Ultraviolet digital imaging of volcanic plumes

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The role of gas in volcanism

“The observatory worker who has lived a quarter of a century with Hawaiian lavas frothing in action, cannot fail to realize that gas chemistry is the heart of the volcano magma problem.”

– Thomas Jaggar, HVO founder

- Gases drive eruptions, can affect viscosity, explosivity
- Models for volcanic seismicity involve bubbly fluids
- Temporal resolution of emission rates and composition often poor in comparison to seismic, deformation, or acoustic data
SO$_2$ and volcanoes

- Decreasing pressure and temperature as magma rises cause gases to exsolve

- SO$_2$ 3$^{rd}$ most abundant gas in volcanic emissions (after H$_2$O and CO$_2$)

- But H$_2$O and CO$_2$ already present in high, and variable, concentrations in background atmosphere

- No background atmospheric SO$_2$ → easy detection, often the choice gas for monitoring volcanoes
How to monitor $\text{SO}_2$?

- Direct sampling — Giggenbach bottles, multi-gas sensors, etc. at fumaroles
  - Doesn’t measure emission rate, just variations in ratios of different gases
How to monitor SO$_2$?

- Satellite remote sensing – TOMS, OMI, etc.
  - Only sees one instant at a time, just determines (daily) burden of SO$_2$
Ground-based UV remote sensing used for volcanic $\text{SO}_2$ since 1970s

- **COSPEC**
  - Analogue data, bulky, expensive ($>60,000$ USD)
Ground-based UV remote sensing used for volcanic SO$_2$ since 1970s

- Mini-DOAS / FLYSPEC
  - Digital, smaller, cheaper
    (~10% cost of COSPEC)
Ground-based UV remote sensing used for volcanic SO$_2$ since 1970s

- Increased scattering
- Traverse under plume
- Helicopter flying towards you
- COSPEC

- One-dimensional profile of plume
Limited temporal resolution

- Galeras, 1993 - \(~1/\text{week}\)

(Fischer et al., Nature, 1994)
Limited temporal resolution

- Soufrière Hills, 1997 - ~1/day

(Watson et al, JVGR, 2000)
Limited temporal resolution

- Soufrière Hills, 2002 - ~10/hour

(Edmonds et al., Bull. Volc., 2003)
Limited temporal resolution

- Karymsky, 1999 – repeated COSPEC scans

(Fischer et al., Geology, 2002)
Limited spatial resolution

- Erebus, 2006 – continuous wide-angle DOAS

(Boichu et al., JVGR 2010)
UV camera enables two-dimensional view of SO$_2$ plume

- Plume dynamics
- Plume speed
- Sampling rate up to 1 Hz; integration with other geophysical datasets
The principles

- UV spectroscopy
- Beer’s Law:
  - \( I(\lambda) = I_0(\lambda) \exp(-L\alpha(\lambda)c) \)
- Radiation source is scattered sunlight
The camera itself – an Apogee Alta U6

105 mm Coastal Optics quartz lens

307 nm and 326 nm bandpass filters (+ filter wheel or on separate cameras)

1024 x 1024 pixel CCD sensor with 16 bit quantization
Using the camera in the field

- Scattered skylight → sun behind or to side
- Clouds in front of plume block absorption signal; data collection impossible
Converting images to SO$_2$ maps

- $A = -\log (l/l_0)$

- Beer’s Law: $A \propto [SO_2]^d$
Converting images to SO$_2$ maps

Motivation

Goals

UV Camera

Fuego

Kilauea

Pacaya

Elsewhere

Conclusions

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<th>Concentration path-length (ppmm)</th>
<th>Absorbance</th>
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<tr>
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<tr>
<td>1000</td>
<td>0.35</td>
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$y = 0.0002x + 0.074$
Initial data processing protocol not fit for increasingly large datasets

- Individual images rather than series
- User-intensive processing of each image, using two programs
- Ideal day of data collection yields 10,000+ images
Program Development

- Minimal user input
- Handles variable plume geometries
- MATLAB® only
- Full datasets of 1,000s of images can be processed at once
Automatic derivation of plume speed

\[ \text{ER} = [\text{SO}_2] \cdot \cos \theta \cdot d \cdot v \cdot c \]

(Williams-Jones et al., 2006)
Results thus far are comparable to those from standard methods
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(Dalton et al., JVGR 2009)
Fuego volcano, Guatemala

- Basaltic strato-volcano (~3800m); high-Al, 2-6 wt% H₂O
- Range of explosion sizes, lava flows, pyroclastic flows; cycles of activity
- Last large eruption was sub-Plinian in 1974; currently experiencing small, ashy ‘degassing explosions’

(Lyons et al., 2009)
Models for low-frequency seismicity

- Crack resonance
- Bubble coalescence
- Choked flow
- Others

(Ripepe and Gordeev, 1999)
Methodology

- 2008: 1 day of UV camera with concurrent seismic and acoustic; 5 station array
- 2009: 3 days of concurrent data; 12 seismo-acoustic stations, 5 in antenna array
Results - 2009

Concentration pathlength (ppm-m)

SO₂

ICA (ppm²-m)

Seismic

Counts

Seismic

Acoustic

Counts

Time (s)

Acoustic

Time relative to image (s)
Results - 2009

(Nadeau et al., GRL, 2011)
Results - 2009

(Nadeau et al., GRL, 2011)
Results - 2008

- VLP seismic events followed by peak in SO$_2$ emissions
- Larger VLPs are generally followed by longer, higher peaks in SO$_2$
- Time between VLPs inversely related to size
Kilauea Volcano, Hawaii

(Schmincke, 2004)
Methodology

- Focus on Halema`uma`u activity
  - 2 UV cameras, simultaneous images, different filters
  - Broadband seismo-acoustic array (permanent at summit, HVO network)
  - FTIR spectrometer
  - Visible camera for in-vent activity
  - FLYSPEC traverses/scans
  - 3-station infrasound array
  - Continuous gravity

- ~1 month deployment, May 2010 (also few days of data, February/March 2010)
Methodology
SO₂ correlates almost exactly with RSAM during lava level high-stands and drops.
### Preliminary Results

- **SO₂** correlates almost exactly with **RSAM** during lava level high-stands and drops.
SO\textsubscript{2} correlates almost exactly with RSAM during lava level high-stands and drops
Preliminary Results
Background days show longer term correlated trends?
Deflation/Inflation (DI) events also thought to possibly be caused by variations in deep supply of gas-rich magma; should be reflected in SO₂ record.
Pacaya – mass validation with infrasound

(Dalton et al., GRL, 2010)
Comparison of gas masses from UV camera and infrasound

- Infrasound generally underestimates gas mass based on camera-derived estimates
- Other source/style of degassing

(Dalton et al., GRL, 2010)
FLYSPEC validation
Seismometer; continuous tremor
Continuous gravimeter
Other volcanoes

- Mori and Burton (JVGR, 2009):
  - quantification of gas mass in individual explosions at Stromboli, Italy
Other volcanoes

- Tamburello et al. (JVGR, 2011):
  - Gas emissions from individual fumaroles at Vulcano, Italy

- Kazahaya and Mori (AGU fall meeting, 2010):
  - Decreases in SO$_2$ emissions concurrent to increases in tilt in explosions at Sakurajima, Japan
Future work

- Spectral analysis of SO$_2$: Lomb-Scargle method, FFT
- Used on Erebus; didn’t result in anything we can see on Fuego
- May still yield useful results at places like Kilauea or Masaya
UV camera is a powerful, new tool for quantifying SO$_2$ emissions

- New methodology makes data processing manageable
- Exploiting 2-D nature of imagery improves method further
- Detailed analysis of SO$_2$ with seismo-acoustic data has given insight into behavior at Fuego, Kilauea, Pacaya, and other volcanoes