Volcanic CO_2 Abundance of Kilauea Plume Retrieved by Meand of AVIRIS Data

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1. INTRODUCTION

Absorbing the electromagnetic radiation in several regions of the solar spectrum, CO_2 plays an important role in the Earth radiation budget since it produces the greenhouse effect. Many natural processes in the Earth's system add and remove carbon dioxide. Overall, measurements of atmospheric carbon dioxide at different sites around the world show an increased carbon dioxide concentration in the atmosphere. At Mauna Loa Observatory (Hawaii) the measured carbon dioxide increased from 315 to 365 ppm, in the period 1958–2000 [Keeling et al., 2001]. While at the large scale, the relationship between CO_2 increase and global warming is established [IPCC, 1996], at the local scale, many studies are still needed to understand regional and local sources of carbon dioxide, such as volcanoes. The volcanic areas are particularly rich in carbon dioxide; this is due to magma degassing in the summit craters region of active volcanoes, and to the presence of fractures and active faults [Giammanco et al., 1998]. Several studies estimate a global flux of volcanic CO_2 $(34 \pm 24)10^6$ tons/day from effusive volcanic emissions, such as the tropospheric volcanic plume (Table 1) [McClelland et al., 1989]. Plumes are a turbulent mixture of gases, solid particles and liquid droplets, emitted continuously at high temperature from summit craters, fumarolic fields or during eruptive episodes. Inside the plume, water vapour represents 70 – 90% of the volcanic gases. The main gaseous components are CO_2, SO_2, HCI, H_2, H_2S, HF, CO, N_2 and CH_4. Other plume components are volcanic ash, aqueous and acid droplets and solid sulphur-derived particles [Sparks et al., 1997]. Volcanic gases and aerosols are evidences of volcanic activity [Spinetti et al., 2003] and they have important climatic and environmental effects [Fiocco et al., 1994]. For example, Etna volcano is one of the world's major volcanic gas sources [Allard et al., 1991]. New studies on volcanic gaseous emissions have pointed out that a variation of the gas ratio CO_2/SO_2 is related to eruptive episodes [Caltabiano et al., 1994]. However, measurements and monitoring of volcanic carbon dioxide are difficult and often hazardous, due to the high background presence of atmospheric CO_2 and the inaccessibility of volcanic sites.

Hyperspectral remote sensing is a suitable technique to overcome the difficulties of ground measurement. It permits a rapid, comprehensive view of volcanic plumes and their evolution over time, detection of all gases with absorption molecular lines within the sensor's multispectral range and, in general, measurement of all the volatile components evolving from craters. The molecular and particle plume components scatter and absorb incident solar radiation. The integral of the radiation difference composes the signal measured by the remote spectrometer. The inversion technique consists of retrieving the plume component concentrations, hence decomposing the signal into the different contributions. The accuracy of remote sensing techniques depends primarily on the sensor capability and sensitivity.

Table 1. Volcanic CO_2 Emissions [McClelland et al., 1989]

Volcano	CO_2 (T/d)
Mt. Etna	11000–70000
Popocatepetl	6400–40000
Oldoinyo Lengai	7200
Augustine	6000
Mt. St. Helens	4800
Stromboli	3000
Kilauea	2800
White Island	2600
Erebus	1850
Redoubt	1800
Grimsvotn	360
Vulcano	270

2. KILAUEA VOLCANO–HAWAII

The Kilauea volcano system, called Hot Spot, has been active for 300,000–600,000 years, with no known prolonged periods of quiescence. Hot Spot means that magma penetrates the plate and rises up to the surface, leaving a string of volcanoes. The Hot Spot is merely an anomalous concentration of heat that is transferred constantly from the Earth's interior to the surface. Beginning in 1983, a series of short-lived lava fountains built the massive cinder and spatter cone named Pu'u 'O'o vent. This eruption of Kilauea is the most voluminous outpouring of lava in the volcano's east rift zone in the past five centuries.

Kilauea emits more than 700,000 tons of CO_2 each year, less than 0.01% of the yearly global contribution by human sources. For instance, this is about the same amount of CO_2 emitted by 132,000 sport utility vehicles [USGS, 2002].

3. DATA SET

An airborne study was performed on Kilauea volcano with the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) at the end of April 2000.

Spring is the ideal time to acquire high-quality images because of the relatively low humidity in this tropical region [NOAA, 2000]. Several flights were performed in order to acquire different views of the site. On the day of acquisition over the Pu'u 'O'o vent, some clouds obscured the target and only one clear image of the degassing plume was acquired (Figure 1).

Weather conditions presented some clouds at the cone altitude during the morning. A temperature mean value of (13.8 ± 0.5) °C, a height relative humidity of $80\% \pm 5\%$, a pressure of (884 ± 3) hPa, a wind speed about 10 knot and wind direction of about 70 degree North were measured during the radiosounding at the cone altitude.

Ground-based measurements of different volcanic gases were performed at the same time as the AVIRIS flight. The USGS Volcano Observatory analysed gas samples of SO_2 and CO_2 using a Cospec Correlation Spectrometer and Li-Cor system [Gerlach et al., 1998]. In addition, instrumentation installed near the Pu'u 'O'o vent periodically measures the air quality with chemical sensors, as well as wind speed and direction. The data from this station are transmitted to the observatory every 10 minutes, providing near-real-time data on degassing from the Pu'u 'O'o vent [Sutton et al., 1992].

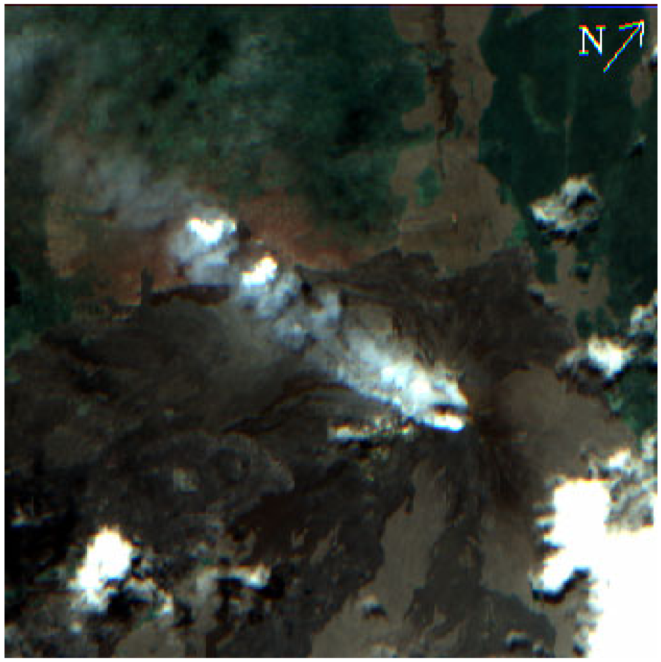

Figure 1. Pu'u 'O'o vent plume image acquired by AVIRIS 4/26/2000.

4. INVERSION TECHNIQUE

The hyperspectral sensor measures the solar irradiance reflected by the surface in its view angle, using contiguous bands at a high-spectral resolution. The algorithm was developed in the wavelength range from 1.9 to 2.1 µm, where the CO_2 molecules have absorption lines partially overlapped by the water vapour absorption lines. The near-2000-nm CO_2 absorption range has been selected because the AVIRIS spectra are more sensitive to different amounts of carbon dioxide than in the near-1600-nm CO_2 absorption range [Green, 2001].

The inversion algorithm to calculate volcanic CO_2 concentration is based on a differential absorption technique, which assumes that the absorption deep in the atmospheric spectrum curve is related to the volcanic CO_2 concentration in the column. Following the CIBR 'Continuum Interpolated Band Ratio' remote-sensing technique [Carrere and Conel, 1993] used to calculate water vapour columnar abundance, the CO_2 concentration is retrieved by solving the following equation:

$$CIBR = \exp\left(-\alpha \cdot [CO_2]^{\beta}\right) \tag{1}$$

Where:

- *CIBR* is given by the following ratio:

$$CIBR = \frac{L}{a \cdot L_1 + b \cdot L_2} \tag{2}$$

- *L* is the band interpolated radiance;

- a and b are the weighing coefficients ($a + b = 1$);
- L_1 and L_2 the continuum radiances.

- $[CO_2]$ is the CO_2 columnar abundance;
- α and β are parameters related to the model variables.

5. RESULT

In order to invert equation (1) on CO_2 concentration, α and β have been estimated. To this purpose, the MODTRAN radiative transfer code [Berk et al., 1989] was used to simulate the radiances acquired by the AVIRIS sensor in the Pu'u 'O'o vent image. In order to accurately represent the atmosphere and the measurement conditions, the input information for the model reflects the following conditions:

- atmospheric vertical profile (Pressure, Temperature, Humidity and Wind Speed), as measured at the Hilo site during the AVIRIS flight;
- atmospheric CO_2 concentration equal to 371.59 ppmv, as derived from in situ air samples collected at Mauna Loa Observatory [Keeling et al., 2001];
- surface reflectance equal to 0.1 for basaltic lava rock in the IR wavelength range, as derived from the USGS reflectance database;
- geometrical parameters, i.e., flight altitude, sensor view angle, volcano altitude;
- rescaling factors for carbon dioxide.

The radiance simulated at different CO_2 concentrations at AVIRIS spectral resolution is reported in Figure 2. The depth of the absorption bands is mathematically represented by the CIBR (2). Each CIBR corresponds a value of CO_2, as reported in Figure 3. The calibration curve follows equation (1) with parameter values of $\alpha = 3{,}71*10\text{-}3$ and $\beta = 0.804$, and a fit correlation of 95%.

Replacing the values of parameters α and β, equation (1) has been inverted in order to calculate the volcanic CO_2 abundance in the scene. The CIBR has been calculated using the radiance measured on each pixel by the AVIRIS sensor.

In Figure 4, the result of the inversion is reported. In the crater zone the value is a maximum reaching value of 350 ppmv of CO_2 concentration. Where the plume is dispersed in a large area, the CO_2 concentration is rather low. In the plume area over and near the crater zone, where the CO_2 concentration is expected to be much higher, the algorithm is not able to give reliable results. A possible explanation is the high emissivity of these zones partially overwhelming the CO_2 absorption. The contribution of the emissivity amount is probably due to either the hot ground in the crater area under the plume or the hot components of the plume coming out from crater, or a combination of both. This hypothesis explains why the low concentration of CO_2 is retrieved only in the central part of plume (ideally following the plume axis).

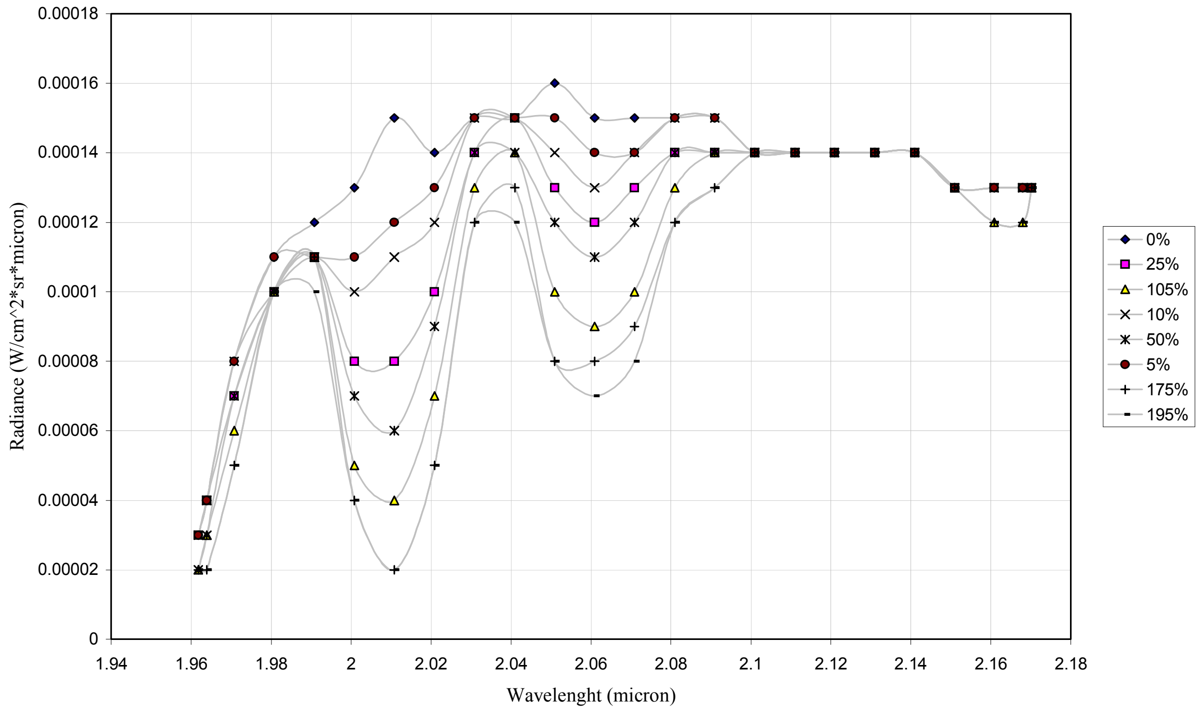

Figure 2. MODTRAN simulations at different carbon dioxide concentrations.

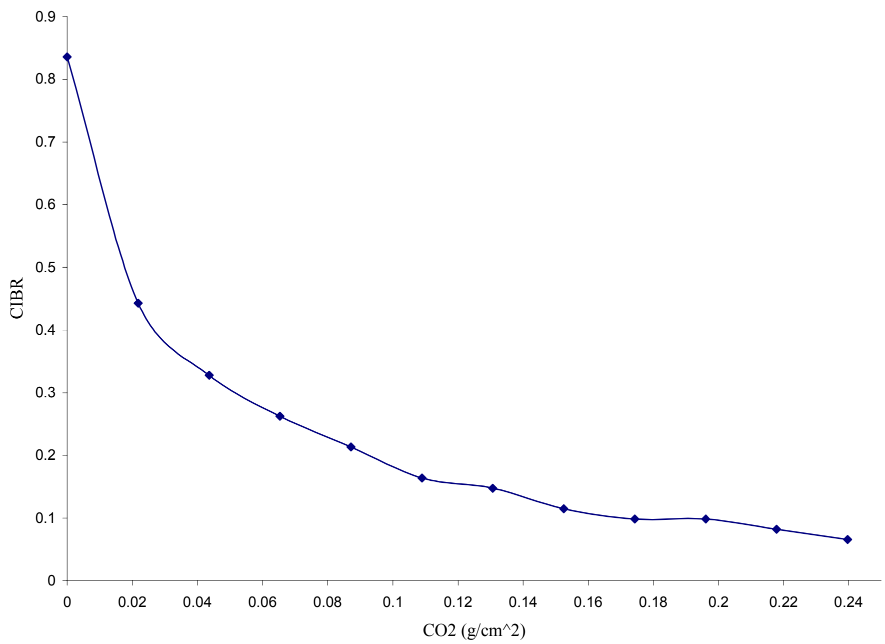

Figure 3. Calibration curve.

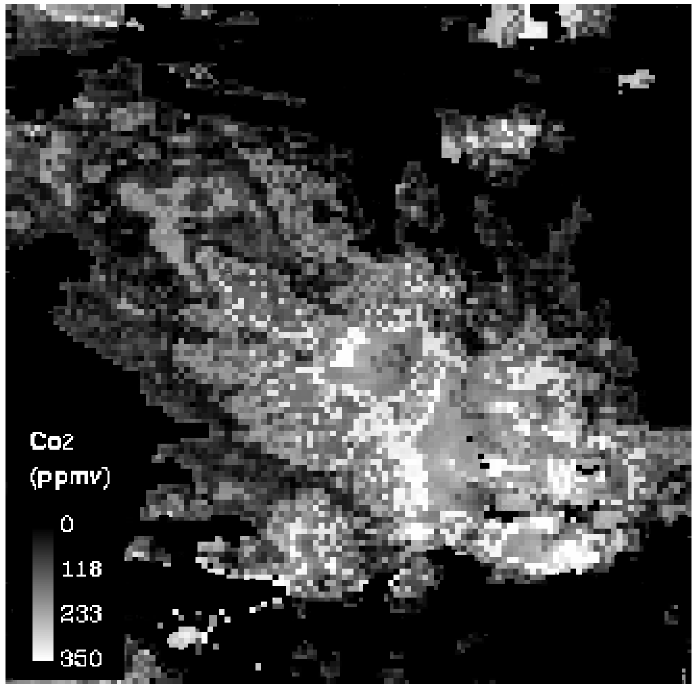

Figure 4. Volcanic plume carbon dioxide spatial distribution.

6. CONCLUSIONS

A remote-sensing technique based on a differential absorption technique has been developed in order to retrieve the tropospheric volcanic plume CO_2 abundance, using AVIRIS data acquired over the Kilauea volcano (Hawaii).

The atmospheric model MODTRAN has been tuned to the atmospheric carbon dioxide concentration measured at the ground during the AVIRIS measurements campaign.

This approach retrieves the volcanic CO_2 concentration in the Pu'u 'O'o vent plume area; the values retrieved are in agreement with ground-based measurements. Otherwise, the technique needs improvements in order to expand its validity to the entire plume area, and to retrieve the concentration of the plume in areas where the results are not reliable, probably caused by the high emissivity of these zones.

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