded that most of the variation was due to differential emittance not reflectance, based on analysis of the differential thermal response of AVHRR's middle and thermal IR channels.

The daytime signal mixing of solar reflectance and terrestrial emission has been suggested as a principal reason for the scant record of MIR applications (Boyd and Petitcolin 2004). However, Boyd and Curran (1998) argued that exploiting this portion of the electromagnetic spectrum may significantly improve inventories of aboveground carbon stocks, especially in forests. Researchers have sought to retrieve the reflectance component by subtracting the emission component (Kaufman and Remer 1994; Roger and Vermote 1998; Petitcolin and Vermote 2002). More recently, Boyd and Petitcolin (2004) provide a useful review of the progress made toward exploiting the mid-IR for terrestrial remote sensing, particularly for land cover and land use change studies in forested ecosystems. However, the utility of the mid-IR is not limited only to the information in the solar signal.

There exist strong spectral contrasts in the 3-5 μm region between the reflectance of active vegetation on the one hand and the reflectance of senesced vegetation, soils, rocks, minerals, and anthropogenic surfaces on the other (Salisbury and D'Aria 1994; Figure 1).

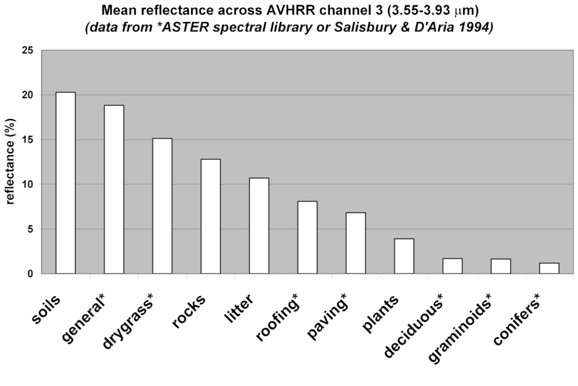

Figure 1. Average mid-IR reflectance of common materials from laboratory measurements.

Spectral contrasts in the mid-IR may offer novel ways to estimate vegetation fraction and impervious surface fraction. Spectral contrasts offer improvements over vegetation index approaches. First. mid-IR saturates at higher levels of leaf area index (LAI). Second, plant canopies exhibit negligible anisotropy in the mid-IR. Third, the strong spectral contrast between soils and live plant tissue suggests the feasibility of linear mixing models. Furthermore, detection of various types of surface perturbations may be possible using mid-IR spectral information, including: (1) removal or reduction of green biomass in forests, shrublands, grasslands, croplands, suburban and urban settings; (2) soil disturbance – subsurface soils exposed or brought to surface during excavation; (3) disturbance or accumulation of dried plant materials at the surface; and (4) change in anthropogenic surfaces, such as concrete, asphalt, roofing materials, paints.

2. BIOGEOPHYSICS OF MID-IR

What follows is a condensed survey of the biogeophysics of middle infrared radiation that is relevant to terrestrial remote sensing. Laboratory studies of infrared spectral reflectance reveal consistent patterns among natural materials commonly encountered (Figure 1). Green leaves exhibit very low reflectance – 2-5% – comparable to that of water – and plant canopies are likely to exhibit even lower reflectance due to multiple scattering (Salisbury and D'Aria 1994). Mid-IR is better able to penetrate anthropogenic haze and smoke (particle radii = 0.1-0.4 nm) than red wavelengths, although worse for dust (particle radii = 1000-2000 nm) (Kaufman and Remer 1994). Soils are mid-IR-bright, reflecting up to one-third of the incident radiation (ASTER Spectral Library 1998). Rocks are generally less reflective than soils but exhibit more definite spectral signatures (ASTER Spectral Library 1998). Cellulose, lignin, hemicelluloses, and other structural plant molecules exhibit enhanced reflectivity between 3.6-4.3 μm (Salisbury and D'Aria 1994) but less than soils (Salisbury and D'Aria 1994; Snyder et al. 1997). View angle dependence of emissivity (and thus reflectance) is greater in the mid-IR than thermal IR (Labed and Stoll 1991), but there is little change in the spectral features (Snyder et al. 1997). View angle dependence becomes an issue when the scene is composed of objects of sharply contrasting reflectance and emission characteristics (Smith et al. 1997). Change in spectral emissivity across 3-5 μm region is greater than temperature sensitivity (Wan and Dozier 1996).

For the purposes of spectral contrast, the mixing of solar radiation (as reflectance) and terrestrial radiation (as emittance) is a benefit rather than a problem: it stabilizes the contrast signal for several reasons. First, the solar mid-IR irradiance exhibits very low variability (<0.1%) despite significant periodic variation in other regions of the solar spectrum (Lean 1991). Second, the differential partitioning of the surface energy budget between latent and sensible heat fluxes on vegetated versus bare soil surfaces leads to strong thermal contrasts that reinforce the mid-IR spectral contrast. Third, the variation in spectral emissivity due to material differences is greater in the mid-IR than temperature dependence (Wan and Dozier 1996), suggesting that even subpixel surface alterations may be detectable, if they result in significantly different proportions of component materials. Fourth, the thickness of the mid-IR thermal skin is only a few millimeters (Wan and Dozier 1996). Much work remains to evaluate the efficacy of mid-IR spectral contrasts, but these examples indicate promise.

3. EXAMPLES FROM AVHRR

Mid-IR spectral contrast between vegetation and soils is a seasonal phenomenon due to canopy development. As the canopy closes and covers the soil surface that is mid-IR bright, the image tone darkens due to the high absorption of mid-IR by green leaves. Human settlements and transportation corridors appear as bright patches against darker backgrounds (Figs. 2-4), when these occur within a vegetated matrix.

These examples from AVHRR data were generated from the USGS EROS Data Center maximum NDVI biweekly composites for the conterminous US. The data were converted to brightness temperatures and then averaged across the latter part of the growing season to maximize the spectral contrast between the dark vegetated canopy and bright non-vegetated anthropogenic surfaces. Bodies of water are masked to black.

Figure 2. AVHRR channel 3 mean brightness temperature after canopy closure 1997. Bright patches correlate with high concentrations of anthropogenic building materials. Bright lines correlate with highway rights-of-way. Increasingly dark gray tones correlate with increasing canopy density. Note the pervasive pattern of settlements from Virginia to Boston.

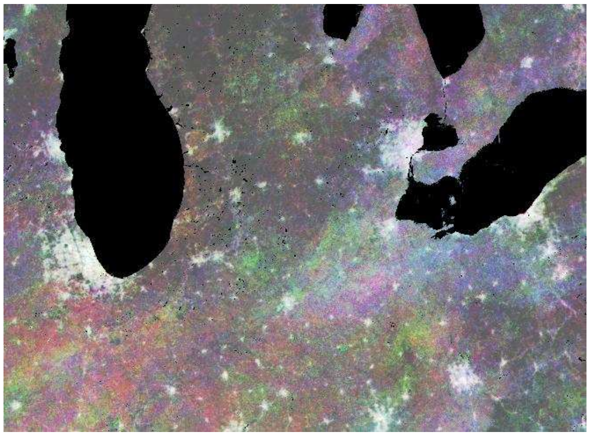

Figure 3. Human settlement patterns south of the Great Lakes revealed by the mean AVHRR mid-IR signal following canopy closure in 1993 (blue), 1994 (green), and 1995 (red).

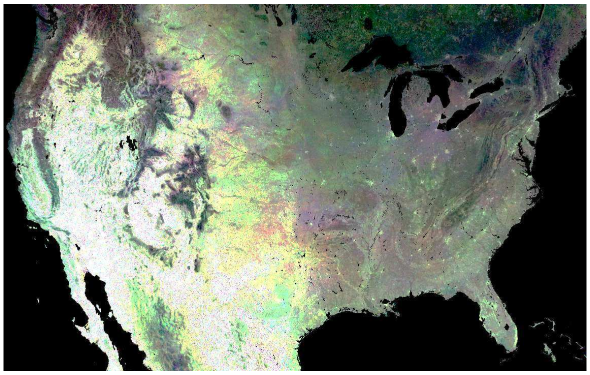

Figure 4. Mid-IR portrait of CONUS reveals the vegetation fraction gradient. Human settlements are mostly veiled in the western US by mid-IR bright soils.

4. EXAMPLE FROM MASTER

The MODIS/ASTER airborne simulator, MASTER, offers higher spectral resolution in the mid-IR at finer spatial resolution than MODIS proper—13 bands at 50m versus 4 bands at 1000m (Hook et al., 2001). There is no mid-IR capability on ASTER and the MODIS mid-IR imagery is affected by instrument noise; thus, MASTER data offer a rich source of multispectral data across the mid-IR. MASTER data are available across a range of targets, including urban transects (http://masterweb.jpl.nasa.gov/).

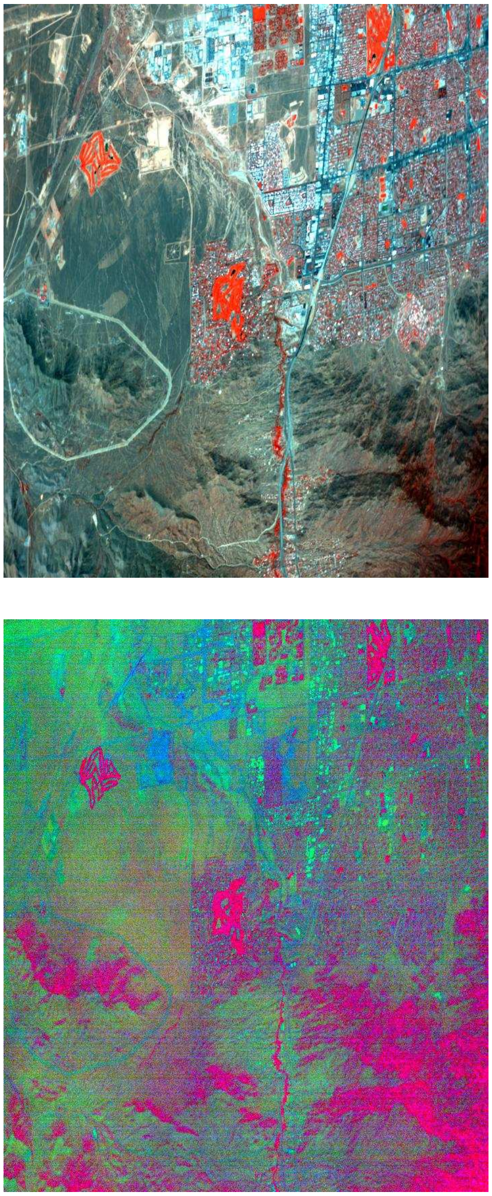

Figure 5. False color composites from a MASTER image of Albuquerque, NM acquired June 3, 1999: (above) conventional RGB composite displaying Near Infrared/Red/Green bands; (below) RGB display of the experimental mid-IR indices Organic Matter Index/Quartz Soils Index/Carbonate Surfaces Index. Magenta tones indicate high levels of dried plant materials at the surface. Green tones indicate concrete surfaces. Bright blue tones reveal exposed subsoils (caliche).

5. ACKNOWLEDGMENTS

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6. REFERENCES

ASTER Spectral Library Version 1.1 1998. http://speclib.jpl.nasa.gov. California Institute of Technology.

Boyd, D.S., and P.J. Curran, 1998. Using remote sensing to reduce uncertainties in the global carbon budget: the potential of radiation acquired in the middle infrared wavelengths. *Remote Sensing Reviews*, 16:293-327.

Boyd, D.S. and F. Petitcolin. 2004. Remote sensing of the terrestrial environment using middle infrared radiation (3.0-5.0 μm). *International Journal of Remote Sensing*, 25(17):3343-3368.

Hook, S. J., J.J. Myers, K.J. Thome, M. Fitzgerald, and A.B. Kahle, 2001. The MODIS/ASTER airborne simulator (MASTER) - a new instrument for earth science studies. *Remote Sensing of Environment*, 76(1):93-102.

Kaufman, Y.J., and L.A. Remer. 1994. Detection of forest using mid-IR reflectance: an application for aerosol studies. *IEEE Transactions on Geoscience and Remote Sensing*, 32:672-683.

Kerber, A.G., and J.B. Schutt. 1986. Utility of AVHRR channels 3 and 4 in land-cover mapping. *Photogrammetric Engineering and Remote Sensing*, 52:1877-1883.

Lean, J. 1991. Variations in the Sun's radiative output. *Reviews of Geophysics*, 29:505-535.

Labed, J. and M.P. Stoll, 1991. Angular variation of land surface spectral emissivity in the thermal infrared: laboratory investigations on bare soils. *International Journal of Remote Sensing,* 12:2299-2310.

Petitcolin, F., and E. Vermote. 2002. Land surface reflectance, emissivity and temperature from MODIS middle and thermal infrared data. *Remote Sensing of Environment,* 83:112-134.

Salisbury, J.W. and D.M. D'Aria. 1994. Emissivity of terrestrial materials in the 3-5 μm atmospheric window. *Remote Sensing of Environment,* 47:345-361.

Simpson, J.J., and S.R. Yhann. 1994. Reduction of noise in AVHRR channel 3 data with minimum distortion. *IEEE Transactions on Geoscience and Remote Sensing*, 32:315-328.

Smith, J.A., N.S. Chauhan, T. Schmugge, J.R. Ballard. 1997. Remote sensing of land surface temperature: the directional viewing effect. *IEEE Transactions on Geoscience and Remote Sensing*, 35(4):972-974.

Snyder, W.C., Z. Wan, Y. Zhang, and Y.-Z. Feng. 1997. Thermal infrared (3-14 μm) bidirectional reflectance measurements of sands and soils. *Remote Sensing of Environment,* 60:101-109.

Wan, Z. and J. Dozier. 1996. A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Transactions on Geoscience and Remote Sensing*, 34:892-905.