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Applying UV cameras for SO_2 detection to distant or optically thick volcanic plumes

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ABSTRACT

Ultraviolet (UV) camera systems represent an exciting new technology for measuring two dimensional sulfur dioxide (SO_2) distributions in volcanic plumes. The high frame rate of the cameras allows the retrieval of SO_2 emission rates at time scales of 1 Hz or higher, thus allowing the investigation of high-frequency signals and making integrated and comparative studies with other high-data-rate volcano monitoring techniques possible. One drawback of the technique, however, is the limited spectral information recorded by the imaging systems. Here, a framework for simulating the sensitivity of UV cameras to various SO_2 distributions is introduced. Both the wavelength-dependent transmittance of the optical imaging system and the radiative transfer in the atmosphere are modeled. The framework is then applied to study the behavior of different optical setups and used to simulate the response of these instruments to volcanic plumes containing varying SO_2 and aerosol abundances located at various distances from the sensor. Results show that UV radiative transfer in and around distant and/or optically thick plumes typically leads to a lower sensitivity to SO_2 than expected when assuming a standard Beer–Lambert absorption model. Furthermore, camera response is often non-linear in SO_2 and dependent on distance to the plume and plume aerosol optical thickness and single scatter albedo. The model results are compared with camera measurements made at Kilauea Volcano (Hawaii) and a method for integrating moderate resolution differential optical absorption spectroscopy data with UV imagery to retrieve improved SO_2 column densities is discussed.

1. Introduction

Originally developed for measuring SO_2 in industrial effluent plumes (McElhoe and Conner, 1986), the advent of ultraviolet (UV) sensitive CCD detectors has recently made it possible to design small, lightweight instruments for imaging two dimensional sulfur dioxide (SO_2) distributions in volcanic plumes (Mori and Burton, 2006; Bluth et al., 2007). The standard approach is to derive the differential optical depth τ from two wavelength channels (referred to as "long" and "short" in the following) using images of the plume as well as images of the background sky (e.g., Mori and Burton, 2006; Kern et al., 2010).[1]

$$\tau = \ln\left(\frac{I_{long}^{plume}}{I_{short}^{plume}}\right) - \ln\left(\frac{I_{long}^{sky}}{I_{short}^{sky}}\right) \quad (1)$$

The camera systems exploit the fact that SO_2 effectively absorbs radiation at wavelengths between 300 and 320 nm, while it has little effect on radiation at longer wavelengths. Therefore, a narrow bandpass filter transmitting radiation at wavelengths around 310 nm is used to isolate the short channel and a second filter with a transmittance maximum around 330 nm is used to measure radiation in the long channel. Images are either acquired through these two filters in rapid alternation (Kern et al., 2010) or two sensors are used contemporaneously to measure incident radiation through filters permanently mounted in front of each (Kantzas et al., 2010).

Monochromatic radiation propagating along a straight line in the atmosphere will be attenuated according to the Beer–Lambert–Bouger law of absorption. Thus, the radiance will decrease exponentially as a function of the column densities of the gases along the light path and their absorption cross-sections (for a detailed discussion see Platt and Stutz, 2008). The camera differential optical depth (Eq. (1)) is defined such that it is approximately proportional to the SO_2 column density along the light path.

In reality, however, deviations from a constant linear relationship occur for a number of reasons. For one, scattering effects cannot be perfectly corrected by normalization with the long channel radiance,

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[1] For a complete list of the notation used in this article, see Table 1.

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Table 1
Notation.

α	Viewing angle
D	Distance between instrument and plume axis
f	Focal length of object lens
φ	Relative orientation of incident ray on object lens
$F/\#$	Relative aperture ("f-stop") of object lens
G	Gaussian bell curve
I	Intensity
L	Radiance
λ	Wavelength
λ_C	Effective center wavelength of bandpass filter
λ_F	Nominal center wavelength of bandpass filter
M	Magnification of optical system
n_{air}	Refractive index of air
n_F	Refractive index of interference filter
ω_0	Aerosol single scattering albedo
r	Distance from center of object lens
R	Aperture radius of object lens
σ_F	Bandwidth of interference filter transmittance
T	Transmittance
T_C	Effective maximum transmittance of bandpass filter
T_F	Nominal maximum transmittance of bandpass filter
τ	Camera differential optical depth
θ	Filter illumination angle
v	Wind speed perpendicular to plume cross-section
V	SO_2 straight column density
x	Distance from center of detector
X	SO_2 abundance in plume cross-section
y	Lateral displacement of ray by imaging optics

since the scattering phase functions for all atmospheric scattering are dependent on wavelength. Therefore, scattering will be different in the long channel than in the short channel (Lübcke et al., 2013). Also, changes in the solar zenith angle can lead to changes in the background sky spectrum, thus influencing an instrument's sensitivity to SO_2 (Kern et al., 2010). Non-perpendicular illumination of the bandpass interference filters affects the system's sensitivity (see below), as does the fact that the imaging instruments integrate the radiance, not the optical depth, over a finite wavelength bandwidth in each channel (Kern et al., 2010), and this can lead to a non-linear response to SO_2 at high column densities (Dalton et al., 2009). However, the most severe variations in instrument response often originate in changes of the radiative transfer of a given scene (i.e. changes in the complex paths that radiation propagates along on its path from the sun to the detector), especially for distant, optically thick plumes. It is this issue that we wish to address in this study.

To this extent, we develop a methodology for describing the spectral radiance transmitted through the interference bandpass filters used in UV camera systems. We then use a radiative transfer model to simulate the response of a camera system to volcanic plumes containing various amounts of SO_2 and aerosols. Focusing mainly on plumes with high optical thicknesses, the effects that three-dimensional radiative transfer has on the sensitivity of these systems to SO_2 are analyzed, caveats of certain measurement practices are identified, and finally we describe a method for making more accurate SO_2 measurements even in non-ideal conditions.

2. Interference filter transmittance in imaging systems

Interference filters used in SO_2 imaging applications typically have a Full Width at Half Maximum (FWHM) bandpass of about 10 nm around their central transmittance wavelength λ_F. Their spectral transmittance $T(\lambda)$ for collimated, perpendicular illumination can be approximated with a Gaussian bell curve G.

$$T(\lambda)\approx T_0\cdot G(\lambda,\lambda_F,\sigma_F)=\frac{T_0}{\sigma_F\sqrt{2\pi}}e^{-(\lambda-\lambda_F)^2/\left(2\sigma_F^2\right)} \tag{2}$$

Here σ_F parameterizes the transmittance bandwidth (FWHM $= 2\sigma_F\sqrt{2\ln 2}$) and T_0 is a normalization factor that scales G to the filter's nominal maximum transmittance T_F. However, when placed in an optical imaging system, perpendicular illumination for all rays is not possible and the effective transmittance of the filter will deviate from the manufacturer's specifications. For rays crossing through the filter non-perpendicular to its surface, the effective bandpass center λ_C depends on the filter's central wavelength for perpendicular illumination λ_F and its refractive index n_F, and moves towards shorter wavelengths with increasing angle of incidence θ (Kern et al., 2010).

$$\lambda_C\approx\lambda_F\left[1-\left(\frac{n_{air}}{n_F}\right)^2\sin^2(\theta)\right]^{1/2} \tag{3}$$

In addition to a shift of λ_C towards shorter wavelengths, the maximum transmittance T_C of the interference filters also decreases when not illuminated perpendicularly. For the bandpass filters typically used in UV camera systems (e.g., the Standard Bandpass Filter series from Andover Corporation, Salem, NH), the relative maximum transmission $T_C(\theta)/T_F$ was found to decrease by approximately 2% per degree off axis illumination for θ below about 20° (Kern et al., 2010), and this linear estimate is used throughout this study.

If the interference filters are mounted in front of the camera's object lens, θ is equal to the viewing angle α (Fig. 1A). This means that the filter spectral transmittance is different for radiation arriving at the detector edges (i.e., image edges) than for light arriving at the center of the detector. Using Eqs. (2) and (3), this was demonstrated by modeling the effective transmittance curve of a 10 nm FWHM bandwidth ($\sigma_F = 4.2$ nm), $\lambda_F = 313$ nm, and $T_F = 0.18$ filter, for example analogous to the Andover Corporation 313FS10 or the Edmund Optics Inc., Barrington, NJ, 313 nm CWL 10 nm BW filters. Fig. 2 (dashed lines) shows the modeled transmittance for radiation entering such a system at the viewing angles of $\alpha = 0°$, 10° and 15°. Both the effective maximum transmittance T_C and the central bandpass wavelength λ_C vary significantly over this range of α. While a decrease in T_C is undesirable because it will lead to a decrease in the signal-to-noise ratio towards the detector edges, variations in λ_C are arguably more problematic as this behavior actually influences the system's sensitivity towards SO_2, as is shown in Section 4.

The undesirable variation in T_C and λ_C towards the image edges can be significantly reduced if the filter is positioned behind the object lens. Because the filter is now illuminated by converging rays, the rays reaching each detector pixel have all passed through the filter at a different illumination angle θ (Fig. 1B). θ can be parameterized in terms of the lateral displacement y between the position of intersection of a specific ray with the object lens and the detector position at which the ray ends.

$$\theta = \arctan\left(\frac{y}{f}\right) \tag{4}$$

Here, f is the camera's focal length and we assume the focus is on infinity. On the other hand, the viewing angle α and the angular magnification M of the object lens determine the lateral displacement x of the position at which a ray arrives on the detector (measured from the detector center).

$$x = f\tan(M\alpha) \tag{5}$$

Using relations 4 and 5 and the law of cosines, the illumination angle can now be written in terms of the position at which the ray intersects the lens. Here, this position is expressed using the polar coordinates r and φ, where r is the distance to the center of the lens, and φ is the orientation relative to x (see Fig. 1B):

$$\theta(r,\varphi) = \arctan\left(f^{-1}\left(f^2\tan^2(M\alpha)+r^2-2fr\tan(M\alpha)\cos\varphi\right)^{1/2}\right). \tag{6}$$