Estimation of Biomass Fire Temperature and Areal Extent from Calibrated AVIRIS Spectra

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ABSTRACT

Biomass burning is an important process on the Earth at the local, regional and global scales. To investigate issues related to biomass burning, a range of remotely acquired data were measured as part of the NASA Smoke Cloud Aerosol and Radiation experiment in Brazil, 1995. As part of this experiment, images of calibrated spectral radiance from 400 to 2500 nm at 10 nm intervals were acquired by AVIRIS.

To investigate the expression of biomass fires in AVIRIS spectra, a model of the upwelling radiance from a burning fire was developed. This spectral model accounts for four components in the 20 by 20 m AVIRIS spatial resolution element. These are: (1) the atmospheric path radiance, (2) the solar reflected radiance from unburnt vegetation and soil, (3) the apparent temperature and area of a primary fire, and (4) the apparent temperature and area of a secondary fire. A nonlinear least squares spectral fitting algorithm was developed to invert this model for the AVIRIS spectra. The derived biomass burning parameters from this algorithm are presented for AVIRIS spectral images acquired over Cuiaba, Brazil on 25 August 1995.

INTRODUCTION

Biomass burning is an important process on the Earth at the local, regional and global scales. At the local scale, destruction of human infrastructure is the dominant concern. At the regional scale, destruction of habitat and modification of regional climate are at issue (Kirchhoff 1989). At the global scale, production of carbon dioxide (a greenhouse gas), modification of the terrestrial carbon balance, and introduction of aerosols into the atmosphere (direct and indirect impacts on the global energy balance) are at issue (Levine, 1995). Biomass burning occurs unpredictably in detail around the globe where there is dry vegetation as a function of numerous natural and human factors. Because of this global and intermittent nature, a satellite or airborne method to detect, measure and monitor biomass burning and fire parameters is desirable.

This paper describes an approach to derive a range of biomass fire parameters from spectra measured by NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). AVIRIS measures images of the upwelling spectral radiance from 400 to 2500 nm at 10 nm intervals. Images are measured of 11 by up to 100 km with 20 by 20 m spatial resolution.

Biomass fires emit radiance as a function of temperature. Spectra across the AVIRIS range for Planck function emitted radiance over a range of fire temperatures are shown in Figure 1. The shape and intensity of spectrally emitted radiance vary strongly over this spectral range for these temperatures. This spectral sensitivity to temperature was investigated with AVIRIS for volcano hot spots (Oppenheimer 1993). Related satellite multi-spectral approaches to estimate fire temperature and fraction were pursued previously (Dozier 1981; Prins, 1992). However, there is additional leverage on these fire parameters in the combined shape and intensity measured in the AVIRIS spectrum.

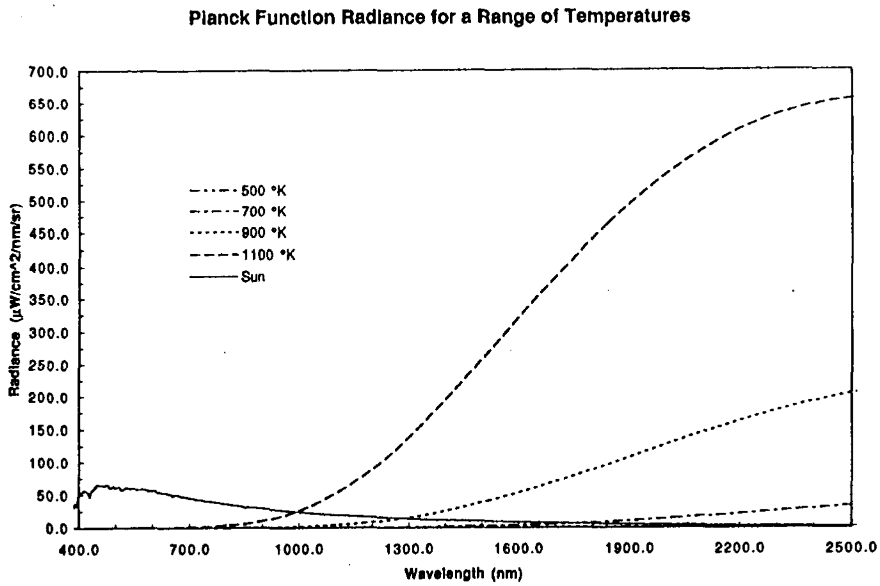

Figure 1. Planck function emitted radiance spectra for a range of fire temperatures from 400 to 2500 nm.

A model of the radiance incident at AVIRIS for 20 by 20 m spatial resolution has been developed. The model relies on the MODTRAN3 (Kneizys, 1988, Berk, 1989) radiative transfer code for calculation of atmospheric parameters. MODTRAN3 was used to model the atmospheric path radiance. A mixture of measured spectra of vegetation and soil was used to represent unburnt components of the surface. The Planck function was used to model the radiance emitted by two fires having different temperatures and areal extents. This model was linked to the simplex nonlinear least squares fitting algorithm (Press 1986) to invert the AVIRIS measured radiance for biomass fire parameters. The algorithm has been applied to an AVIRIS data set acquired near the city of Cuiaba, Brazil on the 25th of August 1995. Results of the application of this algorithm to the Cuiaba data set are presented in this paper.

MEASUREMENTS

An image from the 500.5 nm wavelength region from the AVIRIS August 25 Cuiaba data set is shown in Figure 2. Several fires are burning with the most prominent in the central left portion of the image. The smoke plume from the biomass fire is dominant at this wavelength and trends towards the city of Cuiaba in the lower right corner of the image. Figures 3 and 4 show the spectral images at 1000.2 nm and 2000.5 nm wavelength respectively. In the 1000.2 nm AVIRIS wavelength image, the smaller particle and less dense portions of the smoke plume are no longer evident and the higher temperature edges of the fires are showing emitted radiance. In the 2000.5 nm AVIRIS wavelength image, the smoke plume is largely transparent and the entire burning area is evident through the fire emitted radiance. These effects are shown spectrally in Figure 5. The first AVIRIS spectrum of the non-burning vegetation at some distance from the smoke plume shows the solar reflected radiance due to absorption and scattering in the atmosphere and reflection at the surface. The surface vegetation absorption due to chlorophyll is expressed between 680 and 720 nm in this spectrum. The second spectrum of non-burning vegetation in the smoke plume shows little to no influence of surface reflectance below 1000 nm due to the scattering of smoke. Beyond 1000 nm the influence of smoke scattering is decreased and this spectrum resembles the first vegetation radiance. The third radiance spectrum from burning vegetation shows the smoke scattering effects below 1000 nm. Between 2000 and 2500 nm this spectrum is higher in radiance than the non-burning spectra. This increased radiance results from the emission of the fire. A full AVIRIS spectrum from 400 to 2500 nm for every 20 by 20 m spatial element is present in the Cuiaba data set. These spectra provide the basis for derivation of the fire temperature, areal extent and associated parameters.

Figure 2. AVIRIS image at 500.5 nm of the biomass fires at Cuiaba, Brazil. Smoke particles are scattering the solar radiance at this wavelength.

Figure 3. Image at 1000.2 nm. At this wavelength the smoke is penetrated. The blackened burned area is evident. At the fringe of the burned area active burning is apparent as radiance emitted by the fire.

Figure 4. Image at 2000.5 nm showing emission of active fire dominating the calibrated radiance measured by AVIRIS. Scattering due to smoke is not apparent.

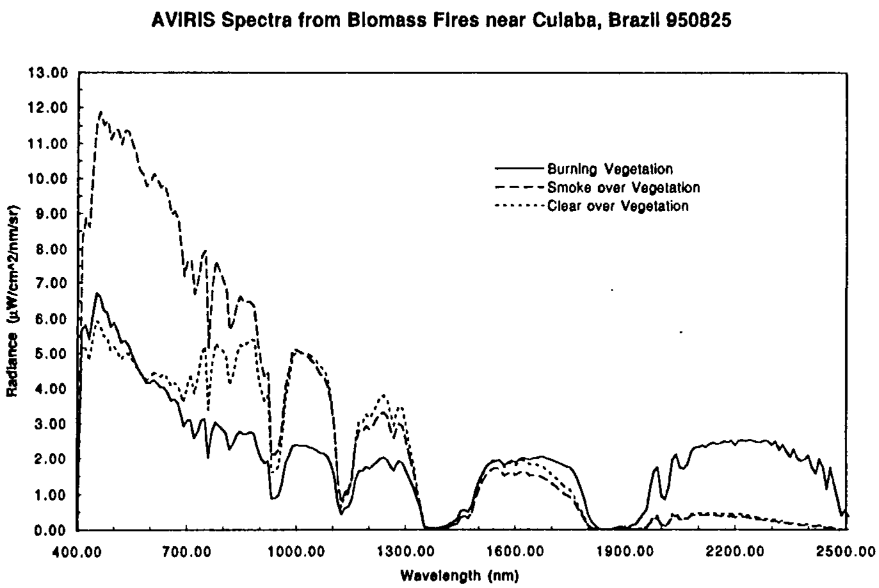

Figure 5. Three spectra from the 25th of August 1995 Cuiaba AVIRIS data set. Non-burning vegetation spectra both in and out of the central smoke plume as well as a spectrum from the burning area are shown. Towards 2500 nm the fire emitted radiance dominates the spectrum from the burning vegetation.

MODEL

To derive biomass burning parameters from the calibrated spectra, a model of the upwelling radiance incident at AVIRIS that included fire emitted energy was developed. The spectral radiance incident at AVIRIS from a 20 by 20 spatial element is modeled as the sum of the path radiance from the atmosphere; the reflected radiance from unburnt vegetation and soil; and the emitted radiance from two fire sources. A simplified expression of the model is given in equation 1.

$$Lt = Lp + Lr + Lb1 + Lb2 \qquad (1)$$

Lt is the total upwelling spectral radiance measured by AVIRIS for a 20 by 20 m spatial resolution element. Lp is the atmospheric path radiance incident at AVIRIS that has not been reflected by the surface. Lr is the reflected radiance. Lr is modeled as the two way transmitted radiance from the sun for a mixture of vegetation and soil. Lb1 is the one way transmitted radiance from a Planck function source for a given temperature and areal extent. Lb2 is the radiance from a second Planck function source and areal extent. The areal extent of the solar reflected radiance and the two Planck function radiance sources are constrained to a value of 1.0. The reflectance of the vegetation and soil were selected from a library of pre-existing field measurements. The MODTRAN3 radiative transfer code was used to provide the atmospheric path radiance for a range of highly scattering atmospheric conditions. MODTRAN3 was also used to calculate the one way and two way transmittances of the atmosphere. A recent compilation of the exoatmospheric solar irradiance was used (Gao and Green, 1995). Radiance emitted by the fires was modeled by the Planck function. The spectral region fit by the model was limited to wavelengths greater than 1000 nm, where the smoke scattering is reduced and the fire emitted radiance effect is strong. The illumination and observation geometry for the model are based on the time and place of AVIRIS data acquisition.

The model was linked to a downhill simplex nonlinear least squares algorithm (Press, 1986) and applied to the Cuiaba AVIRIS data set. Portions of spectra where AVIRIS saturation occurred were excluded from the fit. However, no spectra were fully excluded due to saturation.

ANALYSIS AND RESULTS

Figure 6 shows an example of the spectral fit for a single spectrum in the central Cuiaba fire. To achieve a good fit for this AVIRIS measured spectrum, emitted radiance from two Planck functions with two temperatures and areal extents was required: one at 1183 K and 0.04 fractional extent and a second at 691 K and 0.42 fractional extent. Also shown is the radiance expected for a surface of 1.0 reflectance.

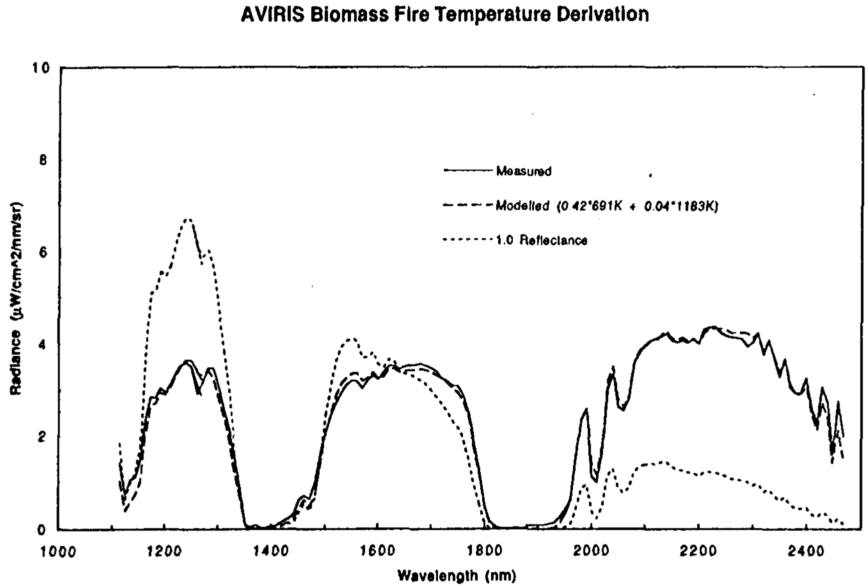

Figure 6. Spectral fit from inversion of the forward model. The measured spectrum, model fit spectrum and residual spectrum are shown. Two fire temperatures and areal extents were required to model these measured spectrums.

This spectral fire parameter algorithm was applied to the entire Cuiaba AVIRIS data set covering 11 by 20 km at 20 by 20 m spatial resolution. Images of the primary fire temperature and areal extent produced by the algorithm are shown in Figures 7 and 8. Fires are mapped throughout the image with temperatures ranging from 500 K to 1700 K. Smaller fires are detected and mapped that were not well expressed in the 2000.5 nm radiance image. Temperatures of the smaller fires and the edges of the larger fires are typically higher than the internal regions of the larger fires. Fire fractional areas range from 0.01 to 0.30. The hotter, smaller and edge fires show lower fractional extent. This temperature distribution and this areal extent distribution are consistent with the availability of unburnt fuel near the small fires and edges of larger fires. These temperature and areal extent results are constant with the biomass burning process. Furthermore, the agreement between the AVIRIS measured radiance and physically based model radiance of the fires supports the validity of this approach and algorithm for deriving fire parameters from calibrated AVIRIS spectra.

The algorithm generated additional image parameters of the secondary fire and areal extent for each spectrum. Unburnt soil and vegetation fractions as well as estimates of atmospheric scattering attenuation by smoke were produced.

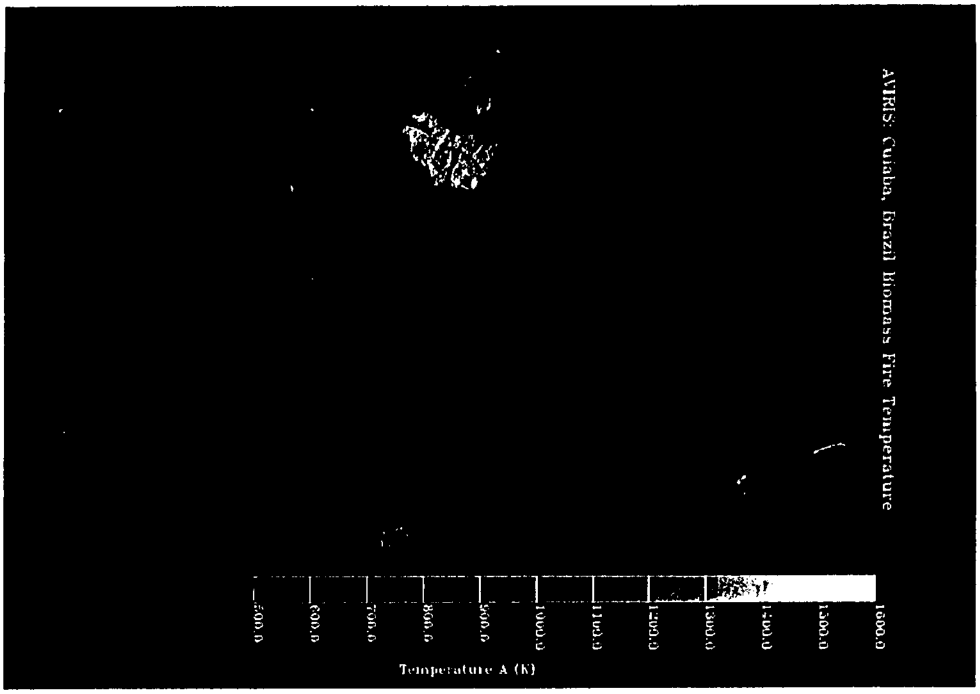

Figure 7. Image of the derived dominant fire temperature for AVIRIS Cuiaba spectra.

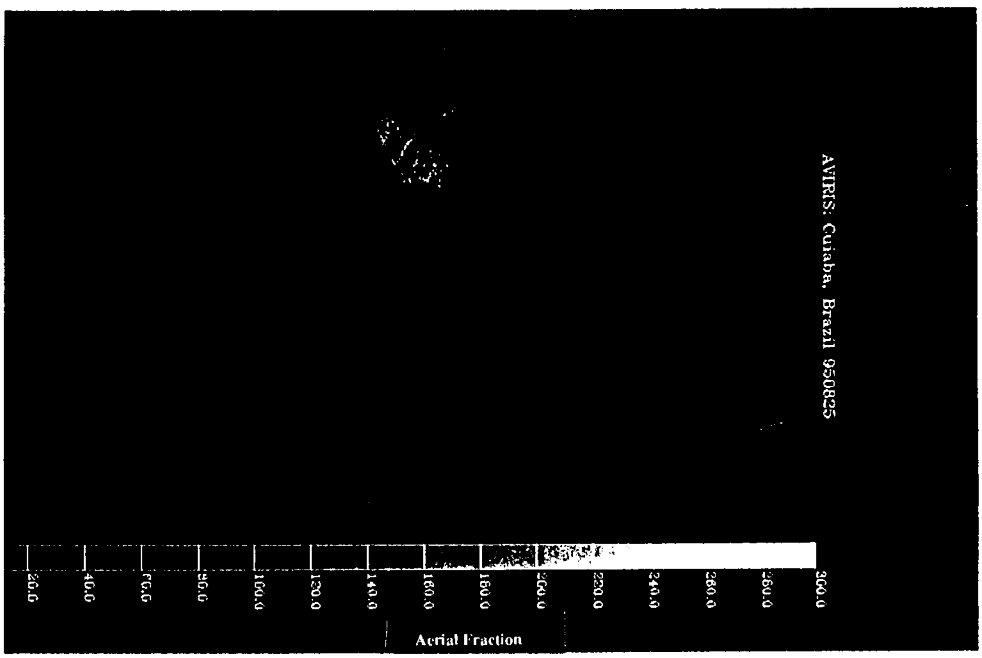

Figure 8. Image of areal fraction of dominant fire for AVIRIS Cuiaba spectra. The units of this image as numbered on the "Aerial Fraction" scale are parts per thousand.

CONCLUSION

A spectral fire parameter algorithm was developed to derive fire temperature and areal extent information from calibrated spectra measured by AVIRIS as images with 20 by 20 meter spatial resolution. The algorithm is based on the spectral shape and intensity of the fire emitted radiance expressed in the AVIRIS spectra. Fires are spectrally modeled as both primary and secondary fire sources in each AVIRIS spatial element. Effects of atmospheric path radiance, atmosphere transmittance, and solar reflected radiance from unburnt vegetation and soil are accounted for. Good agreement is achieved between the measured AVIRIS spectra and modeled spectra of the algorithm. The spectral fire temperature algorithm was applied to an 11 by 20 km AVIRIS image near Cuiaba, Brazil. The spatial distribution of the fire temperatures and areal extents was consistent with the biomass burning process. This algorithm coupled with AVIRIS data provides an improved strategy for derivation of biomass fire parameters. Remotely derived biomass fire parameters are needed to detect, measure and monitor fires at the local, regional and global scales.

FUTURE WORK

Future work will focus on validation of the derived biomass fire parameters. In addition, the algorithm model will be extended to allow for variation in water vapor and carbon dioxide. A sensitivity analysis will be performed to understand the influence of the constraining parameters on the modeled spectrum.

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