Two surface temperature retrieval methods compared over agricultural lands

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ABSTRACT

Accurate, spatially distributed surface temperatures are required for modeling evapotranspiration (ET) over agricultural fields under wide ranging conditions, including stressed and unstressed vegetation. Modeling approaches that use surface temperature observations, however, have the burden of estimating surface emissivities. Emissivity estimation, the subject of much recent research, is facilitated by observations in multiple thermal infrared bands. But it is nevertheless a difficult task. Using observations from multiband thermal sensors, ASTER and MASTER, estimated surface emissivities and temperatures are retrieved in two different ways: the temperature emissivity separation approach (TES), and the normalized emissivity approach (NEM). Both rely upon empirical relationships, but the assumed relationships are different. TES relies upon a relationship between the minimum spectral emissivity and the range of observed emissivities. NEM relies upon an assumption that at least one thermal band has a predetermined emissivity (close to 1.0). Experiments comparing TES and NEM were performed using simulated observations from spectral library data, and with actual data from two different landscapes– one in central Oklahoma, USA, and another in southern New Mexico, USA. The simulation results suggest that TES's empirical relationship is more realistic than NEM's assumed maximum emissivity, and therefore TES temperature estimates are more accurate than NEM estimates. But when using remote sensing data, TES estimates of maximum emissivities are lower than expected, thus causing overestimated temperatures. Work in progress will determine the significance of this overestimation by comparing ground level measurements against the remote sensing observations.

Keywords: ASTER, emissivity, thermal infrared, MASTER, temperature-emissivity separation, TES, NEM

1. TEMPERATURE-EMISSIVITY SEPARATION

The best land surface temperatures from remote sensing observations are obtained from multiband thermal infrared (TIR) instruments. The reason multiband TIR observations are superior to single and dual band observations is that they help resolve spectral variations in surface emissivity. Since accurate emissivity determination over land surfaces is crucial to the retrieval of surface temperatures,[1] the use of multiband instruments is important for applications such as surface energy balance modeling.[2] Neither single band observations from instruments such as ETM7, nor observations from dual band instruments such as AVHRR satellites, can resolve the important spectral variations of common land surfaces between 8 and 12μm.

Wide availability of multiband TIR data is relatively new, since most instruments have been in aircraft, but not satellites. Currently the most prominent satellite sensor is ASTER,[3] a five band instrument on board the Terra satellite. ASTER collects 90m TIR resolution images, each 60x60km, spanning the 8-12μm wavelengths. A similar sensor for aircraft is the Modis-ASTER simulator[4] (MASTER), with 10 TIR bands over the same wavelengths.

Production of temperature and emissivities from multiband data, for the most part, is a non-unique problem. Except for multiple observations,[5] there will always be one more unknown than observations available. Only the spectral shape of surface emissivities can be uniquely determined. Consequently, at least one assumption is needed to determine absolute emissivities.[6] For ASTER, standard temperature and emissivity products are obtained from an algorithm known as Temperature-Emissivity Separation (TES),[7] which is an iterative approach that resolves the non-uniqueness problem by relying upon an empirical relationship. Determined from laboratory samples, and constrained by the sensor's spectral response functions, this relationship estimates the minimum emissivity of a surface from the observed range of apparent emissivities. TES has been tested under actual conditions[8] and has been shown to be in qualitative good agreement with ground-based measurements.

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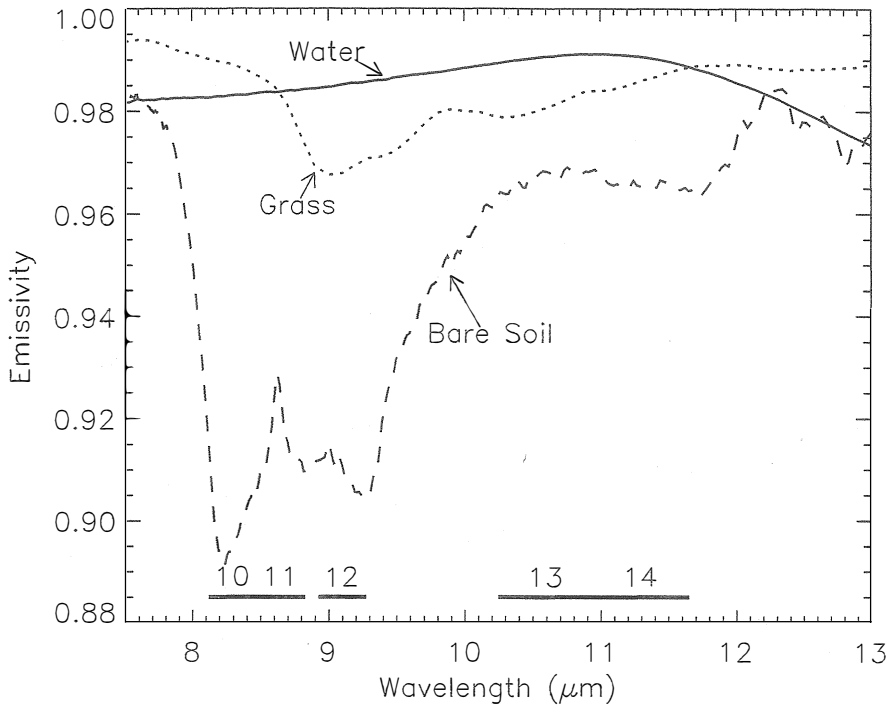

Figure 1. Emissivity spectra examples for bare soil, grass and water. ASTER bands are shown at the bottom.

However, use of the TES approach, though carefully considered and based on aircraft and field experiments, might not be the optimum approach for all applications. In particular, when viewing agricultural lands, typical emissivities are high, and are not well constrained by laboratory scale calibrations. To determine how well TES performs, an alternative procedure needs to be considered.

A suitable one is the Normalized Emissivity Method (NEM).[9,10] Unlike TES, NEM does not rely upon band differences, nor does it require calibration against a spectral library. It is simple to apply and requires no iteration. NEM is in fact used as an initializer for TES, but its assumption is significantly different from TES. NEM assumes that there exists at least one TIR band with a pre-established, maximum emissivity, identified as the one with the largest apparent surface temperature. Although the precise value of the maximum emissivity is unknown, the assumption is usually made that it is between 0.97 and 0.99. This is reasonable for common land surfaces, particularly where ample vegetation is present, since the resulting multiple scattering causes emissivities to approach 1.0.

To assess the merits of the TES and NEM techniques, two sets of comparison tests are performed to determine which technique is most accurate and best follows assumptions. One set uses spectral library data to simulate remote sensing observations under controlled conditions. The other set uses actual multiband TIR observations over two different landscapes: a sub-humid central Oklahoma scene and a semi-arid southern New Mexico scene.

2. ASTER SPECTRAL LIBRARY TESTS

Using simulated, but realistic surfaces derived from data in the ASTER spectral library,[11] a fundamental question can be addressed. Which approach, TES or NEM, is likely to be the most accurate estimator of surface temperature and emissivity? To help answer this question for agricultural land cover conditions, tests were made using simulated ASTER observations. The simulations were based on 54 samples from the ASTER spectral library, representing soil, vegetation and water spectra. Examples of spectral library data (Fig. 1) show that the greatest variability occurs within the 8-9μm spectral region, equivalent to ASTER bands 10, 11 and 12. Maximum emissivities, typically >0.965, occur at ~11μm and correspond to ASTER bands 13 and 14. Two simulation sets were performed: one set checked the assumptions required by TES and NEM, the other checked temperature retrieval accuracy.

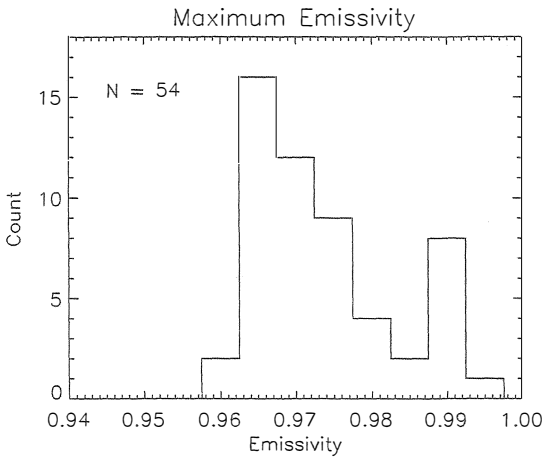

Figure 2. ASTER band emissivities for selected JHU spectral library samples.

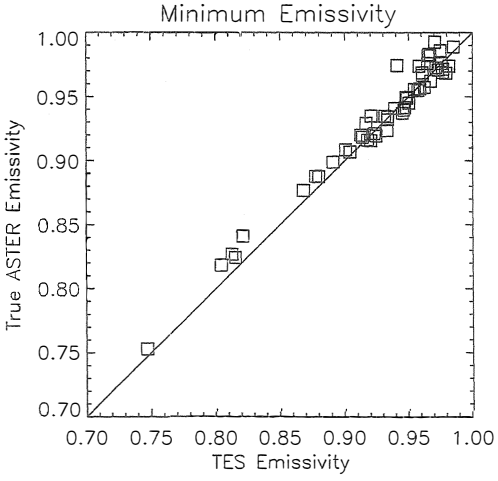

Figure 3. TES minimum emissivity vs. band averaged spectral library minimum emissivity.

To check the assumptions of NEM and TES, the spectral library selection was used to model radiances received by ASTER. Sensor radiances were modeled by using a common summertime surface temperature, 37°C , and an atmospheric profile derived from radiosonde data from central Oklahoma (collected from the CART-ARM site on 10 June 2001, precipitable water = 2.7cm). After filtering the original spectral library data by ASTER spectral response functions, the NEM assumption could be immediately tested. Is there a well defined maximum emissivity for all samples? The distribution of the maximum band averaged emissivities (Fig. 2) indicates that the answer is no. Maximum emissivities from the spectral library subset range between 0.96 and 0.995, with no best value. Using a pre-selected maximum emissivity at the mid-point, ~0.98, would lead to frequent emissivity errors up to 2%, or equivalently a temperature prediction error of ~1.5°C . On the other hand, modeling sensor radiances (atmospheric estimation error not considered) and then estimating surface emissivities from TES, leads to typical emissivity errors less than 1%. Using the TES procedure and a 'standard' coefficient set[7] for predicting minimum emissivities ($\epsilon_{\min} = 0.994 - 0.687\mathrm{MMD}^{0.737}$, where MMD is a range of relative emissivities), most emissivity errors are small (Fig. 3).

Comparing TES and NEM predicted surface temperatures against the original modeled temperature shows the effect of the resulting emissivity errors (Fig. 4). The dashed and solid histogram respectively represent TES and NEM temperature estimate errors. For TES most estimates were less than 1°C , with negligible bias. For NEM, temperature estimates errors ranged up to 1°C , with significant (~4°C) bias. The source of larger temperature estimate errors for NEM is its greater inaccuracy across all ASTER TIR bands (Fig. 5), with frequent occurrences of emissivity errors exceeding 2%.

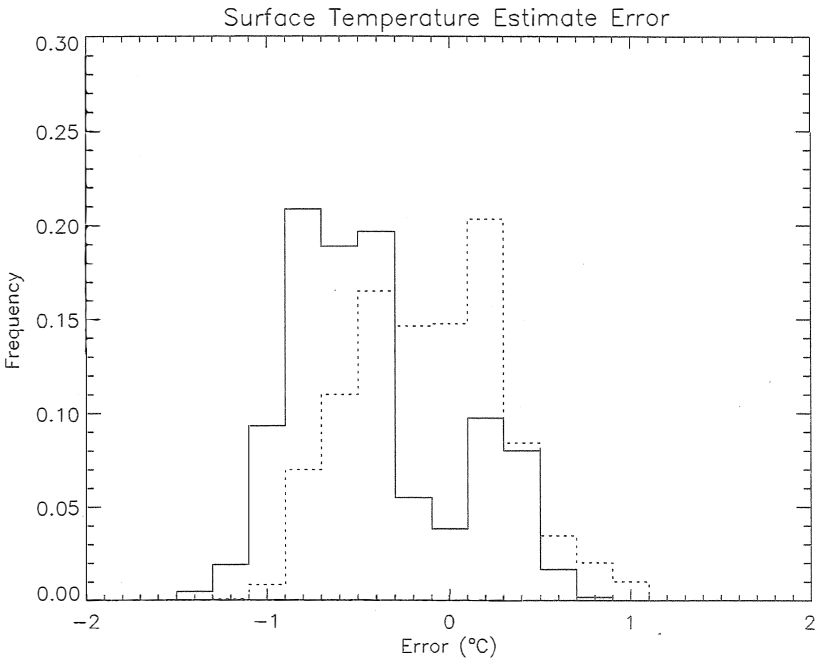

Figure 4. Surface temperature prediction error from NEM and TES techniques. Solid histogram from NEM, dashed from TES.

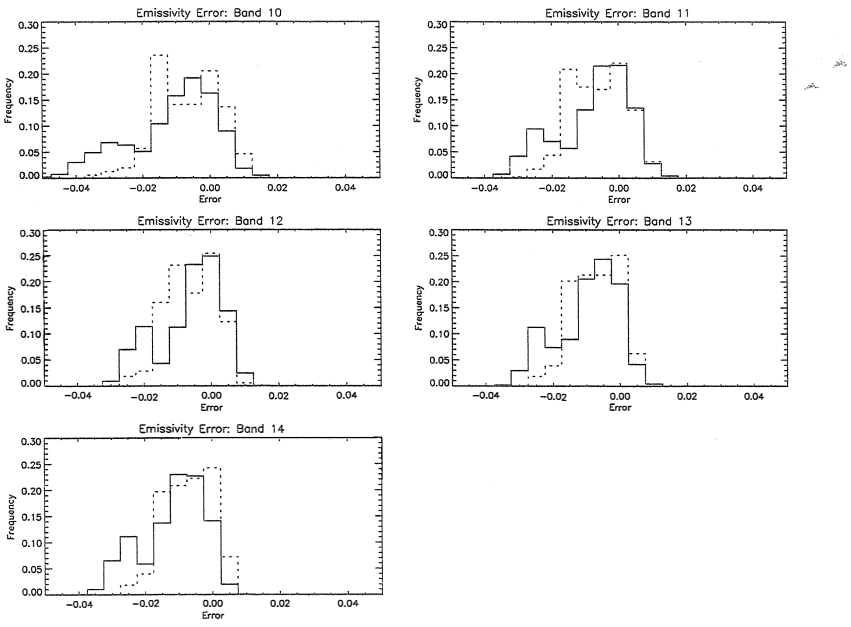

Figure 5. Surface emissivity prediction error from NEM and TES techniques for ASTER TIR bands 10-14. Solid histogram from NEM, dashed from TES.

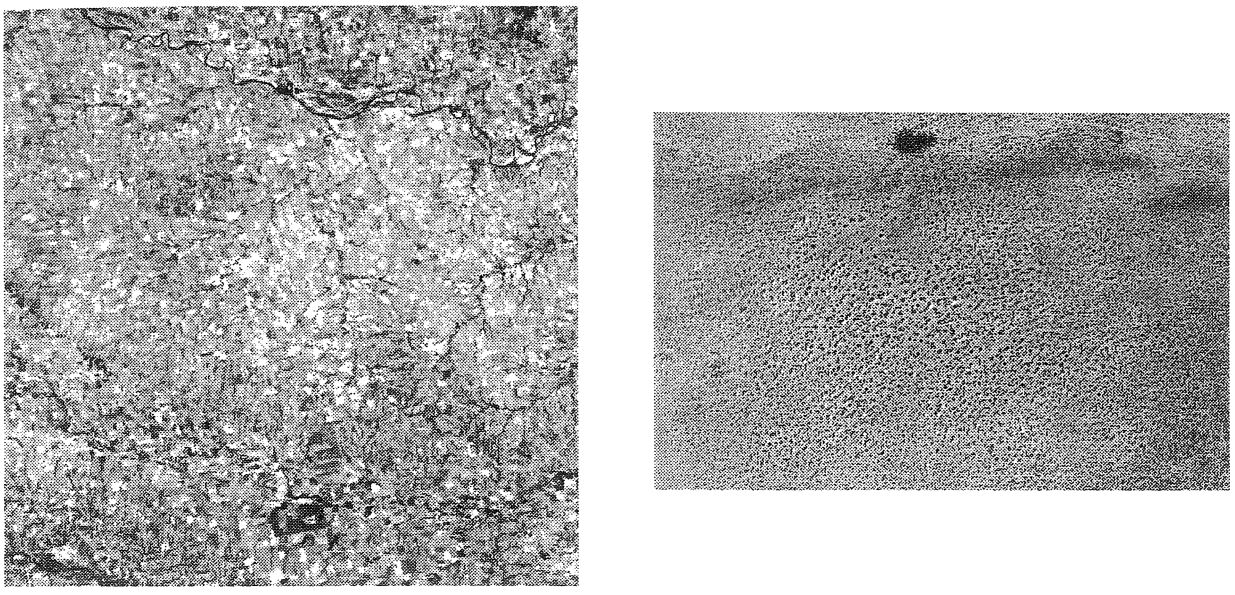

Figure 6. ASTER view of El Reno, Oklahoma region from 10 June 2001 (left), and MASTER view of Mesquite site at Jornada Experimental Range, New Mexico from 27 September 1999 (right). Both display surface temperatures, ranging between 30 and 50°C (black to white). The Oklahoma scene is 60x60km at 90m resolution. The Jornada scene is ~3x1.5km at 3m resolution.

3. REMOTE SENSING TESTS: OKLAHOMA & NEW MEXICO

Using spectral library data to model with TES and NEM is good for controlled surface conditions, and theoretical accuracies can be determined. But the dimensions of emissivity spectral library reference samples are significantly different from the pixel dimensions of remote sensing imagery, and test results from them might not be representative. For remote sensing data, samples are typically no less than 10m, frequently >100m, and would be expected to have high emissivities due to multiple scattering. Therefore, two remote sensing scenes have been selected to examine the TES and NEM approaches under more practical conditions. The scenes are taken from active study sites[2, 8, 12] in central Oklahoma and southern New Mexico (Fig. 6). One is a 10 June 2001 ASTER scene near El Reno, Oklahoma, the other is 27 September 1999 MASTER scene over mesquite lands in the USDA Jornada Experimental Range, New Mexico.

There are primarily four surface types for the ASTER Oklahoma scene: bare soil fields, senenscent winter wheat fields, grazing lands, and water bodies. Previous investigation using 12m resolution remote sensing data collected in 1997[13] showed that emissivities in this region were mostly high, 0.96-0.99, for vegetated fields and water bodies. Bare soil fields commonly showed emissivities <0.9, a characteristic verified by laboratory emissivity spectra.[14] Using the 2001 ASTER scene, the qualitative emissivity variation between vegetation and bare soil was largely confirmed by both TES and NEM approaches, but predicted magnitudes were different. For TES, the empirical coefficients used were the same as noted previously. For NEM, the maximum emissivity was chosen to be 0.98. A sequence of histograms (Fig. 7) generated from NEM and TES analyses (surface temperature at upper left, followed by bands 10-14 emissivities) illustrates the differences. TES and NEM results are respectively shown by dashed and solid lines. TES emissivities are lower than NEM emissivities, sometimes by as much as 5%. Consequently TES temperatures are higher than NEM temperatures, typically by 1-2°C . Both methods agree that the maximum emissivity is usually found in ASTER band 13 (10.6μm).

The TES-NEM comparison was repeated over the Mesquite site, Jornada, New Mexico using MASTER aircraft TIR imagery at 3m resolution. The Mesquite site has abundant dry, coarse soil, and interspersed Mesquite bush. MASTER bands 42-50 were used, spanning 7.8-13.3μm wavelengths. Because the Mesquite data were acquired at higher resolution than the Oklahoma data, and because of greater expanses of exposed soil, the specified maximum emissivity for NEM was lowered slightly, to 0.975. Results from TES and NEM were as before. TES produced uniformly lower emissivities than NEM throughout the 8-12μm band. Hence surface temperature estimates from TES were typically 2°C greater than NEM

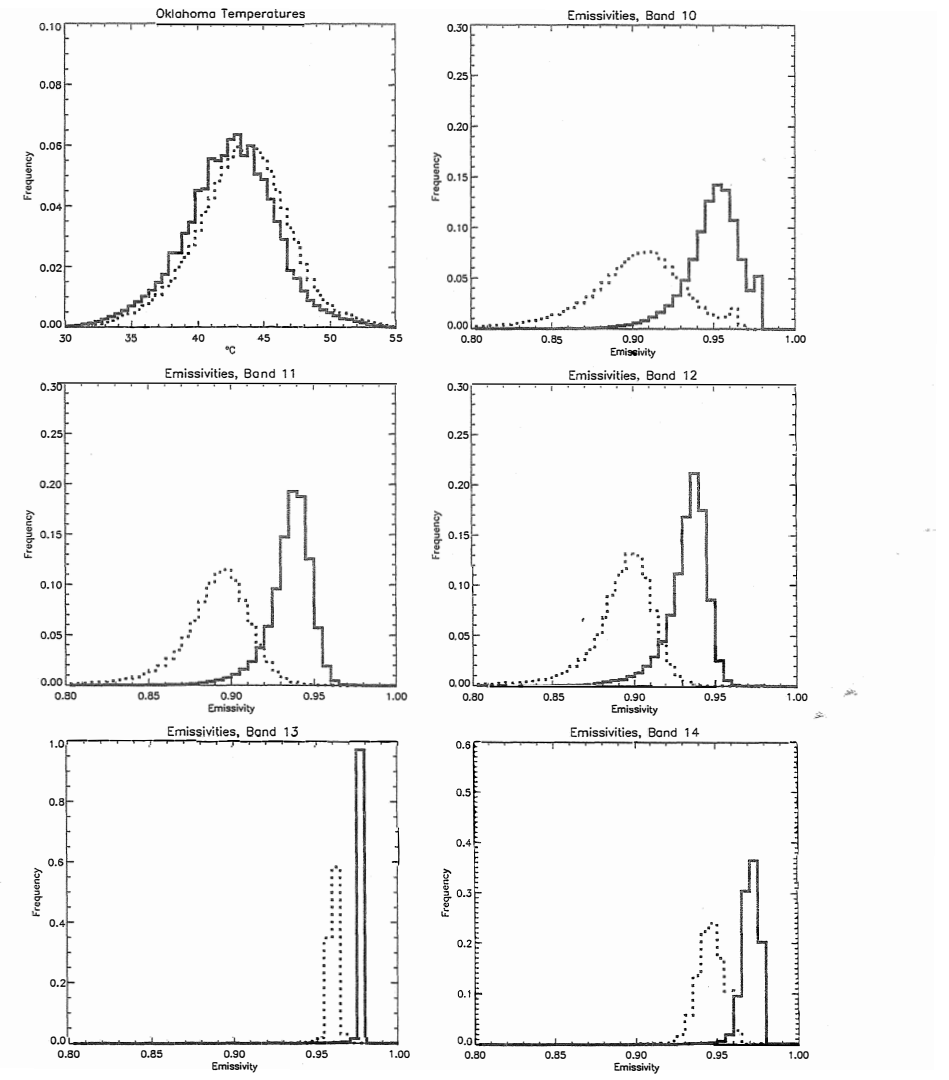

Figure 7. Surface temperature and ASTER band emissivities over central Oklahoma, 10 June 2001. Solid histograms for NEM. Dashed for TES.

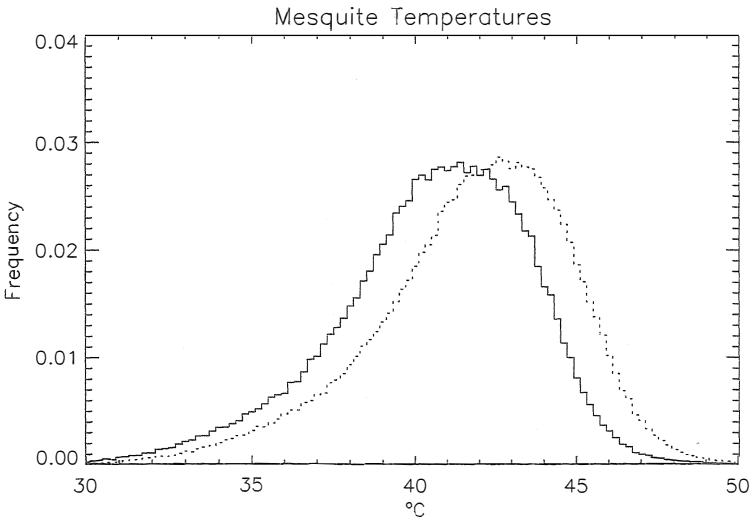

Figure 8. Estimated surface temperatures over Mesquite site, 27 September 1999 derived from MASTER aircraft TIR data. Solid histogram is NEM, dashed line histogram is TES.

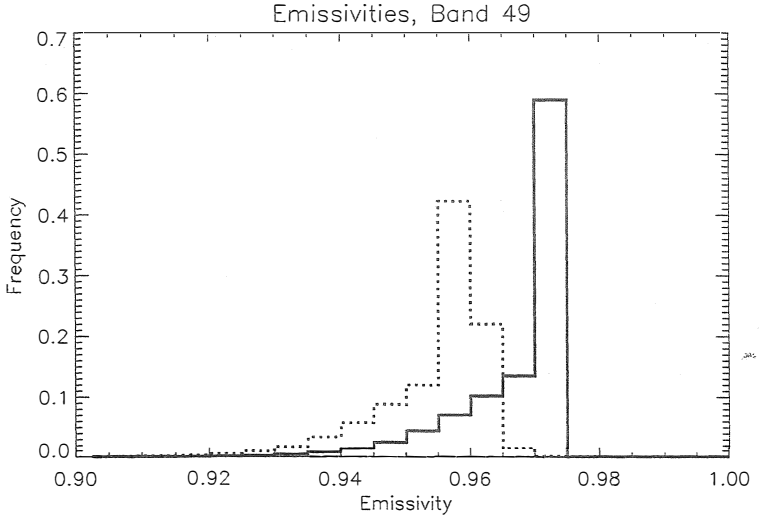

Figure 9. Estimated MASTER band 49 emissivities over the Mesquite site, 27 September 1999. Solid histogram derived from NEM, dashed from TES.

estimates (Fig. 8). The cause for the relatively high TES temperature estimates is due to its lower emissivity estimates. The NEM approach, on the other hand, produces cooler temperatures because its constrained maximum emissivity of 0.975 is higher than most TES estimates. An illustration of the resulting emissivities for MASTER band 49 (12.μm) is shown in Fig. 9, where NEM emissivities typically are higher and span a narrower range than do TES emissivities.

4. DISCUSSION

Testing the accuracy of temperature retrieval using two techniques, TES and NEM, against simulated and actual remote sensing data sets shows that neither technique is clearly superior to the other. TES does appear to produce more accurate temperature estimates when viewing simulated surfaces derived from spectral library data, but TES tends to produce low maximum emissivity estimates. Low emissivity estimates will cause overestimated surface temperatures, and is

undesirable when modeling the surface energy balance over agricultural regions. The NEM approach, because of its artificial constraint on the maximum emissivity, will not develop this overestimate bias. TES has previously been shown to be potentially precise to 0.3°C , vs. an NEM precision of 1.7°C.[7] But based upon comparison of temperature distributions over vegetated terrain (Figs. 7 and 8), both TES and NEM appear to have similar precision. A more definitive comparison, using multiple scenes over the Jornada area, along with ground-based temperature observations is underway.

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