

MAPPING VOLCANIC GAS EMISSIONS IN THE MAMMOTH MOUNTAIN AREA USING AVIRIS

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1. INTRODUCTION

The Long Valley Caldera located in the eastern Sierra Nevada (California) shows new signs of volcanic activity (Langbein et al., 1993; Farrar et al., 1995). This renewed activity is expressed by gas emissions, hydro-thermal activity and frequent earthquakes. Analysis of the gas composition regarding the percentage biogenic carbon and the ³He/⁴He-ratio (Farrar et al., 1995) revealed that the gas source is the magma body approximately 7 km beneath the Long Valley Caldera. The gas from the magma body surfaces not only via the fumaroles but also emerges along geological faults. Some of the spots where gas surfaces, are marked by dead or stressed trees. Other spots may not yet be identified. It is only recently known, from research at Volcano Island in southern Italy, that volcanoes release abundant carbon dioxide from their flanks as diffuse soil emanations (Baubron et al., 1990). Mammoth Mountain seems to behave in a similar manner. The research described in this paper is designed to determine whether AVIRIS high spectral resolution imaging spectrometry can be used to identify areas of volcanic gas emissions.

2. BACKGROUND

The composition of volcanic gases can vary largely. The ten most common volcanic gas species are: H₂O, CO₂, SO₂, HCl, H₂S, S₂, H₂, CH₄, HF, CO, SiF₄ (Andres & Rose, 1995; Sorey et al., 1993; Gerlach & Graeber, 1985). A number of these gases do not have absorption features in the spectrum covered by AVIRIS (0.4 -2.5 μm) and are consequently not suitable to map volcanic gas fluxes. In any case, the volcanic gas emissions must be monitored through the earth's atmosphere. The atmosphere contains approximately 30 gases from which several are also found in volcanic gas emissions.

Two approaches can be followed to map the volcanic fluxes near Mammoth:

1. To detect volcanic gas species not normally present in the atmosphere;
2. To image the abundance of normally present gases to detect spatial anomalies.

The most promising approach to trace the volcanic emissions is using the following two gases: carbon dioxide (CO₂) and/or methane (CH₄) as both gases have absorption features in the AVIRIS spectral range. Absorption features for CO₂ are found near 1270, 1575, 1610, 1960, 2005 and 2055 nm (Pieters & Englert, 1993; Wolfe & Zissis, 1989). Fairly strong gaseous absorption occur in the latter two bands. CH₄ has only absorption features near 2350 nm in the AVIRIS spectral range.

The most promising gas is CO₂ because 1) fumarole gas analysis has shown that 90% of the gas is CO₂ near Mammoth (Farrar, pers. comm.; Sorey et al., 1993), 2.) CO₂ is distributed fairly homogeneous throughout the atmosphere and 3) field measurements have shown that the CO₂ flux is large (approximately 1200 tonnes per day for the 20 ha. dead tree area) from the flanks of Mammoth Mountain (Farrar et al., 1995). Unfortunately, it is not

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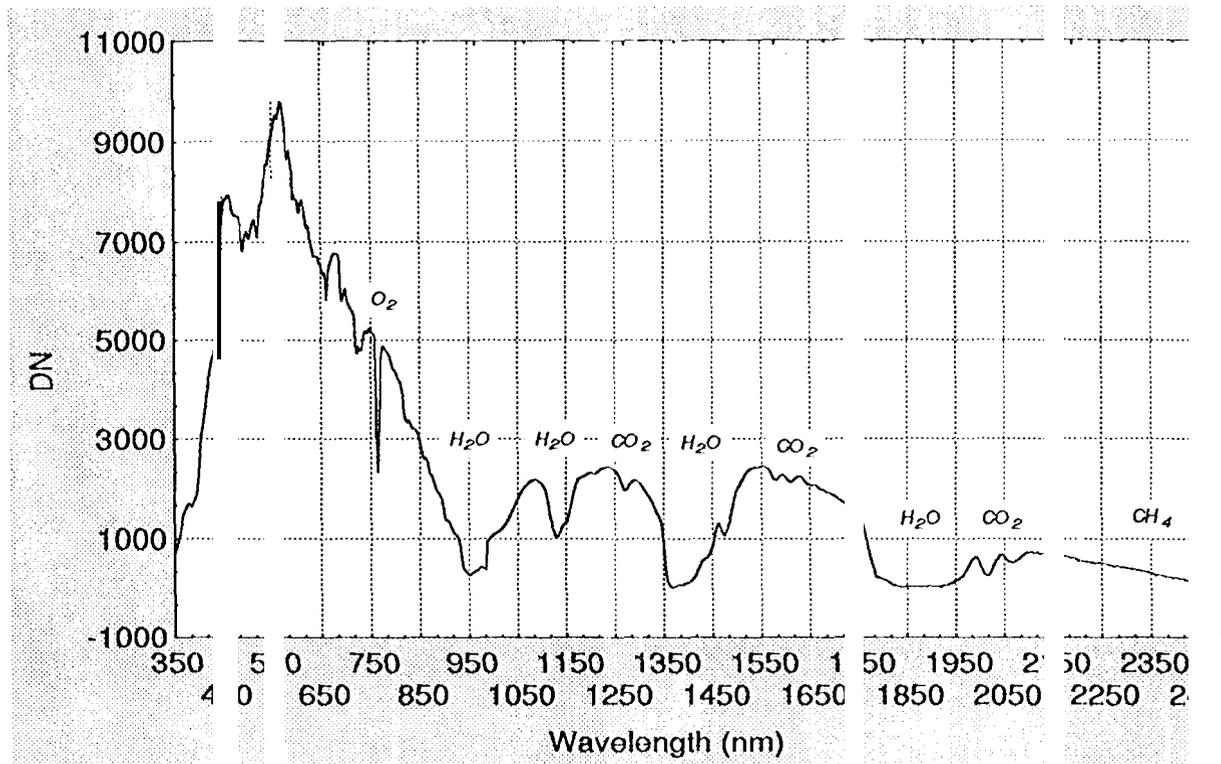


Figure 1: Raw Field Spectrum (Average of Eight Samples) of a Gas Discharge of a Fumarole at Hot Creek Measured over a White Reference Plate. Several CO₂ Absorption Features (1270, 1575, 1610, 2005, 2055nm) are Visible, no Feature at the CH₄ position is visible.

known whether this CO₂ flux at Mammoth is constant in time. The flux depends among others on magma activity, barometric pressure and changes in soil moisture content.

Some of the problems that play a role in the mapping of volcanic CO₂ emission are the temporal, spatial and vertical distribution of gases in the atmosphere and the temporal (and spatial) distribution of the volcanic CO₂ flux, which is unknown. Research at Volcano Island (Italy) has shown that Fumarole gas composition varies largely over time (Tedesco, 1995) and that the concentration of Cl₂ in the gas flux might be too small to detect using AVIRIS (Sorey et al., 1993). Other problems are the low-energy solar irradiance in the 2.0 -2.5 μm spectral region resulting in a low signal-to-noise ratio at the CO₂ absorption bands. Furthermore, no sufficient field data are available to verify any mapping results.

3. FIELD SPECTRA

In October 1995 a field campaign was organized in the Mammoth Mountain region to survey dead tree areas and to collect field spectral measurements. Field spectra were taken using JPL's FieldSpec spectrometer (ASD, 1994). This instrument covers the spectral region from 350 to 2500 nm using three individual spectrometers. It samples every 2 nm and the resolution varies between 10 and 11 nm. Together with each set of target measurements a white reference plate and the instrument's dark current was determined. Multiple target measurements were averaged to increase the signal-to-noise ratio. The dark current was subtracted from the raw DN spectral measurements and the white reference measurements were used to convert the raw data to reflectance. Figure 1 shows an raw spectra (average of 8) covering the entire AVIRIS spectral range of a fumarole near Hot Creek in Long Valley Caldera. The raw spectra shows clear absorption features for water, oxygen and carbon dioxide. An artefact occurs near 980 nm due to a switch of the spectrometers. Figure 2 shows reflectance spectra (1950 -2250 nm) of the gas from the Hot Creek fumaroles. Fum1 and Fum2 are measured over the white target, Fum3 is a gas spectra taken towards the sun. Each spectrum is an average of 8 measurements. The 2005 CO₂,

absorption features are visible in all three spectra although the contribution of noise in the spectrum is considerable and a small shift to longer wavelengths seems to occur. Methane absorption is not found in any of the field spectra.

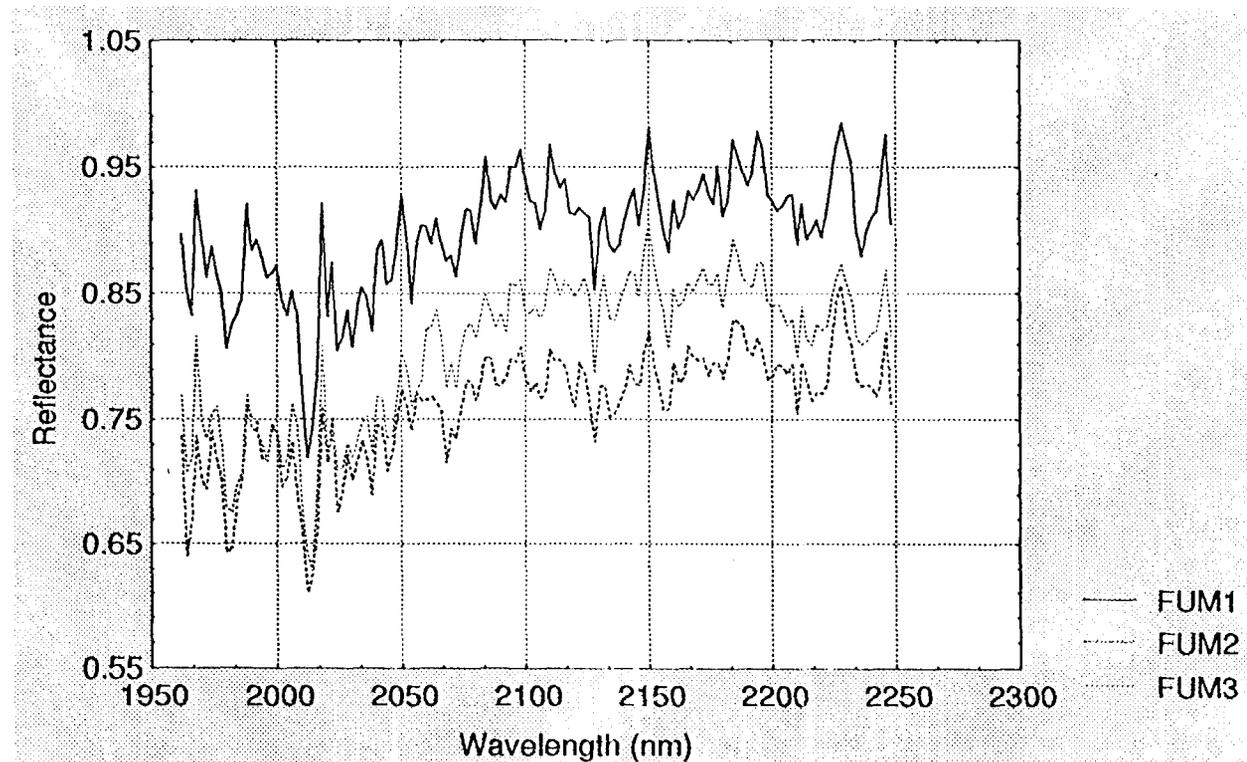


Figure 2: Reflectance Field Spectra (1950 -2250 nm) of Gas Discharges of Three Fumaroles at Hot Creek. Each Spectrum, Although Noisy, Show the CO₂ Absorption Features near 2000nm.

4. IMAGE ANALYSIS

Three AVIRIS images of the Mammoth were extracted from the JPL archive from the following dates: 940521, 940823 and 950622. Radiance images and empirical line corrected images were both used for analysis in this study. Radiance spectra of areas inside and outside the suspected volcanic gas emissions regions were gathered from the August '94 image. Next a darkest pixel correction was applied to these spectra. Spectra inside the gas emission region were expected to have stronger absorption features in the CO₂ bands than spectra sampled outside this region. The selected areas comprise two areas of rock outcrops at Mammoth Crest and near Heart Lake, the Fumarole area at the flank of Mammoth Mountain, the dead tree area near Horseshoe Lake and the beach of Horseshoe lake. The spectra of the selected areas were visually interpreted and analyzed using a convex hull transformation.

4.1 Convex Hull Transformation

In order to compare the spectra, they were first normalized using a convex hull method (De Jong, 1994; Green and Graig, 1985; Sedgewick, 1983). The convex-hull technique is analogous to fitting a rubber band over a spectrum to form a continuum (or hull). The difference between the hull and original spectrum is subtracted from a constant e.g. 1000 to obtain a hull-difference. The advantage of analyzing the transformed data is that the depth of absorption features remain constant with respect to the hull whereas depth and position of absorption features in the original spectrum are influenced by the overall shape and brightness of the spectrum. After transformation a feature finding algorithm was applied (Grove et al., 1992) to quantify the absorption features of the spectra in terms of

spectral position, depth, area and asymmetry.

Table 1 and figure 3 show the results of the convex hull transform for the 1900-2500 nm spectral region. Table 1 and figure 3 show that both the CO₂ absorption features (2004 and 2054) are identified by the feature finding algorithm. For all test areas these two absorption features are dominant regarding depth and area in this spectral region. However, the suspected emission areas (area 3 and 4) do not produce significant stronger CO₂ absorption in spite the fact that the convex hull algorithm corrects for differences in brightness.

4.2 CIBR - Algorithm

Several (ratio) algorithms were applied to the spectral domain of the AVIRIS images to detect or enhance the CO₂ absorption. So far, the continuum interpolated band ratio (CIBR) algorithm (Carrère & Conel, 1993) provided the best results. The CIBR algorithm uses the 'shoulders' at either side of the absorption feature to interpolate a radiance continuum over the absorption feature of interest. Next, a ratio is computed between the absorption band and the interpolated continuum:

$$\text{CIBR} = B_2 / (c_1 B_1 + c_2 B_3)$$

where B_2 is the radiance at the absorption feature position, B_1 and B_3 are the radiance values at the shoulders and c_1 and c_2 are coefficients. The values of c_1 and c_2 depend on the symmetry of the continuum at either side of the absorption feature. Complete symmetry results in c_1 and c_2 values of 0.5.

The CIBR algorithm shows better results i.e. spatial patterns for the 2003 absorption feature than for the 2053 feature. The CIBR spatial pattern for the 940823 AVIRIS images shows several areas of large CIBR-values near the Mammoth Lakes, near Crater Meadow, near Minneret Summit and north of the main Mammoth Mountain Lodge. Furthermore, all the lakes show large CIBR values in a salt and pepper pattern. The lakes might show up

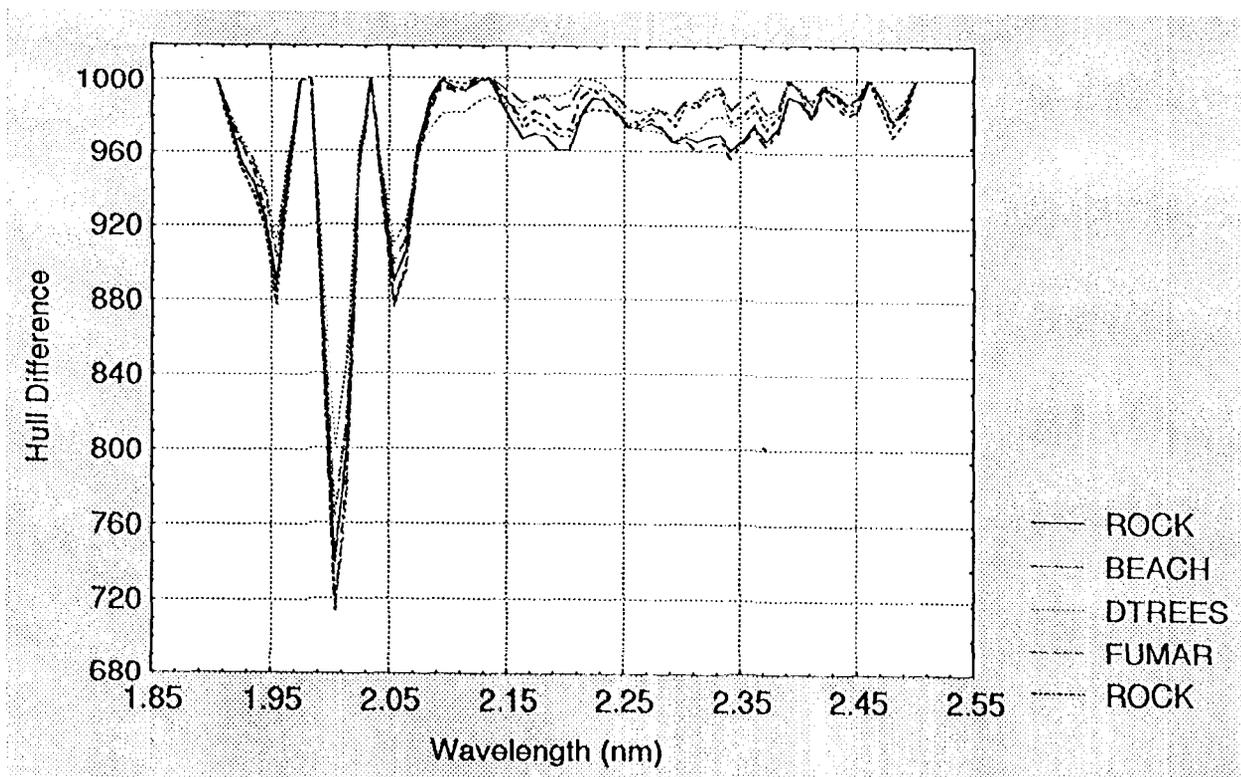


Figure 3: Results of the Convex Hull Transform of Selected Areas in the 940823 AVIRIS Scene. Absorption Features for CO₂ are Identified near 2005 and 2055 nm.

not because they contain vast amounts of carbon dioxide but because the reflected radiance near the 2003 absorption feature is small. The CIBR algorithm enhances the noise when the radiance values are small. In order to verify the latter theory, the CIBR algorithm was also applied to the 760 nm oxygen and the 940 and 1140 nm (minor) water absorption bands, which also resulted in a bright salt and pepper pattern for the lakes. The interpretation of the spatial pattern remains very difficult as it does not display clearly the dead tree areas nor does it present the geologic pattern of faults, fumaroles or other geologic features shown on the geologic map (Huber & Rinehart, 1986).

5. RESULTS

Preliminary results show that spatial patterns of carbon dioxide absorption can be derived from AVIRIS images. However, it is difficult to separate atmospheric carbon dioxide from the diffuse carbon dioxide emanations from the soil. The soil flux of CO₂ is not visible in the three selected AVIRIS images although the volume of the soil gas flux is considerable. Estimates of the CO₂ gas flux by Farrar et al. (1995) approximate 1200 ton/day for the 20 ha dead tree areas. The reflected radiance around the 2003 absorption feature might be too small (and the resulting AVIRIS spectrum too noisy) to reveal the subtle carbon dioxide concentration differences. Another explanation might be that the temporal variability of the CO₂ does not coincide with the three AVIRIS data acquisition times. The use of methane (CH₄) to trace diffuse volcanic gas release using AVIRIS was not possible. Methane absorption features (near 2350 nm) could not be identified in the field spectra nor in the image spectra. The volume of methane in the gas flux is most probably too small. Future work will investigate spatial patterns in AVIRIS images collected at other dates and times and will refine algorithms to enhance the CO₂ absorption feature.

Acknowledgments

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Table 1. Results of the Feature Search on Aviris (940823 image) Spectra 2.0-2.5 pm.

| Wavelength | Depth | Area | Asymmetry |
|--|----------------|---------------|-----------|
| 1. Results Rock Outcrop near Heart Lake: | | | |
| 2.0040 | 194.6203 | 6.3370 | 0.7637 |
| 2.0540 | 83.5510 | 2.8988 | 0.6137 |
| 1.9440 | 77.14s1 | 3.1312 | 0.8106 |
| 2.1930 | 33.4868 | 2.1069 | 1.5353 |
| 2.3420 | 31.4441 | 2.1767 | 0.3884 |
| 2.3020 | 30.2106 | 2.1063 | 2.5787 |
| 2. Results Beach of Horseshoe Lake: | | | |
| 2.0040 | 216.8107 | 7.1612 | 0.7876 |
| 2.0540 | 96.3700 | 3.4231 | 0.6072 |
| 1.9440 | 87.1081 | 3.6082 | 0.8017 |
| 2.1930 | 28.2608 | 1.9079 | 1.2454 |
| 2.2630 | 20.2279 | 0.7563 | 2.9223 |
| 2.2830 | 19.2256 | 0.7830 | 0.3156 |
| 2.3720 | 18.5714 | 1.1094 | 2.3487 |
| 3. Results Dead Trees Area near Horseshoe Lake: | | | |
| 2.0040 | 148.8698 | 4.9070 | 0.7591 |
| 2.0540 | 70.6569 | 3.4368 | 0.3795 |
| 1.9440 | 61.2487 | 2.4824 | 0.7761 |
| 2.2930 | 29.0505 | 2.2499 | 1.3394 |
| 2.3420 | 21.1022 | 1.0482 | 0.2474 |
| 2.1530 | 12.8426 | 0.7047 | 0.4311 |
| 4. Results Fumarol SSF Area McCloud lake: | | | |
| 2.0040 | 178.2256 | 5.8844 | 0.7572 |
| 2.0540 | 78.5885 | 2.9428 | 0.5580 |
| 1.9540 | 67.9872 | 2.7497 | 2.1012 |
| 2.2830 | 16.2666 | 1.2004 | 1.4645 |
| 2.4800 | 13.6296 | 0.3108 | 1.5631 |
| 2.1930 | 12.7289 | 0.7406 | 1.8204 |
| 2.3720 | 11.7063 | 0.7021 | 2.1843 |
| 5. Results Rock Outcrop Mammoth Crest: | | | |
| 2.0040 | 211.6600 | 6.8818 | 0.7687 |
| 2.0540 | 92.6647 | 3.3673 | 0.5694 |
| 1.9540 | 77.102.7 | 2.9865 | 1.9977 |
| 2.3320 | 34.9856 | 4.4646 | 1.3758 |
| 2.1930 | 21.2710 | 1.1864 | 1.7262 |

To: Ms . G. Peralta
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4800 Oak Grove Drive
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Date: January 2, 1995

Dear Ms. Peralta,

I would like to submit the enclosed paper for publication in the proceedings of the 6th Airborne Earth Science Workshop, March 4--8, 1996.

Sincerely yours,

A handwritten signature in black ink, appearing to read "S. de Jong", with a large flourish extending to the right.

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