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## Accurately measuring volcanic plume velocity with multiple UV spectrometers

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**Abstract** A fundamental problem with all ground-based remotely sensed measurements of volcanic gas flux is the difficulty in accurately measuring the velocity of the gas plume. Since a representative wind speed and direction are used as proxies for the actual plume velocity, there can be considerable uncertainty in reported gas flux values. Here we present a method that uses at least two time-synchronized simultaneously recording UV spectrometers (FLYSPECs) placed a known distance apart. By analyzing the time varying structure of SO<sub>2</sub> concentration signals at each instrument, the plume velocity can accurately be determined. Experiments were conducted on Kīlauea (USA) and Masaya (Nicaragua) volcanoes in March and August 2003 at plume velocities between 1 and 10 m s<sup>-1</sup>. Concurrent ground-based anemometer measurements differed from FLYSPEC-measured plume speeds by up to 320%. This multi-spectrometer method allows for the accurate remote measurement of plume velocity and can therefore greatly improve the precision of volcanic or industrial gas flux measurements.

**Keywords** FLYSPEC · Plume velocity · Volcanic emissions · Ultraviolet correlation spectrometer

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### Introduction

Correlation spectrometry (COSPEC) has been used for over 30 years to determine and monitor the emission rates of industrial plumes (SO<sub>2</sub>, NO<sub>2</sub>) and degassing volcanoes (SO<sub>2</sub>) (e.g., Moffat and Millan 1971; Stoiber et al. 1983). While there are a number of methods of making COSPEC measurements (stationary scanning, mobile ground or airborne traverses, etc.), the most commonly used technique involves ground-based vehicular traverses at some distance downwind of the gas source (e.g., Elias and Sutton 2002; Stoiber et al. 1983; Williams-Jones et al. 2000).

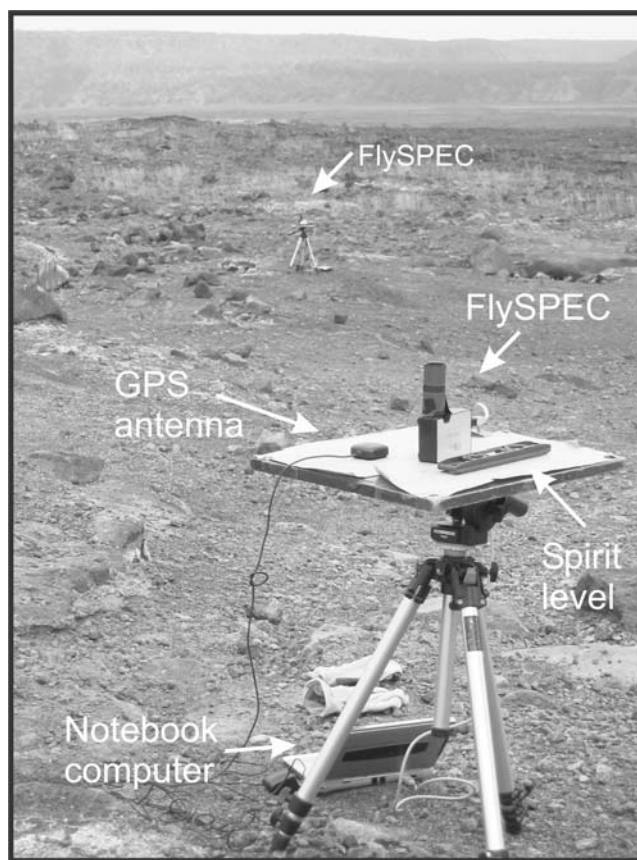
Gas flux is typically calculated by multiplying the average concentration-pathlength (ppm-m) of SO<sub>2</sub> by the plume width and average plume velocity. This calculation is thus strongly dependant on accurate knowledge of plume velocity. However, direct measurement of plume speed or direction is often exceedingly difficult and therefore, one generally measures a representative wind speed and direction as a proxy. Ideally, this information would be obtained from instruments in the gas plume (e.g., using a radiosonde, tethered balloon or in situ airborne measurements; Doukas 2002). However, for ground-based gas flux measurements, these data are often not available and thus other methods are required. Should the volcano be near an airport or large city, it is sometimes possible to obtain the wind speed and direction over a range of elevations from a local meteorological station (from radiosondes or approaching aircraft). If this information is unavailable, wind speed measurements may be made using an anemometer (handheld or mast-mounted) and then factored into numerical relationships (log or power law) to estimate the wind speed at a given height up to ~200 m above the ground level (e.g., Stratardakis et al. 1999). At volcanoes where the plume is close to the ground (e.g., Kīlauea, USA; Masaya, Nicaragua), this technique is useful (Elias and Sutton 2002; Williams-Jones et al. 2003). However, while the effects of ground layer shear and topographic effects may be reduced somewhat by mounting the instrument on a 10-m-high mast downwind by 10 times the height of

any nearby obstacles (WMO 1983), there can nevertheless be a significant difference in wind speed measured at the ground versus that at the plume height (Doukas 2002). In an extreme example, a radiosonde profile of wind speeds recorded from the Mexico International Airport (2,230 m a.s.l., NOAA 2003) shows that wind speeds were almost 20 times greater at the summit height of nearby Popocatepetl volcano (5,430 m a.s.l.) than ground level winds at the airport. While some authors have reported low plume speed uncertainties of  $\sim 5\%$  using video measurements (Kyle et al. 1994), the reported uncertainties of 10–40% on the more common anemometer data (e.g., Stoiber et al. 1983; Williams-Jones et al. 2000) may result in significant underestimates (Doukas 2002).

Plumes may be stratified in terms of concentration due to variation of wind speed as a function of height within the plume. UV spectroscopic measurements are given in units of concentration-pathlength; a single wind speed and direction, even measured at the apparent plume height, may not truly represent the average plume velocity. It is not uncommon for gas flux data to be presented without any mention of the apparent wind speeds. Zapata et al. (1997) recommend that gas flux data is normalized to an arbitrary plume velocity of  $1 \text{ m s}^{-1}$ , and while this aids in analyzing time-series data or comparing gas fluxes between different sources or techniques, there are many applications where a measurement of an actual gas flux is needed. Here we present a method of accurately determining the plume velocity and thus an improved measurement of the gas flux for the source in question.

### Multiple spectrometer method

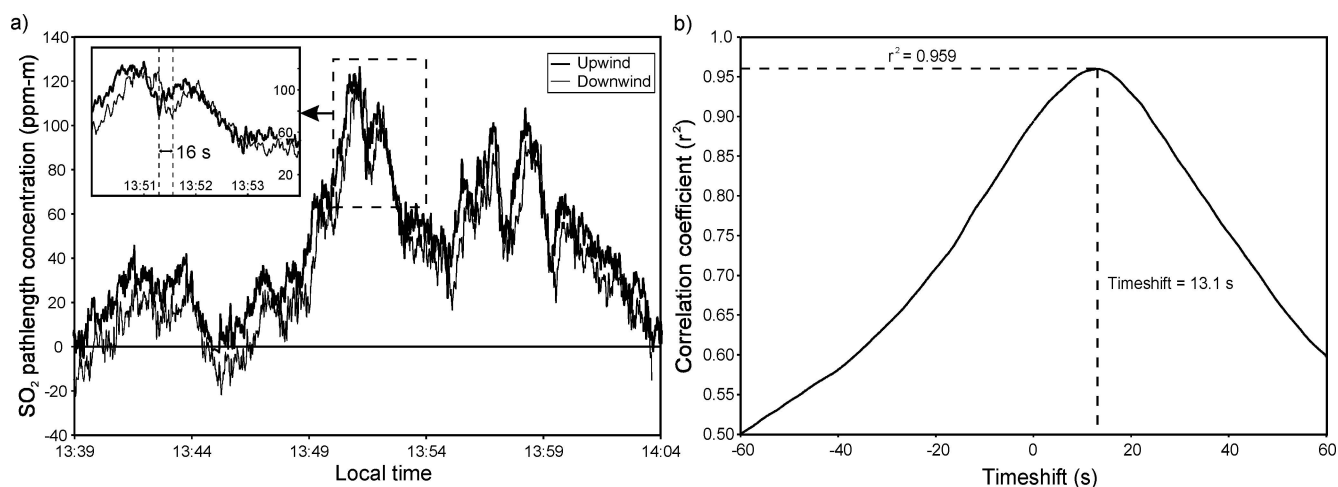
The FLYSPEC consists of a small ( $25 \times 15 \times 10 \text{ cm}$ ) and low-cost Ocean Optics USB 2000 ultraviolet spectrometer, with a field of view (FOV) of  $2.5^\circ$  (Horton et al. 2005). During a typical ground-based gas-flux survey, a number of traverses are performed in order to determine the integrated  $\text{SO}_2$  concentration-pathlength of the plume. The point of maximum concentration can be easily located as the FLYSPEC is able to determine concentration-pathlength in real time (Horton et al. 2005). Determining plume velocity at the point of maximum concentration is assumed to be the most critical for calculating representative gas fluxes. To make this measurement, at least two FLYSPECs mounted on lightweight camera tripods are deployed  $\sim 20\text{--}50 \text{ m}$  apart beneath the gas plume at the point of maximum concentration (Fig. 1). Spirit levels are used to insure that the instruments' optical axes are parallel and that the ground separation represents the plume sampling separation at plume height. The time-synchronized  $\text{SO}_2$  concentration signals are then compared using a simple iterative correlation program to determine the time required for a packet of gas to pass from the FOV of one instrument into that of the other. By knowing this travel time as well as the exact separation of the instruments, it is possible to determine the actual plume velocity (Fig. 2).



**Fig. 1** Example of a temporary field deployment at Kilauea volcano, USA, on March 9, 2003. The FLYSPECs are mounted downwind of the gas source on small, lightweight camera tripods separated by  $\sim 20 \text{ m}$ . A GPS antenna is placed next to each spectrometer to allow for time synchronization. Measurements were made for  $\sim 30 \text{ min}$

In order to determine the accuracy of this technique, the cumulative sources of uncertainty (environmental and instrumental) were investigated. The gas plume will disperse vertically and laterally with increased distance from the source as well as over the separation of the two instruments. This can be estimated using a Gaussian dispersion equation for a point source at a given elevation, wind speed and atmospheric stability. Thus, for a 500-m-high plume measured 5 km downwind of the source, in a moderately unstable atmosphere (Pasquill Stability Category B; Turner 1994) and rural conditions, the uncertainty due to inline downwind dispersion would range from 0.28 to 2.73% for instrument separation of 10–50 m. Any potential uncertainty due to vertical dispersion of the plume is negated by the fact that the FLYSPECs sample a vertical integrated atmospheric column.

There is  $<0.1 \text{ s}$  uncertainty on the GPS-synchronized computer time stamp and a small uncertainty in determining the distance between the instruments on the ground ( $\sim 10 \text{ cm}$  using a tape measure). The greatest uncertainty, however, is ensuring that the instruments' FOV are parallel, as determined with spirit levels, which have a sensitivity of better than  $0.1^\circ$ . A  $0.1^\circ$  ambiguity would be equivalent to 0.87 m pointing uncertainty for each



**Fig. 2** **a** The SO<sub>2</sub> pathlength concentration signals for two FLYSPECS at Masaya volcano, Nicaragua on March 25, 2003. The *thick black line* denotes the upwind instrument. The instrument separation is 40.5 m, determined by tape measure. Inset is a 4-min window showing an apparent time separation (16 s) between the 2 signals. **b** The SO<sub>2</sub> signals for the entire 30-min sampling period are compared

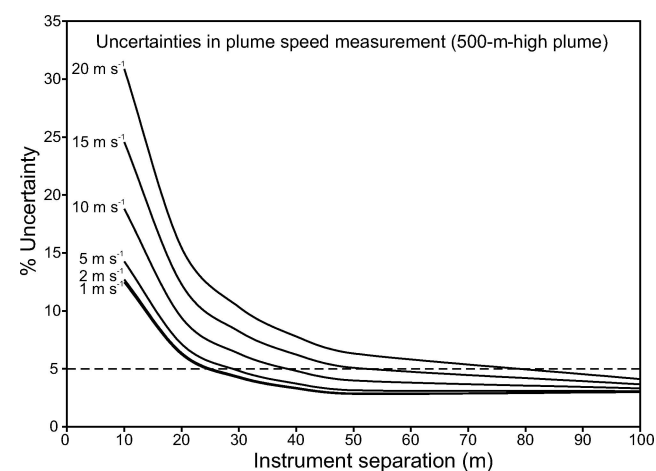
to each other for time shifts between -60 and 60 s at 0.1 s iterations. The maximum correlation coefficient ( $r^2=0.959$ ) for the signals occurs at a time difference of 13.1 s, which for a 40.5 m separation, results in a plume speed of  $3.1 \text{ m s}^{-1}$ . This approach is also used over shorter sampling windows (e.g., 2 min) to investigate plume speed variations. See Table 1

FLYSPEC for a 500-m-high plume. If it is impractical to make measurements from directly beneath the plume, the FLYSPECS can be aimed laterally at the plume. For higher plumes or lateral measurements, greater leveling precision of the instruments would be required in order to maintain the same level of uncertainty. In order that the FOVs of the two instruments do not overlap, the radius of the FOV “footprint” is calculated for a given plume height:

$$\text{for } \text{FOV} = 2.5^\circ \quad \text{FOV}_{\text{radius}} = \text{plume height} * \tan(2.5/2)$$

For a 500-m-high plume, the instruments should be at least 20 m apart in order to avoid overlapping FOVs. Decreasing the FOV can reduce this “footprint”. The cumulative RMS uncertainty for each measurement will vary with the plume velocity, height and the separation of the instruments. Thus, for a 500-m-high plume traveling  $5 \text{ m s}^{-1}$  over a 50 m separation measured 5 km downwind of the source, there is an RMS of  $0.14 \text{ m s}^{-1}$  or  $\sim 3\%$  uncertainty. The greater the plume velocity, the further apart the instruments should be separated to minimize uncertainty. For ground-based vehicle measurements, a 20–50 m separation would allow for easy deployment yet maintain uncertainties of  $<15\%$  at plume velocities up to  $20 \text{ m s}^{-1}$ . Figure 3 summarizes the relationships between instrument separation, plume speed, and the estimated uncertainties.

Ideally, at least two FLYSPECS should be aligned with the primary wind direction. However, in practice, the wind direction may vary sufficiently with time such that the two instruments do not necessarily detect the same packet of gas. The true plume velocity varies as the cosine of this angular variation in wind direction: a change in wind direction of up to  $25^\circ$  during the measurement period would add 10% uncertainty. When at least three FLYSPECS are used, it becomes possible to more accurately determine a wind speed vector between each instrument and thus



**Fig. 3** The relative uncertainties in plume speed measurement for a 500-m-high plume, measured 5 km downwind from the source, over a range of instrument separations for plume speeds between 1 and  $20 \text{ m s}^{-1}$ . The optimum separation is  $\sim 20\text{--}50 \text{ m}$  in order to minimize uncertainty ( $<5\%$ ) yet allow for easy field deployment. The instruments should be further apart for higher plume speeds, however, even  $20 \text{ m s}^{-1}$  plumes have only  $\sim 10\text{--}15\%$  uncertainty over 20–50 m separations

the integrated plume velocity. Over an extended measurement period (e.g., 30 min or greater), it was found that by maximizing the signal correlation over small time windows (e.g., 2 min) and using those windows with high correlation ( $r^2 \geq 0.8$ ), there were sufficient instances of good correlation to allow for reasonable determination of plume speed.

### Field measurements

Field experiments were conducted in March and August 2003 at two passively degassing volcanoes, Kīlauea, USA,

**Table 1** Plume velocities and wind speeds at Kilauea and Masaya volcanoes determined from multiple UV spectrometers

Volcano	Date	Sample period (Local time)	Separation (m)	Complete time series		2 min windows, $r^2 > 0.8$				Wind speed		Airport (m s <sup>-1</sup> )
				Max $r^2$	Plume speed (m s <sup>-1</sup> )	Max $r^2$	SD	Plume speed (m s <sup>-1</sup> )	SD	Anemometer (m s <sup>-1</sup> )	$SF$ $EC$ (m/s <sup>-1</sup> ) SD (m/s <sup>-1</sup> ) SD	
Kilauea	09/03/03	12:44–13:12	18.5	0.244	3.43	0.908	(0.05)	5.80	(3.69)	1.9	(0.23)	5.9
USA	09/03/03	13:15–13:41	9.5	0.966	1.36	0.991	(0.05)	1.39	(0.10)	2.3	(0.30)	5.9
Masaya, Nicaragua	24/03/03	15:43–16:08	23.4 <sup>a</sup>	0.955	1.61	0.989	(0.06)	1.76	(0.20)		6.0 (1.3)	5.1
	24/03/03	16:13–16:38	23.4 <sup>a</sup>	0.88	1.6	0.953	(0.07)	1.77	(0.10)		6.1 (1.2)	4.5
	25/03/03	11:28–11:54	22.1	0.729	13.8	0.981	(0.09)	8.43	(1.40)		7.5 (1.1)	5.1
	25/03/03	13:37–14:03	40.5	0.959	3.1	0.923	(0.05)	3.00	(0.65)	7.4 (1.7)	6.5 (0.9)	5.1
	28/03/03	12:04–12:34	38.2	0.705	25.5	0.956	(0.06)	10.5	(2.58)	8.0 (0.7)	1.7 (1.3)	4.1
	29/03/03	11:58–12:29	22.4	0.838	3.2	0.985	(0.04)	4.32	(3.42)		4.4 (1.2)	4.1
5 min windows, $r > 0.8$												
Kilauea, USA	21/08/03	10:47–11:56	20	0.938	7.77	0.982	(0.04)	7.51	(0.60)	7.6	(0.7)	5.0
	21/08/03	10:47–11:56	30	0.914	7.11	0.97	(0.05)	7.09	(0.59)	7.6	(0.7)	5.0
	21/08/03	10:47–11:56	50	0.895	7.32	0.945	(0.04)	7.15	(0.55)	7.6	(0.7)	5.0
	21/08/03	13:26–14:33	10	0.98	7.83	0.984	(0.05)	7.66	(0.73)	8.3	(0.3)	3.9
	21/08/03	13:26–14:33	40	0.93	7.35	0.967	(0.04)	7.23	(0.66)	8.3	(0.3)	3.9
	21/08/03	13:26–14:33	50	0.94	7.38	0.969	(0.04)	7.24	(0.38)	8.3	(0.3)	3.9
Plume velocity experiment												
	21/08/03	14:49–15:56	45	0.88	8.58	0.904	(0.04)	8.40	(2.16)	7.8	(0.6)	4.1
	21/08/03	14:49–15:56	42	0.94	5.98	0.971	(0.05)	6.21	(0.54)	7.8	(0.6)	4.1

Plume speeds for 2 and 5-min windows based on  $r^2 > 0.8$ . *SF* San Fernando crater; *EC* El Crucero. *SD* standard deviation. Masaya anemometer data from (CCVG-IAVCEI, 2003). Kilauea data courtesy of the USGS. Airport ground wind speeds from the NOAA National Climatic Data Center.

<sup>a</sup>From GPS, error  $\pm 2.8$  m. All other separations determined by tape measure (error  $< 10$  cm)

and Masaya, Nicaragua, the results of which are summarized in Table 1. The instruments were internally calibrated outside of the plume using known concentration-reference gas cells. Measurements were made over a range of instrument separations for approximately 30–60-min periods. The SO<sub>2</sub> concentration signals were iteratively offset to maximize the correlation coefficients over the entire sampling period (Fig. 2b) as well as over 2-min and 5-min windows. In instances where the wind direction varied so that the two instruments may have not been fully aligned with the plume direction for the entire observation period, the correlation coefficient dropped below 0.8 and thus calculated plume speeds are suspect (e.g., Kilauea, 03/09/03 12:46–13:10, Table 1). However, when the sample period is broken down to 2-min windows and the signals are compared, excellent correlations (and therefore more representative plume speed measurements) are possible. For example, measurements at Masaya on March 28, 2003 yield a correlation coefficient of 0.71 for the 30-min sampling period resulting in improbably high calculated plume speeds ( $> 25$  m s<sup>-1</sup>), which were inconsistent with observations of ambient conditions. However, when the signals are compared for 2-min periods, there is a maximum correlation of  $0.96 \pm 0.06$  (for eight 2-min windows with  $r^2 > 0.8$ ) resulting in a measured plume speed of  $10.5 \pm 2.6$  m s<sup>-1</sup> (Table 1).

In August 2003, experiments with three instruments were also performed at Kilauea in order to investigate optimal instrument separation distances as well as the variations in plume direction and speed. Two tests were made with three simultaneously recording spectrometers in line with the general plume direction and with instrument spacing varying between 10 and 50 m (Table 1). Plume speeds calculated between each pair of instruments resulted in an average of  $7.46 \pm 0.3$  m s<sup>-1</sup>, confirming that a 10–50-m separation is optimal for these measurements. In order to measure plume velocity, three spectrometers were also setup in an inverted T-formation, with one instrument up wind and two downwind. By calculating the plume speed vector for each pair of instruments (Table 1), it was possible to accurately determine a plume velocity of  $7.1$  m s<sup>-1</sup> at  $47^\circ$  from the NE. The plume velocity differed from the previous dual spectrometer measurements by 5%.

For the Kilauea measurement sets, concurrent ground-based anemometer measurements were made using 10-min averages from a Handar ultrasonic wind sensor mounted 3 m above ground level on the rim on the Kilauea caldera (Elias and Sutton 2002). At Masaya, data was collected with two temporary continuously recording 3-cup anemometers (Young, model# 12005) installed  $\sim 3$  m above the ground level near the summit ( $\sim 600$  m

upwind of the vent) and  $\sim 5$  m above the ground level at  $\sim 15$  km downwind (SF and EC, respectively, in Table 1; CCVG-IAVCEI 2003). Sampling rates for SF and EC were 15 s and 1 min, respectively, with average wind speeds for the FLYSPEC sampling period shown in Table 1. At Masaya, ground-based anemometer measurements for March 25, 2003 ranged between  $7.4 \pm 1.7$  m s<sup>-1</sup> at the near-vent location (SF) to  $6.5 \pm 0.9$  m s<sup>-1</sup> at the downwind location (EC), significantly overestimating the plume speed of  $3.0 \pm 0.7$  m s<sup>-1</sup> measured by dual FLYSPECs. On March 28, the proximal anemometer recorded wind speeds almost 5 times greater than those measured downwind ( $8.0 \pm 0.7$  m s<sup>-1</sup> vs.  $1.7 \pm 1.3$  m s<sup>-1</sup> for SF and EC, respectively). This large variation is likely due to topographic effects. Similarly, ground-based wind data from Hilo International Airport ( $\sim 50$  km distant) and the Augusto C. Sandino International Airport ( $\sim 20$  km distant), for Kīlauea and Masaya, respectively, were also inconsistent with plume speeds measured by FLYSPEC (Table 1). Airport ground wind speeds for Masaya on March 24, 2003 were almost 3 times greater than those measured in the field.

## Conclusion

Plume velocity measurements are the major source of uncertainty in gas flux estimates. Traditionally, wind speed and direction have been used as a proxy for plume velocity, however, challenges in monitoring wind speed include: appropriate site selection given local topography, the inability of ground-based wind measurements to correctly estimate the speed of lofting plumes, and the cost and logistical difficulty in using techniques such as radiosondes, tethered balloons, and airborne measurements. The multiple spectrometer method presented here improves and simplifies gas plume velocity measurements. This method has the flexibility to measure plume velocity from a distance when accessibility beneath the plume is difficult. In contrast to ground-based wind speed measurements, the multiple spectrometer method measures the actual velocity of the plume at the plume height. Uncertainty due to wind speed stratification within the plume is also minimized because the instruments measure integrated concentration-pathlength, which incorporates variations in wind behavior. The simple multi-instrument method described here can be used with any series of spectrometers that are sufficiently portable and are time synchronized. Although it is more accurate to measure the plume velocity with at least three spectrometers, if care is taken locating two instruments in the predominant direction of the plume, a comparable plume speed can be accurately determined. While it is possible to use this method in a variety of situations, the low cost of this new instrument makes it feasible to deploy several FLYSPECs as a telemetered network for semi-permanent monitoring of volcanic or industrial emissions (Edmonds et al. 2003; Horton et al. 2005) and use multi-instrument measurements to accurately constrain plume speed and direction, and thus the gas flux in near real time.

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