Theoretical Study on Volcanic Plume SO\textsubscript{2} and Ash Retrievals Using Ground TIR Camera: Sensitivity Analysis and Retrieval Procedure Developments.

Stefano Corradini, Cecilia Tirelli, Gabriele Gangale, Sergio Pugnaghi, and Elisa Carboni

Abstract—In this paper, a sensitivity analysis and procedure development for volcanic-plume sulfur dioxide and ash retrievals using ground thermal infrared camera have been carried out. The semiconductor device camera, considered as a reference, has a spectral range of 8–14 μm with noise equivalent temperature difference that is better than 100 mK at 300 K. The camera will be used to monitor and assess the hazards of Mt. Etna volcano to mitigate the risk and impact of volcanic eruptions on the civil society and transports. A minimum number of filters have been selected for sulfur dioxide (SO\textsubscript{2}) and volcanic ash retrievals. The sensitivity study has been carried out to determine the SO\textsubscript{2} and volcanic ash minimum concentration detectable by the system varying the camera geometry and the atmospheric profiles. Results show a meaningful sensitivity increase considering high instrument altitudes and low camera-elevation angles. For all geometry configurations and monthly profiles, the sensitivity limit varies between 0.5 and 2 g · m\textsuperscript{-2} for SO\textsubscript{2} columnar abundance and between 0.02 and 1 for ash optical depth. Two procedures to detect SO\textsubscript{2} and ash, based on the least square fit method and on the brightness temperature difference (BTD) algorithm, respectively, have also been proposed. Results show that high concentration of atmospheric water vapor columnar content significantly reduces the ash-plume effect on the BTD. A water vapor-correction procedure introduced improves the ash retrievals and the cloud discrimination in every season, considering all the camera geometries.

Index Terms—Ground measurements, Mt. Etna volcano, remote sensing, sulfur dioxide (SO\textsubscript{2}), thermal infrared (TIR) camera, volcanic ash.

I. BACKGROUND AND MOTIVATION

Volcanoes represent one of the most important natural sources of environmental pollution in the atmosphere both during eruptions and in the period between them [1]. Good knowledge of the volatile volcanic emissions in time and space is of fundamental importance to understand, on a global scale, their impact on the world climate and, on a local scale, to prevent problems to human activities and air transport.

The most abundant gases typically released into the atmosphere from volcanic systems are water vapor (H\textsubscript{2}O), carbon dioxide (CO\textsubscript{2}), and sulfur dioxide (SO\textsubscript{2}). Volcanoes also release smaller amounts of other gases such as H\textsubscript{2}S, H\textsubscript{2}, He, CO, HCl, HF, N and Ar. In addition to the release of a number of gases, volcanoes emit aerosols and, during explosive eruptions, eject solid-rock fragments and ash into the atmosphere.

The volcanic ash particles are composed of fragments of pyroclast rocks smaller than 2 mm which are released during explosive events. Volcanogenic aerosols have a significant effect on the Earth’s radiative budget even if their emission strength is lower than that of anthropogenic sources. Many volcanoes degas in the free troposphere, in contrast to anthropogenic emissions that are generally restricted to the boundary layer where species lifetimes are reduced [2], [3]. The radiative effects of volcanic aerosol depend on particle-emission rates, particle-size distributions, chemical compositions, and particle morphologies. Particle radiative effects depend strongly on size; small particles tend to backscatter incoming shortwave radiation and large particles tend to absorb outgoing terrestrial radiation [4]. Particle-size distribution and composition determine the ability of particles to act as cloud condensation nuclei and affect the atmospheric lifetime and indirect radiative effects of the particles [1]. Eruptions that do not penetrate into the stratosphere are usually regarded as being unimportant for long-term or local-climate impacts. However, if such an effusive eruption persists with for an extended period, it can produce a large radiative forcing over local or regional scales. Such tropospheric eruptions can have a number of deleterious effects on the local population including respiratory problems [5], damage to agricultural and industrial productivity [6], and hazards to aviation [7]. The particles with dimension of some millimeters can damage the aircraft structure (windows, wings, ailerons), while particles less than 10 μm may be extremely dangerous for the jet engines and undetectable by the pilots during night or in low-visibility conditions [8]. Theoretical calculations indicate that volcanic ash clouds with a high concentration of silicate particles show an opposite spectral behavior with respect to water droplets in the infrared 10–13-μm spectral range [9], [10]. Such characteristics can be used to discriminate between volcanic and meteorological clouds.

Remote sensing is the most suitable technique to detect and retrieve volcanic emissions because of the sporadic nature of...
volcanic eruptions, the large geographic extent of volcanoes, and the difficulties of direct sampling. The volcanic ash retrieval and cloud-discrimination procedures have been applied using different satellite platforms, such as the Advanced Very High Resolution Radiometer [9], [11]–[14], Geostationary Operational Environmental Satellite [14]–[16], Total Ozone Mapping Spectrometer (TOMS) [13], the MODerate resolution Imaging Spectroradiometer (MODIS) [16]–[21], and the Spin-Enhanced Visible and Infrared Imager (SEVIRI) [21], [22].

As aerosol, volcanic SO$_2$ plays an important role in the world climate [23]–[26]. The study of volcanic SO$_2$ emission is very important to compare the natural and the anthropogenic contributions; recent estimates has placed the global volcanic SO$_2$ emissions at 10% to 15% of the total anthropogenic sulfur output [27]. The study of volcanic gaseous emission also provides important insights into subsurface magmatic processes [28], and flux variations can help to predict eruptive activity [29]–[31]. SO$_2$ is also an important volcanic gas because of its effects on the environment (e.g., acid rain, effects on plants, and public health) and also because once it is high in the atmosphere (> 6 km), it can be transported over long distances, has a greater residence time, and can be oxidized to form sulfates. Sulfate aerosols in the atmosphere counteract the global warming produced by a high concentration of greenhouse gases [32]–[35] and their principal effects are backscattering of solar radiation (direct effect) and increased of cloud reflectivity (indirect effect) [36]. Volcanic SO$_2$ columnar abundance and flux can be measured in many ways. On the ground, remote sensing of SO$_2$ in the ultraviolet (UV) and thermal-infrared (TIR) spectral region is used for volcanic-plume monitoring. Instruments most commonly used in the short wavelengths are the CORrelation SPECTrometer [37]–[39], the Differential Optical Absorption Spectroscopy [40], [41], the Light Detection and Ranging (LIDAR) [42]–[44], the Differential Absorption LIDAR [45] and the Fourier Transform Infrared Spectrometer [46]–[48]. Airborne, the TIR Multispectral Scanner [49], [50] and the Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) [51] have been used. The first satellite data used for SO$_2$ stratospheric volcanic-eruption retrieval were the TOMS UV measurements [52], [53]. In 1993, Read et al. [54] used the microwave measurements of the Microwave Limb Sounder, on board NASA’s Upper Atmosphere Research Satellite, for the Mt. Pinatubo volcano-eruption SO$_2$ retrieval. More recently, MODIS has been used to estimate the SO$_2$ of some eruptions [18], [21], and the TIR bands of the Advanced Spaceborne Thermal Emission and Reflection Radiometer has been used to compute an SO$_2$ map of a volcanic plume in the low troposphere [55]–[57]. SO$_2$ volcanic-columnar content has been retrieved using the High Resolution Infrared Spectrometer [58], the Atmospheric Infrared Sounder [59], [60], the Ozone Monitoring Instrument [61], [62], and SEVIRI [21], [22].

Mt. Etna is the largest active volcano in Europe, and its position is hazardous because of its proximity to the airport of Catania and Reggio Calabria. The ash particles emitted by Mt. Etna during eruptions, indiscernible from meteorological clouds by airplane radar, were able to cause serious damages to airplane engines [8]. Moreover, the annual passenger traffic volume at the international Catania–Fontanarossa airport is more than five million (5.4 during 2006), and the numerous days of closure during the 2001 and 2006 eruptions caused large losses to the Sicilian economy. An effective volcano-monitoring program is essential for public safety and economic reasons.

The aim of this paper is to analyze the possibility of using an on-ground TIR camera system to retrieve SO$_2$ columnar abundance and ash in a volcanic plume. This paper presents the theoretical basis of a future ground-based TIR camera which will augment the existing monitoring systems on Mt. Etna volcano. We have conducted a theoretical study of the sensitivity of a TIR system to volcanic ash and SO$_2$ and developed methods for retrieving ash and SO$_2$ amounts. The sensitivity study is aimed at computing the minimum SO$_2$ columnar abundance and the minimum aerosol optical depth (AOD) and effective radius ($r_e$) detectable by the system varying the instrument altitude and viewing angle. The retrieval procedures are based on the TIR radiative-transfer equation inversion (least square fit) and on the brightness-temperature difference (BTD) algorithm for SO$_2$ and ash, respectively. As reference, a semiconductor device camera, composed of a matrix of uncooled vanadium oxide microbolometric sensors has been considered. This instrument has a spectral range varying from 8 to 14 µm and a noise equivalent temperature difference (NETD) that is better than 100 mK at 300 K. Three channels centered around 8.7, 11 and 12 µm have been chosen within this spectral range; the first channel is used for the SO$_2$ retrieval, while the second and third channels are used for ash retrievals and for cloud discrimination. In this paper, calculations have been performed for a number of viewing geometries (altitude and angle) and for different atmospheric mixing ratio, temperature, and pressure profiles which span the range of mean observed atmospheric conditions throughout the year. To reduce the water vapor’s masking of the BTD effects of an ash plume in the summer months, we have developed a method for atmospheric water vapor correction. All the simulations used in the sensitivity study and the water vapor correction have been performed with the MODTRAN 4 radiative-transfer model (RTM) [63], [64].

Organization of this paper is as follows: In Section II, the main TIR camera-system characteristics and the criteria adopted to select the filters for the volcanic species retrievals are presented. Section III describes the rationale for the sensitivity study, the retrievals, and the cloud-discrimination procedure. The SO$_2$ and volcanic ash sensitivity study and retrieval procedures are described in Sections IV and V, respectively. We present our conclusions in Section VI.

II. REFERENCE INSTRUMENT DESCRIPTION

Nowadays the uncooled focal-plane array (FPA) microbolometer takes a large part in infrared-imaging applications. In fact, new thermal-imaging applications and new developments are focused on improving the sensitivity to enable the possibility of obtaining high-performance small pixel-pitch detectors.\footnote{Pixel pitch is a specification for pixel-based devices that describes the distance between dots on the inside of a display screen. It may be measured in linear units, usually millimeters, with a smaller number meaning closer spacing.}

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Uncooled FPA microbolometers are currently available [65] in a range of pixel arrangements (160 × 120, 320 × 240, 640 × 480 pixels), pixel pitch (25, 35, or 45 μm), response in different bands within the region of 7 to 14 μm, and NETD ranging from 100 to 30 mK at 300 K. To perform the sensitivity tests described in the following, a total spectral range of 8–14 μm and an NETD of 100 mK at 300 K have been assumed. No reduction of the instrument detectivity has been considered for detector dimension or noise bandwidth due to the used filters.

The minimum radiance (noise equivalent spectral radiance [NESR]) detectable by the camera system, in the 8–14 μm (1250–714 cm⁻¹) spectral range, is the difference between the radiance emitted by a blackbody at \( T_R + \text{NETD} = 300.1 \) K and that emitted at \( T_R = 300 \) K

\[
\text{NESR} = \frac{\int_0^\infty \Phi_\lambda [B_\lambda(T_R + \text{NETD}) - B_\lambda(T_R)] d\lambda}{\int_0^\infty \Phi_\lambda d\lambda} \tag{1}
\]

where \( B \) is the Planck function and \( \Phi_\lambda \) is a generic response function. Using a square instrument-response function whose value is one in the 8–14 μm spectral range and zero elsewhere, NESR results to 14 mW · m⁻² · sr⁻¹ · μm⁻³.

The numerator of (1) represents the noise equivalent power per unit area and unit solid angle, which is able to stimulate the sensor. This value (84 mW · m⁻² · sr⁻¹, with no filter, \( T_R = 300 \) K, and NETD = 100 mK) has been assumed to be the minimum value required to get a change in the sensor signal in any condition of temperature background or filter response function. Clearly, to have that minimum radiance, the NETD in (1) will increase if the background (or reference) temperature \( (T_R) \) decreases, or if a filter, reducing the energy at the sensor, is used.

### A. Channels Definition

The \( \text{SO}_2 \) and ash-retrieval procedures, described in this paper, need three different measurements taken in the 8–14 μm range. These measurements can be obtained by means of three interferential filters sequentially located in the optical path of the camera. In this paper, the spectral response function of each filter considered is a Gaussian function with unitary transmittance at the central wavelength and a full-width at half-maximum (FWHM) of 0.5 μm. Nowadays, interferential filters with similar characteristics are readily available. The choice of the FWHM value (0.5 μm) is based on the compromise between the need to collect a revealable energy amount and the requirement that the adjacent species influence must be as small as possible. The channel central wavelengths have been chosen analyzing the transmittance spectra of the different species considered in this study. All the simulations have been realized using MODTRAN 4 RTM for a sensor placed at sea level pointed in the zenithal direction. Fig. 1(a) shows the \( \text{SO}_2 \) transmittance considering a columnar abundance of 5 g · m⁻². The channel selected, widely used in many satellite instruments [18], [49], [51], [55], [57], [66], is centered around the maximum \( \text{SO}_2 \) absorption wavelength.

The retrieval of volcanic ash optical properties (\( r_e \) and AOD at 0.55 μm) and the discrimination between volcanic and meteorological clouds is generally carried out using channels centered around 11 and 12 μm. In particular, the discrimination between clouds is based on the different spectral absorption between volcanic aerosols and water droplets in the 10–13-μm spectral range [9], [10] [see Fig. 1(b) and (c)]. In such a spectral range, the absorption, then the transmittance, result is decreasing for volcanic ash and increasing for water droplets. Fig. 1(d) shows the total atmospheric-transmittance spectrum with the superposition of the three selected channels.

The NESR of each channel \( (\Delta R_{\min}) \) can be computed using (1), where the numerator has the fix value of 84 mW · m⁻² · sr⁻¹, and knowing the filter-response function at the denominator. In this paper, all the filter response functions have a Gaussian shape, with unitary transmittance at the central wavelength and with the same FWHM (0.5 μm); therefore \( \Delta R_{\min} \) (157.8 mW · m⁻² · sr⁻¹ μm⁻¹) is the same for all the three filters. Note also that this value could be computed simply by multiplying the instrumental total NESR with the ratio between the area of the instrument square response function and the filter Gaussian response function.

In Table I are reported, for each filter, the central wavelength and three NETD values, obtained by numeric inversion
TABLE II
PARAMETER SETTING FOR SO₂ AND ASH-PLUME MODTRAN SIMULATIONS. THE PARTICLES’ EFFECTIVE RADIi AND THE OPTICAL-DEPTH VALUES HAVE BEEN SELECTED TO BE EQUISPACED IN A LOGARITHMIC SCALE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric profiles (PTH)</td>
<td>12 mean monthly profiles</td>
</tr>
<tr>
<td>Camera altitude</td>
<td>0-2400 m, step 800 m</td>
</tr>
<tr>
<td>Camera elevation</td>
<td>15-90°, step 25°</td>
</tr>
<tr>
<td>SO₂ columnar abundance</td>
<td>0-15 g m⁻², step 1 g m⁻²</td>
</tr>
<tr>
<td>Particle effective radii</td>
<td>0.8, 1.1, 1.6, 2.3, 3.4, 4.8, 6.9, 10, 15 μm</td>
</tr>
<tr>
<td>AOD at 0.55 μm</td>
<td>0, 0.1, 0.3, 0.7, 1.5, 3.1, 6.3</td>
</tr>
</tbody>
</table>

Fig. 2. February and August monthly mean precipitable water and temperature atmospheric profiles computed considering 23 years of Trapani WMO Meteo station measurements.

(1) with the aforementioned NESR and three different \( T_r \) background temperature values: 200, 250, and 300 K. The trend of the NETD in the range 200–300 K is not linear, but the values, computed at the edges of this quite realistic temperature interval, can give a good idea of its variation.

III. RATIONALE OF SENSITIVITY ANALYSIS AND RETRIEVAL SCHEMES

The sensitivity study for SO₂ and ash-plume retrievals has been carried out by means of RTM computations simulating the radiance measured by the camera looking through the volcanic plume. The simulations have been obtained varying the camera altitude and viewing angle and the plume characteristics as SO₂ columnar abundance and ash optical depth considering different effective radii (see Table II). For each camera configuration (altitude viewing angle), the minimum SO₂ columnar abundance (see Section IV-A) or ash optical depth and effective radius (see Section IV-B) able to produce a signal detectable by the camera channels (see Section II-A) has been obtained. All the simulations have been realized using MODTRAN 4 RTM. To take into account the strong atmospheric-profile seasonal variation and, in particular, the influence of water vapor in the spectral range of measurements, the RTM simulations have been carried out considering all the monthly atmospheric profiles. The mean monthly atmospheric profiles of pressure, temperature and humidity (PTH) were derived from the analysis of 23 years of radiosounding measurements made at Trapani WMO Meteo Station. Trapani is located at the western tip of Sicily and is the closest meteorological station to the Mt. Etna volcano. Fig. 2 shows an example of the mean precipitable water and atmospheric-temperature profiles for February and August, the months with the lowest and the highest water vapor content, respectively.

The ash optical properties (single-scattering albedo, extinction coefficients, and asymmetry parameter) necessary for the ash-plume characterization have been computed using the Oxford University Atmospheric, Oceanic, and Planetary Physics Mie Code [67]. The aerosol-size distribution has been considered log-normal (with fixed spread = 1.77 and different values of mode radius between 0.34 and 4.42 μm in order to obtain the effective radius in Table II) and the refractive index derives from Volz (1973) [68].

The procedure proposed for the SO₂ columnar abundance retrieval is based on the least square fit method (see Section V-A) considering the channel centered around 8.7 μm, while the retrieval of the ash optical depth and effective radius, as well as the ash and water plumes discrimination, are based on the BTD procedure (see Section V-B) considering the channels centered around 11 and 12 μm. Results obtained in Section V-B emphasize that the atmospheric water vapor radiative effect counteracts the radiative effect of volcanic ash on BTD, and, in case of high water vapor (as in summer season), reduce meaningfully the ash-plume detection and retrieval. A water vapor correction has been carried out in order to make effective the ash retrievals and the cloud discrimination, also, in case of high-precipitable water content in the atmosphere.

IV. SENSITIVITY ANALYSIS

In this section, the SO₂ columnar abundance and ash-retrieval sensitivity study will be presented.

As described previously, the sensitivity study has been performed by means of MODTRAN 4 simulations varying the camera geometry, the mean monthly atmospheric profiles, the SO₂ columnar abundance, the ash-particle effective radius, and the ash optical depth. For the SO₂ columnar abundance sensitivity analysis, the top plume altitude has been set at 3400 m and the depth at 100 m. This geometry describes well the Mt. Etna volcano during its quiescent state. For the ash sensitivity analysis, the top plume altitude has been set at 5000 m and the depth at 1000 m. This scenario simulates properly the Mt. Etna volcano during a tropospheric eruption. All the simulations have been convoluted with the response function of the instrument selected channel (see Section II-A).

A. SO₂ Sensitivity Study

Fig. 3 shows a zoom (only up to 5 g/m²) of the sensitivity curves varying the instrument view angles for the different altitudes for February and August atmospheric profiles; all the other monthly sensitivity curve results were included. The radiance on the ordinate axis represents the difference between the radiance computed with the SO₂ columnar content indicated in the abscissa \( R_z \) and the one obtained without SO₂ plume \( R_0 \). The horizontal line is the minimum radiance variation detectable by the camera channels \( \Delta R_{\text{min}} \) (see Section II-A).

The presence of a SO₂ plume clearly increases the radiance at the camera with respect to the case without it. The extra
radiance contribution due to the SO$_2$ plume presence depends on many parameters and, in particular, on the viewing angle and on the atmospheric transmittance underneath the plume. Fig. 3 shows that, in all our scenarios, the lower the camera elevation (minimum 15°) the greater the added radiance, i.e., the greater the sensitivity. A small SO$_2$ sensitivity increase occurs also for high instrument altitudes. No meaningful seasonal dependence has been revealed. Note that both the lower camera elevations and higher camera altitudes produce a similar sensitivity improvement even if the path through the atmosphere (the water vapor effect) is increasing and decreasing, respectively. The contradiction is only apparent because, in the first case, together with an increase of the path through the atmosphere, there is also an increase of the path through the plume. Until 15° of elevation, the plume contribution (plume radiative effect) overlaps the water vapor effect. Further simulations indicate that for a defined camera altitude, there is a camera elevation angle below which the atmospheric water vapor contribution overlaps the plume contribution; such angle results always to less than 15°. Both for February and August and for all the geometries, the SO$_2$ sensitivity varies between 0.5 and 2 g · m$^{-2}$.

B. Ash Sensitivity Study

Fig. 4 shows the volcanic ash sensitivity curves considering 0 and 2400 m camera altitudes for channels 2 and 3, varying the viewing angle for February and August, respectively, in logarithmic scale. Each curve shows, for the effective radius in the abscissa, the value of the minimum AOD at 0.55 μm detectable by the considered channel. It means that a plume of ash particles with the indicated effective radius and AOD produces a radiance variation, with respect to the same atmosphere with clear sky, which is equal to NESR. This sensitivity analysis has been performed for channels 2 and 3 that are the ones involved in the BTD algorithm. Considering that the sensitivity depends on the central wavelength of the used channel, for every configuration, the worst sensitivity between
the two has been considered. The graphs show in the ordinate the minimum aerosol optical depth detectable by the instrument for each value of the particle effective radius in the abscissa. This sensitivity increases for lower viewing angles, increasing camera altitudes, and strongly, for the particle effective radii that are greater than 2 μm. The figures also show that the channel 3 minimum retrievable AOD results are greater than channel 2 for each configuration. Taking into account that the ash effective radius and AOD retrieval is performed using the combination between the two channels (see Section V-B), the sensitivity of channel 3 has been considered as reference. For all configurations and seasonal atmospheric profiles, the AOD sensitivity results are better than 0.1 for particle effective radius that are greater than 2 μm. Conversely, for smaller particles, the minimum retrievable AOD varies between 0.2 and 1 considering 15° and 90°, respectively.

V. RETRIEVAL PROCEDURE DEVELOPMENT

A. SO₂ Retrieval

The SO₂ retrieval scheme proposed is based on a least squares fit procedure [18], [49], [57] using the channel 1 camera measurements and the simulated on-ground radiances for different SO₂ columnar abundances. The function to be minimized may be written as

\[
\chi^2_{c_s} = \left( \frac{L_{m,\lambda} - L_{s,\lambda}(c_s)}{L_{m,\lambda}} \right)^2
\]

where

\- \lambda \quad \text{the central wavelength of channel 1;}
\- L_{m,\lambda} \quad \text{the measured radiance;}
\- L_{s,\lambda}(c_s) \quad \text{the simulated radiance varying the SO₂ columnar abundance } c_s.

The simulated radiances will be computed from MODTRAN RTM using as input the atmospheric profiles (PTH) of the day of measurements.

B. Ash Retrievals and Discrimination Between Ash and Water-Droplet Volcanic Plumes

The aim of this section is to verify the possibility to retrieve the ash characteristics (AOD at 0.55 μm and rₑ) from the camera measurements as well as to discriminate between ash and water-droplet volcanic plumes. Note that we are considering the extreme cases from which only ash or only water droplets are present in the volcanic plume. The effect of the contemporaneous presence of ash and water droplets is out of the aim of this paper.

The ash retrievals are computed from the inverted arch curves of the BTD versus brightness temperature at 11–μm curves by varying AOD and rₑ [12]–[16], [69]. All the simulations needed for the brightness temperature computation have been made by using MODTRAN RTM. The ash and water-droplet plumes discrimination is made by using the BTD technique, based on the difference between the brightness temperatures computed from the 11- and 12-μm channels [9], [10], which will have opposite signs by considering ash and water droplets; such difference will be positive for ash clouds and negative for water-droplet plume clouds. Note that the sign of the difference results are inverse with respect to the BTD sign considering satellite remote sensing. The reason is that, looking at the sky from ground in the TIR spectral range and neglecting the cases of thermal inversion above the plume, the plume acts as emitter at the plume temperature. The greater the absorption, the greater the emission, then, greater radiation is reaching the sensor, i.e., positive BTD. Conversely, looking at the ground from a satellite, the plume acts as absorber for the radiation coming from the surface; therefore, the greater the absorption, the lower is the radiation reaching the sensor, i.e., negative BTD.

Fig. 5 represents the way the results will be presented; the plot concerns a camera placed at 2400 m, looking at the zenith for February atmospheric profile. The inverted arch curves for volcanic ash and water-droplet plumes lay in the upper and lower part of the figure (over and under zero BTD), respectively. The solid lines represent different effective radii decreasing toward the zero BTD line, while the dashed lines represent the AOD at 0.55 μm increasing from left to right. As the figure shows, the ash and water-droplet plumes results are very well discriminable. Solid- and dashed-line grid allows estimating both the effective radius and the AOD.

Fig. 6 shows the inverted arch curves considering the February and August mean atmospheric profiles for camera altitudes of 0 and 2400 m and camera viewing angle of 90° and 15°. As the plates show, the lower the altitude and the lower the view angle (i.e., the greater the atmospheric water vapor abundance in the camera line of sight), the worse is the plume discrimination and the effective radius and AOD retrievals. The two inverted arch curves results are well defined and separated for the 2400-m 90° February mean-profile configuration (best case) but are extremely compressed for the 0-m 15° August mean-profile configuration (worst case). The results indicate that the atmospheric water vapor deteriorates both the plume discrimination and the particle retrievals, i.e., the highly precipitable
water in the summer season dramatically reduces the radiative effects on BTD of both volcanic ash and water droplets.

### C. Atmospheric Water Vapor Correction

To make easier both the ash and water plume discrimination and the AOD and \( r_e \) retrievals, an atmospheric water vapor correction has been introduced. In literature, the water vapor corrections proposed for satellite measurements \([14],[20],[69]\) are based on the experimental relationship between the BTD and the 11-\( \mu \)m channel brightness temperature varying with the atmospheric water vapor. The correction proposed in this paper, however, is based on the separation between the atmospheric water vapor and plume terms considering a simplified radiative-transfer equation in the TIR spectral range. Considering a ground instrument looking at the sky through a volcanic plume, the radiative-transfer equation can be approximated by the sum of the contribution of the atmosphere under the plume and the contribution by the plume itself

\[
L_\lambda = L_{a,\lambda} + L_{p,\lambda} \tau_{a,\lambda} \quad (3)
\]

where
- \( \lambda \) the central wavelength of channel 2 or 3;
- \( L_\lambda \) the radiance reaching the camera;
- \( L_{a,\lambda} \) the downwelling atmospheric radiance underneath the plume;
- \( L_{p,\lambda} \) the downwelling plume radiance;
- \( \tau_{a,\lambda} \) the atmospheric transmittance underneath the plume.

In (3), the contribution due to the atmosphere above the plume has not been inserted because it is negligible compared with the considered terms. To minimize the effect due to the approximation described, \( L_{a,\lambda} \) and \( \tau_{a,\lambda} \) have been considered as the total downwelling path radiance and the total atmospheric transmittance. Separating the water vapor terms from the plume terms, (3) can be written as

\[
L_{p,\lambda} = \frac{L_\lambda - L_{a,\lambda}}{\tau_{a,\lambda}} \quad (4)
\]

\( L_{p,\lambda} \) is not affected by atmospheric water vapor absorption. Note that (4) is valid within the 10–13-\( \mu \)m spectral range in which the atmospheric transmittance varies approximately between 0.4 to 0.8 considering the extreme cases of very high and low atmospheric water vapor.

Fig. 7 shows the inverted arch curves derived applying (4) for the same configurations shown in Fig. 6. The atmospheric correction terms \( L_{a,\lambda} \) and \( \tau_{a,\lambda} \) have been computed using MODTRAN RTM and the February and August mean atmospheric profiles. As the plates show, the inverted arch curve results are well defined and separated by the zero BTD, i.e., the water vapor correction procedure meaningfully improves either the plume discrimination or the particle effective radius and AOD retrieval. As can be noted, for every inverted arch curves, three different regions have been emphasized. The region delimited by the green lines is the region where the retrievals are possible. It means that for the same effective radius, each AOD variation produces a radiance variation greater than NESR, and it can be detected by the sensor in both channels. The regions delimited by the red and blue lines are the regions where the retrievals are not permitted. The red regions represent the lowest limit of detection (NESR) according to the sensitivity study presented in Section IV-B, i.e., the ash signal computed considering the effective radii and AOD included in the red area is lower than the instrument limit of detection and not retrievable. The blue regions represent the effect of the instrument sensitivity for high AOD values. In this region, there is a reduction of AOD resolution, i.e., a greater AOD variation is required to produce a signal variation greater than the instrument NESR. Fig. 7 also shows that in the case of August atmospheric profiles, with a camera altitude of 0 m and an elevation of 15°, the discrimination is effective because the two curve results are well separated, but the retrieval is not permitted because the red region borders the blue region. The AOD and \( r_e \) retrievals are preserved by simply placing the camera at 800 m.

The results obtained applying the water vapor correction show that both the discrimination and retrievals are possible in every season by placing the instrument at least at 800 m.
VI. CONCLUSION

In this theoretical work, a sensitivity study and a procedure development for SO\textsubscript{2} and volcanic ash retrievals using a new on-ground TIR camera system have been carried out. The camera will be used to improve Mt. Etna volcano’s monitoring, i.e., to mitigate the volcanic eruption impact on civil society and transport (the highway and international airport of Catania are about 20 km from the craters).

Three channels have been chosen within the camera spectral range (8–14 \(\mu\)m) to allow the detection of SO\textsubscript{2} and volcanic ash. A typical NESR has been computed assuming for the total range a common NETD of 100 mK at 300 K.

The sensitivity study has been realized for different camera geometries and monthly atmospheric profiles (PTH) obtained by the analysis of 23 years of measurements made at Trapani WMO Meteo Station. The simulations have been obtained by MODTRAN 4 RTM varying the SO\textsubscript{2} columnar abundance, volcanic ash particles and water-droplet effective radius and AOD.

In all the scenarios considered here, the SO\textsubscript{2} columnar abundance sensitivity on channel 1 improve, decreasing the elevation and the instrument altitude, while no meaningful seasonal dependence has been revealed. Considering a 15° and 90° camera viewing angle, the SO\textsubscript{2} sensitivity varies between 0.5 and 2 g \cdot m\textsuperscript{-2} for all the geometries. Similarly, the volcanic ash AOD sensitivity, computed for channels 2 and 3, increases, lowering the viewing angle, increasing the camera altitude, and considering particles greater than 2 \(\mu\)m effective radius. For all configurations, the AOD sensitivity results are better than 0.1 for the particle effective radius greater than 2 \(\mu\)m. In the typical range of Mt. Etna SO\textsubscript{2} emission, the sensitivity gets slightly worse, increasing the columnar abundance. The same happens for AOD sensitivity for high values of AOD.

An SO\textsubscript{2} columnar abundance retrieval procedure, based on the least square fit method, has been proposed.

The ash and water-droplet plume discrimination, the effective radius, and the AOD retrievals has been realized by means of BTD procedure, based on the difference between the brightness temperatures of channels 2 and 3. The results show the strong effect of atmospheric water vapor on plume discrimination and particle retrievals. In particular, during the summer season, the high water vapor content significantly reduces the volcanic ash and water-droplet radiative effects. To improve both the cloud discrimination and the particle retrieval, a water vapor correction, based on the separation between the atmospheric water vapor and plume terms on the radiative-transfer equation, has been developed. The sensitivity study provides the minimum AOD variation required to produce a signal variation greater than the instrument noise. In case of high integrated water vapor (usually during summer season) for low altitudes and low camera elevations, the AOD and \(r_e\) retrievals are nearly impossible. Notwithstanding, placing the camera at least at 800-m altitude makes effective a contemporary SO\textsubscript{2} volcanic ash retrievals and cloud discrimination.

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REFERENCES


