Techniques to measure SO_2 in volcanic plumes and geometrical considerations

by

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Photo: L. Rodriguez

Outline

- Techniques to measure SO_2 in the field, using ground-based instrumentation:
    - Stationary scanning measurements (horizontal scanning, tracking buoyant vertical plumes, vertical scanning, and others)
    - Traverse measurements (car, plane, helicopter, boat, walking, etc.)
    - Geometrical considerations for the techniques

Photo: L. Rodriguez

Cont. Outline

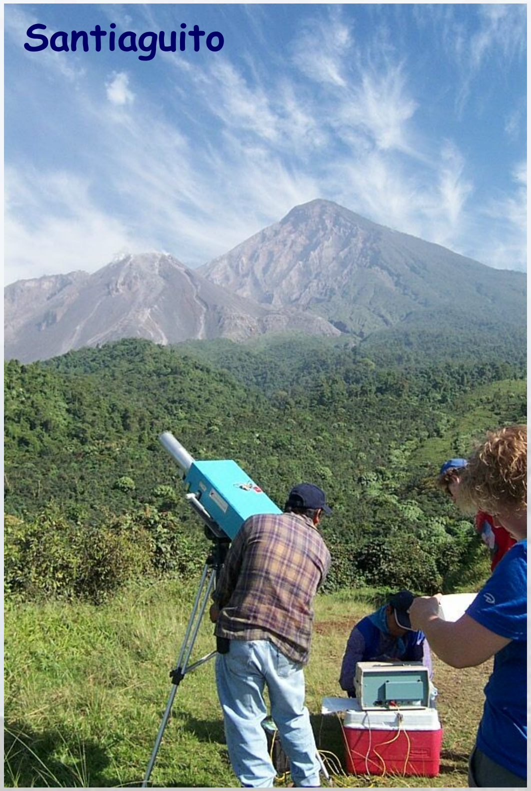
- **Wind (plume) speed estimation**
  - **Anemometer/weather stations**
  - **Plume tracking**
  - **Radiosonde**
  - **Using multiple spectrometers**
  - **Dual-beam technique**
  - **Numerical models**

Techniques to measure SO_2 in the field: Ground -based

Photo: L. Rodriguez

Instruments:

Correlation Spectrometer (COSPEC)



Photos: L. Rodriguez

Mini-UV spectrometers/Mini-DOAS

FLYSPEC

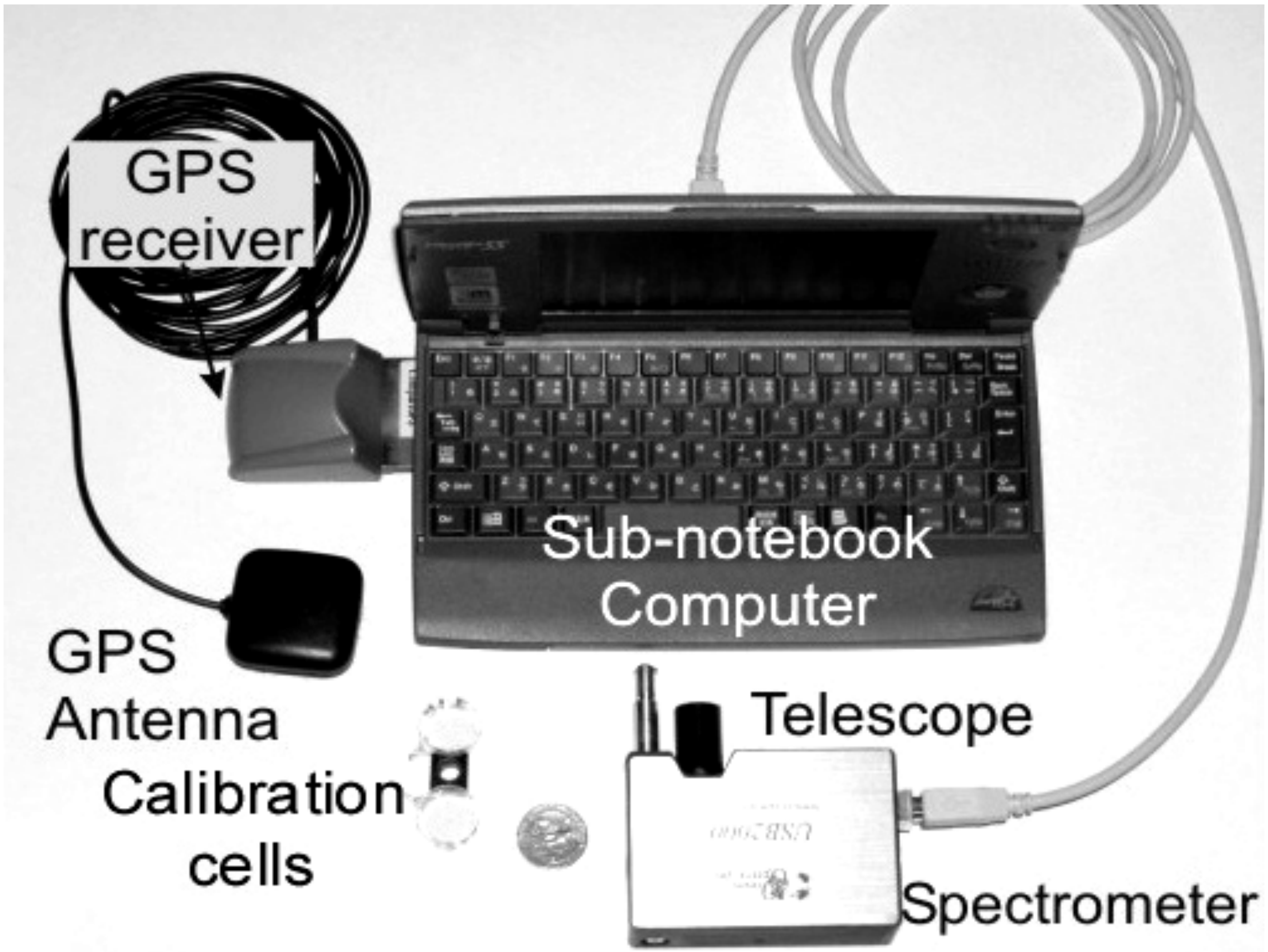


Photo: JL Palma

Calculation of SO_2 Emission Rate

- Convolve signal to the spectrometer's library spectrum (fit routine)

- Output: ppm · m
- Plume width: m
- Plume speed: $m \cdot s^{-1}$

- Output x Plume Width = SO_2 plume cross section

$$(ppm \cdot m)(m) = ppm \cdot m^2$$

- SO_2 plume cross section x Plume speed = SO_2 emission rate

$$(ppm \cdot m^2)(m \cdot s^{-1}) = ppm \cdot m^3 \cdot s^{-1}$$

- Conversion to metric tonnes per day ($t \cdot d^{-1}$):

(Density of SO_2 gas: $2.86 \times 10^{-3}\ g \cdot ppm^{-1} \cdot m^3$; STP correction factor: 273/293)

$$(ppm \cdot m^3 \cdot s^{-1})(2.86 \times 10^{-3}\ g \cdot ppm^{-1} \cdot m^3)(10^{-6}\ t \cdot g^{-1})(86400\ s \cdot d^{-1})(273/293) = Y\ \text{tonnes} \cdot \text{day}^{-1}$$

Errors in emission rate measurements

1. **Plume speed (based on wind speed calculations)**
2. **Errors in calculating plume geometry (plume width and direction)**
3. **Scattering and absorption of UV radiation by other plume components (e.g. H_2O, ash, etc.). Multiple scattering can influence the column amounts retrieved and result in overestimated fluxes.**
4. **DOAS method: errors related to the smoothing, filtering and spectral fitting routine**
5. **Signal-to-noise changes (determining plume edges accurately when the concentrations are low)**
6. **Errors caused by the techniques employed (example: variable speed of aircraft)**
7. **SO_2 loss rates**

Edmonds et al., 2003; Rodriguez et al., 2008

Example of error analysis - COSPEC

Instrumental errors:

Calibration cells concentrations – COSPEC V:

339.2 ppm·m = -2%

(based on Williams-Jones et al., 2008)

Chart record reading error: ±0.5 mm (0.5 mm = 6 ppm·m)

For average deflection of 100 ppm·m = ±6%

(based on Stoiber et al., 1983)

Technique errors:

Errors related to the techniques used at each volcano

Variable vehicle/aircraft speed = ±5%

(based on Williams-Jones et al., 2008)

Wind speed errors: -5%, +30%

(based on Edmonds et al., 2003)

Distance determination error (related to calculation of plume width and direction):

±5% (used) to

±10% (worst case)

(based on Stoiber et al., 1983)

Example of error analysis

Processing errors in the DOAS method (e.g. smoothing, filtering, and fitting) ±5% (up to ±10%)

(based on this research and Edmonds et al., 2003a)

Signal-to-noise changes cause errors ±5%

(based on Edmonds et al., 2003a)

Multiple scattering effects cause an error -5%

(Edner et al., 1994, using data from Stromboli volcano),

Variable vehicle/aircraft speed = ±5%

(based on Williams-Jones et al., in press)

Wind speed errors:

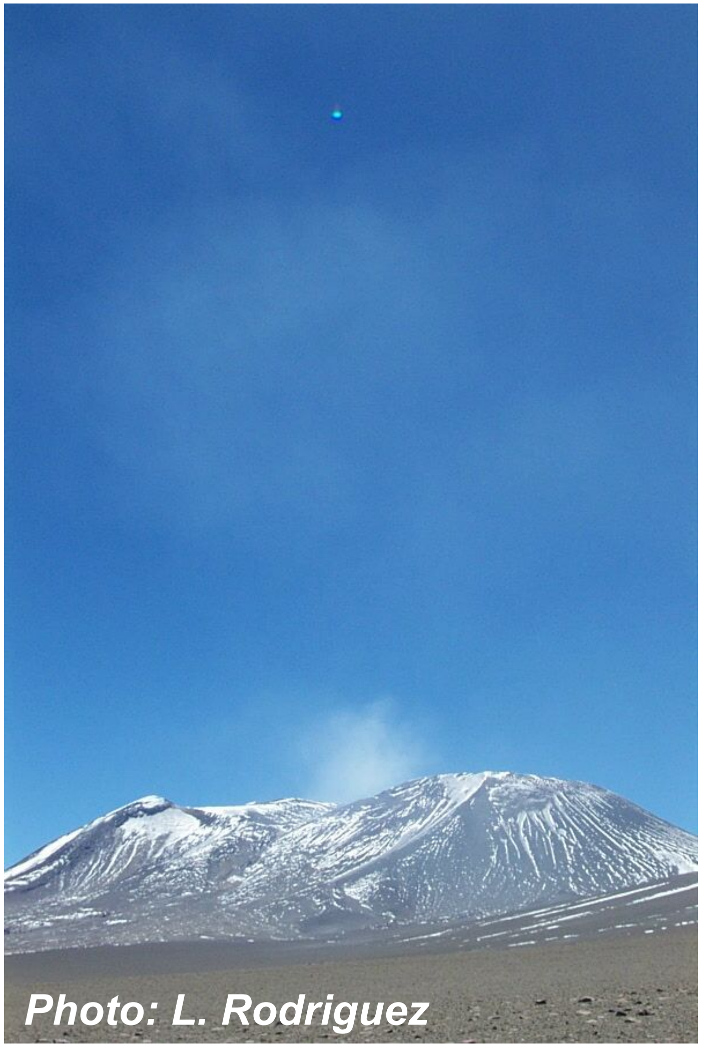
when calculated at helicopter altitude ±5%

when estimated from the weather station data -5% +30%

(based on this research and Edmonds et al., 2003a)

Errors related to determination of plume width and direction are deemed negligible (because of technique) ±0.3-1.2%

Examples of volcanic plumes



Lascar, Chile

Villarrica, Chile

Photos: J. Palma

Pacaya, Guatemala

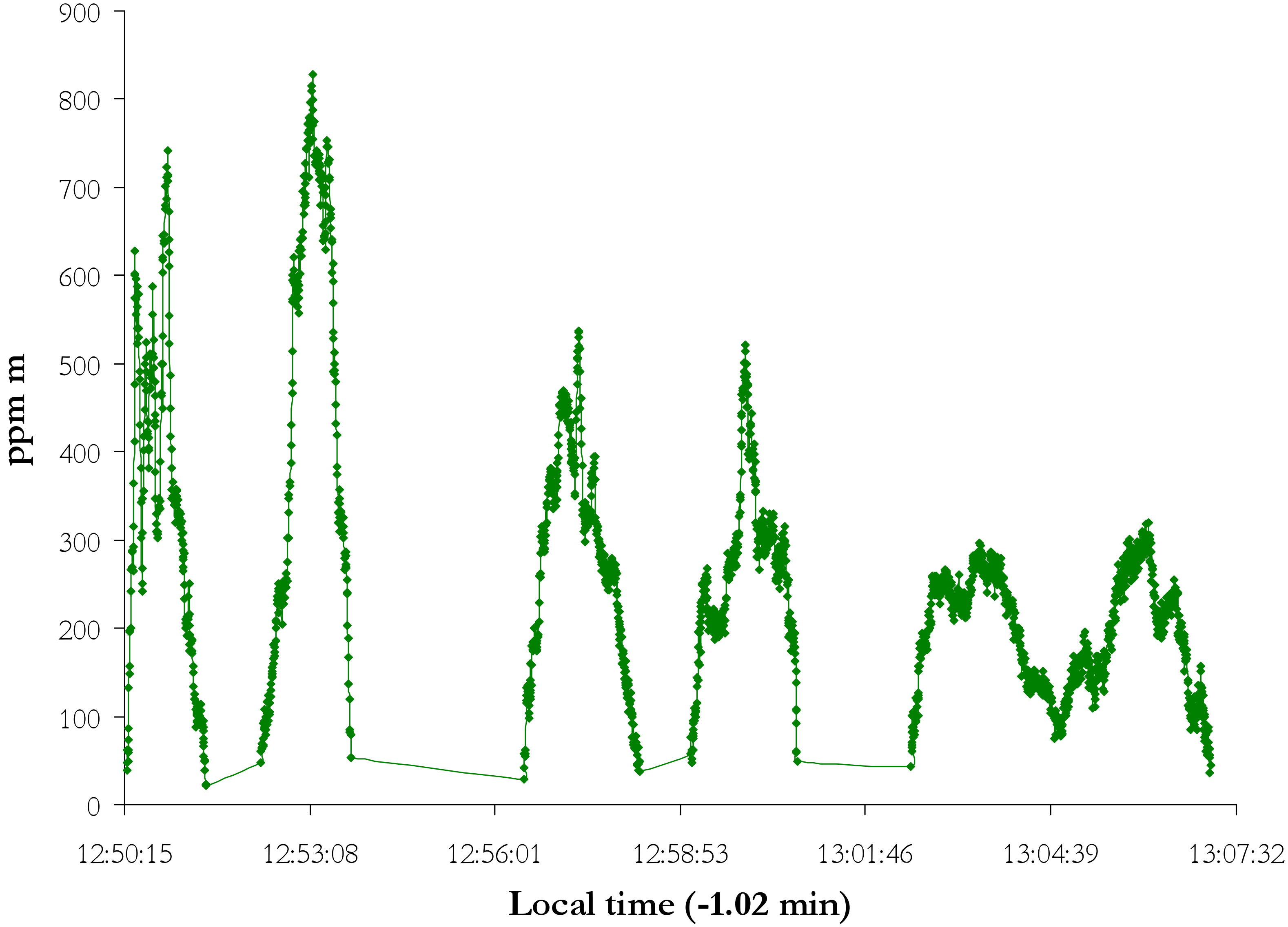
Popocatepetl, Mexico

Measuring SO_2 fluxes:
helicopter or airplane traverses

Photo: L. Rodriguez

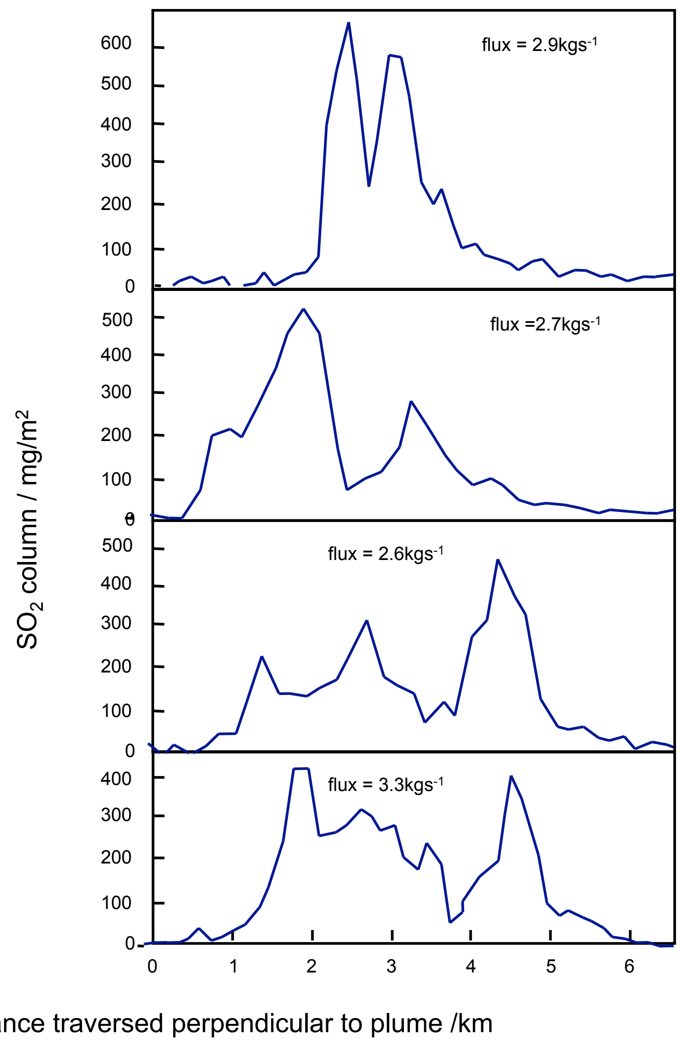
Photo: L. Rodriguez

Example: Soufriere Hills, Montserrat



By: L. Rodriguez

Helicopter traverses: Stromboli 2002



McGonigle *et al*., JGR, 2003

SO_2 flux = 110-290 t/d

Measuring SO_2 fluxes:
boat traverses

Example: Soufriere Hills, Montserrat

Measuring SO_2 fluxes: car traverses

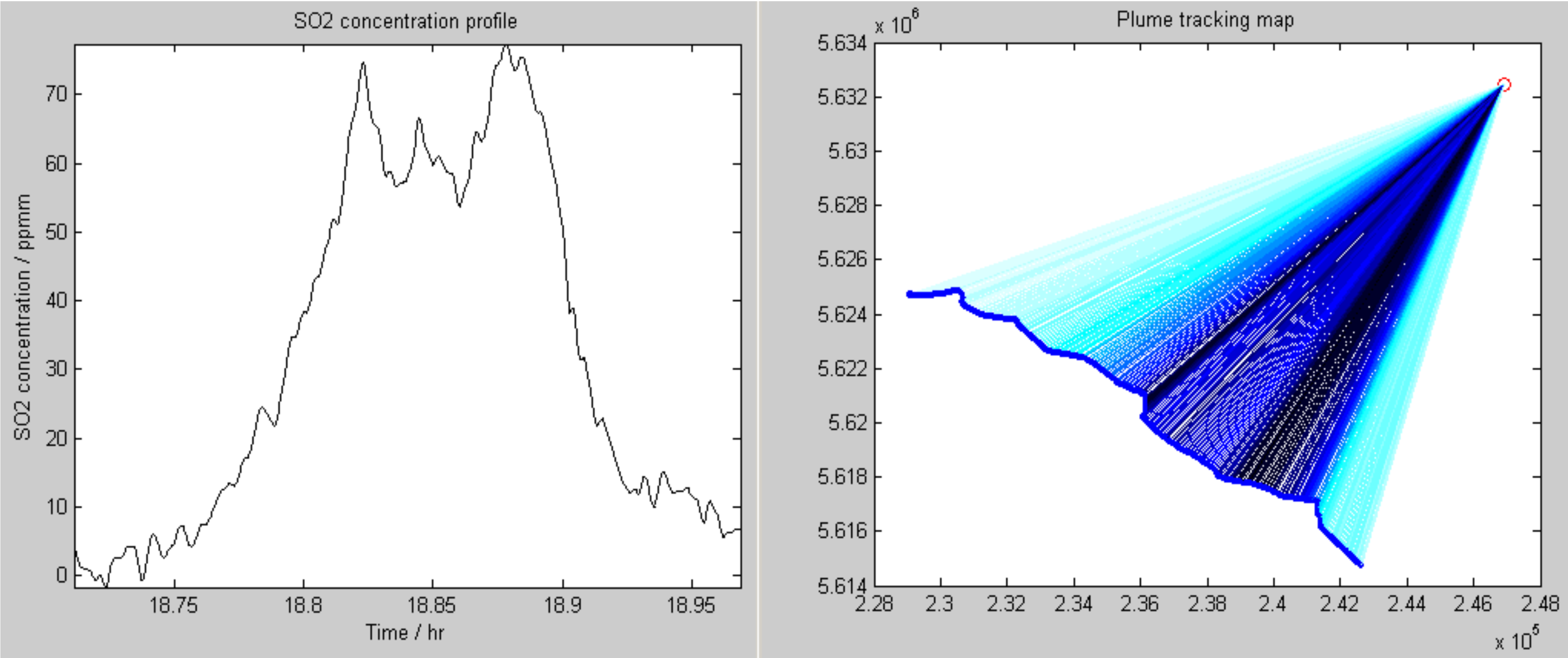
Optics + UV spectrometer + laptop + GPS.

Villarrica, Chile

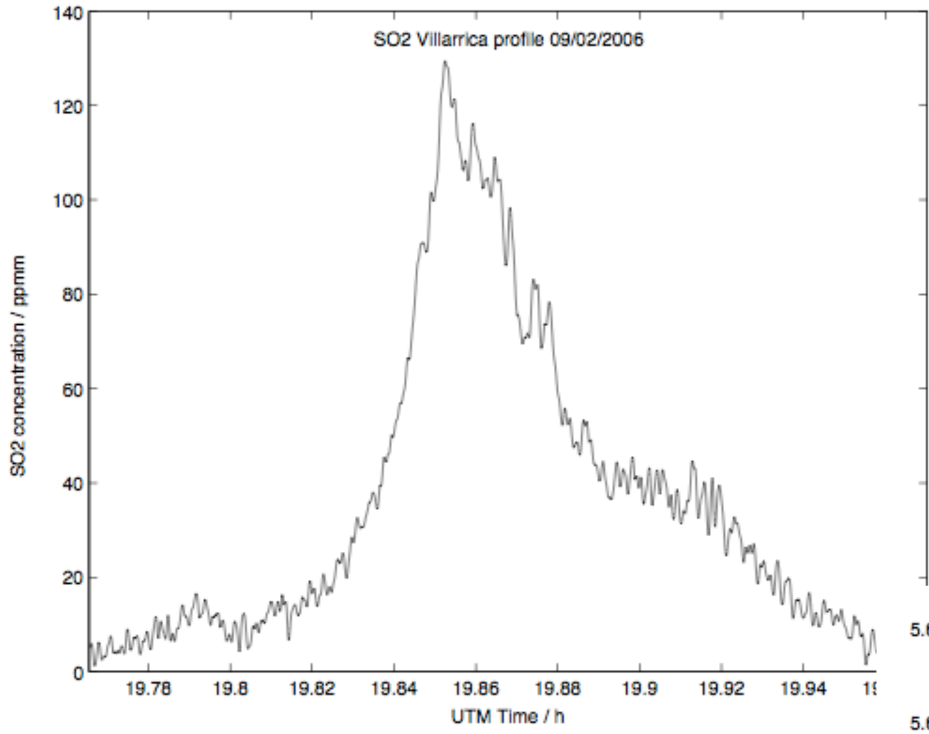
Photos: J Palma

We drive underneath the plume and measure the vertically-integrated concentration of SO_2.

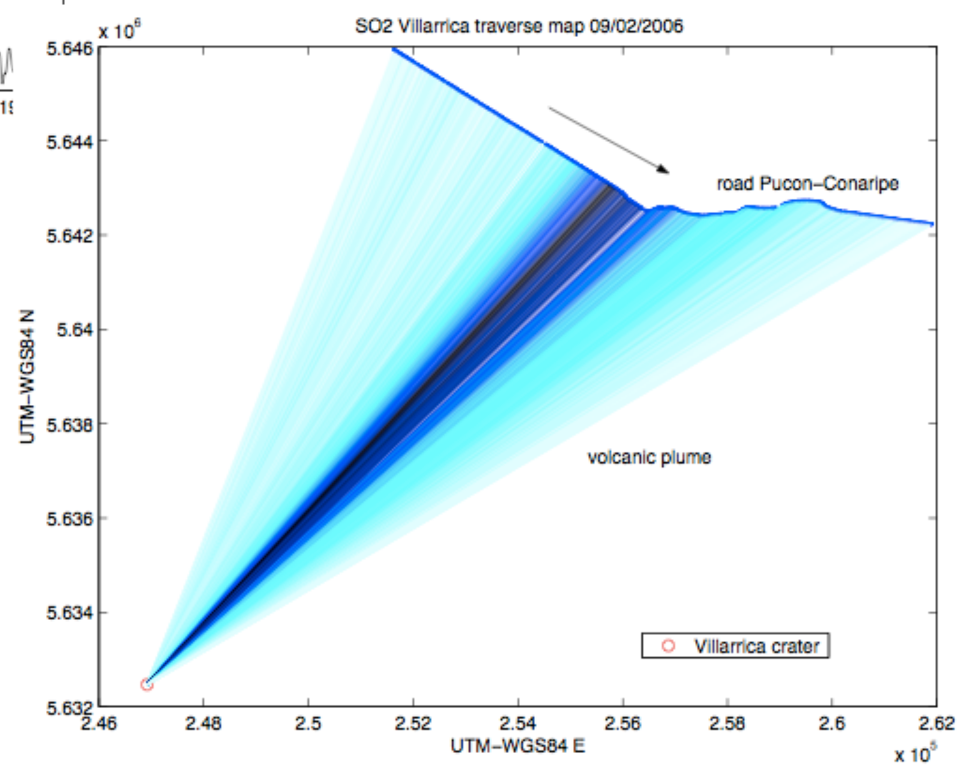
Example



From: J Palma



SO2 Villarrica profile 09/02/2006
SO2 concentration / ppmm
UTM Time / h

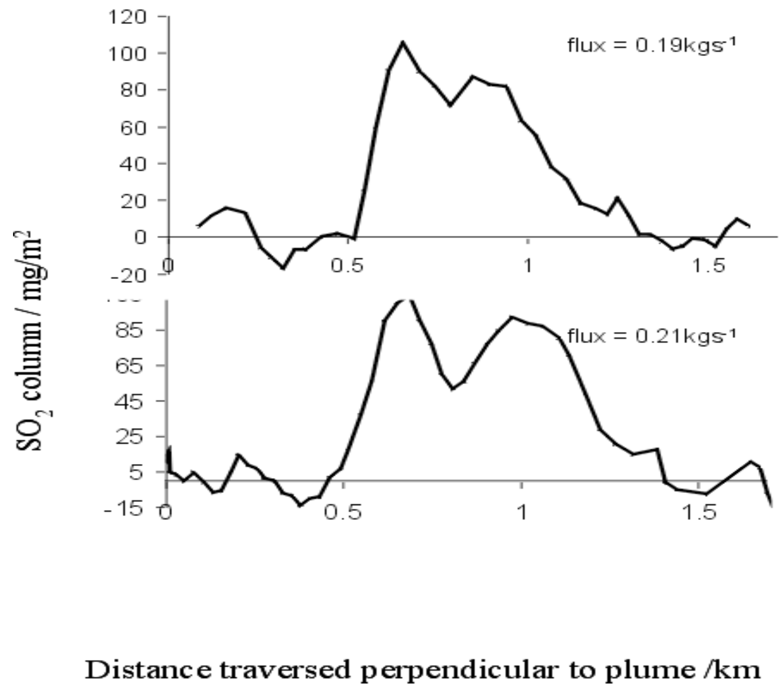


SO2 Villarrica traverse map 09/02/2006
road Pucon–Conaripe
volcanic plume
Villarrica crater
UTM–WGS84 N
UTM–WGS84 E

From: J Palma

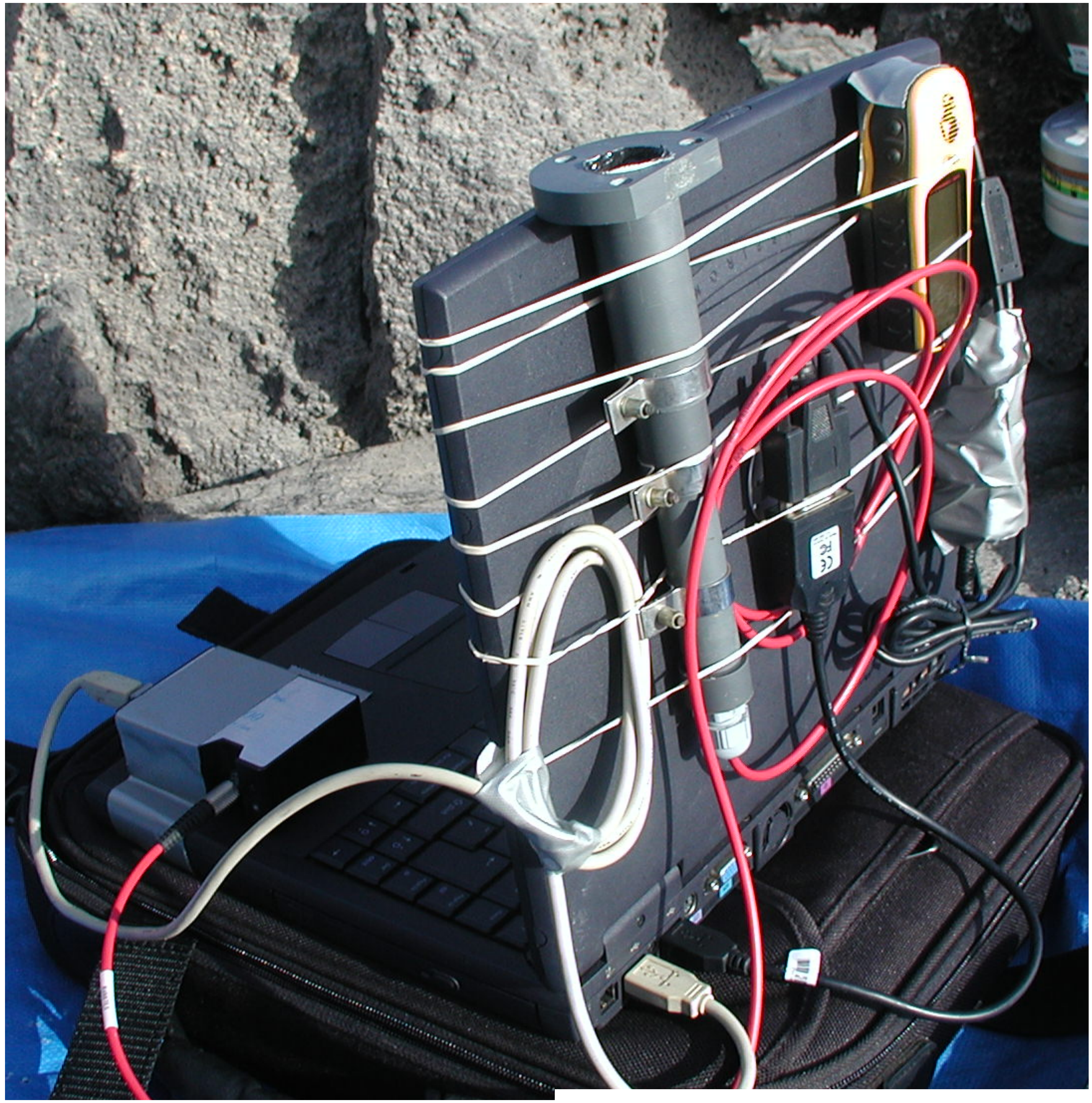
Easy Rider II: Vulcano 2002

SO_2 flux = 10-20 t/d



McGonigle *et al*., JGR, 2003

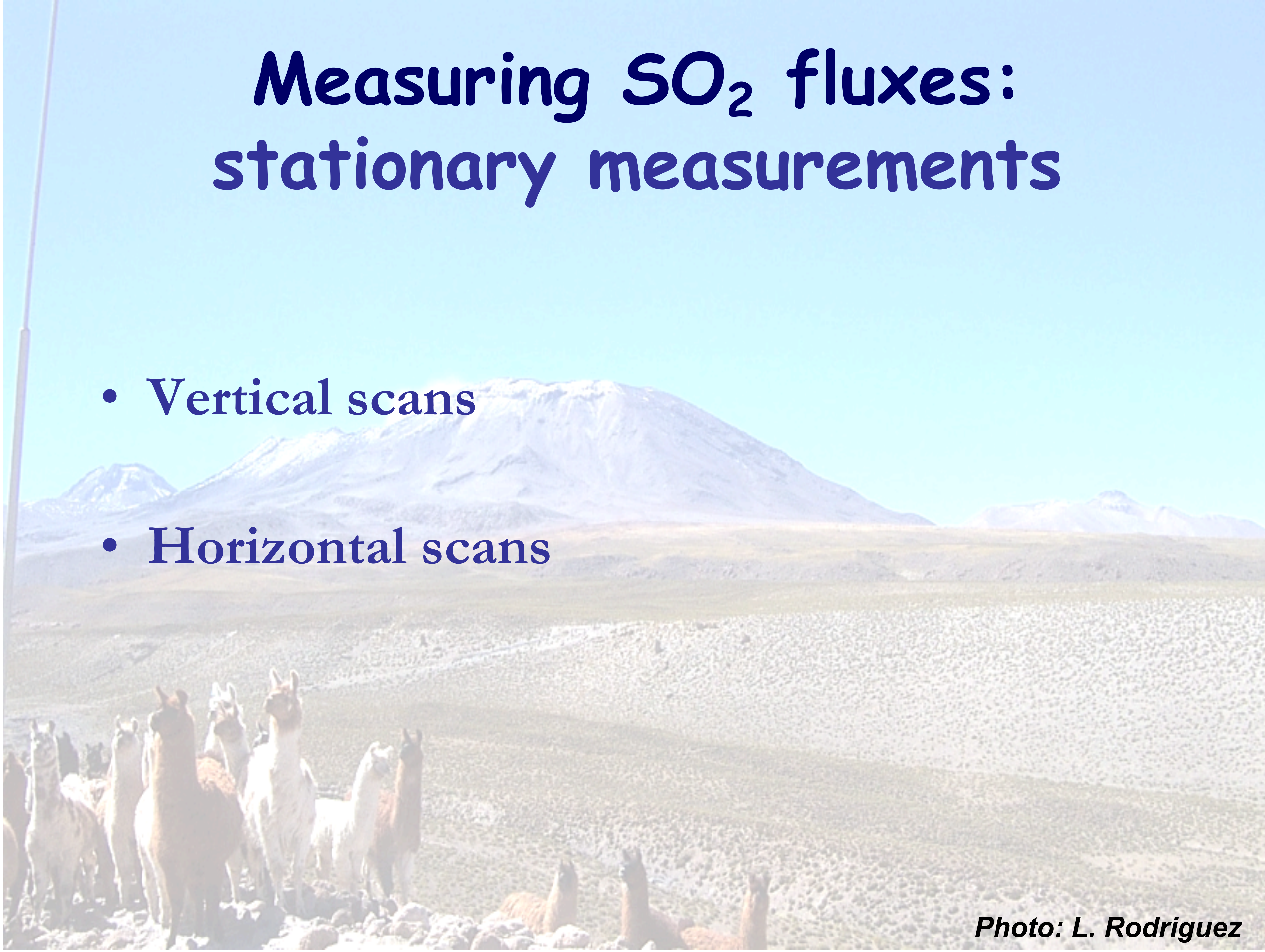
Measuring SO_2 fluxes: walking traverses



McGonigle *et al.*, 2002, GRL

McGonigle *et al.*, 2002, GRL

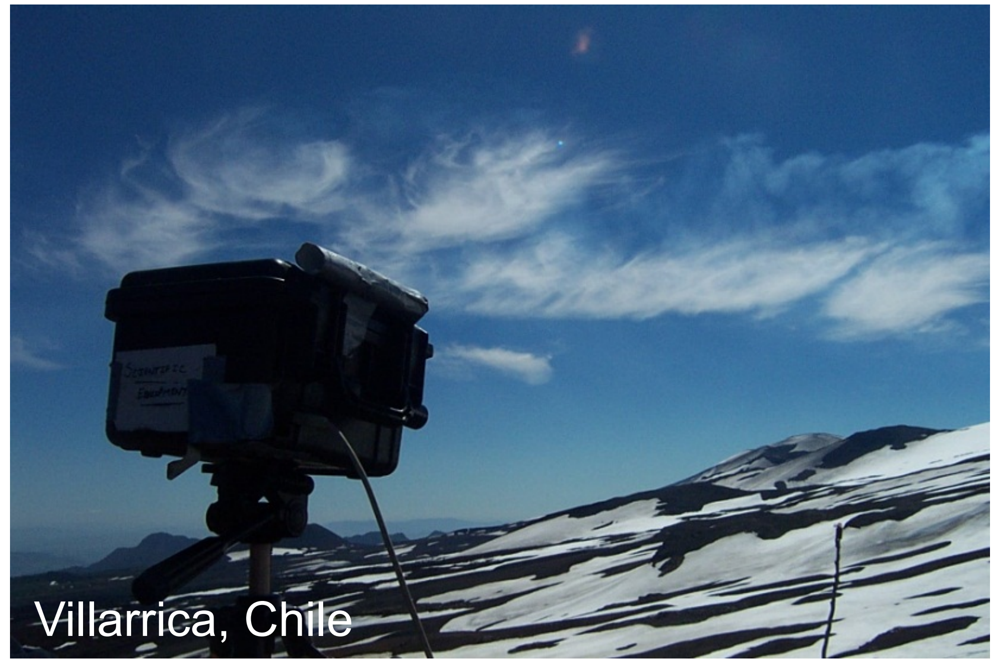
Measuring SO_2 fluxes: stationary measurements



- Vertical scans
- Horizontal scans

Photo: L. Rodriguez

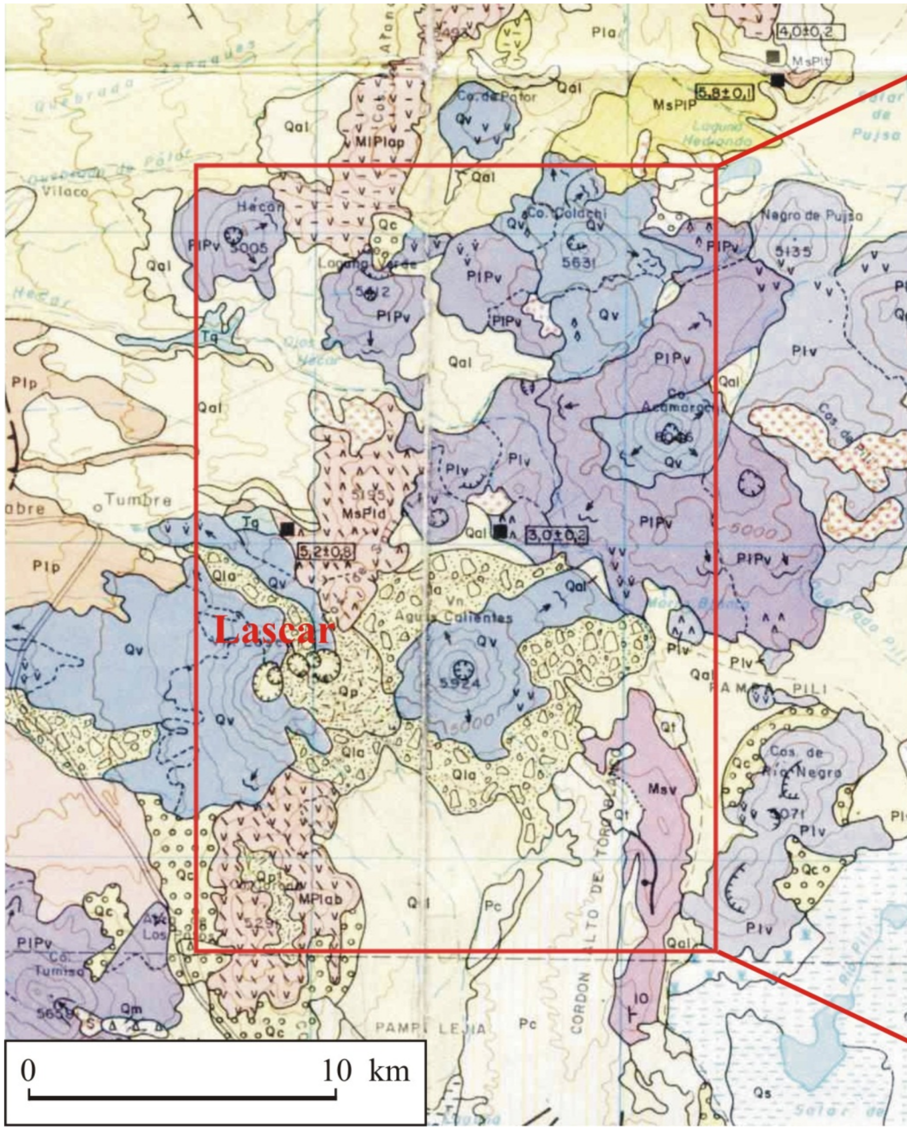
Lascar, Chile



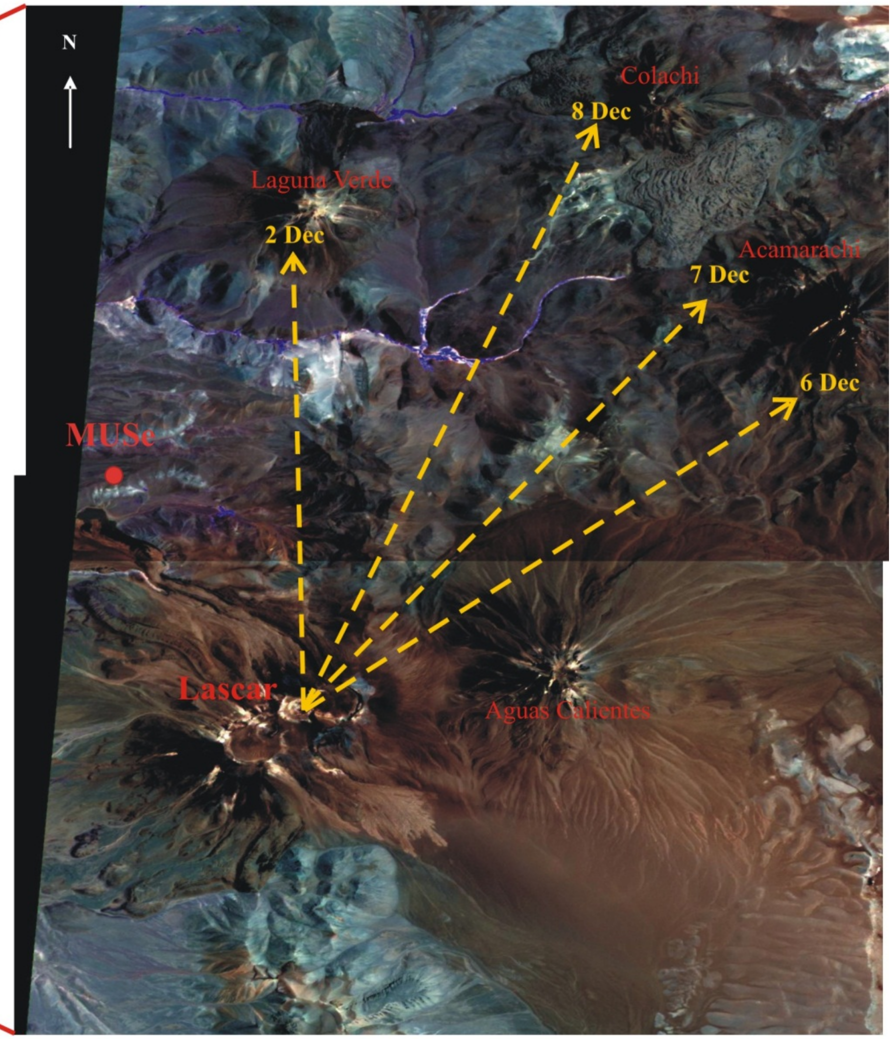
Villarrica, Chile

Photos: L. Rodriguez

Plume direction during vertical scans of Lascar's plume



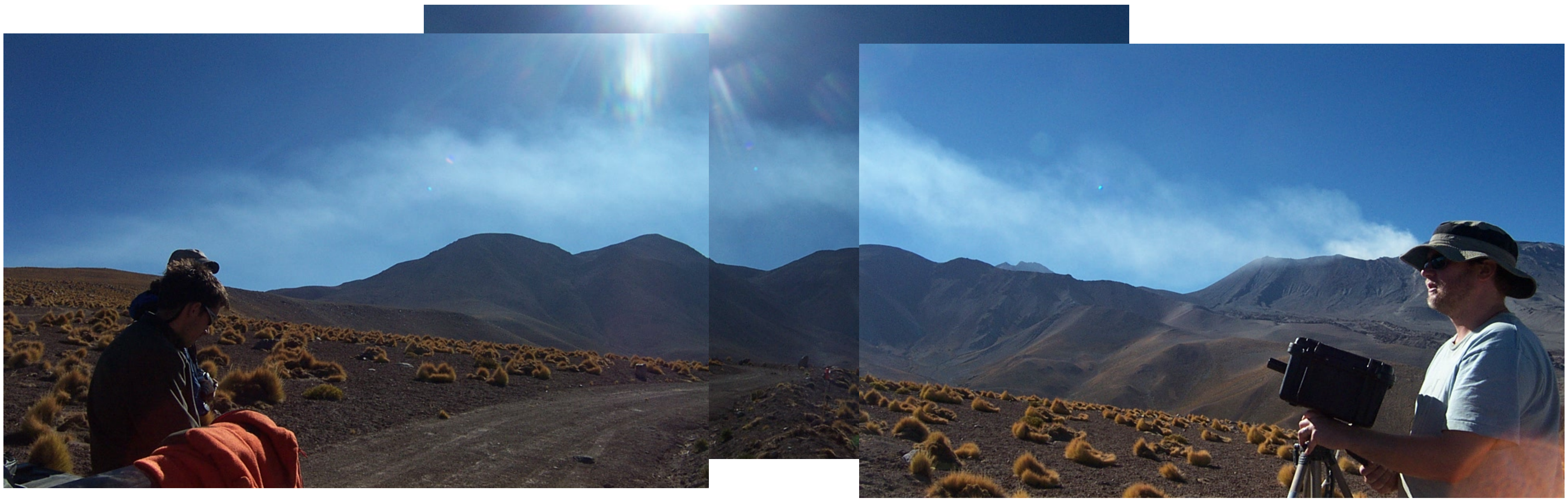
Toconao quadrangle (1:250,000)



ASTER image (1-2-3 visible composite)

From Rodriguez et al., in prep.

Plume at Lascar, Chile

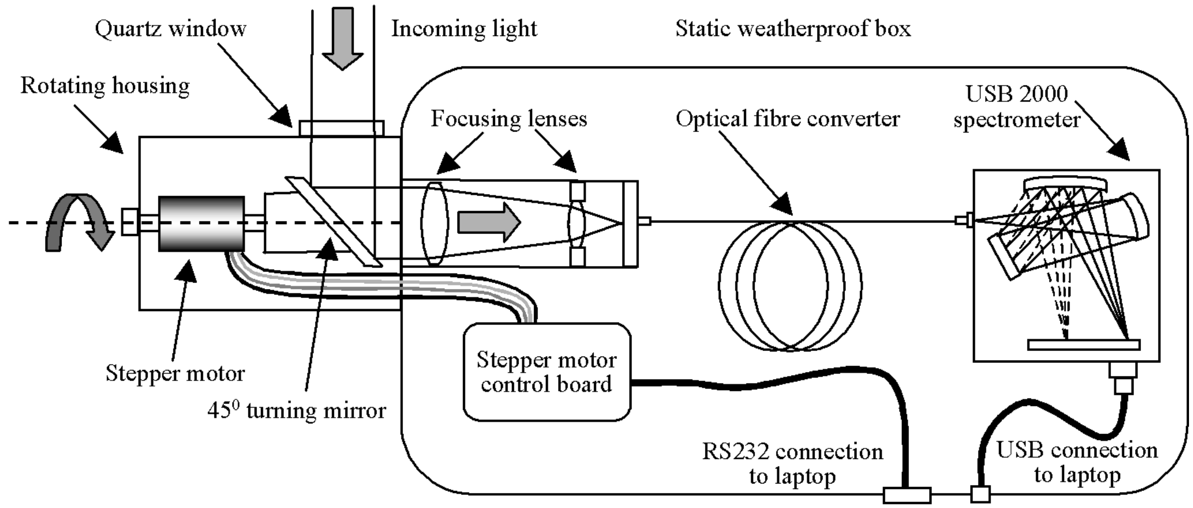


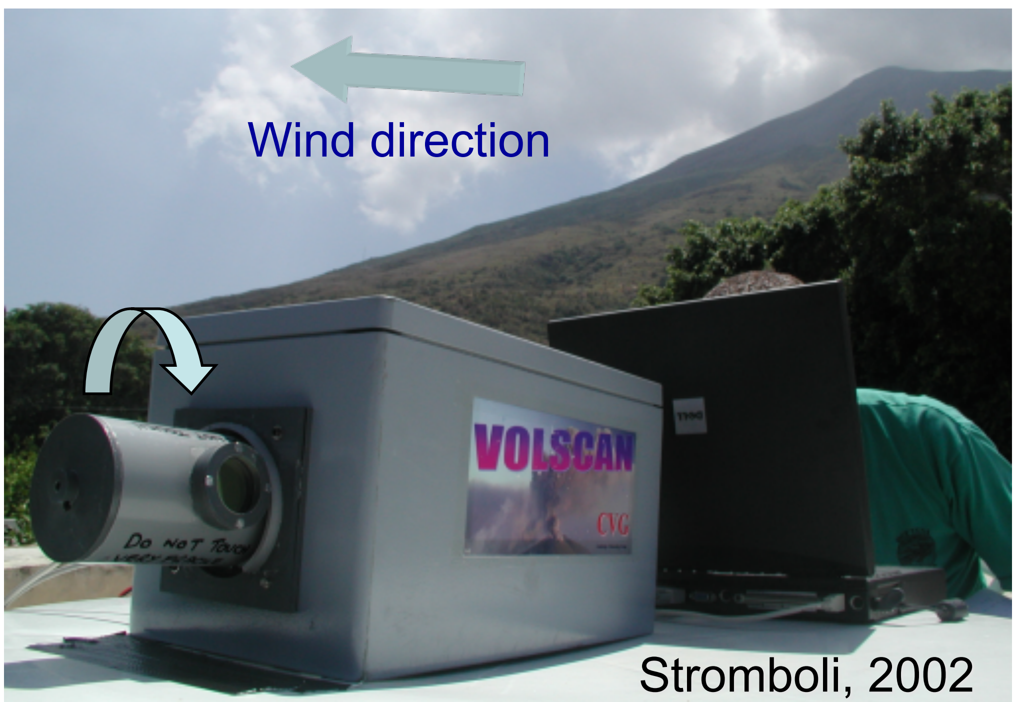
Photos: L. Rodriguez

Santa Maria Volcano, Santiaguito Dome

Photo: Yvonne Branan

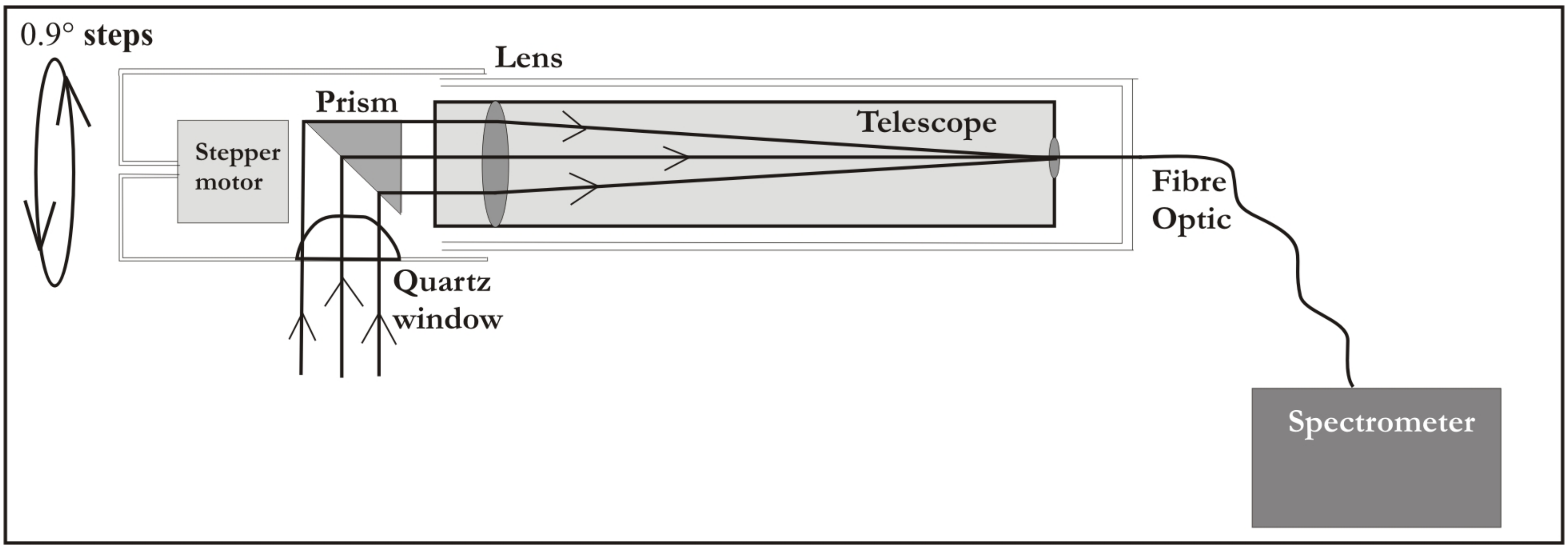
Scanning systems



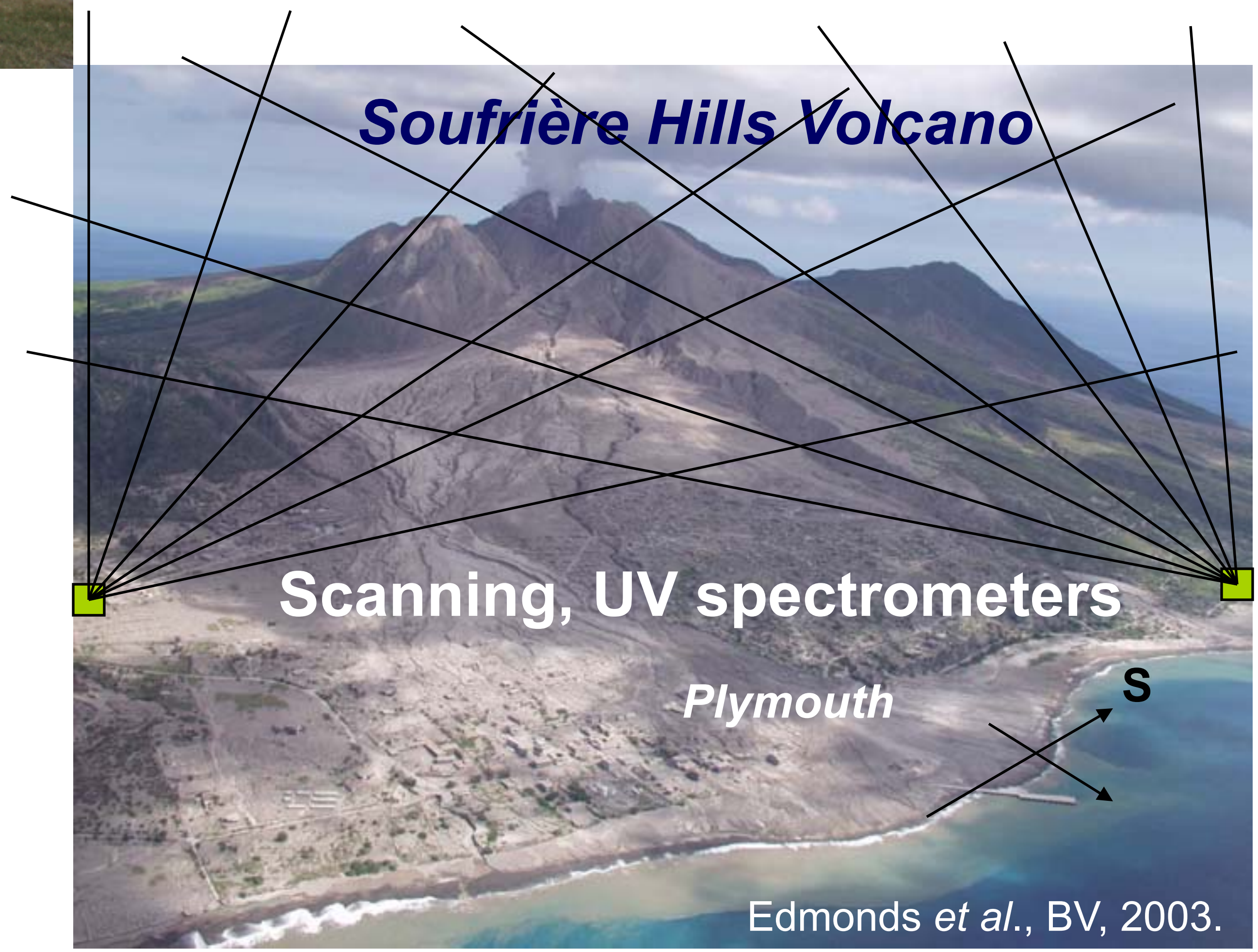


McGonigle *et al.*, JGR, 2003

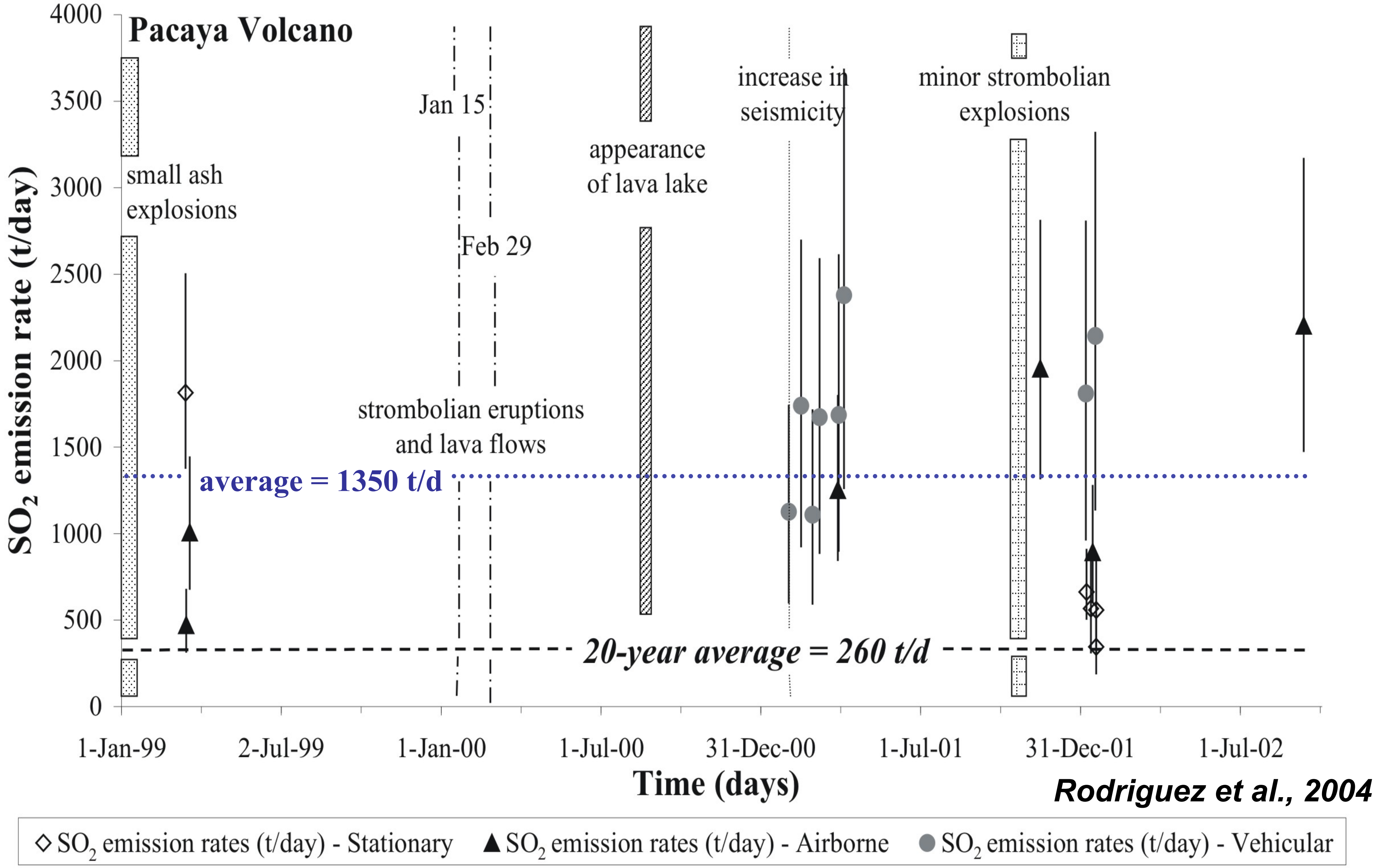
Schematic view of the optical layout of the scanning instrument used at the Montserrat Volcano Observatory. The prism and the protective cover are rotated around the optical axis of the telescope, thereby scanning the field of view of the instrument in a plane perpendicular to the optical axis (Edmonds et al, 2003a).



Fully-automated scanners at Soufrière Hills Volcano



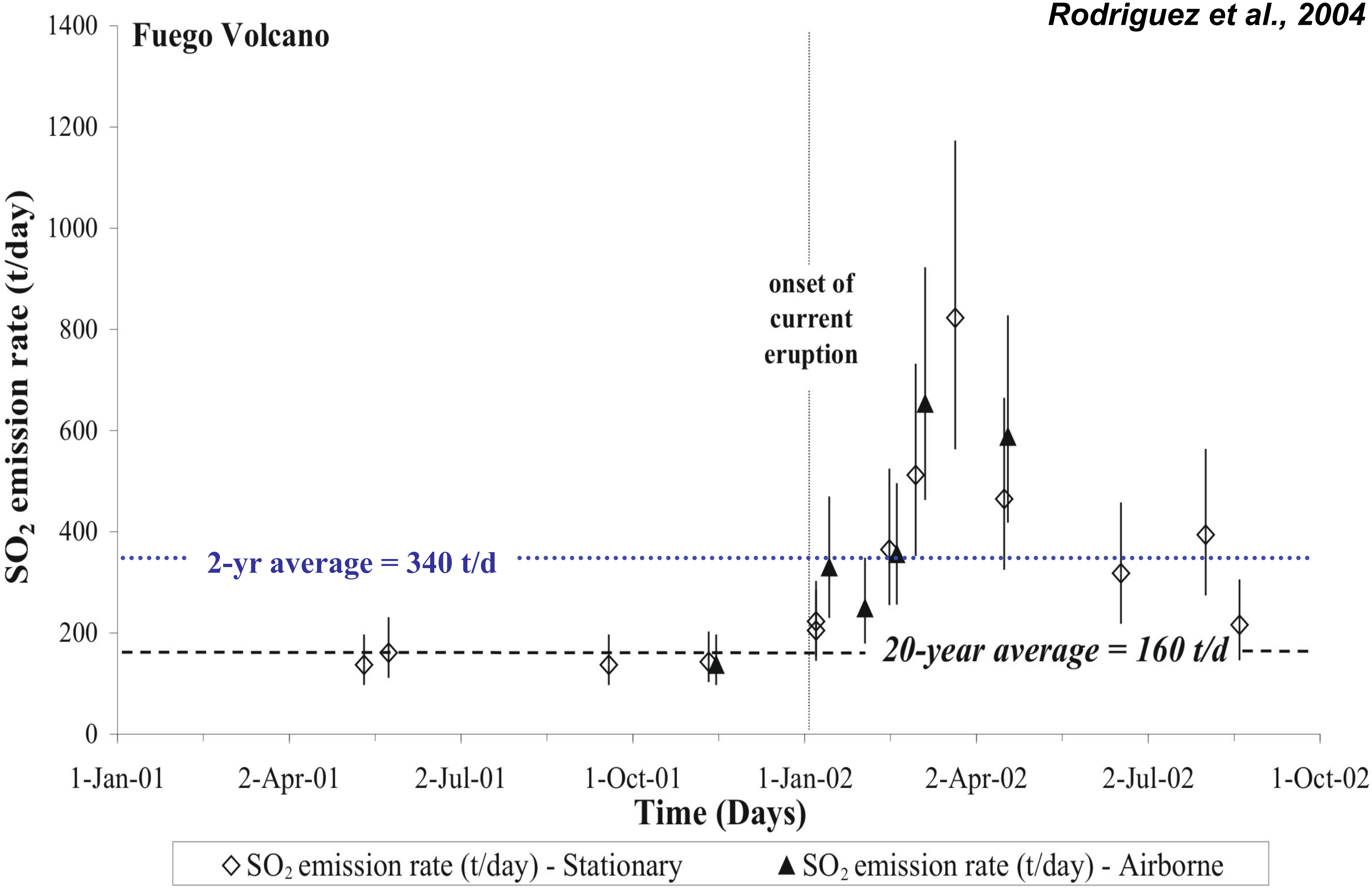
SO_2 emission rates at Pacaya volcano (1999-2002)



Rodriguez et al., 2004

SO_2 emission rates at Fuego volcano (2001-02)

Rodriguez et al., 2004

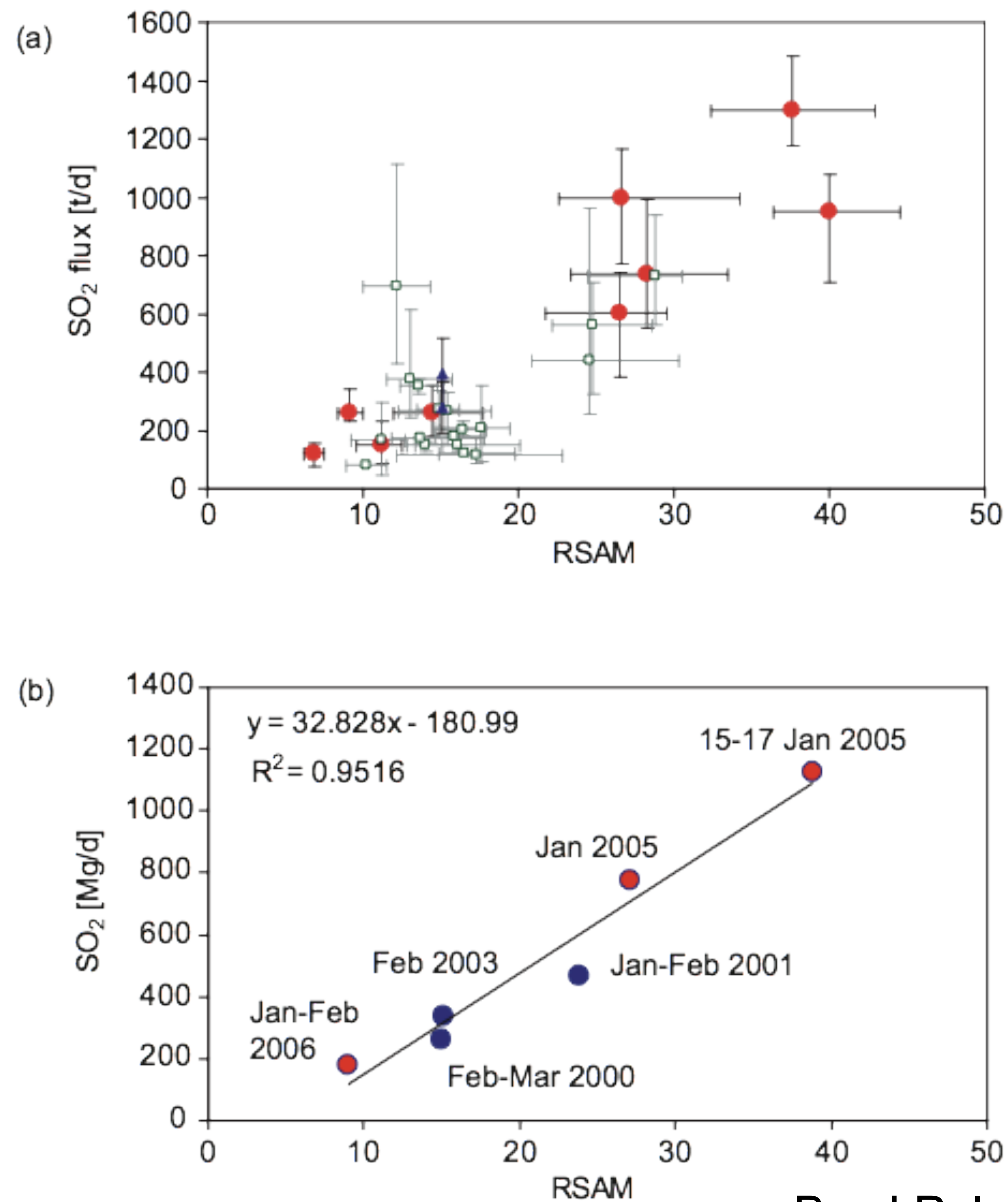


Geometrical considerations for the techniques

1. Airplane or helicopter traverses
2. Car traverses
3. Stationary/scanning

Examples of other applications

Integration of gas measurements with geophysical data – Villarrica, Chile



By: J Palma

Santiaguito, Guatemala

Correlations between SO_2 gas emissions, seismicity and temperature

By: Yvonne Branan

Determination of plume speed

Photo: L. Rodriguez

I. Using anemometers, portable or permanent weather station data

- Anemometers and portable weather stations at measurement site: errors range around +30%, depending on the altitude difference between site and plume
- Permanent weather stations:
  - Useful if installed close to summit. Errors will be lower than for anemometers and weather stations used at the measurement sites
- Using data from weather stations at helicopters and airplanes - close to plume altitude

Portable weather station at Lascar: ~1 km below plume

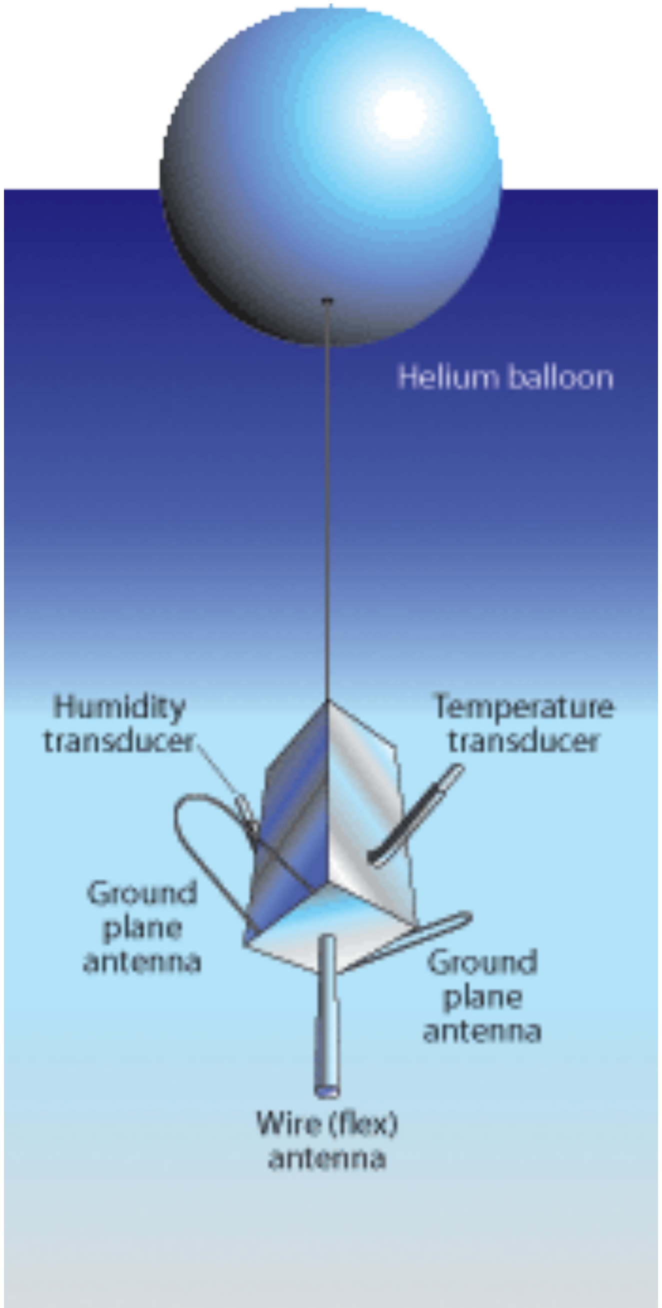
II. Plume tracking

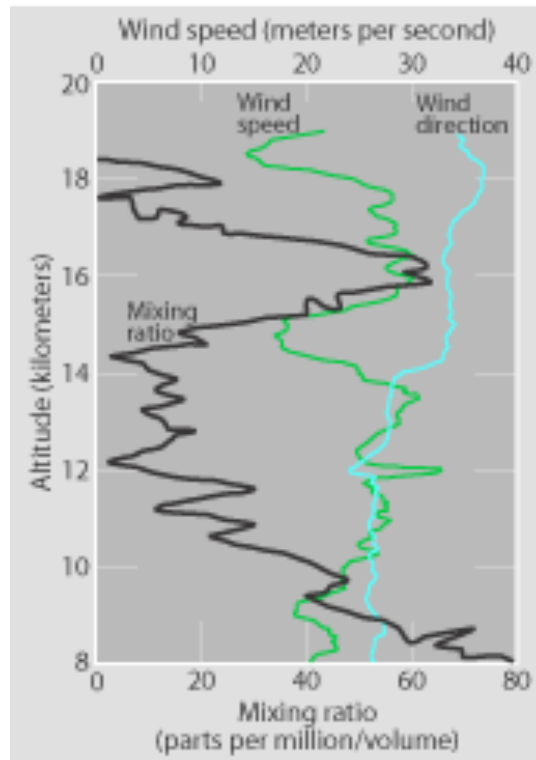
- Finding features identifiable in a topographic map, and follow plume portions from point A to point B

Photo: L. Rodriguez

III. Using Radiosonde data

- A radiosonde is an instrument package carried by a balloon that ascends to altitudes of 20 to 30 kilometers. It measures various atmospheric parameters: T, RH, P, and transmits them to a ground station/fixed receiver. A GPS is used to record the trajectory during ascent to determine wind speed and direction.
- About 800 radiosonde launch sites in the world.
- Important for weather forecasting, severe weather watches and warnings, and atmospheric research.





http://www.aero.org/publications/crosslink/summer2000/02.html

IV. Measuring volcanic plume velocity with multiple UV spectrometers (Williams-Jones et al., 2005)

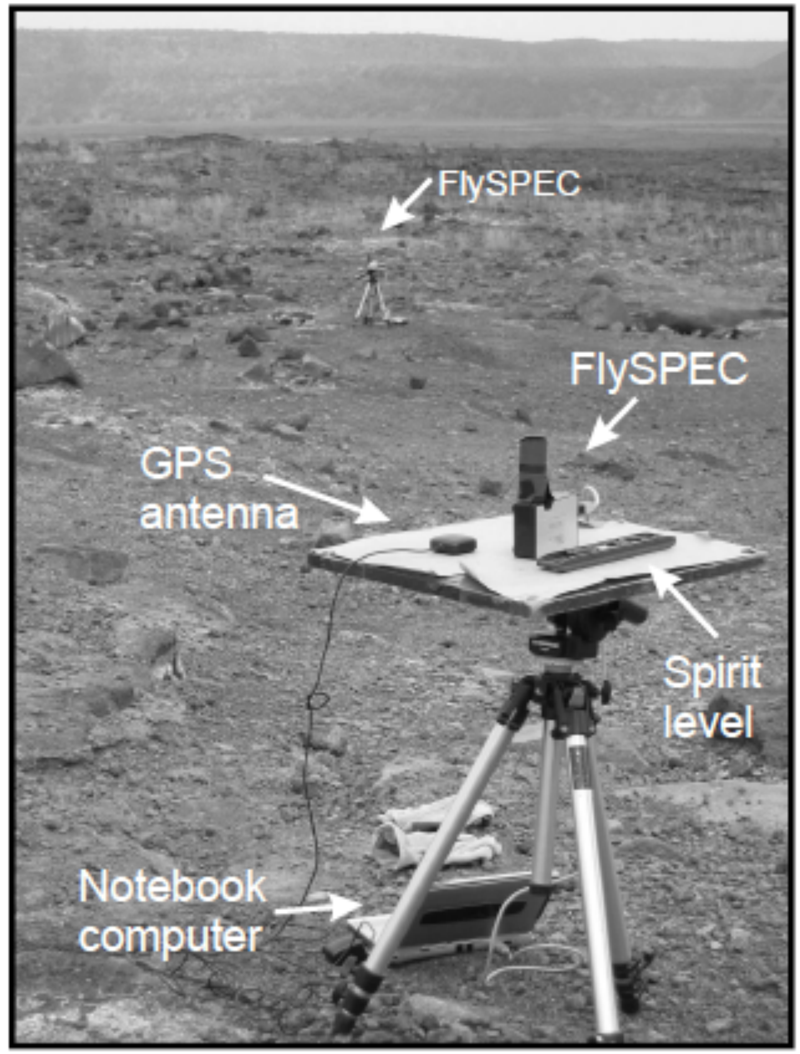


Figure 1. Example of a temporary field deployment at Kilauea volcano, USA, on March 9, 2003. The FlySPECs are mounted downwind of the gas source on small, lightweight camera tripods separated by ~20 m. A GPS antenna is placed next to each spectrometer to allow for time-synchronization. Measurements were made for ~30 minutes.

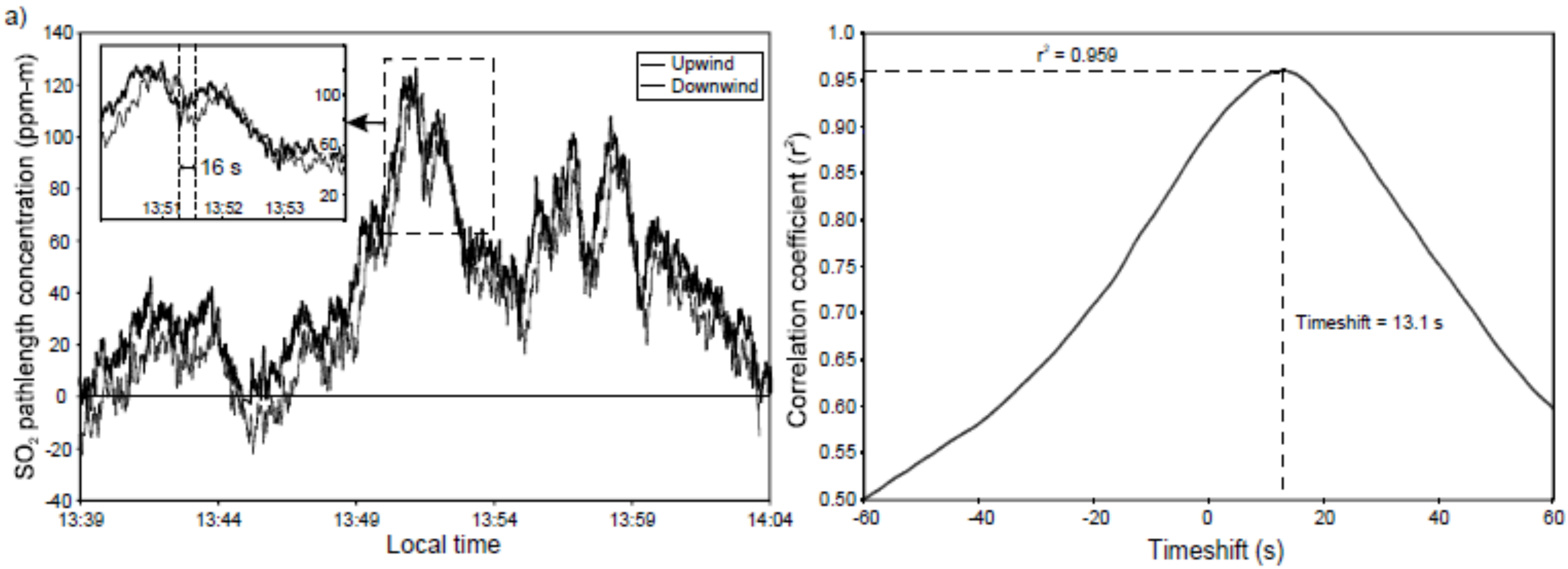


Figure 2. a) The SO_2 pathlength concentration signals for two FlySPECs at Masaya volcano, Nicaragua on March 25, 2003. The thick black line denotes the upwind instrument. The instrument separation is 40.5 m, determined by tape measure. Inset is a 4-minute window showing an apparent time separation (16 s) between the 2 signals. b) The SO_2 signals for the entire 30-minute sampling period are compared to each other for timeshifts 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 m s^{-1}. This approach is also used over shorter sampling windows (e.g., 2 min) to investigate plume speed variations. See Table 1.

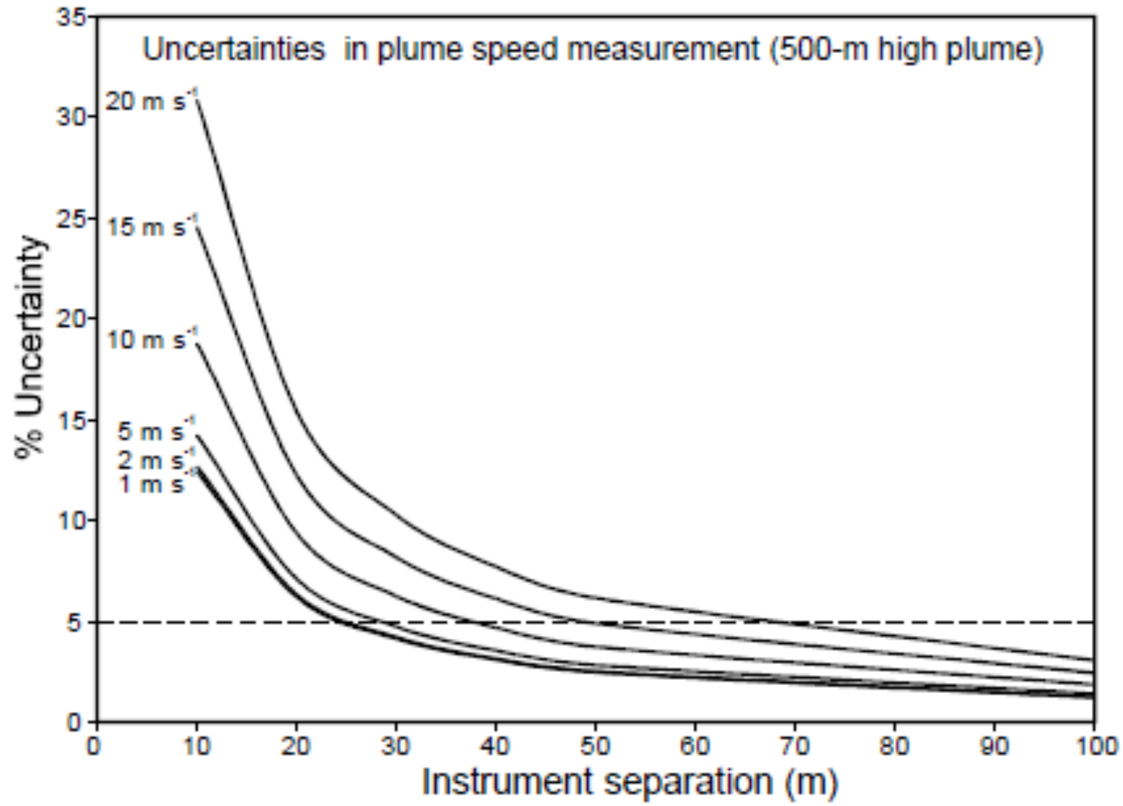


Figure 3. The relative uncertainties in plume speed measurement for a 500-m high plume over a range of instrument separations for plume speeds between 1 and 20 m s^{-1}. The optimum separation is ~20-50 m in order to minimize uncertainty (<5%) yet allow for easy field deployment. The instruments should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

V. Dual-beam mini-DOAS technique

- **Measurements of volcanic gas emission, plume height and plume speed with a single instrument (Johansson et al., 2009): simultaneously collecting scattered sunlight in two directions.**

- **The angle between the two measurement directions is fixed.**

Questions?