Volcanic Water Vapour Abundance Retrieved Using Hypespectral Data

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Abstract— *In the present study a remote sensing differential absorption technique, already developed to calculate the atmospheric water vapour abundance, has been adapted to calculate water vapour columnar abundance in tropospheric volcanic plume. Water vapour is the most abundant gas of a volcanic plume released into the atmosphere from an active volcanic system. The technique is based on the correlation between the dip in the spectral curve measured by the spectrometer were water vapour absorptions bands are presents, and the precipitable water content in the column. Airborne and satellite remote sensing images in the infrared wavelength range were used. The technique has been applied to data acquired over two different degassing volcanoes. The Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) acquired data over the Hawaiian Pu'u'O'o Vent cone of the Kilauea volcano on April 2000. The Hyperion sensor on EO-1 satellite has been requested to acquire data on July 2003, during a ground-based measurements campaign on Mt. Etna (Italy). The result is the spatial distribution of water vapour abundance of the Mt. Etna and of the Pu`u` O`o Vent volcanic plumes. A comparison between the two results has been done, showing the differences in the volcanic activity. The algorithm produces reliable results compared to the ground based measurements in the plume area acquired during a measurements campaign over Mt. Etna.*

Keywords- Water vapour, Kilauea volcano, Mt. Etna, Aviris, Hyperion

I. *INTRODUCTION*

Volcanic emissions in atmosphere are often the most visible indicators of volcanic activity. They are a turbulent mixture of solid particles, liquid droplets and various gases exsolved from magma, emitted continuously from summit craters, fumarolic fields or during eruptive episodes.

Different volcanic activities, such as such as volcanic eruption, volcanic clouds and plumes, disperse into the atmosphere large quantities of gases and aerosols with different altitudes, latitudes and residence times [1]. Volcanic eruption plumes affect the climate in different ways and cause a direct hazard for humans and animals populations [2]. As new studies have pointed out those explosive volcanoes are able to inject large quantities of water vapour into the stratosphere causing a significant increase in upper tropospheric and lower stratospheric water amount in several years following the eruption. This increasing, related at the amplitude and at the frequency of volcanic eruptions, is a positive radiative agent, forcing surface temperatures to rise in the same way as carbon dioxide does [3].

Conversely, the continuously magma degassing from summit craters of actives volcanoes produce tropospheric volcanic plumes. They are rich of water vapour that represents 70% to 90% of the plume component. Water vapour presence supports the sulfate aerosols reacting with the sulfuric acid, as they may cause acid rains and contaminate local water supplies; moreover they are hazardous for local human and animal populations [4].

Monitoring volcanic plumes is a key to understand the magma motions in the volcano conduit; due to the role of volatiles as propellants for eruptions (magmatic, phreatic, and phreatomagmatic) and as potential quantitative indicators of subsurface processes including crystallization, magma ascent, fractured development, and fluid/rock interactions. Moreover, they are difficult and often hazardous to direct measure. For these reasons in the recent years the new airborne and satellite remote sensing instruments allow a large and fast view of volcanic plumes. They permit to detect volatiles components exolving from craters applying sophisticated techniques to the signal measured by a remote sensor, since the incident solar radiation is scattered and absorbed by the molecular and particle plume components.

II. THE DATA SET

A. Measurements campaign at Kilauea

An airborne campaign was performed with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) imaging spectrometer on Kilauea volcano. Kilauea volcano has been active since 300,000-600,000 years, with no prolonged periods of quiescence known. It is a particular volcanic system called Hot Spot. This 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, ranks as the most voluminous outpouring of lava on the volcano's east rift zone in the past five centuries.

AVIRIS is an optical sensor for Earth remote sensing that delivers calibrated images of the upwelling spectral radiance in

224 contiguous spectral channels in the wavelengths range from 400 to 2500 nm. It flies on NASA ER-2 jet aircraft platform modified for increased performances, at approximately 20 km above sea level at about 730 km/h [5].
The campaign took place at the end of April 2000. Spring is the ideal season to acquire good quality images because the weather in this tropical region shows low humidity values [6]. Several flights were performed in order to acquire different scene of the Kilauea volcano site. The day of acquisition over the Pu`u` O`o Vent cone some clouds appeared and only one clear image of the degassing plume was acquired. The time weather conditions present 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% ± 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 lunched from Hilo.

B. Measurements campaign at Mt. Etna

In the framework of the 'Asi-Hypeso' project, funded by the Italian Space Agency, the 'Sicily 2003' field measurements campaign was organized to acquire high-resolution hyperspectral remote sensed images together with ground-based measurements. At this purpose Hyperion on EO-1 satellite has been requested to acquire data over Mt. Etna. Hyperion is a hyperspectral sensor flying on EO-1 satellite platform, in the same polar orbit of Landsat7 following of few minutes. It acquires data in the spectral range from 400 to 2500 nm in continuos bands with a spectral resolution of 10nm.

Mount Etna is a continually degassing volcano located in Sicily, one of the world's most actively volcanoes [7]. It is a large strato-volcano with a summit height approx. of 3300m a.s.l. and a circumference of about 200Km at ground level; it produces alkaline and basaltic lava during summit and flank eruptions [8]. An important feature of its activity is the continuous and abundant noneruptive gas emissions from the summit craters. This degassing process produces an effusive plume rich of gases like H20, C02, S02, HCI, H2, H2S, HF, CO, N2, CH4 [9, 10].

The campaign took place at the end of July 2003. This period was chosen to meet suitable weather conditions since the solar irradiance is near to its yearly maximum, expected relative humidity is low and expected wind direction is N-W prevalently. These factors allow the acquisition of good quality images since the area under the plume is well illuminated and, especially in the early morning, the formation of orographic clouds is limited. Indeed, in this period, the time weather conditions were stable as expected. The sky was cloudless during the entire period. The day of Hyperion acquisition was the 19th July. This day radiosoundings vertical profile and meteorological station at the craters zone (3000 m a.s.l.) show a temperature mean value of (15 ± 0.5) °C, a low relative humidity of 11% ± 2%, a pressure of (730 ± 1) hPa, a wind speed between 9 to 3 m/s and wind direction of North.

III. THE ALGORITHM

The retrieval algorithm is a differential absorption technique termed CIBR 'Continuum Interpolated Band Ratio' [11]. The CIBR technique retrieve the water vapour abundance starting from the radiance measured by the sensor in the spectral range were water vapour molecules have absorption lines at the wavelengths of 940 nm and 1130 nm. This means assuming that the absorption deep in the atmospheric spectrum curve is related to the volcanic water vapour concentration in the column. The water vapour columnar abundance is retrieved inverting the following equation:

$$CIBR = \exp\left(-\alpha \cdot [H_2O]^{\beta}\right). \qquad (1)$$

Where:

- $[H_2O]$ is the Water vapour columnar abundance;
- α and β are parameters related to the model variables.
- *CIBR* is defined by the following ratio:

$$CIBR = \frac{L}{a \cdot L_1 + b \cdot L_2}. \qquad (2)$$

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

The CIBR is formed as the ratio between the radiance measured by the sensor at the center of the absorption band (L) and the radiance values of the continuum (L_1 and L_2). The spectral radiance values simulated at the sensors spectral resolution of 10nm used to calculate CIBR are showing on Fig. 1. The simulation of the spectral radiance in absence of water vapour is used estimated the weighing coefficients a and b.

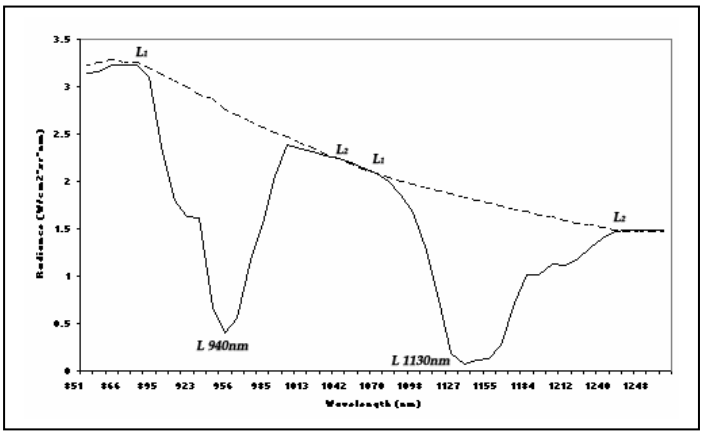

Figure 1. *Wavelengths and Radiance values used to calculate CIBR. The two curves are simulated at the sensors spectral resolution and show the water vapour absorption bands of 940 nm and 1130 nm in the presence or in absence of water vapour content.*

IV. RESULT

In order to invert the equation (1) on the unique unknown water column abundance, α and β needed to be estimated. This means provide the calibration relationship between the CIBR and the column water content. To this purpose the Modtran radiative transfer code [13] was used to simulate the radiances acquired by the two sensors Aviris and Hyperion. In order to well represent the atmosphere and the measurement conditions, the input information for the model are the following:

- atmospheric vertical profile (Pressure, Temperature, Humidity and Wind Speed);
- geometrical parameters, i.e. flight altitude, sensor view angle, volcano altitude.
- surface reflectance equal to 0.1 for basaltic lava rock in the IR wavelength range, as derived from the USGS reflectance data base;

Both for the images of Kilauea and Mt.Etna the input variables are measured during the ground-based campaigns.

The Modtran model was modified in order to provide simulated radiance values for different water vapour amounts. Calculating the CIBR using the radiances simulated the relationship between the CIBR and water column amounts is established, and α and β are parameters can be calculated by a linear fit of equation (1).

A. *Inversion of Aviris image*

α and β parameters have been estimated using both the absorption bands of 940 and 1130 nm. Values of $\alpha = 3{,}71*10^{-3}$ and $\beta = 0.804$ with a fit correlation of 95%, was retrieved for both bands. The water vapour columnar abundance has been retrieved calculating CIBR with the radiance measured on each pixel by the AVIRIS sensor. In Fig. 2 the water vapour columnar abundance spatial distribution is showed.

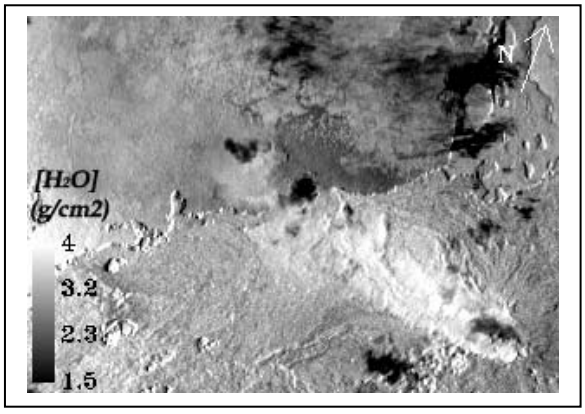

Figure 2. *Pu`u` O`o Vent volcanic plume water vapour spatial distribution retrieved using Aviris data (26/4/00).*

B. *Inversion of Hyperion image*

Before inverting the equation (1) on Hyperion image, a signal noise of the scene has been estimated. The low values of radiances measured by Hyperion are due to the low reflectance of the lava surfaces and to the low values of water vapour at Mt. Etna altitude (3300 m a.s.l.). These reasons causing a signal to noise ratio value < 10 in the 940nm bands. Was not possible applying the techniques using this band. Instead the signal to noise ratio for the 1130 band show a value close to 100, that permits measuring the spectral absorption bands of water vapour.

In order to taking into account of the variables water vapour amounts due to the variables altitudes of the Mt. Etna surfaces (from 800 m to 3300m a.s.l.), the Hyperion scene was coregistraded to a terrain digital elevation model. A this purpose a Digital Elevation Model (DEM) constructed starting from digital topographic maps at a scale 1:10000 and using digital photogrammetric techniques was used.

In fig. 3 the water vapour map retrieved is showed. The volcanic water vapour of plume is clear in the map. The values retrieved in the map are in agreement with the value retrieved by the Sunphotometer of 0.5 cm. Otherwise the high noise the radiance values affect the result on an estimated error of 40%.

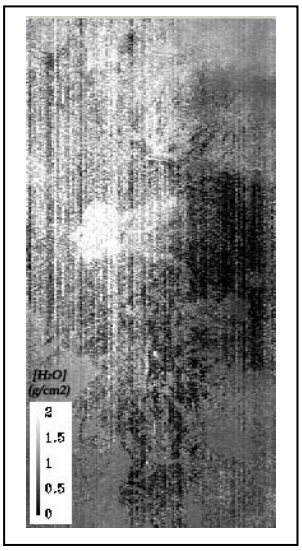

Figure 3. *Mt.Etna volcanic plume water vapour spatial distribution retrieved using Hyperion data (19-7-03).*

V. CONCLUSIONS

A remote sensing technique based on a differential absorption technique has been applied to hypespectral images in order to retrieve the volcanic plume water vapour abundance. The data used was acquired by AVIRIS over the Pu`u` O`o Vent degassing cone of Kilauea volcano (Hawaii) and by Hyperion on EO-1 satellite over Mt. Etna.

The atmospheric model Modtran has been tuned with the ground based measurements acquired during the two campaigns over Kilauea and Mt. Etna.

Different amounts of volcanic water vapour are retrieved by the same technique. The technique retrieves the volcanic H_2O concentration in the Pu`u` O`o Vent plume area. The values retrieved are in agreement with the contemporaneous ground based measurements at Mt. Etna retrieved by the sunphotometer. Otherwise, the technique needs improvements in order to extend the result validity on all the plume area and to retrieve the concentration also in the zone of the plume where the results are not reliable probably caused by the complex thermodynamics of the volcanic zone.

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