Development of a laser remote sensing instrument to measure subaerial volcanic CO_2 fluxes

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CO_2VOLC
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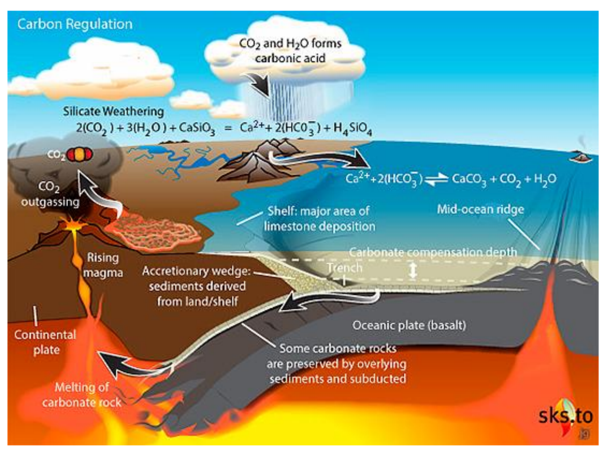
INO-CNR Istituto Nazionale di Ottica
ENEA

Motivation

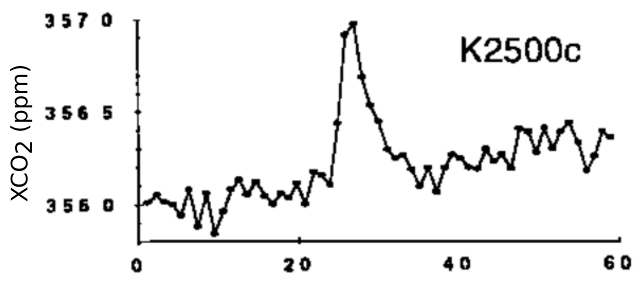
The work presented here is part of the ERC project CO2Volc. CO2Volc is a five year scientific project that started in 2012 with the objectives of improving our understanding of both volcanic carbon emissions and volatile recycling at subduction zones, thereby fundamentally improving constraints on global volcanic CO_2 emissions, which are currently very poorly understood. These objectives are achieved through the development of innovative new optical instruments for the quantification of CO_2 and other volatile species, which are utilised in field campaigns to measure subaerial volcanic emissions along the length of a subduction arc. This poster presents an overview of the development of one of those instruments.



The first 3 years of the project are dedicated to instrument development, laboratory testing and demonstration field campaigns on Italian volcanoes. The fourth and fifth years are dedicated to the main field campaign, development of models of volatile recycling and construction of a CO_2 inventory catalogue.

State of the art techniques

Measuring magmatic CO_2 fluxes is challenging as concentrations are modest compared with the ambient CO_2 concentration (~400 ppm) and magmatic CO_2 quickly dilutes with the background. For this reason many volcanic CO_2 concentration measurements focus on in situ techniques, such as direct sampling with Giggenbach bottles, chemical sensors, IR absorption spectrometers or mass spectrometers (Burton et al., 2013). By operating these techniques airborne while traversing the volcanic plume, CO_2 concentration profiles are obtained from which fluxes can be retrieved. The Figure shows profiles from airborne in situ CO2 measurements acquired with Fourier transform infrared spectrometry (FTIR).

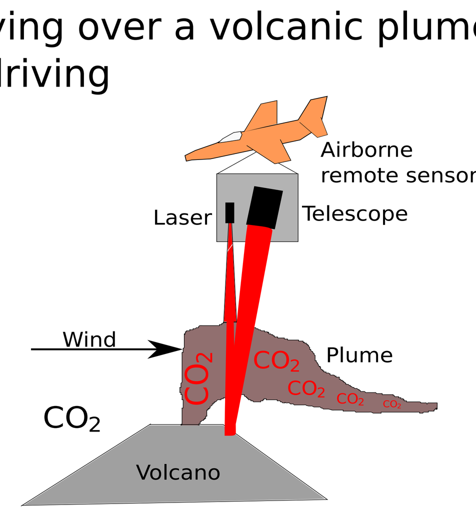


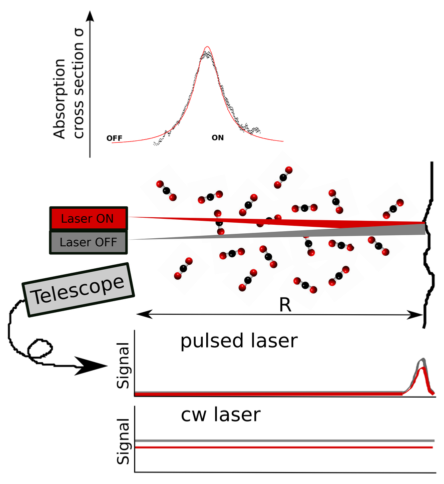
Airborne XCO2 from Kilauea volcano plume ~ 1 km downwind. From Gerlach et al., 1998.

However, emission rates are highly variable in time and space. Subsequent point measurements fail to account for this variability. Inferring 1-D or 2-D gas concentration profiles, necessary to estimate gas fluxes, from point measurements may thus lead to erroneous flux estimations. Moreover, in situ probing is time consuming and, since many volcanoes emit toxic gases and are dangerous, may raise safety concerns. In addition, degassing is often diffuse and spatially extended. This makes a measurement approach with spatial coverage desirable. Relating in situ CO_2 concentrations to correlated SO_2 concentrations and SO_2 fluxes, allows indirectly the estimation of CO_2 fluxes. SO_2 fluxes are measured with passive remote sensing techniques. However, passive remote sensing of SO_2 is prone to errors (e.g., due to light dilution) that propagate into CO_2 flux estimates.
An active remote sensing instrument able to directly retrieve CO_2 concetration profiles would allow to greatly refine the budget of volcanic CO_2 emission rates.

Methodology

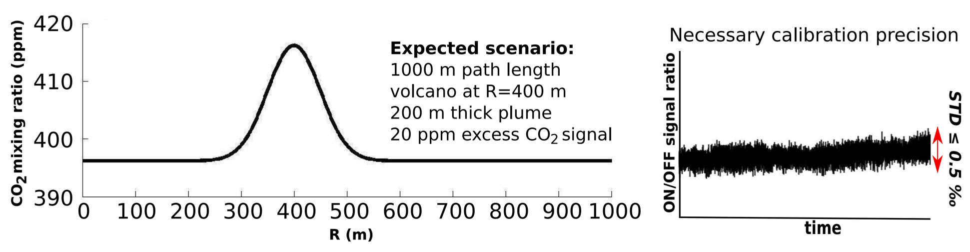
We propose a fit-for-purpose differential absorption LIDAR (DIAL, Koch et al., 2004). Concentration profiles are obtained by flying over a volcanic plume, or ground based by driving underneath it or statically, by rotating the instrument.





$$C_{CO_2} = \frac{1}{2[\sigma(\lambda_{ON}) - \sigma(\lambda_{OFF})]R} \ln \frac{P_{OFF}}{P_{ON}}$$

DIAL is based on measuring the intensity ratio of light of two (or more) wavelengths emitted by laser: One wavelength (ON) correponds to an absorption maximum of the molecule. The other wavelength (OFF) lies close to ON, but corresponds to zero absorption and serves as the reference.



Model plume illustrating the precision requirements of the DIAL.

Fluxes are obtained by multiplying the average plume CO_2 number density, integrated over the lateral plume extension, with the plume transport speed.

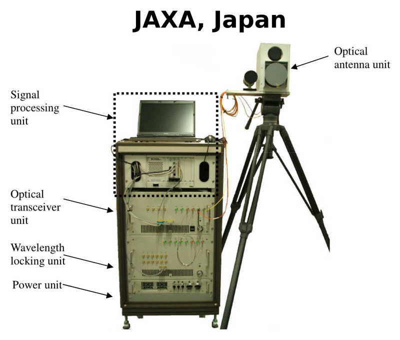
Results

Existing DIAL:

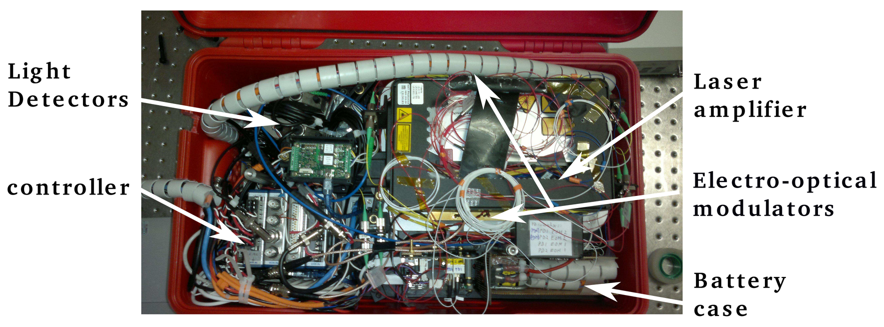
Ecole Polytechnique, France)

NASA, USA

JAXA, Japan

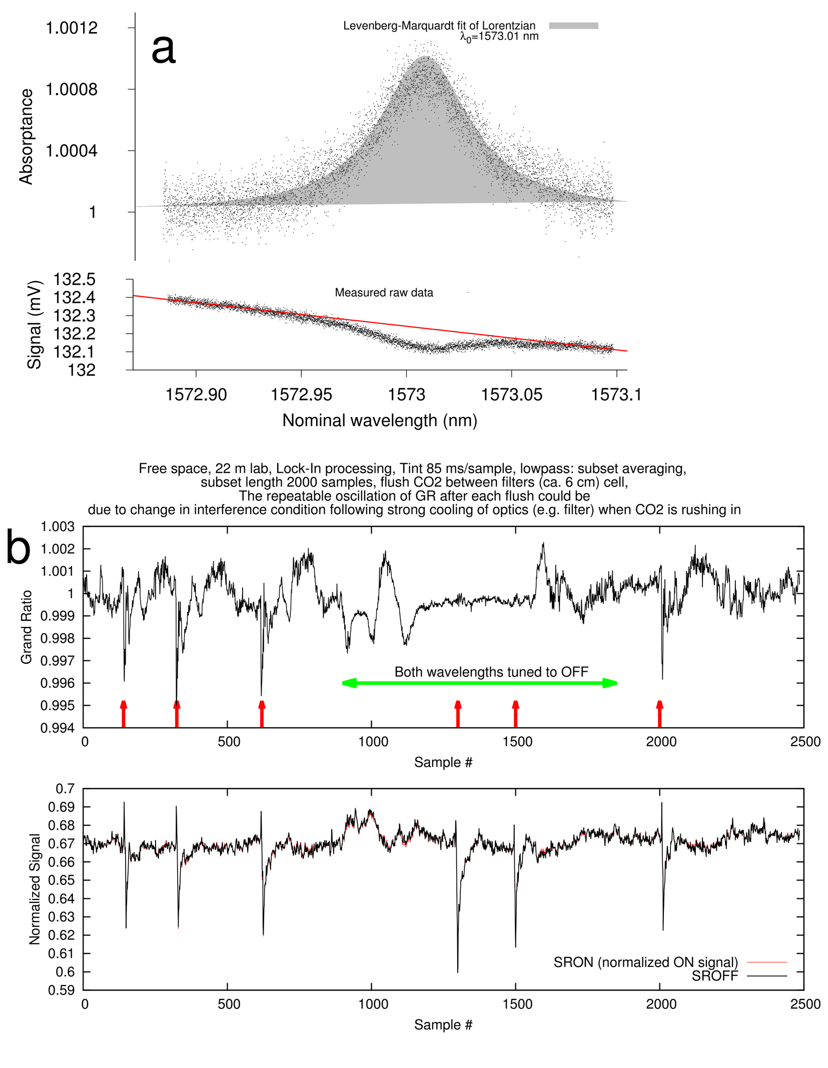


CO_2 DIAL:



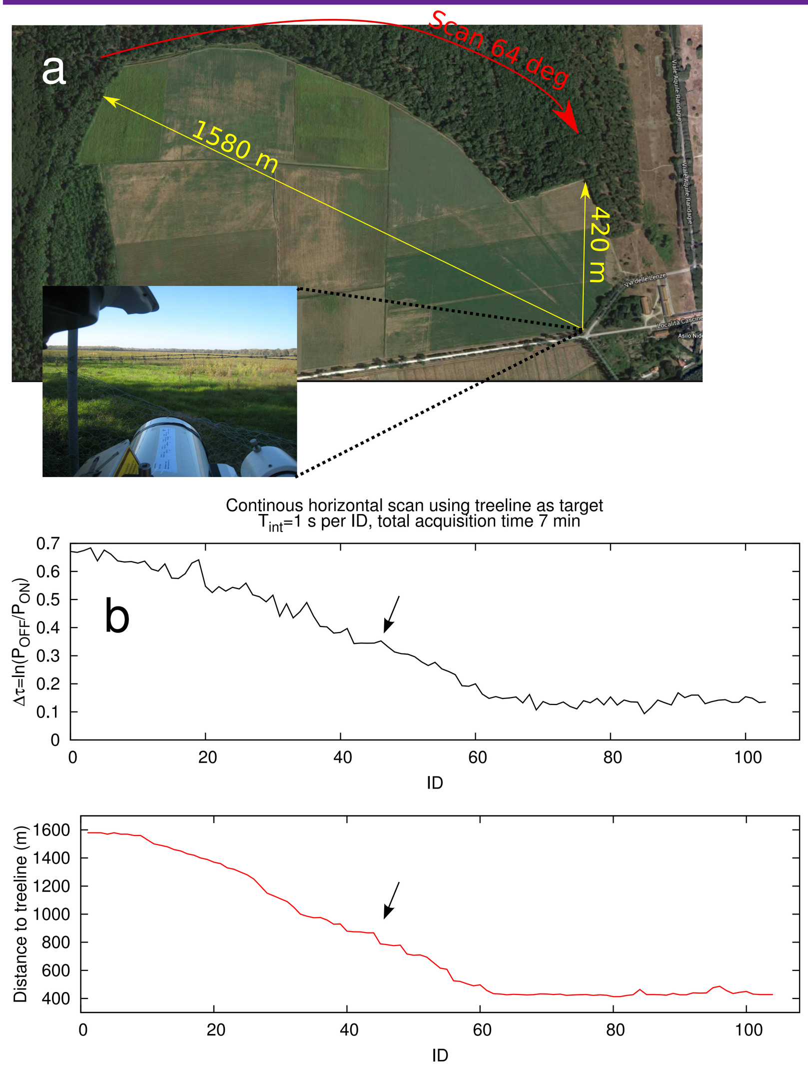
At the current stage the CO_2DIAL uses two amplitude modulated seed lasers (sine tones ~5 kHz) that are simultaneously amplified by an amplifier (EDFA). The instrument has been optimised for ruggedness, low weight (25 kg) and power consumption (70W). It is highly portable and platform independent. The instrument can be quickly mounted on an aircraft, car or operated with a pivot-tripod mode from a fixed point.

Verification and sensitivity tests



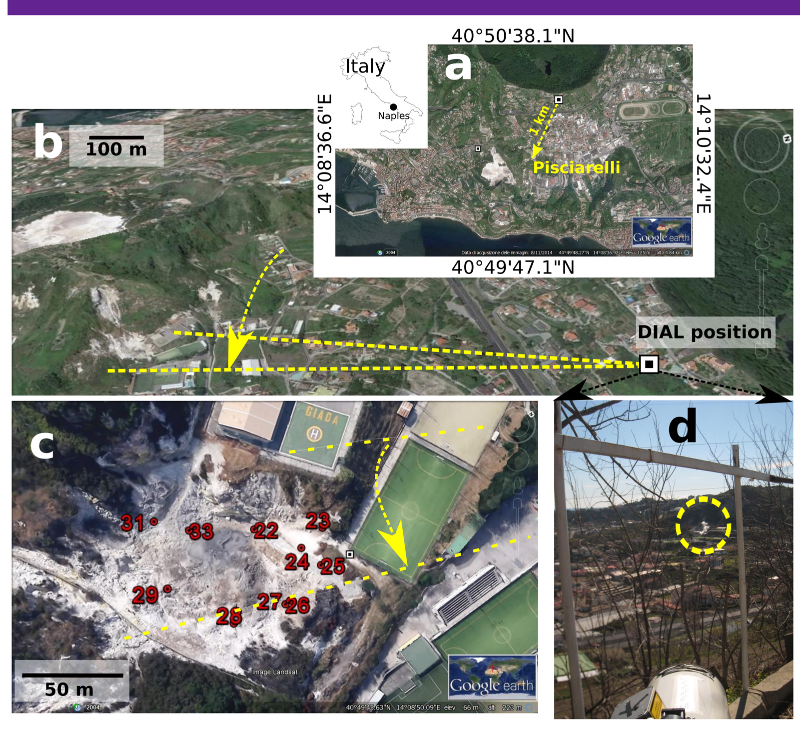
a) Result of a wavelength scan of the DIAL using a glass cell filled with CO_2 to calibrate ON wavelength. **b)** CO_2 was injected into the telescope (red arrows). When both lasers emitted at the OFF wavelength expected CO_2 absorption is zero and intensity ratio (grand ratio) should remain 1. Oscillations are caused by mechanical contraction of optics upon cooling (Joule Thompson effect)

Ambient CO_2 test

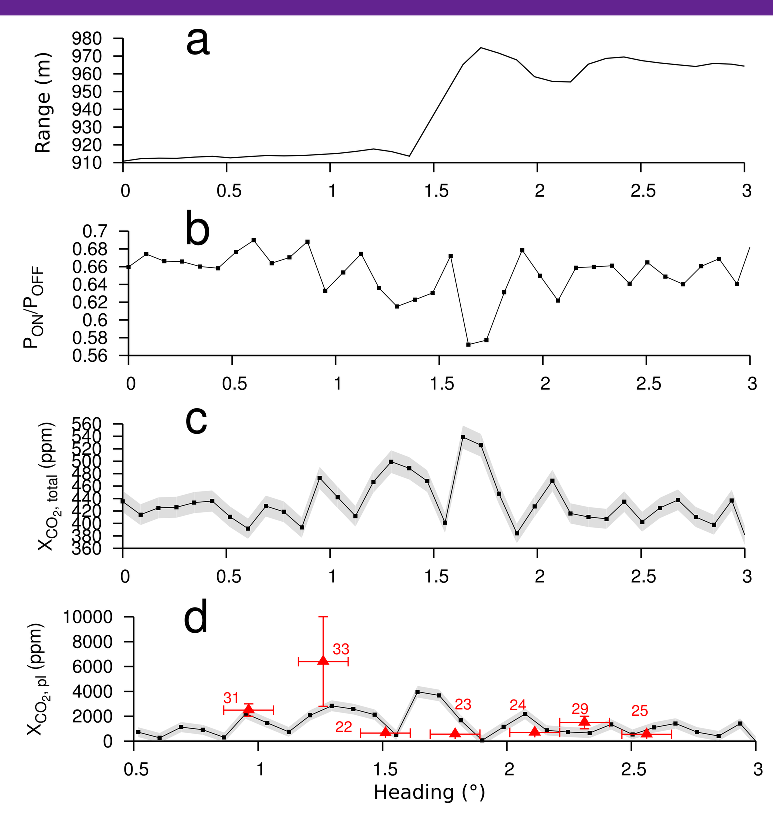


a) Aerial view (Google) showing the extension of an angular scan covering 64°. Tree line serves as hard target, back scattering emitted laser light. Photo shows view from DIAL towards tree line. **b)** Measured differential optical depths (logarithm of intensity ratios) and target distances. Integration time was 1 s per point (ID).

Scanning a volcanic plume at Campi Flegrei (Naples, Italy)



a) Map showing the location Pisciarelli fumaroles at the Campi Flegrei volcanic area. Arrow depicts distance and direction of the measurement field measurements. The origins of the arrow indicatea the CO_2DIAL location. **b)** Overview of the measurement geometry for Pisciarelli. The yellow dotted lines mark the angular extension of the scan **c)** Close up nadir view of the Pisciarelli fumarole field depicting the numbered locations were CO_2 mixing ratios have been measured in situ with a LICOR analyzer. **d)** Photo taken from the DIAL position showing the DIAL telescope aligned with the Pisciarelli fumarole (dotted circle).



Example of far field scan at Pisciarelli. **a)** Range measurements from the DLEM range finder LIDAR versus scan angle (heading) defining the path length. **b)** Grand ratio versus heading. **c)** Total column averaged CO_2 mixing ratio with measurement precision (1 SD) in grey. **d)** Average in-plume CO_2 mixing ratios derived from c). The numbered triangles depict the values and ranges as well as lateral position uncertainties of the in situ measurements (Figure on the left). Note that these have been acquired ~20h earlier thus they serve as approximate reference only. Moreover, mixing ratios in d) from the CO_2DIAL represent column averages with contributions from across the plume, while the in situ values show mixing ratios measured at a single point in the plume. The estimated CO_2 flux for this scan is **6.3 ± 2.7 kg/s (544 ± 233 tons/day)**.

Summary and Outlook

We have produced a DIAL for atmospheric CO_2 that offers unprecedented portability and hence flexibility (platform independent, easy transport overseas). It has a precision of currently 17600 ppm.m (11 ppm at 1600 m path length). We believe that the CO_2 DIAL will make a major contribution to volcano monitoring by providing a methodology to swiftly profile volcanic plumes. To fully realise the potential of the instrument and in preparation of the main field campaign along the Indonesian arc volcanoes, it is currently being further modified to increase precision.

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Nelson, D. H., Walters, D. L., Mackerrow, E. P., Schmitt, M. J., Quick, C. R., Porch, W. M., Petrin, R. R.: Wave optics simulation of atmospheric turbulence and reflective speckle effects in CO_2 lidar. Appl Opt., 39, 1857-71, 2000.