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ABSTRACT

The Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER) has acquired more than a dozen clear sky scenes over the Jornada Experimental Range in New Mexico since the launch of NASA's Terra satellite in December, 1999. To support the ASTER overpasses there were simultaneous field campaigns for the 5/09/00, 5/12/01, 9/17/01 and 5/15/02 scenes. Also, data from an airborne simulator, MASTER, were obtained for the 5/12/01 and 5/15/02 scenes to provide high resolution (3 m) data roughly coincident with ASTER. The Jornada Experimental Range is a long term ecological reserve (LTER) site located at the northern end of the Chihuahuan desert. The site is typical of a desert grassland where the main vegetation components are grass and shrubs. The White Sands National Monument is also within several of the scenes. ASTER has 5 channels in the 8 to 12 micrometer wave band with 90 meter resolution and thus is able to provide information on both the surface temperature and emissivity. The Temperature Emissivity Separation (TES) algorithm was used to extract emissivity values from the ASTER data for 5 sites on the Jornada and for the gypsum sand at White Sands. The results are in good agreement with values calculated from the lab spectra for gypsum and with each other. The results for sites in the Jornada show reasonable agreement with the lab results when the mixed pixel problem is taken into account. These results indicate ASTER and TES are working very well. The surface brightness temperatures from ASTER were in reasonable agreement with measurements made on the ground during the field campaigns.
Keywords: Thermal infrared, emissivity, ASTER, remote sensing, Terra, gypsum, desert.

1. INTRODUCTION

The Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) [1] on the Terra satellite provides a new tool for studying the earth's surface. The multichannel thermal infrared (TIR) bands make it possible to extract both surface temperature and spectral emissivity from the data. The Temperature Emissivity Separation (TES) [2] algorithm is used to extract the temperature and 5 emissivities from the 5 channels of ASTER TIR data. TES makes use of an empirical relation between the range of observed emissivities and their minimum value. This approach will be demonstrated with data acquired over the Jornada Experimental Range in New Mexico. Knowledge of the surface emissivity is important for determining the radiation balance at the land surface. Wilber et al. [3] have shown that uncertainties in the surface emissivity on the order of 0.1 can produce uncertainties in the longwave radiation balance up 5 or 6 W/m^2 which is comparable to or greater than the effect of increased CO_2. For heavily vegetated surfaces there is little problem since the emissivity is relatively uniform and close to one. However, for arid lands with sparse vegetation the problem is more difficult because the emissivity of the exposed soils and rocks is highly variable. This is shown in Fig. 1 where laboratory measurements of emissivity for several relevant soils are presented. In particular note the strong variations of emissivity in the 8 to 9 μm region. The results we will present are from ASTER data acquired over the Jornada Experimental Range and the White Sands National Monument in New Mexico for several dates since the December 1999 launch. The Jornada site is typical of a desert grassland where the main vegetation components are grass and shrubs. It demonstrates the changes in surface emissivity which occur when the grassland is degraded to shrub dominated vegetation with a considerable amount of soil exposed.

The thermally emitted radiance from any surface depends on two factors: 1) the surface temperature, which is an indication of the equilibrium thermodynamic state resulting from the energy balance of the fluxes between the atmosphere, surface and

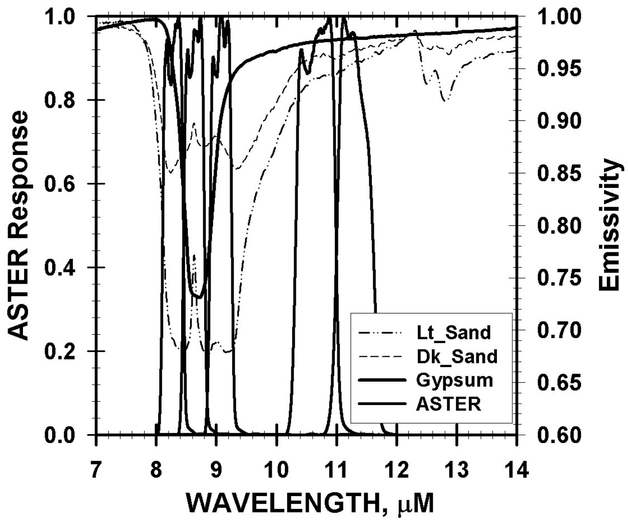

Figure 1: Plots of the spectral emissivity for 3 soils from New Mexico and the response functions for the 5 ASTER thermal infrared channels. Note that the emissivity curve for the light sand is the one that goes below 0.70.

the subsurface soil; and 2) the surface emissivity which is the efficiency of the surface for transmitting the radiant energy generated in the soil into the atmosphere. The latter depends on the composition, surface roughness, and physical parameters of the of surface, e.g. moisture content. In addition, the emissivity generally will vary with wavelength for natural surfaces. Thus to make a quantitative estimate of the surface temperature we need to separate the effects of temperature and emissivity in the observed radiation. In this paper we will be demonstrate the effectiveness of the TES approach with data acquired over the Jornada Experimental Range in New Mexico.

2. JORNADA SITE

The Jornada Experimental Range lies between the Rio Grande flood plain (elevation 1190 m) on the west and the crest of the San Andres mountains (2830 m) on the east. The Jornada is 783 km^2 in area and is located 37 km north of Las Cruces, New Mexico on the Jornada del Muerto Plain in the northern part of the Chihuahuan Desert. The larger Jornada del Muerto basin is typical of the Basin and Range physiographic province of the American Southwest and the Chihuahuan Desert [4].

Five specific sites in the Jornada were chosen for intensive studies. Sites were selected to represent grass, shrub (mesquite, creosote, and tarbush), and the grass-mesquite transition areas. The grass site is in a fairly level area where black grama dominates and encompasses an exclosure where grazing has been excluded since 1969. At the mesquite site, honey mesquite bushes are on coppice dunes which vary in height from 1 to 4 m. Bare soil dominates the lower areas between these coppice dunes with most of this area covered by a darker soil with a consolidated crust. The transition site is between the grass and mesquite site and represents the degradation from a good grassland to the shrub dominated mesquite area. The creosote site is also fairly level with the shrubs being smaller and closer together than those at the mesquite site.

A portion of the interdunal area at the mesquite site is covered by a bright quartz-rich sand. Samples of two soils from this site were taken to the Jet Propulsion Laboratory for measurements of their emissivity spectra. One, a bright sand and other a darker sand which formed the consolidated crust. The results are shown in Fig. 1 along with the ASTER spectral response functions and the emissivity spectra for the gypsum sand from the White Sands area. It is clear that there will be a significant variation of the emissivity for the 5 ASTER channels for these soils with the shorter wavelength ones ($8 < \lambda < 9.5$μm) having noticeably lower emissivities.

3. ASTER

ASTER [1] has 5 thermal infrared channels between 8 and 12 μm as seen in Figure 1. The central wavelengths of the channels are: 8.29, 8.63, 9.08, 10.66 and 11.29 μm. These channels have a spatial resolution of 90 m. The radiance at the surface, $L_j(surf)$, is derived from the measured radiance at the satellite, $L_j(satellite)$, using:

$$L_j(surf) = (L_j(satellite) - L_j(atm \uparrow)) / \tau_j \quad (1)$$

where τ_j and $L_j(atm \uparrow)$ are the atmospheric transmission and upwelling radiance. The latter are calculated using an atmospheric radiative transfer model, e.g. MODTRAN-4 , with atmospheric profile data from the NCEP atmospheric reanalysis program. The profile was adjusted for the surface temperature and humidity conditions at the Jornada. The remaining problem is to relate these radiances to the surface emissivity in the 5 channels without direct knowledge of the temperature, T_{grd} using the relation:

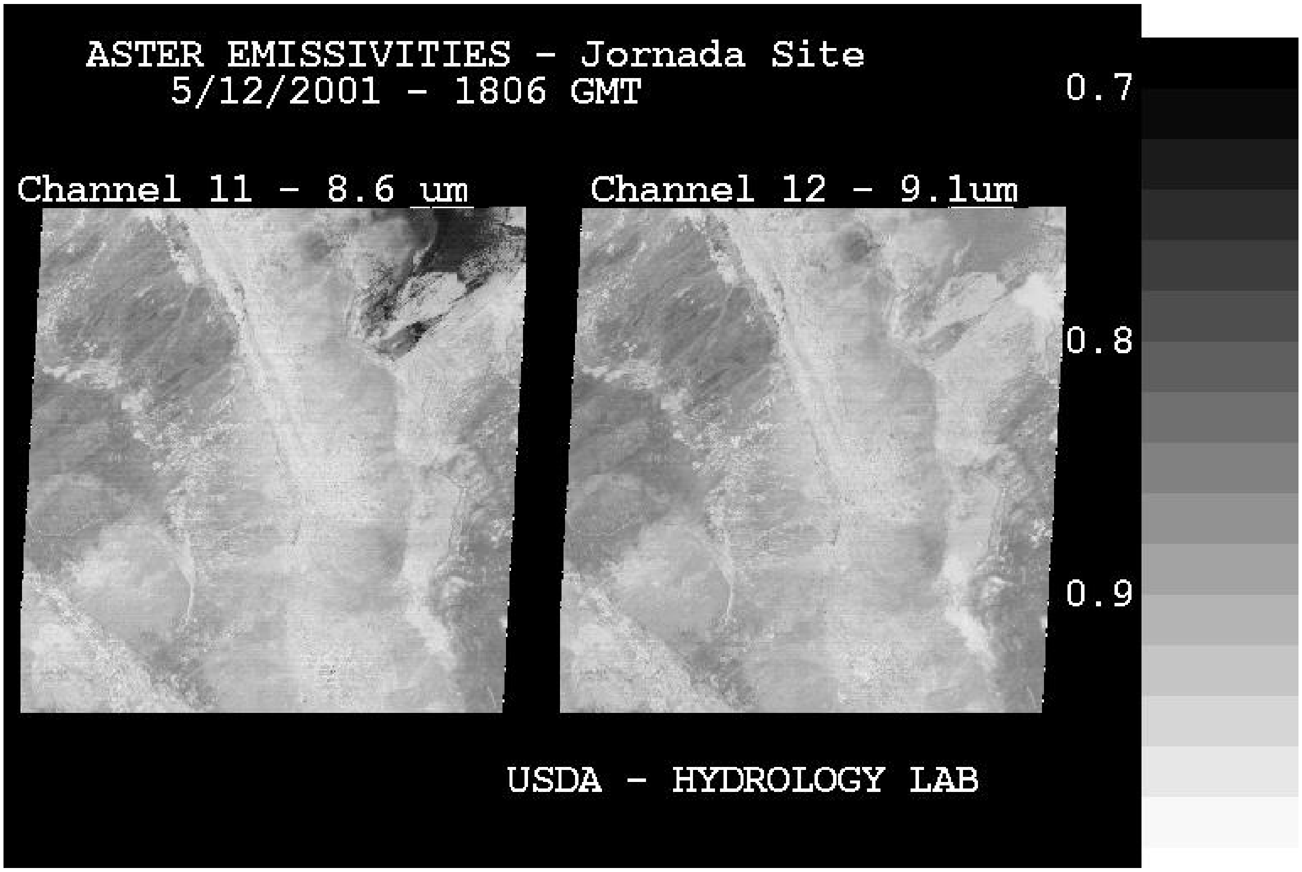

Figure 2: Maps of the emissivities for two of the ASTER channels. The Jornada Experimental Range is at the lower left of the image and the White Sands National Monument is the lower emissivity area at the upper right. Note the difference for this latter region in the 2 images. The emissivity gray scale is at the right.

$$L_j(surf) = \epsilon_j \, BB_j(T_{grd}) + (1 - \epsilon_j) \cdot L_j(atm \downarrow) \qquad (2)$$

where *BB(T)* is the Planck equation for the radiation from a black body, ϵ is the surface emissivity and $L_j(atm \downarrow)$ is the downwelling atmospheric radiance.

Equation 2 indicates that if the radiance is measured in n spectral channels, there will be n+1 unknowns: n emissivities and the unknown surface temperature. The equations described by a set of radiance measurements in n spectral channels is thus under determined, and additional information is needed in order to extract the temperature and emissivity information. Using an empirical relation between the minimum emissivity, ϵ_{min}, and the range of emissivity, $\Delta\epsilon$, for the 5 ASTER channels Gillespie *et al.* [2] developed the TES algorithm for use with ASTER data. The approach has been successfully demonstrated with data from multispectral thermal infrared data from aircraft platforms in HAPEX-Sahel[5] and for this site [6] and will be demonstrated here with data from ASTER.

4. RESULTS

The results of TES being applied to the May 12, 2001 scene over the Jornada and nearby White Sands are presented in Figure 2 for channels 11 and 12. We note that there is considerable variation of the emissivity over the scene, from less than 0.8 to about 0.98 for the 2 channels shown. If we had plotted one of the longer wavelength channels the scene would have been completely white using the same gray scale. The interesting feature for these two bands is the difference in emissivity for the gypsum sand dunes in the White Sands area at the upper right. For channel 11, λ = 8.63 µm, the region is darker i.e. ϵ

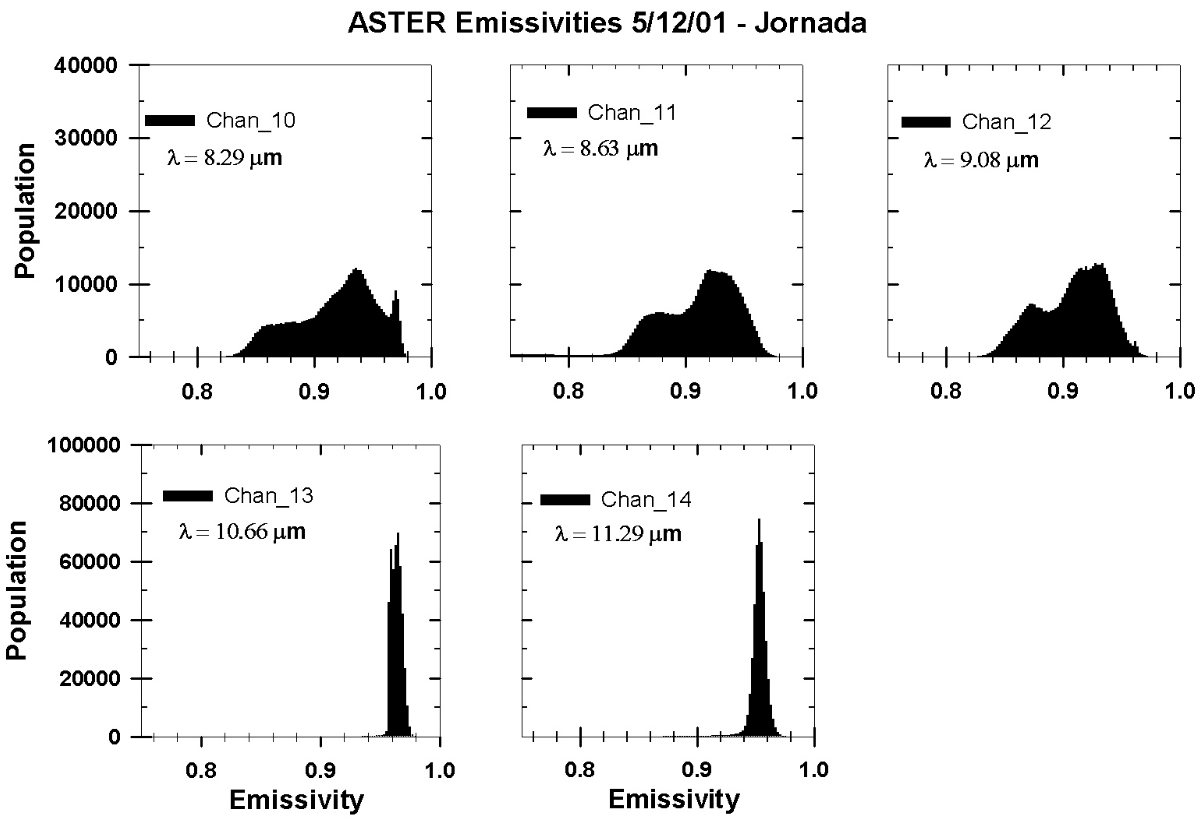

Figure 3: Histograms of the emissivities for the 5 ASTER channels for the May 12, 2001 scene which covers the Jornada Experimental Range and the White Sands National Monument. Note the difference in vertical scales between the short wavelength channels at the top and two longer wavelength channels given in the bottom of the figure..

< 0.75, while for channel 12 the region is much brighter with $\epsilon > 0.85$. This is as expected from Figure 1 where the dip in emissivity for gypsum is centered on the response function for channel 11. Histograms for the 5 channels are presented in Figure 3. The 3 shorter wavelength channels have a much wider range in emissivities, from < 0.85 to about 0.98, while the longer wavelength channels, 13 and 14, have much narrower distributions, from 0.94 to 0.98.

The radiances for a 2 by 2 pixel area (~180 by 180 m) from White Sands were analyzed and the emissivity results are presented in Fig. 4 for 3 days of observation in May 2000 and May 2001. The solid circles are the results from laboratory measurements. The ASTER results show excellent agreement with the laboratory results and with each other for the center 3 bands. The latter were obtained for each ASTER channel by integrating the product of the ASTER response and gypsum emissivity curve shown in Fig. 1. The agreement is particularly clear for the low emissivity 8.6 μm channel. Bands 10 (8.29 μm) and 14 (11.29 μm) show the biggest differences. These are the bands with the strongest atmospheric effects and may indicate inadequate correction. The open symbols are the results from a CIMEL CE312[7] radiometer which has approximately the same 5 spectral bands as ASTER. The shortest wavelength band of the CIMEL is a little longer that of the ASTER band and as a result shows a much lower emissivity than those observed by ASTER band 10. For the other channels the agreement is very good.

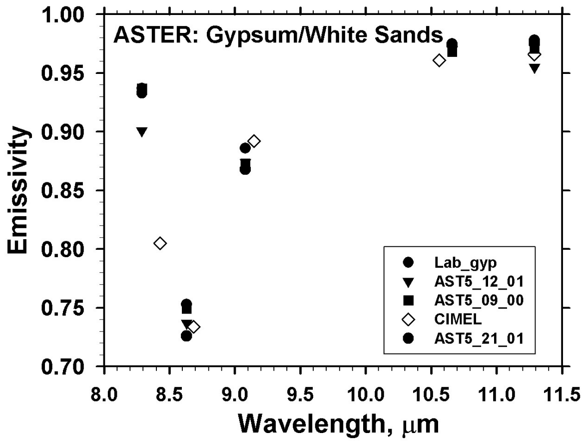

Figure 4: ASTER emissivity results for a gypsum site.

The emissivity results from the four Jornada sites for 5 dates from May 9, 2000 to May 31, 2002 are given in Fig. 5. There is good agreement amongst the ASTER results for all 5 channels for both the mesquite and transition sites. At the mesquite site we made field measurements with the CIMEL 312 [7] radiometer and found that there was good agreement between the ground measurements for the dominant dark soil and the ASTER results. As seen in the figure there is reasonable consistency amongst the ASTER results for the 5 different days.

The results from the grass and creosote sites show reasonably good agreement for the 3 dates in 2000 and 2001. However the two dates in 2002 show consistently lower emissivity values, especially for the short wavelength (8 - 9 µm) channels. At the present time we do not have an explanation for this difference, but we suspect that it could be due lower vegetation cover resulting from the drier than normal conditions.

Ground measurements of surface brightness temperature, T_B, were made on a 7 x 7 grid with 5 meter spacing using a broadband, 7 to 14 µm, radiometer at these sites. A summary of the results is given in Fig. 6 for the four dates on which we have nearly coincident ground measurements and an ASTER overpass. The ground data are presented in boxplots at the times bracketing the overpass, i.e. 11:30 and 12:30 MDT, or coincident with the overpass (about 12:00 MDT) for the four sites. The box shows the range for 50% of the observations and bright line in the box indicates the median for the data. The lines represent outliers in the measurements beyond that expected for a normal distribution indicated by the brackets. The range of T_B for the 5 ASTER channels is presented by the up and down triangles. It is expected that the broadband emissivity for the ground measurements would be within the range of those for the 5 ASTER channels, and thus the average ground T_B should be within the ASTER T_B range as seen in Fig. 6. It is seen that there is reasonable agreement but the ASTER data are a bit cooler. For the May 12, 2001 case, data from the aircraft instrument, MASTER [8], were also acquired. The range of MASTER T_B's is indicated by the triangles to the left of the box. The channels represented by this range cover approximately the same wavelength range as that covered by the ASTER channels. The agreement of MASTER and ASTER is quite good.

5. CONCLUSIONS

These results indicate that the TES algorithm appears to work as well with the data from space as it did with the aircraft data presented earlier [6]. This is encouraging for the application of the technique for mapping emissivity over large areas. An example of this is shown in Fig. 7 where we have plotted an estimate of the broadband (3 - 14 µm) emissivity from a linear combination of the emissivities for the 5 ASTER bands [9]. This result is for the May 12, 2001 scene over the Jornada. The range of emissivities is from 0.92 to about 0.98, with the low values being for the exposed soils at the upper left of the scene and the gypsum of White Sands which is at the upper right. The high emissivity areas are along the San Andres mountain range running roughly north - south through the scene and irrigated agricultural fields along the Rio Grande. The black patches scattered about the image are due clouds.

As noted above, there was also good agreement between the ASTER brightness temperatures and ground measurements with the ASTER brightness temperatures being a bit lower.

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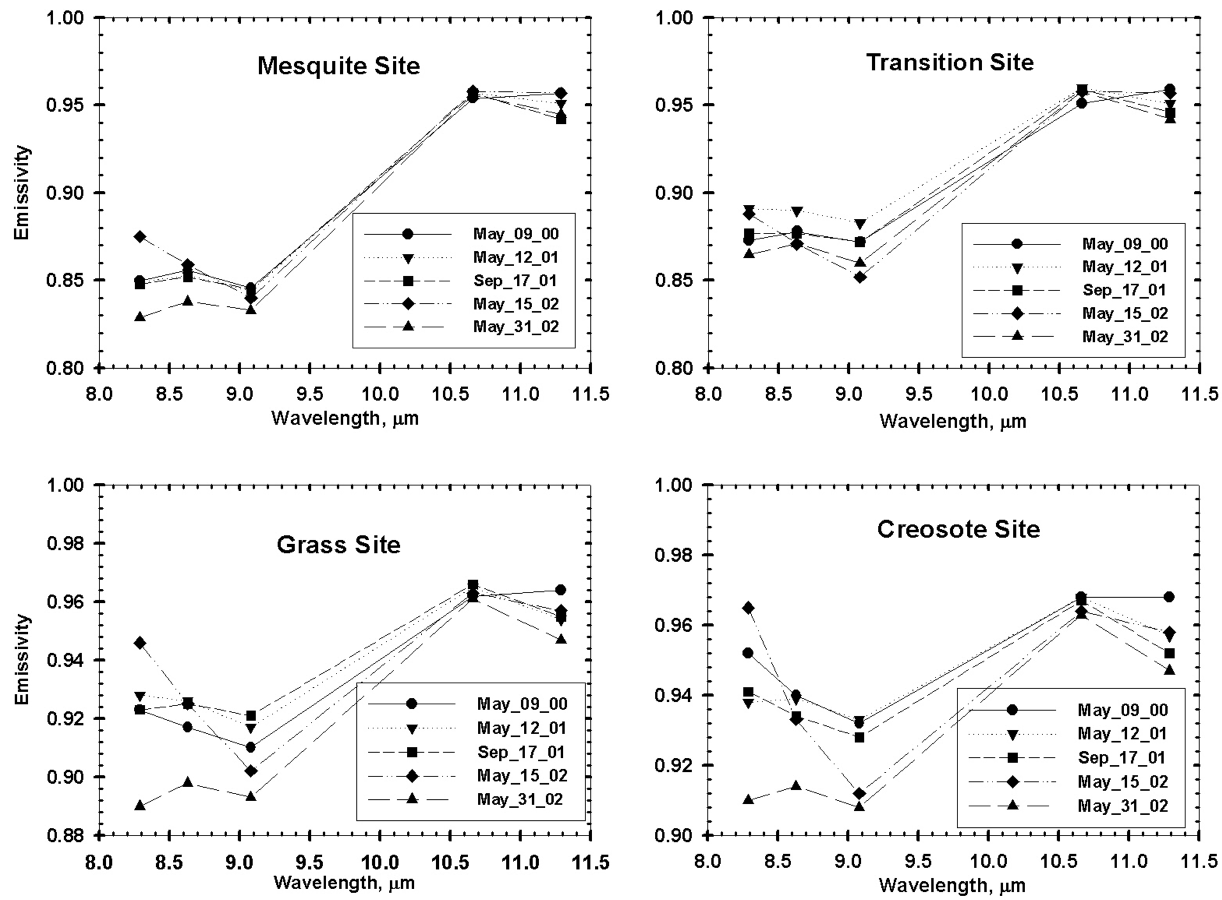

Figure 5: ASTER emissivity results for 4 sites at the Jornada from 5 observations between 5/09/00 and 5/31/02.

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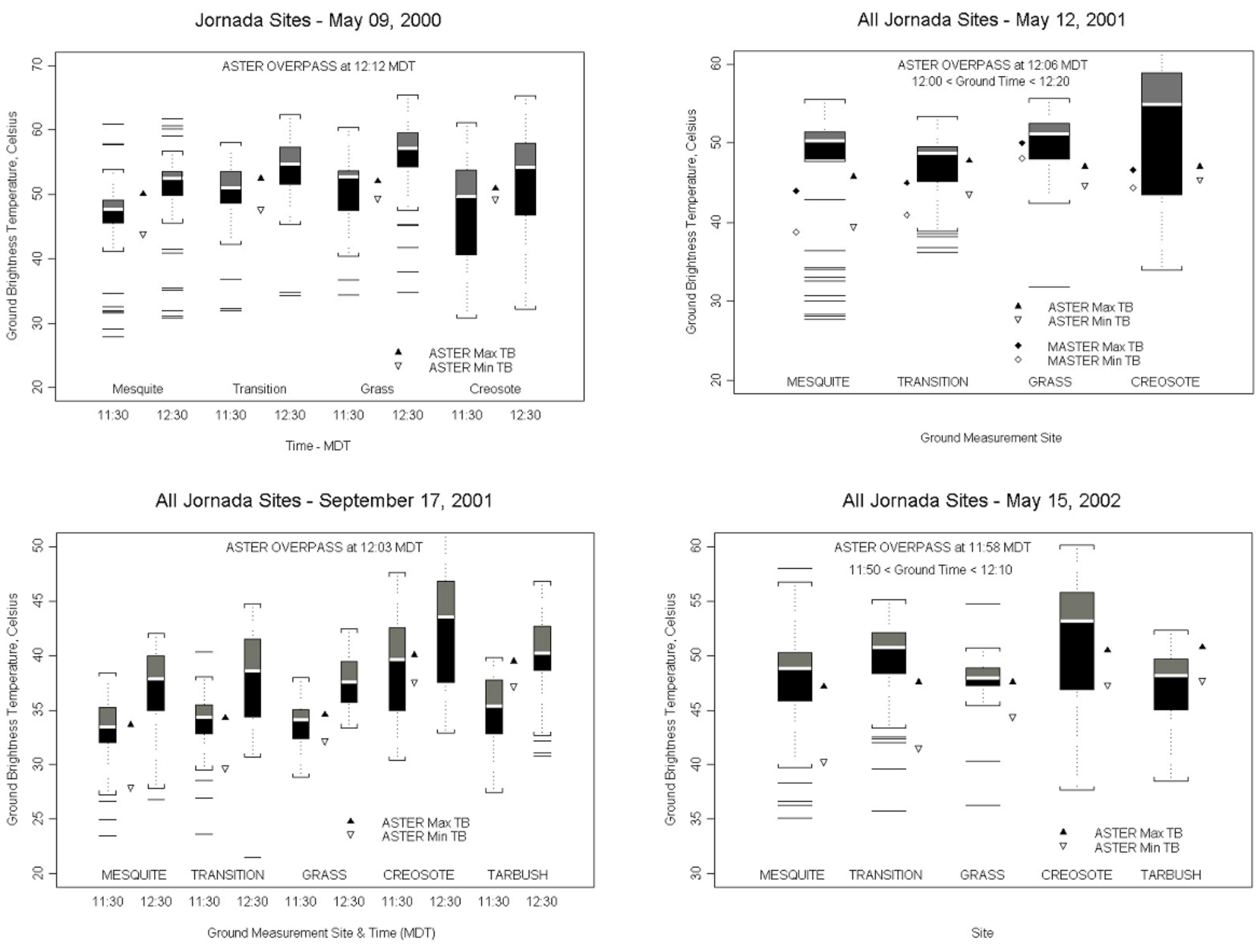

Figure 6: ASTER brightness temperatures at the surface compared with nearly coincident ground observations. Note that the May 12, 2001 case also had MASTER brightness temperatures shown.

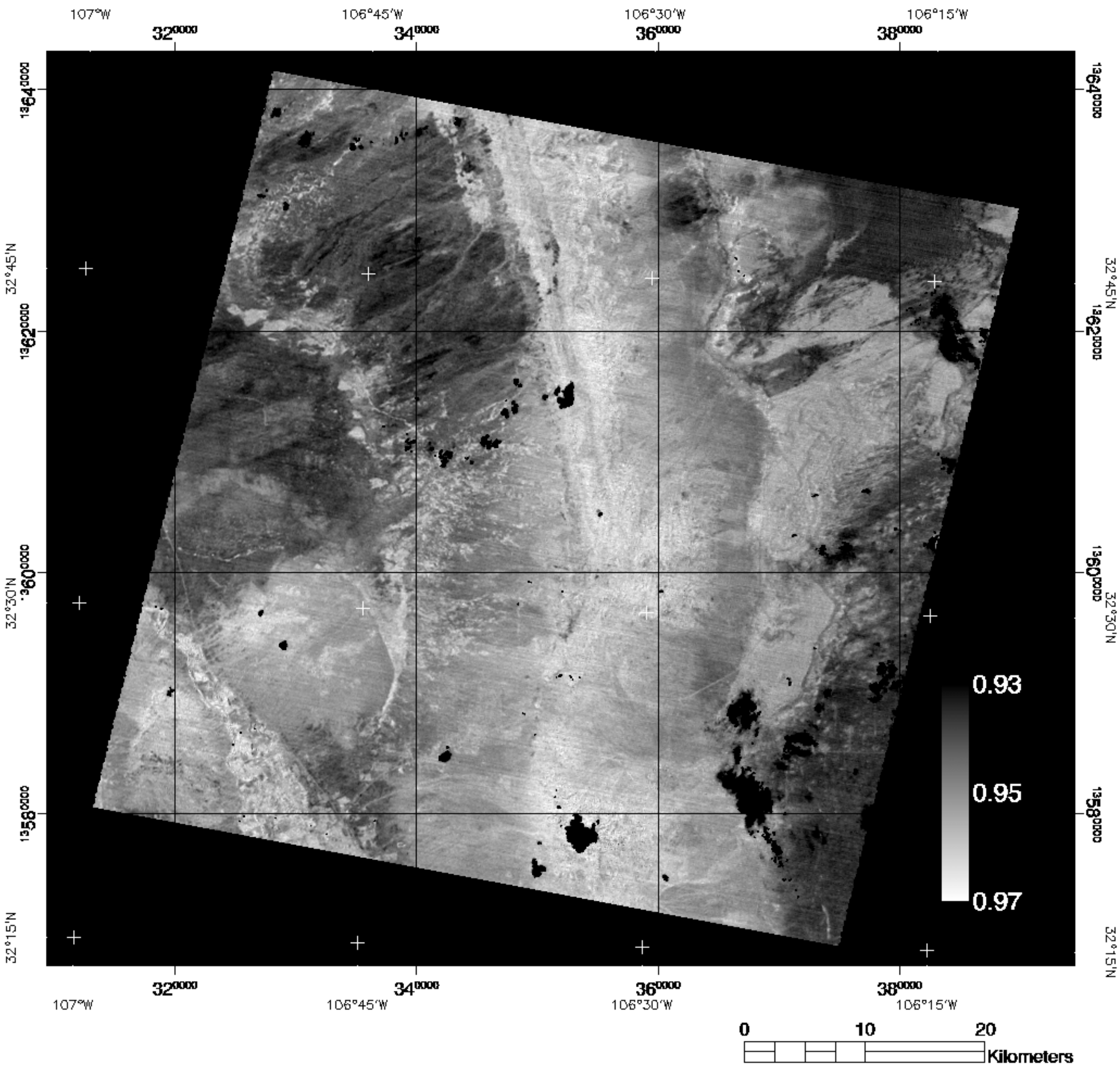

Figure 7: Broadband emissivity map for May 12,2001 ASTER scene of south central New Mexico. The White Sands National Monument is the low emissivity area at the upper right. The irrigated agricultural fields along the Rio Grande are in the high emissivity area in the lower left. The San Andres mountains cause the high emissivity strip running north-south through the center of the image [9]. Note the black patches scattered about the image are due to clouds.