P2.28 LAND SURFACE TEMPERATURE AND EMISSIVITY FROM INFRARED HYPERSPECTRAL OBSERVATIONS

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The University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) is developing algorithms for the exploitation of future hyperspectral sensors on polar orbiting and geostationary satellite platforms. Lessons learned to date are presented from field observations using existing ground-based, aircraft, and satellite instruments. The ground-based observations provide important measurements of pure scene types (bare soil, vegetation) and a measurement of the temporal change in surface temperature. The high altitude aircraft observations provide sub-pixel information for the satellite sounder footprints. The satellite data provides nearly instantaneous coverage of a large region and in the case of a sounding instrument provides an estimate of the atmospheric thermodynamic state needed to account for atmospheric attenuation of the surface emission.

1. INTRODUCTION

The University of Wisconsin has experience with hyperspectral infrared measurements from high spectral resolution observations and with application of these data to land surface remote sensing. This paper contains lessons learned to date from field observations using ground-based (S-AERI), aircraft (S-HIS/NAST-I), and satellite (AIRS) platforms. Techniques for the retrieval of infrared land surface temperature and emissivity from high spectral resolution upwelling radiances also have application to future satellite instruments, e.g. the NPOESS Cross-track Infrared Sounder (CrIS), the NASA Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), and the future Hyperspectral Environmental Suite (HES).

The remote sensing of land surface temperature from satellite requires a detailed knowledge of infrared land surface emissivity (LSE). Generally speaking, a 1% error in the knowledge of the land surface emissivity near 10 microns leads to an error in the derived surface temperature of about 0.5 Kelvin. Since the emissivity of bare soil can vary across the infrared spectrum by 10% or more, errors in the remote sensing of surface temperature from satellites can be substantial. Land surface remote sensing with high spectral resolution infrared data has the potential to determine land surface temperature to higher accuracy than low spectral resolution measurements. However, the relatively large field of view of many of the proposed high spectral resolution infrared instruments complicates the interpretation of the satellite measurements where there is significant sub-pixel variability in land type. This paper addresses 1) the ability of high spectral resolution infrared observations to simultaneously determine land surface temperature and surface emissivity, and 2) the interpretation of "effective" land surface temperature and land surface emissivity for mixed scenes.

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2. THEORY

This paper will follow the theory outlined in Knuteson et al. (2003a). The cloud-free radiative transfer equation, neglecting solar radiation and scattering effects, for a downlooking infrared sensor viewing a homogeneous surface is given by the following equation

$$I_\nu = \int_0^Z B_\nu[T(z)]\frac{\partial \tau_\nu(z,Z)}{\partial z}dz + \varepsilon_\nu \cdot B_\nu(T_S)\cdot \tau_\nu(0,Z) + (1-\varepsilon_\nu)\cdot \tau_\nu(0,Z)\int_\infty^0 B_\nu[T(z)]\frac{\partial \tau_\nu(z,Z)}{\partial z}dz, \tag{1}$$

where I_ν, ε_ν, B_ν, T_S, $\tau_\nu(z_1,z_2)$, Z, and $T(z)$ are observed spectral radiance, spectral emissivity, spectral Planck function, the surface temperature, spectral transmittance at wavenumber ν from altitude z_1 to z_2, sensor altitude, and air temperature at altitude z, respectively. The first term of the equation is the emission from the atmosphere above the surface, the second term is the direct emission from the surface that reaches the sensor, and the third term is the downwelling atmospheric emission reflected off the ground under the approximation of a lambertian surface. The radiative transfer equation applies at monochromatic resolution and has been accurately implemented in several line-by-line radiative transfer models. An approximate solution to the full radiative transfer equation has been been applied successfully to observations of infrared emission at high spectral resolution through the application of a constraint (Bower et al. 1999; Knuteson et al. 2001, 2003a, 2003b). The solution can be written formally as

$$\hat{\varepsilon}_\nu = \frac{[R_\nu^{OBS} - \mathrm{N}_\nu^{\uparrow}] - \tau_\nu \overline{\mathrm{N}}_\nu^{\downarrow}}{\tau_\nu B_\nu(\hat{T}_S) - \tau_\nu \overline{\mathrm{N}}_\nu^{\downarrow}} \tag{2}$$

where R_ν^{OBS} is the observed upwelling radiance, $\mathrm{N}^{\uparrow}$ represents the upwelling emission from the atmosphere only and $\overline{\mathrm{N}}^{\downarrow}$ represents the downwelling flux at the surface. The ^ symbol denotes "effective" quantities as defined in Knuteson et al. (2003a).

3. OBSERVATIONS

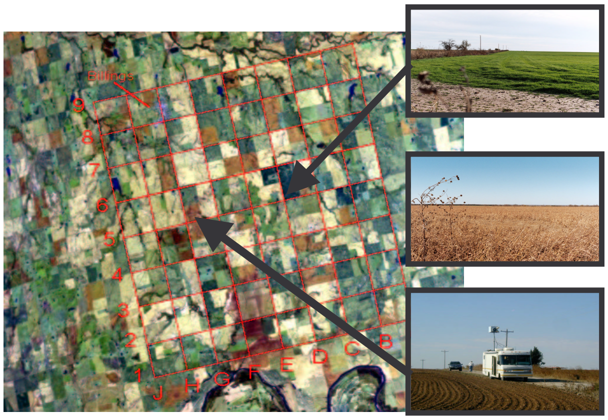

Figure 1. Site survey grid superimposed over a MODIS Airborne Simulator (MAS) image from 31 March 2001.

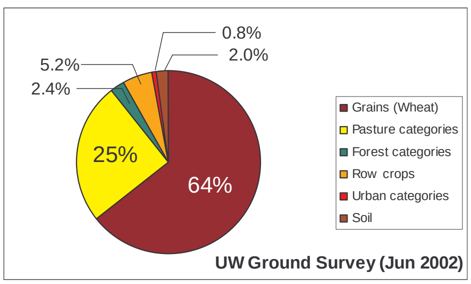

Figure 2. Survey results show the primary land use near the DOE ARM central facility is wheat farming (64%) and cattle grazing (pasture land) (25%).

Several ground surveys were conducted by UW-CIMSS personnel in order to characterize the distribution of land cover in the vicinity of the ARM SGP central facility in North Central Oklahoma (Osborne et al. 2003). The survey grid is superimposed in Figure 1 on a MODIS Airborne Simulator image from 31 March 2001 (north is down on the image). The UW-CIMSS S-AERI sensor was deployed sixteen feet above ground level where it is able to make slant view measurements of the surface and the atmosphere. The S-AERI measurements of upwelling and downwelling radiance are used in Eq. 2 to measure the infrared emissivity of pure scene types (Bower, et al., 1999). The results of the July 2002 survey at the ARM SGP site are shown in Figure 2.

Ground-based observations were made coincident with a validation campaign (Moeller et al. 2001) using the NASA high altitude ER-2 aircraft. The flight mission of 31 March 2001 over the DOE ARM site at 20 km altitude carried the UW-CIMSS Scanning-HIS instrument. (Revercomb, et al., 2003). Figure 3 shows photographs of the NASA ER-2 and the DOE ARM site. The spectral coverage of the Scanning HIS instrument is continuous from 3.3 to 16.7 μm at 0.5 cm^{-1} resolution. Onboard reference blackbodies are viewed as part of each cross-track scan, providing continuous calibration information. Spatial resolution is 2 km with a cross-track swath width on the ground of about 30 km.

Figure 3. The NASA ER-2 high altitude aircraft (upper panel) and the U.S. DOE ARM SGP central facility in North Central Oklahoma (lower panel).

The NASA Atmospheric InfraRed Sounder, AIRS, instrument was launched on the Aqua platform on May 4, 2002. High spectral resolution infrared observations from 16 November 2002 have been analyzed over the DOE ARM central facility for comparison to previous ground-based and aircraft measurements. The AIRS is a grating instrument which uses over 2000 individual detectors to sample the infrared spectrum with a resolving power of about 1200. The AIRS spatial resolution is about 16 km at nadir with 90 footprints in a cross-track scan line. The Aqua platform is in a sun-synchronous polar orbit with overpasses of the DOE ARM site at about 1:30 pm local time from an altitude of 705 km.

4. RESULTS

The S-AERI, S-HIS, and AIRS infrared emission observations have all been analyzed using the same Eq. 2 (Knuteson et al. 2003a, 2003b, 2001). For the S-HIS and AIRS cases, a coincident atmospheric profile (Tobin et al. 2003) has been used as input to a line-by-line radiative transfer model to calculate the downwelling atmospheric emission at the surface as well as the total atmospheric transmission. Since the S-AERI observes both the upwelling and the downwelling atmospheric components at the surface and the instrument is only 16 feet above the ground, no atmospheric radiative transfer calculation is required. The wavenumber range, 960–990 cm^{-1}, was used to find the skin temperature that minimizes the standard deviation of the emissivity derived from Eq. 2. Figure 5 shows the effective temperature and emissivity derived from a mean of 16 km of aircraft data. The “best fit” effective skin temperature is 295.4 K. This 16 km effective temperature is within one degree of the point measurement of the ground-based temperature shown in Figure 6. The aircraft observation was at 18:47 UTC. Fluctuations of the “point” measurements of the S-AERI of about one degree are consistent with the ARM downlooking IRT. The rapid time and space variations of surface temperature (and emissivity) make validation of land surface products a challenging prospect. The combination of the S-HIS high spectral resolution observations with the high spatial resolution observations (50 meter) of the MAS is expected to allow for more direct comparisons to point observations.

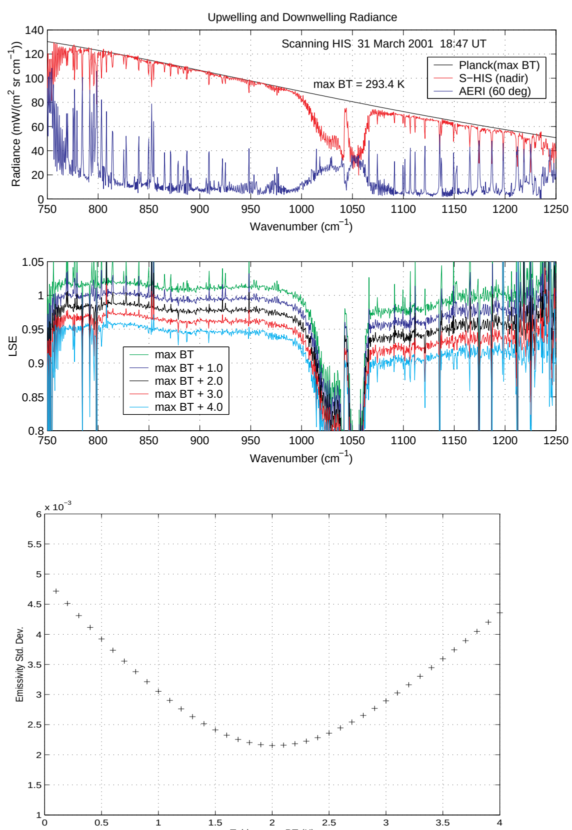

Figure 5. The S-HIS observation of upwelling radiance is shown in the upper panel. The center panel shows the derived emissivity spectrum as the assumed skin temperature is varied. The lower panel shows the standard deviation of emissivity over a selected spectral range as a function of skin temperature.

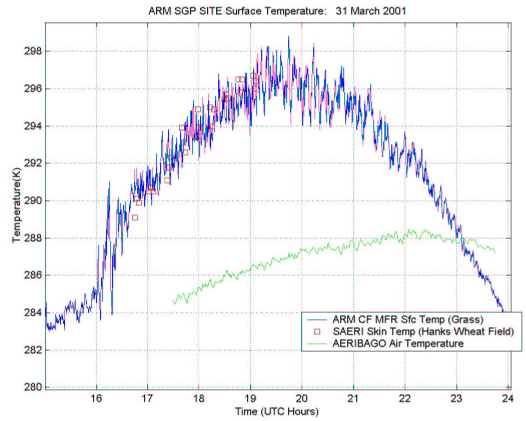

Figure 6. Symbols show the land surface temperature derived from the S-AERI instrument on 31 March 2001 compared to a downlooking IRT at the SPG ARM site.

Since the S-AERI was used to make ground-based measurements of pure scene types, we can examine whether the area averaged effective emissivity obtained by the S-HIS instrument can be composed of a linear combination of pure scene emissivities. The result is shown in Figure 7, which shows the linear combination of vegetation (grasses) and bare soil which best fits the aircraft observations.

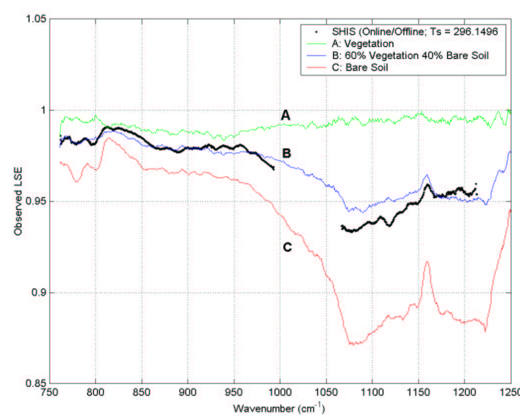

Figure 7. The effective land surface emissivity derived from aircraft observations over a 16 km spatial average agrees (to within 1%) with a weighted average of 60% pure vegetation and 40% pure bare soil.

A similar analysis has been applied to the observations of the AIRS satellite instrument. An overpass of the SGP ARM site on 16 November 2002 is shown in Figure 8. The upper panel is the observed brightness temperature difference between 9 and 12 microns which is sensitive to the presence of exposed soil. The eastern portion of this region is mainly pasture (grassland) while the center and western portion is used for wheat farming and has a higher percentage of bare soil at that time of year. The derived effective emissivity from three selected AIRS fields of view are shown in the lower panel. The fields of view with less spectral contrast are consistent with a higher percentage of vegetation.

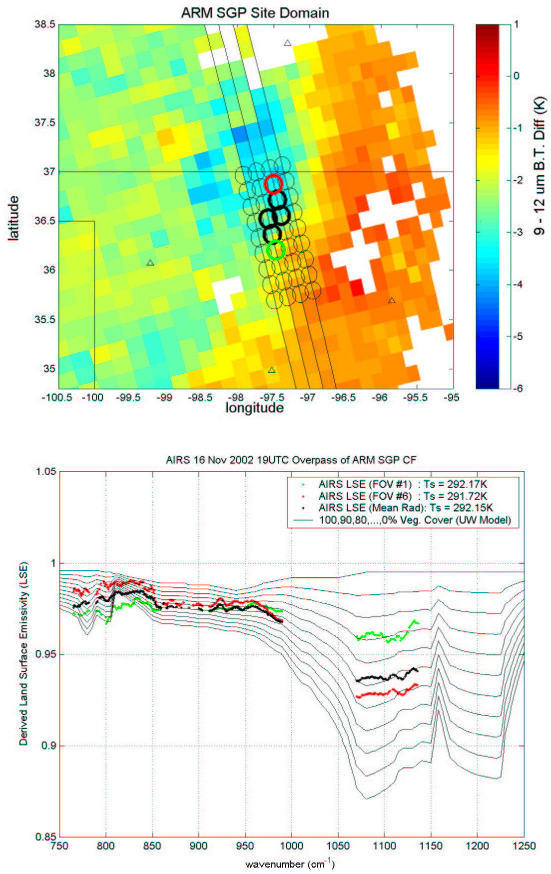

Figure 8. AIRS brightness temperature difference (upper) and derived effective infrared emissivity (lower) compared to vegetation fractions based upon surface observations in the vicinity of the U.S. DOE ARM SGP site on 16 November 2002 at 19 UTC.

5. Summary

Land surface temperature has been determined simultaneously with infrared surface emissivity using ground-based, aircraft, and satellite observations of upwelling infrared emission at high spectral resolution. The retrieval technique takes advantage of the contribution to the observed upwelling radiance that comes from the downwelling infrared atmospheric emission reflected from the surface. The results show that the infrared emissivity in the vicinity of the DOE ARM SGP central facility are consistent with a linear combination of emissivities of pure scene types (bare soil and vegetation). Future work includes the characterization seasonal variations of surface properties at selected sites around the globe.

6. ACKNOWLEDGEMENTS

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