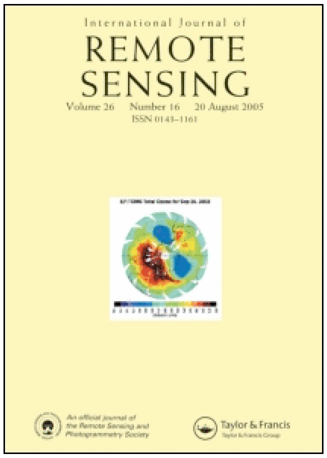

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Remote optical detection of biomass burning using a potassium emission signature

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Abstract. A remotely detectable signature for biomass burning that is specific to flaming combustion is found in the strong emission lines of potassium (K) at 766.5 nm and 769.9 nm. Ground level spectra of a test fire illustrate the high contrast signal provided by K emission. Image data collected at high altitude using the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) sensor and analysed for K emission vividly displays the fire fronts of a 1995 fire in Brazil. Sensors for K emission can use silicon detector technology for advantages in high sensitivity, low cost, wide area coverage and fine spatial resolution.

1. Introduction

Efforts directed at the remote sensing of fires have addressed both the global change and the economic impacts of fires in wildlands. Global satellite-based monitoring of biomass burning using thermal infrared sensors is underway (Matson *et al.* 1987, Prins and Menzel 1992, Kaufman *et al.* 1998) to help us to understand the role fires play in global climatic change. Fires affect the global climate through processes such as trace gas and aerosol production, or by changes to terrestrial carbon dynamics (Crutzen and Andreae 1990, Laursen *et al.* 1992, Stocks *et al.* 1998). The economic impacts of wildland fires include the destruction of assets as well as suppression costs. On a local level, near real-time thermal infrared remote sensing from aircraft is used to aid fire suppression efforts (Stearns *et al.* 1986, Radke *et al.* 2000). However, existing satellite sensors lack either the temporal or the spatial resolution needed for continuous detection and monitoring of fires.

2. Remote fire detection methods

The typical fire detection approach has been to detect the Planckian radiation in the 3.5–5 μm and 8–14 μm regions of the spectrum. The two bands are often analysed using threshold algorithms tuned to avoid false alarms (Dozier 1981, Matson and Dozier 1981). As an alternative, detection of Planckian emission in the

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1.0–2.5 μm spectral region has been suggested (Thomas and O 1993) and employed using the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) (Green 1996). Another approach used an airborne Fourier transform spectrometer operating in the thermal portion of the spectrum to detect thermally excited CO emission lines superimposed on the blackbody radiation (Worden *et al.* 1997).

3. Detection of potassium (K) emission in fires

3.1. *Concept*

This letter builds on a set of ground observations of natural fires and, in particular, the optical emission doublet of thermally excited K at 766.5 nm and 769.9 nm (Latham 1998). While quantitative analysis of K concentration using flame photometry is a well-known laboratory method (Skoog 1997), to our knowledge, observation of K line emission has not been proposed as a remote fire detection technique. K is an omnipresent nutrient in soils and is incorporated into the tissues of plants during growth. Plant tissue is typically 0.4–3.4% K by dry weight (Bowen 1979). Because of its low 4.34 eV excitation energy (NIST 2001), a significant portion (10–20% or greater) of the K in burning biomass may be ionized, producing strong and very narrow emission lines in the near-infrared region of the spectrum upon recombination. In particular, the resonance transitions $^2P_{3/2}$–$^2S_{1/2}$ and $^2P_{1/2}$–$^2S_{1/2}$(*21*) will be produced at the temperatures of wildland fires, which range from about 875°C to 2000°C (Chandler *et al.* 1983). The absolute intensity of K emission from burning vegetation will vary given the complex combination of physical and chemical environmental factors present in the local environment of an uncontrolled flame.

3.2. *Effect of atmospheric O_2 absorption on potassium emission*

The K emission lines are within the range of atmospheric O_2 absorption bands peaking near 762 nm (Pearse and Gaydon 1976). However, the very narrow line shapes of both the O_2 absorption and the K emission bands require analysis of very high resolution spectra to understand the overlap. A FASCODE (Smith *et al.* 1978) simulation was performed to determine the effect of O_2 absorption on the emission lines (figure 1). The parameters for the simulation were nadir viewing from orbit through a mid-latitude summer atmosphere, with a spectral resolution of 0.1 cm^{-1}. The 766.5 nm K line lies between O_2 absorption lines and is attenuated only by the continuum. The 769.9 nm K line overlaps an O_2 absorption line, which will reduce the intensity of that line as observed from space by about 60%, including the continuum transmission. The O_2 absorption will thus alter the ratio of line strengths (766.5 nm/769.9 nm) from about 1.04 in the absence of significant atmospheric attenuation to approximately 1.75 when observed from space.

3.3. *Radiance spectra of fire and background materials*

A ground-level radiance spectrum covering the green to near-infrared spectrum of burning vegetation was obtained from a controlled burn of plant materials typical of the forests of the eastern United States (figure 2). The spectrum was obtained with an Analytical Spectral Devices FieldSpec radiometer (2.7 nm resolution). We work in radiance rather than reflectance because the normalization of emission to downwelling solar irradiance has no physical meaning and can produce apparent reflectance values that greatly exceed 100%. The K doublet at 766.5 nm and 769.9 nm is strongly visible above the Planckian continuum. A weak feature (20 × scale) from the unresolved sodium (Na) doublet appears at 589.3 nm (NIST 2001). Weak Na

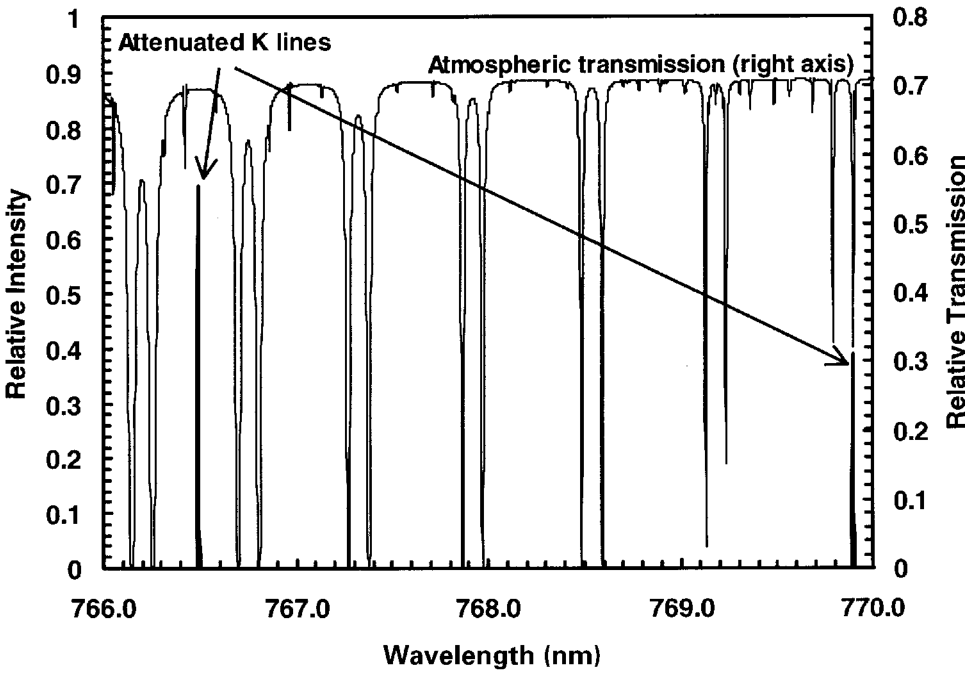

Figure 1. Modelled effect of atmospheric transmission on the intensity of the 766.5 nm and 769.9 nm K emission lines relative to each other. The 769.9 nm line is strongly affected by a narrow O_2 absorption feature as well as the continuum transmission, while the 766.5 nm line is only attenuated by the continuum.

emission is expected because of a higher excitation energy (5.14 eV, NIST 2001) and lower percentage dry weight (0.003–0.15%) in plant material (Bowen 1979). We also show the radiance spectrum for a single pixel in an AVIRIS image of a fire acquired during a 25 July 1995 flight over Cuiaba, Brazil. The K doublet is not resolved at the AVIRIS spectral resolution ($\sim$9 nm). The AVIRIS spectrum also contains strong water vapour absorption lines and O_2 absorption owing to the 20-km flight altitude. To emphasize the unique K emission signature compared with radiance from background materials we show spectra obtained with the field radiometer of grass, asphalt and mixed granitic rock and soil. In contrast to the fire emission spectrum, the background material reflected radiance spectra are strongly influenced by the O_2 absorption band between 750 nm and 775 nm in the downwelling solar irradiance. Other features in the downwelling solar irradiance that affect the background spectra are Fraunhofer lines in the solar spectrum and water vapour absorption bands.

3.4. *Fire detection test using AVIRIS images*

We tested our proposed technique using the Cuiaba AVIRIS images. This scene was analysed by Green (1996) for fire temperatures using the Planck radiance in the 1.0–2.5 μm spectral range. The image at 589 nm (figure 3(*a*)) highlights smoke from the fire while the 770 nm image (figure 3(*b*)) shows good penetration of radiation through all but the densest smoke. The 1501 nm image (figure 3(*c*)) shows excellent penetration through the smoke and the bright blackbody emission signal of the elliptically shaped fire fronts. Dividing the 770 nm image by the 779 nm image isolates pixels with detectable K emission (figure 3(*d*)). The ratio technique eliminates other

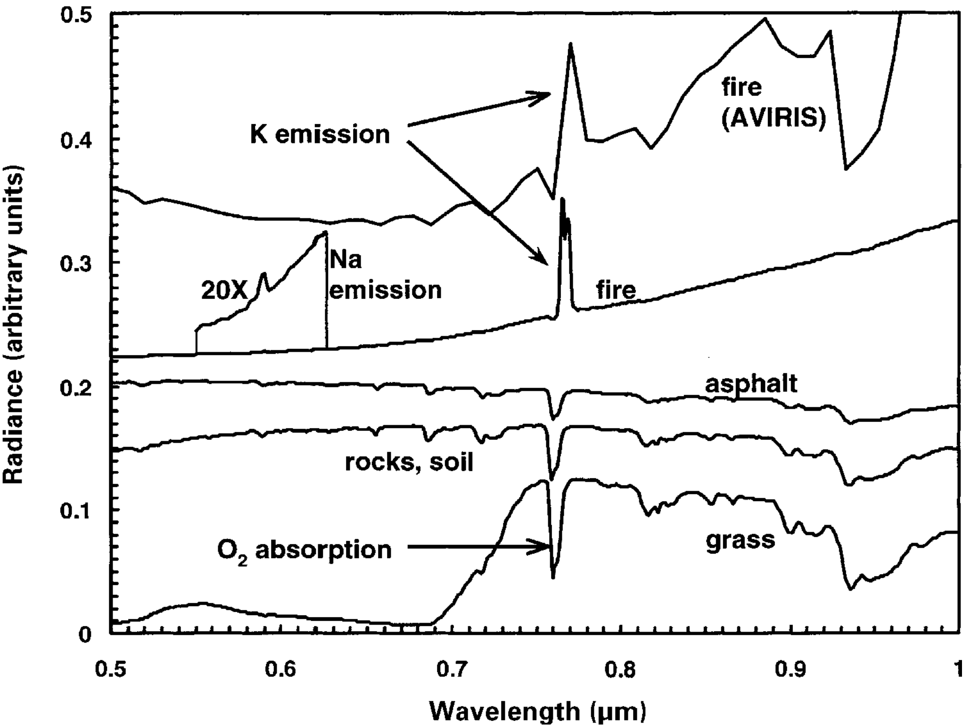

Figure 2. Visible and near-infrared spectral radiance of vegetation fires and background materials. The spectra are arbitrarily offset for clarity.

factors that contribute nearly equally to the observed radiance at 770 nm and 779 nm. These other factors include variations in reflected solar illumination, atmospheric path length differences from different look angles, specular reflections and blackbody emission from the fire.

For the ~9 nm resolution of AVIRIS or other similar sensors, the placement of the band centres with respect to the O_2 feature and the K emission is critical. We tested our approach on another AVIRIS image of a fire from a 20 August 1992 observing path over Linden, California, for which the pertinent band centres were shifted by about 5 nm to shorter wavelengths. With this band configuration most of the K emission is convolved with more of the O_2 absorption band and the ratio algorithm fails in part because of variability in the O_2 signal. Further, the assumption that the atmospheric attenuation is similar at the band containing the K emission and at an adjacent band is not valid. Sensing at finer spectral resolution (<0.5 nm) would avoid this problem while potentially increasing contrast because of the extremely narrow bandwidth of the K emission lines (figure 1).

4. Discussion

The K emission method has advantages for understanding the effects of wildland fires because it is specific to flaming combustion. Together with analysis of blackbody emission of warm or hot spots, there is the potential to separate smouldering from flaming vegetation. This capability is important for quantifying the release of gases and aerosols that affect atmospheric chemistry because some important gases (CO_2,

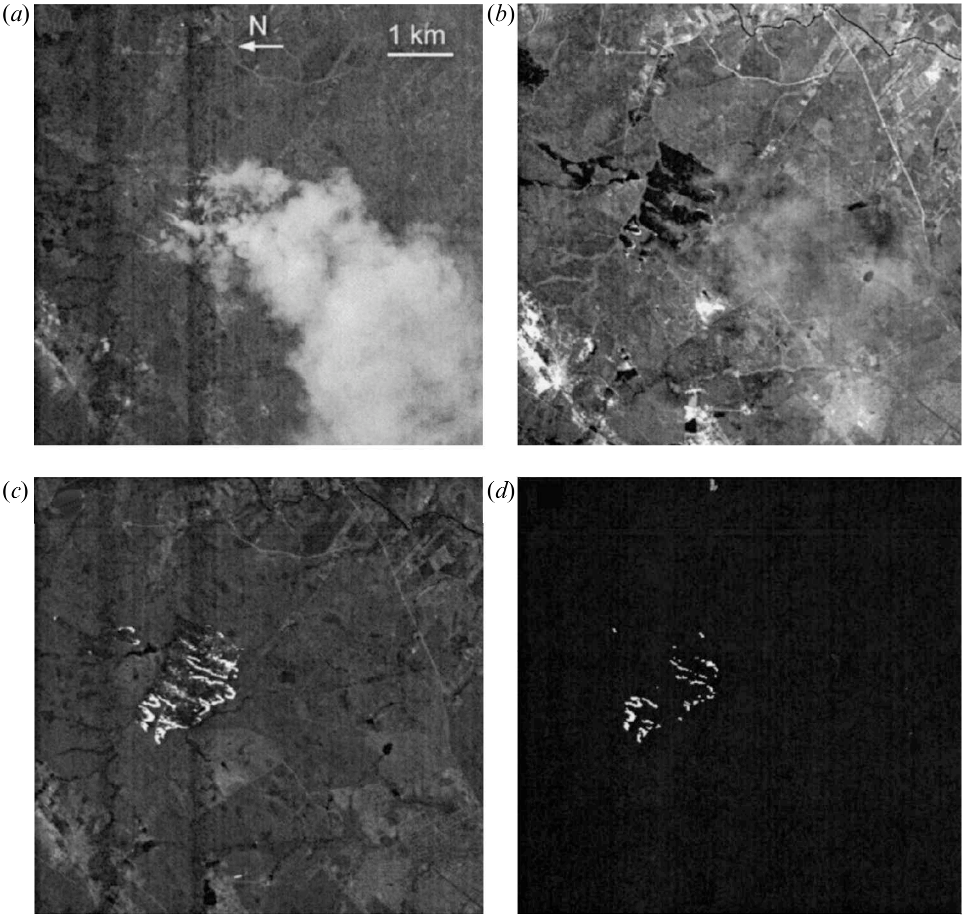

Figure 3. AVIRIS images of Cuiaba, Brazil, at 589 nm (*a*), 770 nm (*b*), 1501 nm (*c*) and a ratio image (770 nm/779 nm) (*d*). The ratio image (*d*) has a threshold applied to show as white only those pixels that are six standard deviations or more above the mean ratio value for the entire image.

NO_x, SO_2, N_2O) are released primarily during the flaming stage and others (CO, CH_4, other hydrocarbons) are released during the smouldering stage (Crutzen and Andreae 1990).

Finally, there may be operational advantages to sensors designed for detecting K emission. The ratio algorithm is simple, works both day and night and is not susceptible to false alarms because of the unique spectral signature. The emission lines are near the peak of silicon detector sensitivity so system cost and complexity could be reduced by the use of silicon detectors with interference filters for spectral selection. Large silicon arrays could provide wide swath widths on the ground while maintaining high spatial resolution. Such a system would be an inexpensive complement or alternative to the cryogenically cooled thermal sensing approach. Sensors of this design could be deployed in space for real-time global fire monitoring or on aircraft (including unmanned airborne vehicles) for real-time fire monitoring in support of suppression efforts.

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