P5.60 INFRARED LAND SURFACE EMISSIVITY RETRIEVAL FROM HIGH-SPECTRAL RESOLUTION UPWELLING RADIANCE

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This study will presents techniques for the retrieval of infrared land surface temperature and emissivity from high spectral resolution upwelling radiances. Results will be presented from aircraft flights of the Scanning High-resolution Interferometer Sounder (S-HIS) and the NPOESS Atmospheric Sounder Testbed – Interferometer (NAST-I). Case studies will be presented from ER-2 underflights of the Terra satellite at the Southern Great Plains ARM site in Oklahoma and over surface features during the NASA SAFARI experiment based in South Africa.

1. INTRODUCTION

The University of Wisconsin Space Science and Engineering Center (UW-SSEC) is developing techniques for the retrieval of infrared land surface temperature and emissivity from high spectral resolution upwelling radiances. These techniques are being used in support of the validation of the NASA Atmospheric InfraRed Sounder (AIRS) on the Aqua platform, but also have application to future satellite instruments, e.g. the NPOESS Cross-track Infrared Sounder (CrIS) and the Geostationary Infrared Fourier Transform Spectrometer (GIFTS).

Remote sensing of the earth's surface with high spectral resolution data has the potential to allow the separation of land surface skin temperature and emissivity while providing a significantly better atmospheric "correction" than low resolution infrared emission measurements. However, the relatively large field of view of many of the proposed satellite instruments (15 km or more) complicates the validation of the satellite measurements over sites where there is significant sub-pixel variability in land type.

The wide array of state-of-the-art instrumentation at the DOE Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site makes it a unique facility for the validation of atmospheric sounding products derived from satellite measurements. The site extends across a 250 km square region in Oklahoma and Kansas dominated by rural agricultural land use with significant variability on scales less than 1 km. This paper describes the use of ground-based and aircraft-based observations near the SGP CART central facility to characterize the surface properties important for IR thermal emission at the SGP site. The techniques are also applied to the measurements made in southern Africa during the recent NASA SAFARI experiment.

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2. THEORY

The radiative transfer equation used to model the upwelling infrared radiance at the top of the atmosphere under cloud free conditions can be written as

$$N_n^{\uparrow} = \int B_n(T(P))\,dt_n + t_n^{tot} \cdot e_n \cdot B_n(T_S) + t_n^{tot} \cdot (1 - e_n) \cdot \overline{N}_n^{\downarrow} \quad (1)$$

where N_ν is the upwelling radiance (up arrow) or the downwelling flux (down arrow) at wavenumber ν, B_ν is the Planck radiation distribution function at each atmospheric temperature profile value T(P), τ_ν is the atmospheric transmittance profile, and e_ν is the surface emissivity. The first term of the radiative transfer equation is the contribution of the atmospheric emission to the upwelling radiation. The second term is the contribution of the surface emission transmitted through the total atmospheric column. The third term is the surface reflection term under the approximation of a lambertian surface.

Two limiting cases are useful to consider. When the observer is near the surface the contribution from the atmospheric upwelling emission can be neglected and the total transmittance can be set to unity for all wavelengths. In this case, equation (1) can be written in the form

$$e_n = \frac{N_n^{\uparrow} - \overline{N}_n^{\downarrow}}{B_n(T_S) - \overline{N}_n^{\downarrow}} \text{ [near surface only]} \quad (2)$$

When the atmosphere is relatively dry, the atmospheric emission and absorption in the microwindows between absorption lines can be neglected and downwelling radiance at the surface can be set to zero. In this case, equation (1) can be written in the form

$$e_n \cong \frac{N_n^{\uparrow}}{B_n(T_S)} \text{ [clean microwindows only]} \quad (3)$$

3. OBSERVATIONS

Three sets of observations are described in this paper; a ground based survey of the ARM SGP site in November 2000, the ARM/FIRE Water Vapor Experiment (AFWEX) in Nov.-Dec. 2000, and the NASA SAFARI experiment in Aug. 2000.

The November 2000 ARM land surface emissivity survey was conducted by personnel from the University of Wisconsin-Madison during the period 29-30 November 2000 to improve our understanding of the variability of surface emissivity in the vicinity of the SGP ARM site central facility. This was the first of several planned surveys designed to capture the seasonal changes of surface emissivity on scales useful to characterize the sub-pixel variability needed to support satellite validation activities. The surface measurements are made with the UW Scanning-Atmospheric Emitted Radiance Interferometer (S-AERI) (Knuteson, et al., 1999). The survey approach was the following; 1) spectral data were collected with the S-AERI at a variety of land types, 2) a corresponding cataloging of land cover found along roads near the CART site was undertaken, and 3) a combination of the observed spectral library and statistical information on the fraction of field types along the survey route was used to determine a weighted emissivity average.

Figure 1 shows the S-AERI sensor deployed vertically sixteen feet above ground level where it is able to make slant view measurements (at 60 degrees) of the surface and the atmosphere. The S-AERI measurements of upwelling and downwelling radiance are used in equation (2) along with the additional constraint that the emissivity should be smoothly varying across atmospheric emission lines (Bower, et al., 1999). Shown in figure 2 are the results from a 22 mile North-South survey illustrating the measured emissivities of pasture, wheat, and bare soil and the weighted average emissivity spectrum along the survey line.

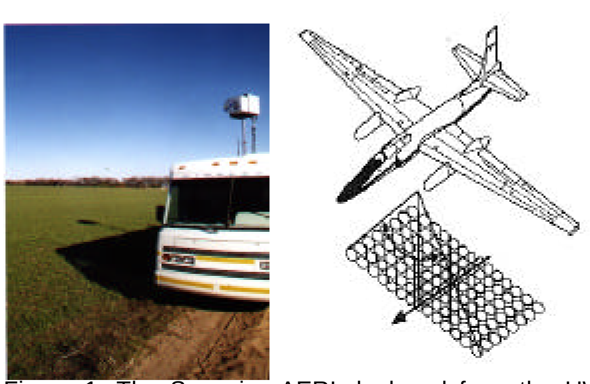

Figure 1. The Scanning-AERI deployed from the UW research vehicle near the ARM SGP site (left). Illustration of S-HIS and NAST-I crosstrack scan (right).

The AFWEX experiment (Nov-Dec 2000, SGP ARM stie) provided an excellent dataset for satellite validation studies under cloud-free conditions. During the AFWEX experiment, the UW S-HIS was operating from the NASA DC-8 aircraft flying at altitudes between 8 and 12 km while the LaRC NAST-I operated from the Proteus aircraft at about 15 km altitude. The atmospheric state is particularly well characterized by instrumentation on the NASA aircraft in addition to ground-based lidars and radars. Observations from 30 March 2000 02:30 UT for the S-HIS and 02:45 UT for the NAST-I are used in this analysis. During this time period the UW S-AERI was operating in surface scanning mode at the DOE SGP central facility. Comparison of the results derived form these observations are given in the next section.

The Scanning-HIS (S-HIS) is an advanced version of the HIS ER-2 instrument, developed between 1996 and 1998 with the combined support of the US DOE, NASA, and the NPOESS Integrated Program Office (Revercomb, et al., 1999). It has flown in seven field campaigns beginning in 1998 and has proven to be very dependable and effective. The continuous spectral coverage from 3.3 to 16.7 μm at 0.5 cm^{-1} resolution is divided into three bands with separate detectors (two photoconductive HgCdTe and one InSb). The bands use a common field stop to ensure accurate spatial co-alignment. The mid-wave band provides the primary water vapor sounding information. The optical design is very efficient, providing useful signal-to-noise performance from a single 0.5 second dwell time. This allows imaging with 2-3 km resolution to be accomplished by cross-track scanning. Onboard reference blackbodies are viewed as part of each cross-track scan, providing updated calibration information every 20-30 seconds. The rapid sampling frequency of the S-HIS allows cross-track imaging at 2 km resolution with a swath width on the ground of 30-40 km, as illustrated in Figure 1, or a nadir only mode with overlapping fields of view.

The NPOESS Atmospheric Sounder Testbed – Interferometer (NAST-I) is an aircraft instrument built by MIT-Lincoln Labs and operated by NASA Langley Research Center. The UW is responsible for on-board and ground calibration of the NAST-I. The NAST-I is of similar design to the S-HIS and has similar spectral and spatial coverage but higher spectral resolution.

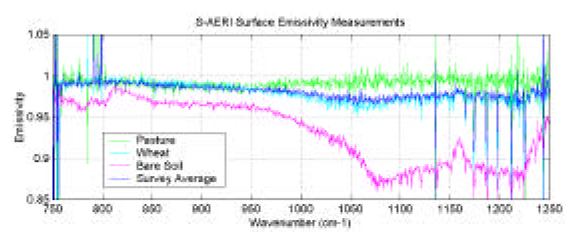

Figure 2. The measured surface emissivity of pasture, wheat, and bare soil near the DOE ARM site in Oklahoma overlaid with the weighted average emissivity as determined by the North/South survey results (39% pasture; 55% wheat; 6% bare soil).

The third observation set is from the NASA SAFARI experiment based in South Africa during Aug-Sept.

2000. The S-HIS flew onboard the NASA high altitude ER-2 aircraft during SAFARI and collected over 90 hours of upwelling radiance spectra on 14 different flights over a variety of surface types. Numerous coincident aircraft underflights of the Terra platform were obtained. The S-HIS data presented in this paper are from the flight of 27 August 2000 over the Okavanga Delta region of Botswana.

4. RESULTS

The approach taken in this paper is to find the weight of the three main surface types which provide the best fit to the average aircraft observations. A best fit weighting of 35% pasture, 40% wheat, and 25% bare soil is shown in figure 3 compared with the average NAST-I aircraft observations. The NAST-I relative emissivity is given in the lower panel of figure 3. In precisely the same manner, a weighting of 45% pasture, 40% wheat, and 15% bare soil was found to be a best fit to the S-HIS observations on this day. The comparison of weighted surface emissivity and aircraft S-HIS relative emissivity is shown in figure 4. The relative emissivity of both the NAST-I and S-HIS has been set equal to 0.99 at 823 cm^{-1} for consistency with the ARM survey results.

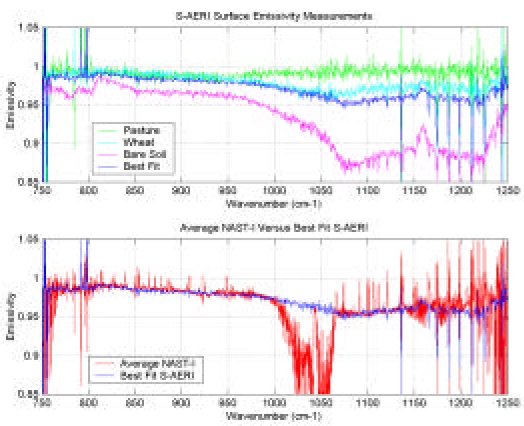

Figure 3. A best fit weighted average of the ground-based S-AERI measurements (35% pasture; 40% wheat; 25% bare soil) shown in the upper panel is overlaid in the lower panel on the average north/south nadir measurements of the NAST-I at 55,000 feet in the vicinity of the ARM SGP central facility. The feature at 1000-1080 cm^{-1} in the aircraft observations is due to absorption by ozone in the path from the aircraft to the ground. The numerous spikes in the data are due to water vapor and carbon dioxide absorption lines where the approximation leading to equation (3) is not valid. The spikes are pointed up because of the presence of a nocturnal surface inversion at the time of the measurements.

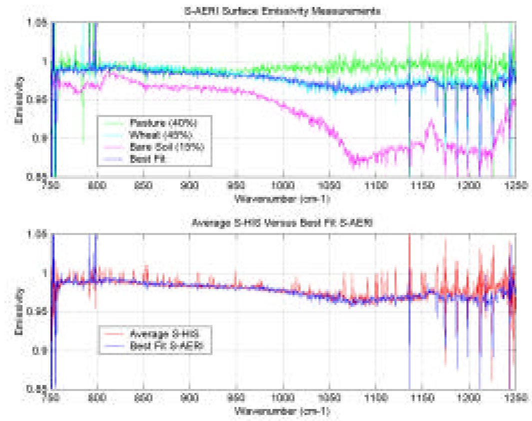

Figure 4. Best fit of a linear combination (40% pasture, 45% wheat, 15% bare soil) of surface emissivity types to surface relative emissivity derived from the Scanning-HIS aircraft observations made from the NASA DC-8 at 25,000 feet. The flight path of the DC-8 was in the vicinity of the ARM SGP central facility but along a different ground path than the PROTEUS. Notice the lack of ozone absorption at this lower altitude though water vapor absorption lines are still present.

For a simultaneous fit of surface temperature and emissivity from the aircraft observations, we can use equation (2) where an calculation has been used to correct for the atmospheric emission. We vary the skin temperature until the deived emissivity is no longer contains gaseous absorption features (Smith, 1996). This is referred to as the online/offline technique. This fit appears to be biased low by an error in the calculated radiance representing the atmospheric emission either due to spectroscopy or water amount.

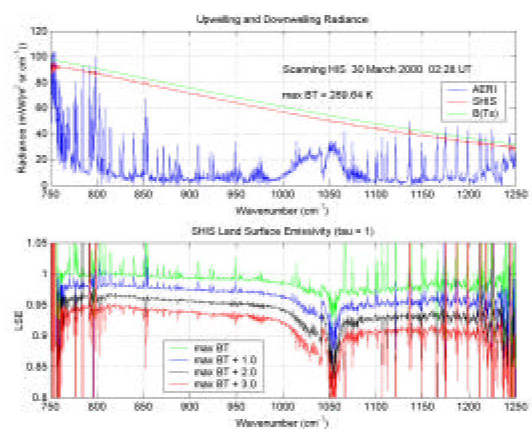

Figure 5. The S-HIS and AERI observations used in the online/off-line fitting technique are shown in the upper panel. The lower panel shows a range of skin temperature values. The best fit is the one which minimizes the spectral line variations of the derived emissivity.

Measurements of the Okavanga Delta region of southern Africa obtained by the UW S-HIS instrument aboard the NASA high altitude ER-2 aircraft are shown in figure 6. The cooler water-filled swamp is surrounded by the high temperature Kalahari desert region. This example illustrates the importance of considering non-black surface types which in this case produce an apparent brightness temperature variation reaching 5 K between 10 and 8 µm. Further analysis of this data is underway to obtain the associated surface emissivity and skin temperature maps.

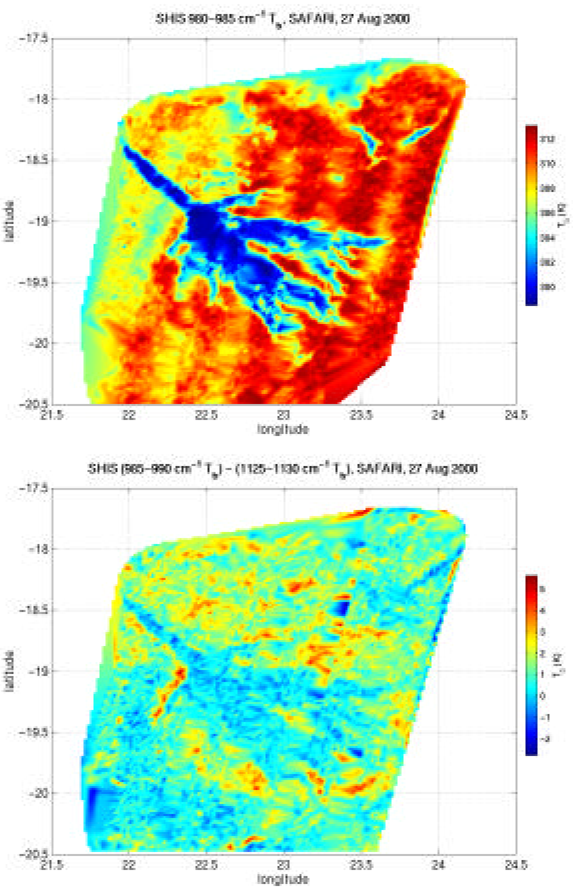

Figure 6. The upper panel is a 10 µm microwindow brightness temperature image created from Scanning-HIS data of the Okavanga Delta in southern Africa. The lower panel shows the temperature contrast in two sets of microwindows (10-8 µm).

5. SUMMARY

The results show that aircraft observations of spectral emissivity in the vicinity of the ARM SGP central facility are generally consistent with a linear combination of bare soil and vegetated emissivity measured in a ground-based site survey. Several factors may influence the differences between the ground-based and aircraft measurements. Nadir aircraft views are being compared with surface measurements made at a view angle of 60 degrees from nadir. The aircraft fields of view do not exactly overlap with the ground survey so that a different fraction of bare soil and vegetated soil types can be expected. Moreover a comparison of the S-HIS results from figures 4 and 5 suggests that the absolute emissivity magnitude derived from the online/offline technique is sensitive to the accuracy of the atmospheric correction; either due to spectroscopy errors or water vapor amount uncertainties.

A more comprehensive analysis of the NAST-I and S-HIS data is anticipated which will extend the results of the ARM LSE Survey to a larger area of the ARM SGP site. Additional measurements at the ARM site at different times of the year will help to characterize the seasonal variation of the land surface emissivity and thus improve our characterization of this site for satellite validation.

6. ACKNOWLEDGEMENTS

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