Ground-based Imaging Cameras for Volcanic Gas and Particle Measurements

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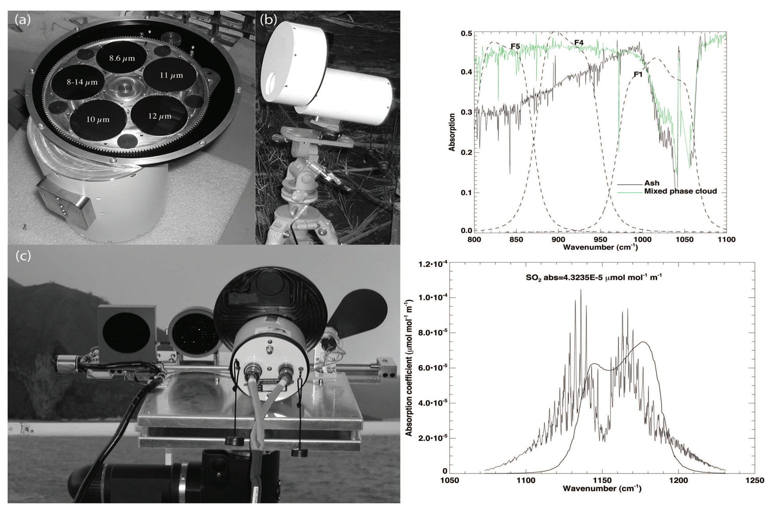
Introduction

An experimental fast-sampling (60 Hz) ground-based uncooled thermal imager (Cyclops), operating with five spectral channels at central wavelengths of 8.6, 10, 11, and 12 μm and one broad-band channel (7–14 μm), has been tested at several volcanoes and at two industrial sites, where SO_2 was a major constituent of the plumes. The results indicate that it is relatively easy to measure SO_2 in plumes, and more challenging to quantify volcanic ash particles. With NEΔT's of the spectral channels between 0.4–0.8 K, path concentration errors of 20% are obtained. Frame averaging and improved NEΔT's can reduce this error to less than 10%, making a stand-off, day or night operation of an instrument of this type very practical for both monitoring industrial SO_2 emissions and for SO_2 flux measurements at active volcanoes. Discrimination of ash from water vapour and/or gas in volcanic emissions is also quite feasible using Cyclops.

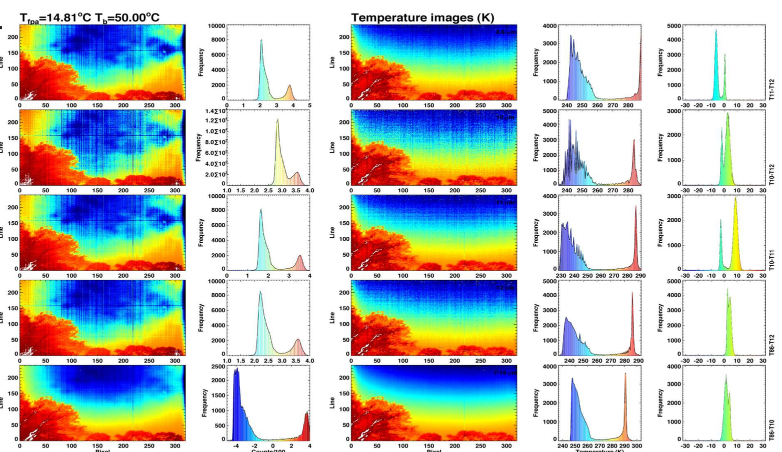
The ultra-violet region of the electromagnetic spectrum can also be exploited to measure several important polluting gases, including SO_2, NO_2, O_3, BrO among others. Low-cost, highly-portable grating spectrometers are commonly used to detect these gases and provide measures of emission rates and atmospheric loadings. These instruments have proved very successful, but suffer from the drawback that they can only provide line-of-sight measurements within a single field-of-view, or along a line if used together with a scanning mechanism. The imaging camera can overcome these spatial sampling deficiencies, but there are several problems to address, not least the loss of spectral resolution. We describe the development of a new UV imaging camera and show results which suggest that recovering SO_2 from UV imagery is practical and has some advantages over UV line-of-sight spectrometers.

Cyclops -An Infrared Imaging Camera



Filters mounted on filter wheel in the arrangement when used for measuring SO_2 gas emissions (central wavelengths in microns are given). (b) "Cyclops" camera mounted on a tripod for field operation. (c) Ship-mounted camera undergoing calibration tests with two moveable blackbodies and an external blackened shutter.

Cyclops spectral images obtained at an SO_2 and particle-free site in Australia. The left-most panels show uncalibrated data (DN's or Counts) and their respective histograms. The right-most panels show calibrated images, their histograms and histograms of selected temperature differences. The order of the images starting from the top is: 8.6, 10, 11, 12 μm and broadband (7–14 μm) channel. Details of the calibration of the camera can be found in Bernardo and Prata (2008a).



SO_2-retrieval scheme. The radiation measured at the imager is described by three terms,

$$I_i(\theta) = I_i^f(\theta,\phi) + I_i^p(\theta,\phi) + I_i^b(\theta,\phi), \quad (1)$$

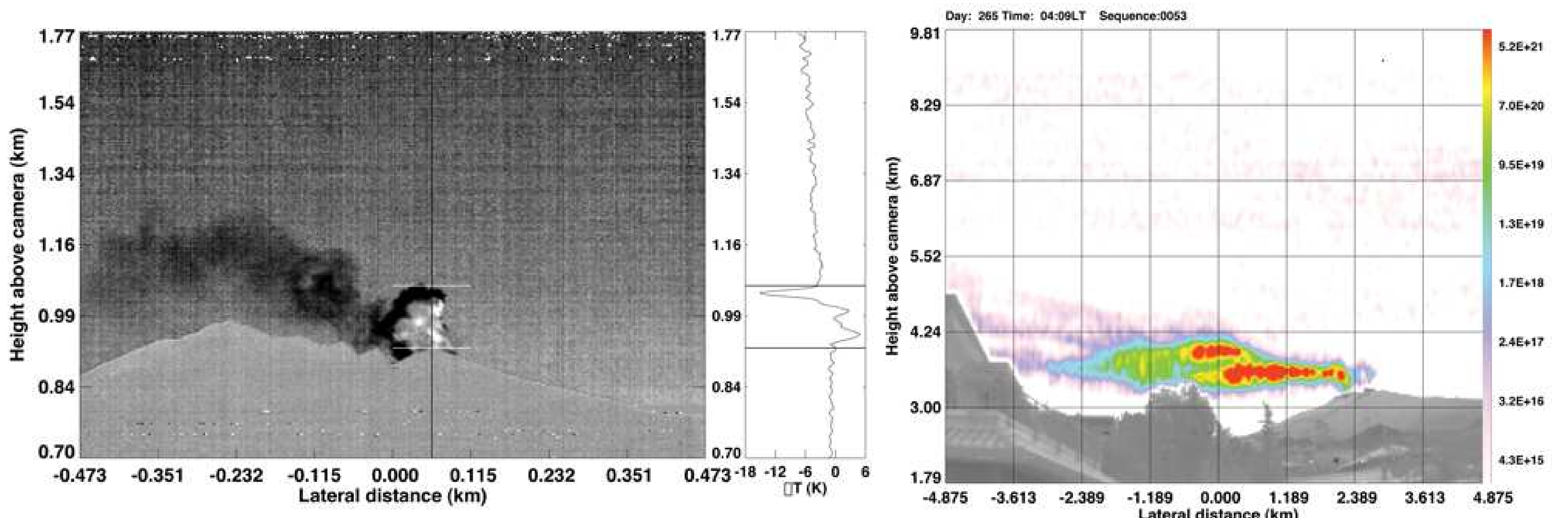
where θ is elevation angle, ϕ is azimuth angle, i is channel number, and the superscripts refer to foreground radiance (f), background (b), and plume radiance (p). The plume radiance may be considered to consist of emitted radiation, and radiation from the atmosphere that has been attenuated as it traverses through the plume. Scattering is ignored. The channel radiances are integrations over the channel filter response functions for each pixel within the 2D image space. The model used assumes no scattering and that variations in the absorption coefficient of the medium are invariant along the absorption path. The plume is assumed to be plane parallel and governed by Schwarzchild's radiative transfer equation. The resulting equation that is used to retrieve the pathlength concentration amount m^*, the product of the absorber density with the pathlength, is:

$$m^* = \rho d = -\frac{1}{k}\cos\theta\cos\phi\ln[1-\epsilon], \quad (2)$$

where ϵ is an effective emissivity of the plume and is given by,

$$\epsilon = \frac{(\Delta T_{i,j}^p - \Delta T_{i,j}^o) - \Delta T_i^p(1-\Delta T_{p,j}/\Delta T_{p,i})}{\Delta T_{p,j}(1-\Delta T_i^p/\Delta T_{p,i})}, \quad (3)$$

and k is the absorption coefficient averaged over the response function of the measurement channel, and all other terms are temperature differences–more details may be found in the paper by Prata and Bernardo (2008b). The retrieval procedure uses 3 of the 5 imager's channels: 8.6, 10 and 12 μm channels. The information regarding SO_2 in the plume is contained in the 8.6 μm channel, while the 12 μm channel is used to correct for atmospheric effects and the 10 μm channel is used to estimate the plume temperature.



12–8.6 μm brightness temperature difference image of the Stromboli plume acquired during a small explosive eruption. The middle panel shows a temperature difference-height profile for an image column that intersects the ash cloud eruption. The right-hand panel shows SO_2 path concentration retrievals for a plume from Etna volcano, Sicily.

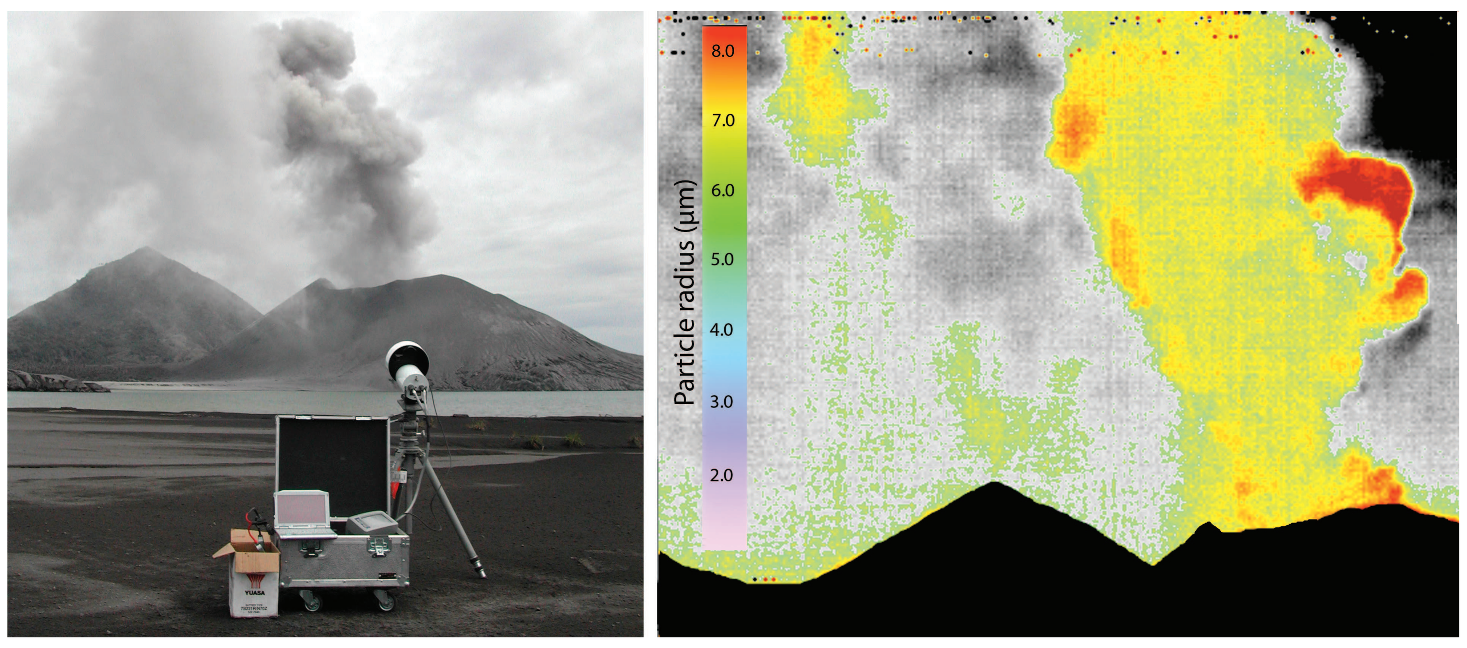
The retrieval scheme uses temperature differences. Most important of these are the thermal contrast, and terms involving differences between the spectral brightness temperatures, with and without the plume present, and brightness temperature differences between the 8.6 and 12 μm channels. For highly opaque plumes these spectral differences may be small and the retrieval scheme becomes unstable. For very thin plumes the thermal contrast is low and the retrieval becomes noise limited.

Ash microphysical retrievals. A discrete ordinates radiative transfer model was used together with optical properties of silicate particles to simulate temperatures for the Cyclops bands and viewing conditions. The calculations provide temperatures as a function of particle radius (r), infrared optical depth (τ), and zenith viewing angle (θ) for a volcanic cloud with uniform temperature T_c and background temperature T_b. A modified γ-distribution is used in the radiative transfer calculations. A three-dimensional data cube with axes, r, τ, θ is derived for scene temperatures T_c and T_b. The data cube is used to perform a retrieval starting from Cyclops temperature measurements and viewing geometry and ending with the microphysical variables, r and τ.

The $r\tau\theta$ data cube is searched along the planes corresponding to constant values of T_i, $\Delta T_{i,j}$ and θ. These planes intersect at solution values of r^*, τ^* and θ^*, which occur when the difference between calculated and measured T_i and $\Delta_{i,j}$ are a minimum. The microphysical retrieval may be represented by

$$\mathcal{R}(r,\tau,\theta;M) \leftarrow \mathcal{G}(T_i,\Delta T_{i,j},\theta;P). \quad (4)$$

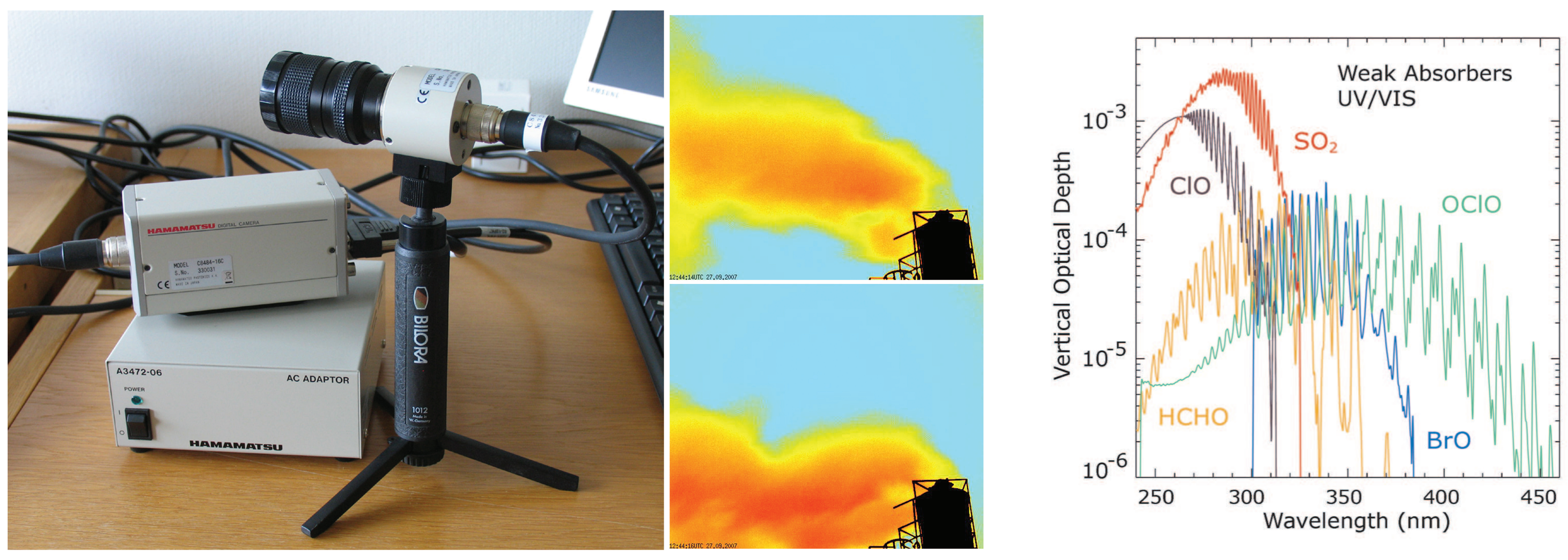
P includes the physical constraints supplied by the microphysical model (*viz.* size distribution, real and imaginary refractive indices, density of ash) and ensures that the problem is well-posed. The symbol $\leftarrow$ represents an interpolation between the data cube (G) and the $r\tau\theta$ cube (R). Further details may be found in Prata and Bernardo (2008c).



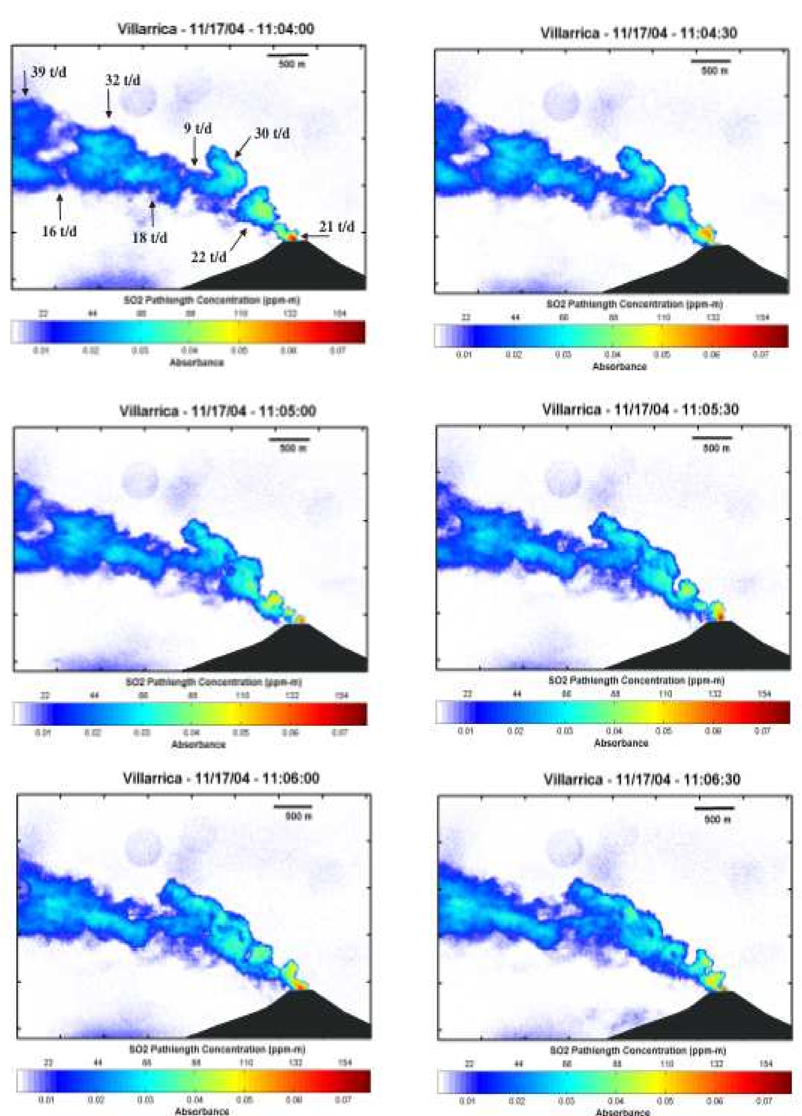
Cyclops *fine-ash particle size retrievals at Tavurvur volcano, Rabaul, PNG.*

NILU UVGasCam -An ultra-violet imaging camera

The NILU Ultra-violet imaging camera (UVGasCam) is a scientific instrument for use in identifying and measuring polluting gases in the troposphere. The camera consists of a highly sensitive CCD array (1344 x 1024 pixels) manufactured by Hamamatsu Photonics, Japan. The quantum efficiency (QE) of the CCD is quite high from 280–320 nm; the main region of interest for studying SO_2, NO_2 and several other polluting gases.



Left: Photograph of the Hamamatsu camera and lens; the basic elements of the NILU UVGasCam.
Middle: SO_2 plumes measure by the UVGasCam at an industrial stack.
Right: UV spectra of some gases, including SO_2.



The UV camera exploits a strong absorption feature of the SO_2 molecule between 280–320 nm (see above, Left panel). Whenever SO_2 is present in the field-of-view of the camera the recorded light intensity is less. By calibrating the camera using gas cells (two are needed) containing known amounts of SO_2, the recorded light intensity can be related directly to the path concentration. Because the camera can sample rapidly (several images per second), features in the images can be tracked and the "in plume" wind speed and gas flux can be derived. An earlier version of the NILU UVGasCam (Bluth *et al*, 2007) was tested at several volcanoes. False color ultraviolet images of the Villarrica plume taken coincidentally from 16.5 km N of the volcano are shown here. The clean, cloud-free atmosphere provided an ideal background, and absorption of UV light by SO_2 in the volcanic plume allows distinct discrimination from the background sky. The SO_2 plume demonstrates significant heterogeneity; calculated fluxes ranged over at least a factor of three in these plume images. This heterogeneity might be difficult to resolve using a scanning technique.

Conclusions

The concept of volcanic gas and cloud particle imaging using new infrared and ultra-violet cameras has been tested at industrial stacks with SO_2 emissions and at active volcanoes. Both devices are capable of measuring SO_2, while the infrared camera can also determine particle properties (particle radii, mass and infrared optical depth). The technology for building these cameras and adapting them for use at volcanoes is commercially available and now relatively inexpensive. The rapid data acquisition of the systems (30–60 Hz frame rates) and the ability to image a large portion of the sky from a safe distance makes these instruments very attractive for use at volcanological observatories or at airports or near town centres where volcanic emissions may pose a hazard. More work is required to establish the precisions and accuracies of these instruments, but even without quantifiable imagery, the infrared camera (Cyclops) with its 24 hr surveillance capability could be used now as a webcam to monitor gas and particle emissions at restless volcanoes.

References

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