Title of research (EQC grant reference number)

Unmanned Aerial Vehicles ("Drones") for Measuring Volcanic Plumes (18/764)

Principal Investigator/s, Organisation/s

C. Ian Schipper (Victoria Unviersity of Wellington)

Bruce W. Christenson (GNS Science)

Yves Moussallam (CNRS-IRD, France)

Philipson Bani (CNRS-IRD, France)

Research team

The original research team (above) was effectively dispanded during the course of the research, such that effectively all development was performed exclusively by PI Schipper. However, a large number of international collaborators contributed directly to the work:

Cynthia Werner (USGS), Santiago Arellano (Chalmers University, Stockholm), Christoph Kern (USGS), Brendan McCormick-Kilbride (U. Manchester, UK), Emma J. Liu (U. College London, U.K.), Kieran Wood (U. Bristol, U.K.), Alessandro Aiuppa (Universita di Palermo, Italy), Gaetano Giudice (INGV, Italy), Marcello Bitetto (Universita di Palermo, Italy), Nicole Bobrowski (Uni Heidelberg, Germany), Céline Mandon (Yachay Tech University, Ecuador)

Key words

Unoccupied Aerial Systems, drones, volcanic gases, aerosols, volcano monitoring

Summary

We present details of a modular Unoccupied Aerial System (UAS, "drone") for comprehensive geochemical analysis of volcanic plumes. Our design prioritizes cost effectiveness, field maintainability, portability, and diversity of measurements. For this, several UAS types were tested before a final design was developed and produced. Furthermore, instruments needed to be minitaurized and made compatible with the flying platform. The result is a system that can be physically carried to remote launch sites by a single operator, yet is capable of: (1) 3D edifice visualization by photogrammetry; (2) measuring SO_2 flux by DOAS; (3) determining major gas (H_2O, CO_2, SO_2, H_2S) concentrations by MultiGAS; (4) collecting bulk aerosols and acidic gases (HCl, HF) with filter packs; (5) collecting size-resolved, native-state aerosols with cascade impactors; and (6) collecting plume gases for analysis of carbon isotopes in CO_2 ($\delta^{13}C_{CO2}$). We describe the UAS itself, its instrument modules, and its universal data telemetry system. The effectiveness of the system is demonstrated with data collected at Bagana volcano (PNG) and Ambrym Volcano (Vanuatu). The UAS system and its instruments represent a signficant advance in our ability to comprehensive measure the full chemistry of plumes emitted from active volcanoes. It is ready for deployment at any and all active volcanoes worldwide.

Introduction

The analysis of volcanic plumes is essential to understanding the degassing and eruptive processes of active volcanoes, and in turn for forecasting eruptions and determining the full range of eruptive hazards. Although essential, difficulty of access means that the gas and particles in volcanic plumes are rarely measured in a comprehensive way at active volcanoes - the primary issue being one of access, not instrumentation. Precise instruments exist for measuring volcanic gases in the field, but the data they can collect is only as good as our ability to physically deploy them directly in active plumes to sample gases that are sufficiently concentrated and that have not been modified by physiochemical dilution or reaction in the atmosphere. We will overcome fundamental barriers to plume studies by developing a modular, state-of-the-art, Unoccupied Aerial System (UAS, or "drone") analysis system, and applying this system to the study of active New Zealand volcanoes.

Objectives

Some crucial components of volcanic plumes (e.g., SO_2) can be measured remotely by spectroscopic methods (e.g., DOAS, UV Camera); but most (e.g., CO_2, H_2O, H_2S, Cl, F, isotopes, aerosols) require direct plume access. A holistic understanding of magmatic systems and their associated hazards can only be gained if all gas species can be determined. For example, influxes of CO_2 exsolved from magma at great depth can produce measurable spikes in CO_2/SO_2 ratios in advance of explosive eruptions (Aiuppa et al., 2007), discharge of halogens (Cl, F) can kill forests and livestock (Lowenstern et al., 2012), and particulate aerosol formation can cause carcinogenic compounds to be dispersed widely and erratically around active volcanic regions (Reich et al., 2009; Ilyinskaya et al., 2017).

There are also myriad physiochemical components of volcanic plumes that remain largely unknown, and that are not routinely measured. Stable isotopes of CO_2 ($\delta^{13}C$ and $\delta^{18}O$) are used to characterize regional variability in magma sources, but are difficult to measure (Sano and Williams, 1996; Schipper et al., 2017). Sulphur compounds are essential to determining the relative dominance of magmatic or hydrothermal processes (Fischer and Chiodini, 2015); however, sulphur is highly reactive and redox sensitive, such that distal measurements are not representative of source conditions (Baker and Moretti, 2011). A vast range of aerosol particles exist in plumes, including toxic metals, carcinogenic SiO_2, and ash; little is known, however, about the dispersal and potential impact of such particles (Ilyinskaya et al., 2017).

Before this project, our team had developed and carried out preliminary tests with a prototype UAS (Fig.1). The UAS allowed autonomous flight, GPS tracking, data telemetry, and stable flight performance to >6000 metres above sea level. Here, we developed, refined, tested, and applied a suite of instrument modules for measuring the full spectrum of volcanic plume components. By making the system modular and flexible, and by rigorously testing this system on currently degassing volcanoes of the Pacific, we arrive at an open platform that will be ready for immediate deployment in the event of future volcanic unrest, and to which new plume-measuring instruments can be adapted as they emerge in future.

The project consisted of three stages: (1) Expansion of the UAS fleet and modification of the UAS for work in active plumes; (2) Optimization of existing plume measurement technology into core modules for seamless integration with UAS; and (3) Development and testing of new equipment and protocols for measuring components of volcanic plumes that could not previously be achieved without UAS.

Conclusions and key findings

The UAS "drone" system

The UAV is a hexacopter with overall weight of 3 kg without battery or scientific payload. The main body is a three-tiered carbon fibre centre frame, from a hobby-grade Tarot® FY560. Unlike the original FY560 kit, the 16 mm carbon fibre boom arms are extended to 320 mm to accommodate 15" carbon fibre propellers. All mounting hardware is anodized aluminium from aftermarket drone hobby suppliers. A key component is the articulated arm mounts, which when extended have a 5° upward tilt for added stability in flight, and fold downward to allow the hexacopter to fit into a standard Pelican® Air 1605 case (Fig. 1A-B). The 16mm carbon fibre boom legs need to be fully removed to fit into the case, but are easily attached with two M3 hex screws.

Each of the six boom arms has a 40A Hobbywing® Electronic Speed Controller (ESC) mounted on the underside of aluminium, vibration-damping motor mounts. The motors are Sunnyskies® 4aXX, 340 kV brushless motors. Each motor and associated propeller is equipped with a spin-on quick release mounting system, so that all propellers can be mounted in less than a minute.

All electronics are sandwiched between the three body plates. The lower cavity contains an octagonal power distribution hub that delivers power to each of the six ESCs, the flight controller, and the auxiliary power system. The upper cavity houses the centre-mounted flight controller, receiver, video transmitter, data transmitter, and electronic switches. The top side of the frame body hosts the post-mounted GPS puck, a video-link antenna, and mounting points that are used for attachment of all instruments. The bottom side of the frame hosts a carbon fibre battery mount, and holders for additional 10 mm carbon fibre booms on which an action camera gimbal can be mounted.

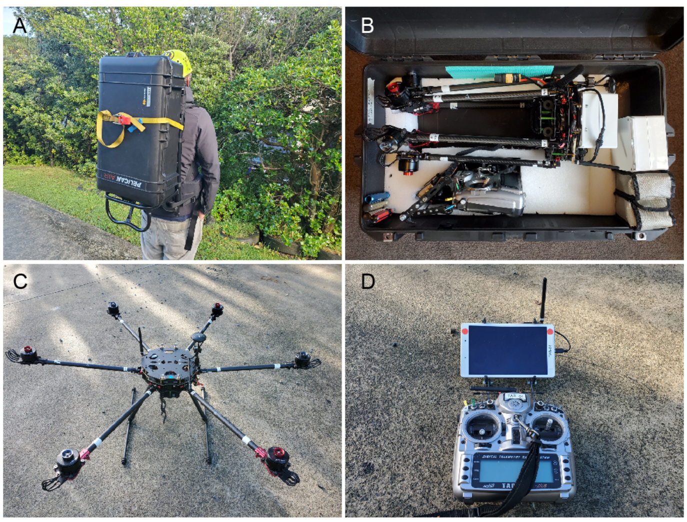

Figure 1. UAS system. A. Operator with full UAS and all modules carried comfortably in a single box. B. Interior of the box, with UAS, controller, multiple instruments and batteries. C. The hexacopter (without instrument) that is the final design from this work. D. The pilot's transmitter, with tablet for flight data and receiving radio for Universal Data Telemetry system.

The hexacopter is powered by 22.2 V (6S) Lithium Polymer (LiPo) batteries. Normally, we use two 8 Ah 3S (11.1 V) batteries connected in series. This is because an 8 Ah 3S battery is below 100 Wh, meaning that on most commercial airlines they can be carried in reasonable numbers without restriction.

Flight is controlled by a Holybro Pixhawk 4 flight controller, with Neo M8N GPS. The receiver is a Team Black Sheep® (TBS) Crossfire 8-channel RX, linked via Mavlink protocol to a 933 MHz TBS Crossfire transmitter module on a FRSky® Taranis XD9 radio. This flight control system was chosen because it gives long-range signal, and also allow native telemetry that can be displayed in real time on an operators tablet via the Qgroundcontrol® software. The hexacopter is also fitted with a TBS Unify Pro 5.8 GHz video transmitter for aerial videography and First Person View (FPV) applications.

All instruments are powered by the UAV battery. For this, auxiliary power is provided by a Castle Creations BEC Pro, set to drop the 22.2 main battery voltage to 12 V for powering instruments. The 12 V auxiliary power is split into five parallel channels: one always-on, three switchable from the radio via dedicated on/off switches, and one that is also switchable but is allotted permanently to the video transmitter.

In addition to the pilot's radio and tablet, there is also option to use a secondary base station. This consists of a laptop computer, FPV video receiver and screen, and data telemetry receiver.

Instrument Modules

(1) Aerial photography, videography, and FPV

Videography and aerial photography are not the main objectives of our UAS system. Although useful for examining volcanic edifices and for conducting photogrammatic structure-from-motion (SfM) surveys, current consumer-grade camera drones now far exceed what is possible with hobby-grade systems. However, having FPV and videography capability is a relatively easy add-on to any UAS: the FPV being useful for targeting certain features with a given scientific payload, and videography providing excellent overviews of the volcanic edifice and/or the opportunity for rudimentary SfM analysis.

Our system has plug-and-play accommodation for two types of camera systems. The default system is a low-cost real-time CCD camera that transmits live, but not recorded, video to a receiver on the base station. This system is useful for FPV verification of where the UAV is in relation to volcanic features. Additionally, there is an action camera (e.g., GoPro®) gimbal system available for tool less attachment in place of the CCD camera. This too transmits a live FPV feed to the base station, but also records HD video and/or photographs, which can then be processed using standard SfM software packages.

(2) Differential Optical Absorption Spectroscopy (DOAS)

The DOAS instrument includes an Ocean Optics Flame® spectrometer, with un ultraviolet window and 100 -140 nm grating, and a Garmin® 18X GPS receiver, both linked to an Azul® stick computer running Windows 10 (Fig. 2A-B). We initially tried using a DOAS system where all data processing and storage was handled with an onboard Beagle Bone computer, but this made data telemetry difficult. Therefore, the second and final design, generously guided by Christoph Kern (USGS) and Santiago Arellano (U. Chalmers), uses instead an oboard Windows computer that can natively run the open-source MobileDOAS program. MobileDOAS drives collection of UV spectra and GPS position data every second, and caluclates an SO_2 column amount linked to position. A simple Python script then takes the column amount and position data and transmits these via the Universal Data Telemetry system to the pilot's ground station.

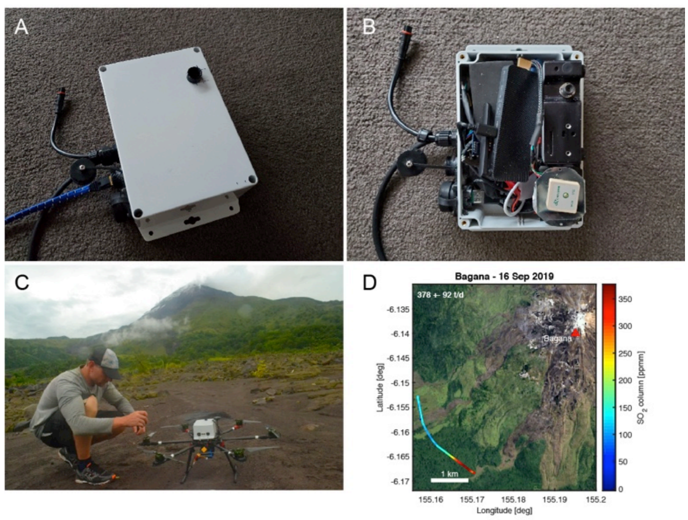

Figure 2. UAS DOAS system. A. Exterior of the DOAS enclosure, showing lens on top of instrument, and connections for power (12V), ethernet, USB data download, and data telemetry. B. Packed interior of isntrument. C. Schipper preparing for a DOAS flight in Papua New Guinea, with Bagana volcano in the background. D. Processed results of a UAS DOAS flight at Bagana volcano, yielding SO_2 flux of ~378 t/day.

Because the DOAS computer is driven by Windows, the enclosure for the instrument includes an ethernet port, via which a laptop computer must be connected at startup. The remote desktop software VPN is used from the laptop to launch mobileDOAS on the instrument. Once running, the laptop is disconnected and the DOAS is ready to fly.

The lens on the DOAS is upward-looking, with a direct-attach collimating lens maounted directly in the lid of the enclosure (Fig. 2A). The methodology for analysis is therefore to fly traverses below a volcanic plume. The UAS should not actually instersect the plume, but fly below it, looking up through the full plume column. The flight methodology for this instrument is therefore different to the others. There is essentially no risk of exposing the UAS to the harsh plume itself. However, long-distance flights are often required to capture the plume, depending on which direction it is being wind blown relative to the pilot's takeoff point.

Having the UAS DOAS technology led to Schipper being invited to join an expedition to Bagana volcano, Papua New Guinea, in Spetember 2019 (Fig. 2C). Satellite-based data suggest that Bagana is one of the world's top gas-emitting volcanoes, but inaccessibility and edifice instability have precluded it from ever having been measured. The expedition was funded by the Deep Carbon Observatory (DCO), led by Brendan McCormick-Kilbride (U. Manchester), and sought to achieve the world's first measurements of Bagana's SO_2 flux and plume chemistry. The DOAS results (Fig. 2D) contributed to the discovery that Bagana was actually emitting less SO_2 that satellite-derived data would suggest, indicating the necessity of not relying on space-based remote sensing techniques to understand degassing of large volcanoes (McCormick-Kilbride et al., 2020).

(3) Multiple Gas Analyzer (MultiGAS)

The MultiGAS instrument design is based on those routinely used by researchers at the Universita di Palermo and INGV (Italy). It draws plume gases through a series of sensors with a small pump operating at 0.6 L/min, recording the concentrations of CO_2, SO_2, H_2S, as well as relative humidity (RH) and temperature. Response times of the different sensors are correlated in the software of the onboard datalogger, and recorded to an onboard SD card and telemetred to the groundstation at 1 Hz. The sensors include a PP-Systems SBA-5 module that includes a near infrared CO_2 sensor (0-2000 ppm) and sensors for RH and and T. The sulfur species (SO_2 and H_2S) are determined with City electrochemical sensors, calibrated over the ranges of 0-200 ppm and 0-50 ppm, respectively. These are all housed in the same instrument box as all modules, with 3D printed housings for the sensors (Fig. 3A). The serial data link for telementry exists the enclosure with a aiplane-type connector that interfaces directly with the universal tata telemetry system onboard the UAS (see below).

One issue that was encountered with the CO_2 sensor (and others from different manufacturers), was electrochemical interference from the motors of the UAS. This tended to cause unstable background noise, to a degree that was unacceptable when attempting to measure dilute plumes. To overcome this, the MultiGAS instrument box was lined with copper tape (not shown), which immediately resolved the issue of interference.

In November, 2018, the UAS MultiGAS was deployed by Schipper at Marum crater of Ambrym volcano (Vanuatu). Ambrym is renowned as the world's most strongly-degassing volcano, and the single biggest point source of SO_2 on Earth. Figure 3B shows one example UAS MultiGAS flight over one of Marum crater's active plumes. The CO_2, SO_2, and H_2O concentrations are shown against time for the duration of this short flight, with excellent correspondence of peaks in volcanic gases for each gas species (Fig. 3C).

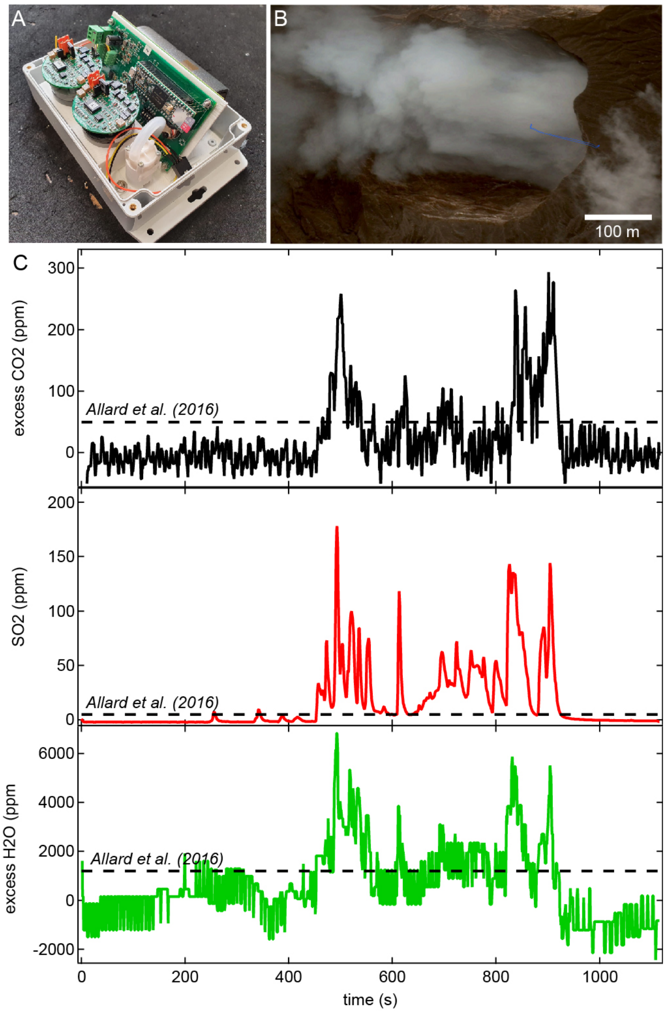

Figure 3. UAS MultiGAS system. A. The interior of the MultiGAS instrument during construction. B. Google Earth image of Marum crater, Ambrym volcano (Vanuatu), with thin blue line showing Uas flight path. C. Timeseries MultiGAs data recorded during the flight shown in B. CO_2 and H_2O are given as "excess" after subtraction of an average atmospheric background. On each panel of C, the horizontal dashed lines show the maximum concentations of these sepcies as determined by ground-based MultiGAS data at the same site (Allard et al., 2016)

The UAS fliglht path taken in this Ambrym example is not particularly ambitious. It involved simply flying ~100 metres from the takeoff point on the crater rim, and hovering in the plume for ~7 minutes. However, even this relatively simple test already demonstrates the utillity of UAS-based MultiGAS for gaining strong data signals. Previous MultiGAS data, using a similar – but ground based – instrument was collected at Marum crater of Ambrym by Allard et al. (2016). With their MultiGAS instrument on the rim of Marum crater, Allard et al. (2016) achieved a maximum excess CO_2 (CO_2 above background atmospheric levels) of ~50 ppm, whereas by flying only 100 metres over the same crater yielded a maximum excess CO_2 of ~300 ppm. Similarly, Allard et al.'s (2016) ground-based MultiGAS recorded up to 5 ppm SO_2, whereas our UAS MultiGAS recorded up to 190 ppm. Magmatic H_2O can be particularly difficult to determine in humid environments such as that in Vanuatu. Consequently, Allard et al. (2016) only measured up to ~1200 ppm above background, which was insufficeint to reliably deconvolute atmospheric and magmatic H_2O. Even in our simple UAS MultiGAS flight, we recorded excess H_2O >6000 ppm, with strong correlation between peaks in H_2O and other gases (Fig. 3C), clearly capturing pulses of magmatic H_2O emission. It reamains possible that there were changes in plume chemistry at Ambrym, between Allard et al.'s time of measurement and ours. However, there were no major changes in eruptive activity at Ambrym in the intervening time between their expedition and ours.

(4) Filter Packs

The filter pack instrument includes 4 components: (1) the filter pack assembly, (2) pump, (3) flow meter, and (4) single-chip processing computer (Fig. 4). The filter pack assembly is a standard 4-stage system. The leading filter is a 47 mm PTFE particulate filter, and this is followed by three 47 mm base-impregnated quartz or paper filters for acidic gases. The pump is a 12V, 5A diaphragm pump delivering ~7 l/min flow rate, which draws plume gases successively through the filter pack assembly and then a flow meter, and its operation is controlled by a switch on the pilot's transmitter. The flow meter operates via an always-on 12V connection, and displays both instantaneous flow rate and cumulative flow volume. The single-chip processing computer in the filter pack assembly receives analog voltages related to SO_2 concentration and temperature from the passive SO_2 sensor (see below) and the instantaneous flow rate from the flow meter. From these raw data, the computer calculates SO_2 concentration, temperature, instantaneous flow rate, cumulative flow volume, and cumulative SO_2 flow through the filter pack. These processed data are sent via serial data telemetry to the pilot and observer's ground stations.

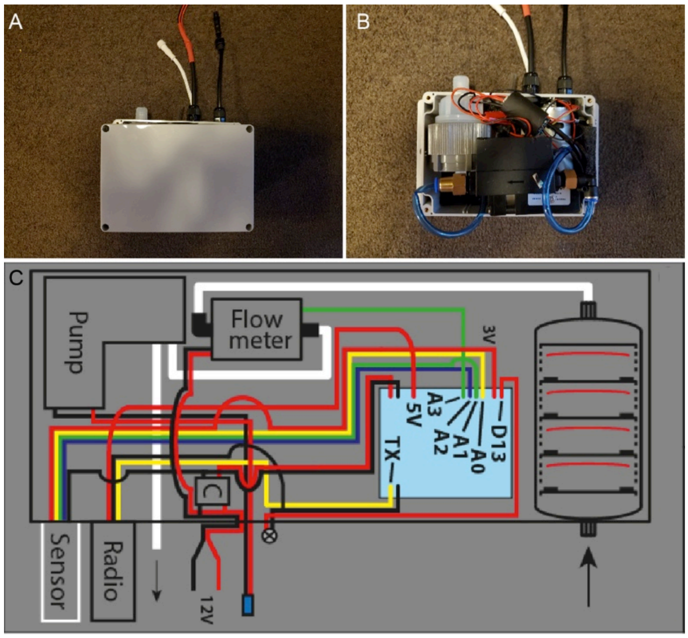

Figure 4. UAS Filter Pack system. A-B. Open and closed Filter Pack enclosures. C. Schematic of the instrument. "Sensor" and "Radio" refer to the Universal Data Telemetry system described below. The light blue box represents the Arduino single-chip computer that handles all incoming data streams and processes them before sending to the telemetry system.

The filter pack housing is bolted to the upper plate of the UAS. A single 12V always-on connection is made to the flow meter and single-chip computer, to ensure continuous data transmission, and to ensure that the cumulative flow volume can be read on the flow meter after the flight. The pump is connected to a switchable 12V connector. The pilot navigates the UAS into the plume, with live-steamed data on SO_2 concentration indicating when the plume has been encountered. The pump is then activated from the transmitter, to collect aerosols on the leading filter and to begin reaction of acid gases on the base-impregnated filters.

A key challenge inherent to the use of filter packs, is in determining when enough plume has been pumped through. It is desirable to have sufficient acidic gases reacted on the base-impregnated filters to get strong signals in ion chromatographic analysis (especially when seeking data on less abundant species such as HF), but without obscuring ratios of acidic gases by saturating the filters. Obtaining the ideal cumulative flow is thus a function of plume concentration and chosen flow rate and duration. Because the single-chip computer delivers measured SO_2 concentration and flow rate, the calculated cumulative SO_2 flow can be used as a guide to ensure that saturation is avoided.

The UAS filter pack instruments are ready for deployment. They were scheduled for deployment at White Island in Jan-Feb 2020, however this has been delayed due to the horrific eruption of December 2019. Plans are in process to deploy them at other volcanoes in the Pacific, and at White Island once it is safe and possible to access the island for scientific purposes. There are, however, good indications that the UAS Filter Packs will be a strong improvement on the traditional deployment of similar sampling devices on the rims of volcanic craters. An early test by our group at White Island. Two Filter pack samples collected by one of our early prototype UAS systems yielded trace metal aerosol concentrations that were two orders of magnitude more concentrated than samples collected on the rim (Mandon et al., 2019). We are confident that when we are able to return to White Island, our refined system will allow us to fully explore this rich data.

(5) Cascade Impactors

The cascade impactor instrument includes 4 components: (1) a 4-stage cascade impactor, (2) a programmable Leland Legacy® pump, (3) a 3-way solenoid switching valve, and (4) a single-chip processing computer (Fig. 5). The cascade impactor requires a precise gas flow rate of 9 l/min to be maintained during operation, even as filters become restricted due to particle accumulation. This requires the use of a programmable pump, which also has data logging capabilities. In this case, the programmable pump cannot be simply switched on and off by the pilot, because it requires manual initiation to achieve and maintain the 9 l/min of flow. Our simple solution to this issue is to install a switch-activated, 3-way solenoid valve between the cascade impactor and the programmable pump. This simple workaround allows the pump to be switched on before the flight, with the swiitching valve activated to direct flow through the cascade impactor. This is only done after the UAS has encountered the concentrated part of the plume from which a sample is to be taken, which is known by the pilot and observer monitoring live-feed of SO_2 concentration, delivered by the single-chip computer.

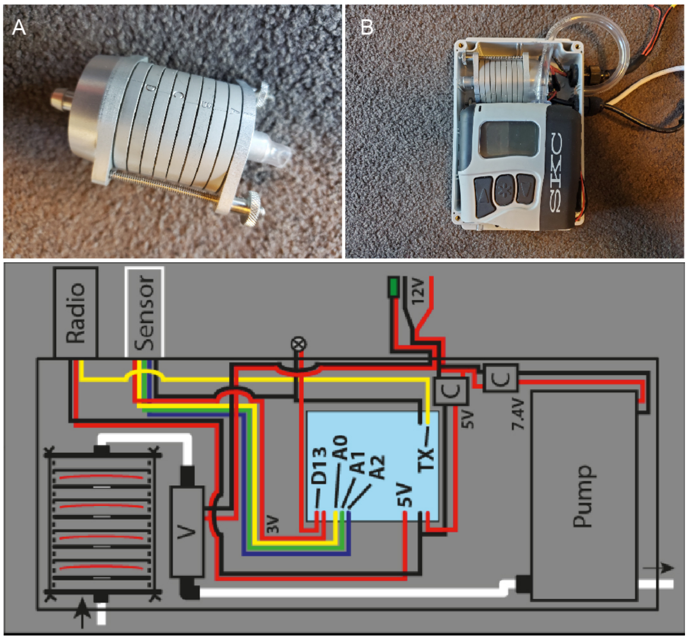

Figure 5. UAS Cascade Impactor system. A. The Souitas cascade impactor. B . Interior of the complete instrument. Note that the housing of the Leland Legacy pump had to be modified to suit attachement to the UAS. C. Schematic of the instrument. "Sensor" and "Radio" refer to the Universal Data Telemetry system described below. The lightblue box represents the Arduino single-chip computer that handles all incoming data streams and processes them before sending to the telemetry system.

The cascade impactor instrument was the last to be designed and built. Unfortunately, we were waiting until its completion for our final deployment trip to White Island, and this has been delayed due to the 2019 eruption. This instrument has only so far been tested in the laboratory.

(6) Plume sampling ($\delta^{13}C_{CO2}$)

For direct sampling of plume gases, we use a system that includes: (1) a pump, (2) three 3-way 12V gas solenoid valves, and (3) a single-chip computer (Fig. 6). With this system, up to three 0.5 – 1.0 l gas sample bags (Tedlar, or bi-layer foil bags) can be filled in a single flight. The usual objective of these samples is to analyze them for carbon isotopes in CO_2 ($\delta^{13}C$), but they are suitable for a wide range of analysis if returned to the laboratory (e.g., gas chromatography, S-isotopes, etc.).

Operation of the plume sampling module is by flying the system with three empty sample bags into the plume. Plume intersection is guaranteed by monitoring the telemetered SO_2 concentration data on the pilot's ground station. Once in the plume, the pump and valves are actuated manually from the pilot's transmitter. As a safeguard against in-air bursting, we use a small pump is insufficiently strong to overinflate or burst the sample bags. Once collection is complete, closure of the valves ensures that no gas is lost while the UAS is piloted back to base.

Tests with this system were completed at White Island in November 2018, and then subsequently in Vanuatu at Yasur and Ambrym volcanoes (Fig. 6D). Future work is planned for over the summit crater lake of Ruapehu. One noteworthy aspect of this system is that it is very inexpensive to build (<$25), but the breadth of information that can potentially gained from it is enormous, limited only by the range of laboratory techniques that are available for the samples' subsequent analysis.

Universal data telemetry system

When any instrument is deployed by UAS, it is crucial to have real-time, in-flight data telemetry as indications of if/when scientific targets are being met. Even in seemingly simple flight conditions, parallax during flights can make it nearly impossible to judge if/when the UAS is in the area of interest for analysis or sampling.

Our UAS system uses a universal data telemetry system, whereby rather than having a different telemetry radio mounted in each instrument, there is a LoRa 433 MHz, 1 W, telemetry unit, equipped with twin 15 dbi antennae, sandwiched permanently in the UAS. This single transmitter is used with all instruments, via different data sources and streams, and provides a live data feed that is observed and recorded directly on the pilot's tablet, and on the base station laptop (if used). In addition to guiding in-flight movements, this system also provides triple redundancy for data storage. Furthermore, most of the instruments also require that the pilot have knowledge of when the UAS is indeed in the voclanic plume. For this, each UAS is equipped with a passive (e.g., no pump is used) SPEC® analogue SO_2 sensor module. Wiring of the SO_2 sensor and data telemetry units are as follows:

1) DOAS: SO_2 sensor not required. Instrument cnnects to radio, and python script sends SO_2 column density and GPS position to ground station.
2) MultiGAS: Passive SO_2 sensor is not used. Full data stream from all sensors in the MultiGAS instrument are directly telemetered to the ground station.
3) Filter Packs: Instrument plugs into both the passive SO_2 sensor and the radio. Data from SO_2 sensor is combined with that from onboard flow meter, and these are sent to the ground station.
4) Cascade Impactor: Instrument plugs into the SO_2 sensor and radio. Only SO_2 concentration and temperature are telemetered to the ground station.
5) Plume Sampling System: As for Cascade Impactor

Data streams from the UAS are received on LoRa radios that are identical to those on the UAS. One of these receivers is permanently mounted on the pilot's tablet mounting system, and connects to the tablet via a Serial-to-USB ("on the go", or "OTG") cable. This allows the pilot to see and log all incoming data. Another radio can be plugged directly into a groundstation laptop, to log data and be observed by the pilot or another observer.

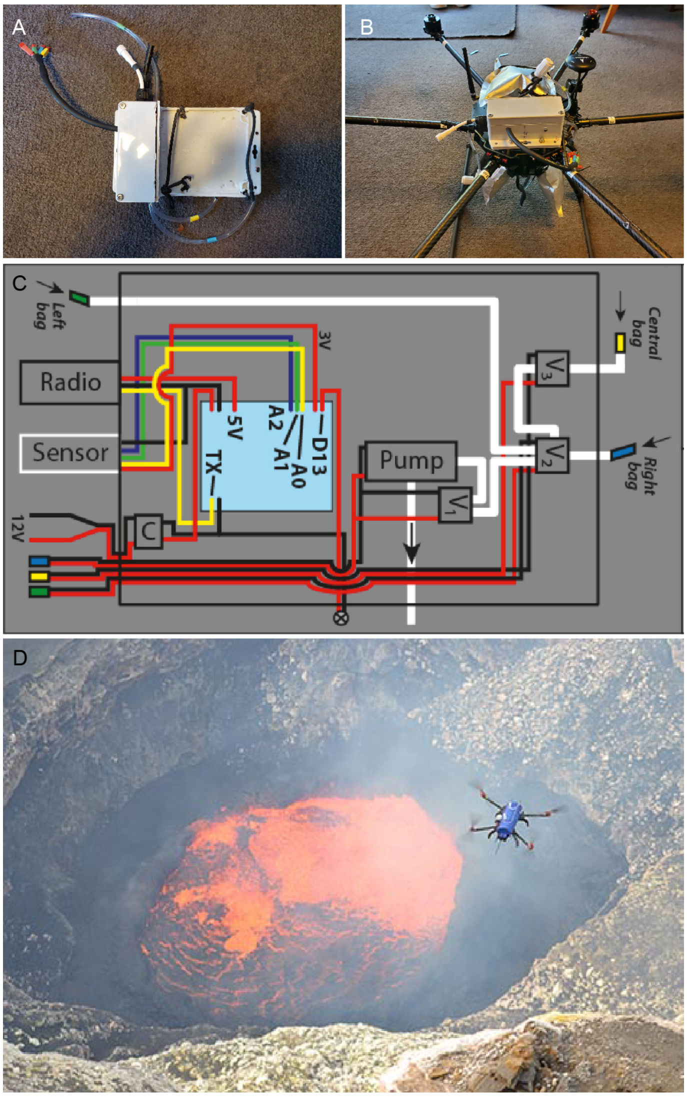

Figure 6. UAS Plume Sampling system. A. image of the enclosure. All electronics are housed wihtin the partial enclosure, with the flat area avaialbel for holding one of the sample bags. B. The plume sampling system (shown with bags inflated) on the final hexacopter UAS. C. Schematic of the instrument. "Sensor" and "Radio" refer to the Universal Data Telemetry system described below. The lightblue box represents the Arduino single-chip computer that handles all incoming data streams and processes them before sending to the telemetry system. D. The plume sampling system in action at Marum crater of Ambrym volcano (Vanuatu). Note that is is shown on the quadcopter, that has now been superceded by the helxacopter as in B.

***Impact** (ie, how this research reduces the impact of natural disaster on people and property)*

Especially now, that the international movement of people and goods has been curtailed by the global pandemic, it is more important than ever that New Zealand have its own, resilient, and self-sufficient means to monitor and understand our active volcanoes. Before this project, similar technologies existed in the international community, but we now have an entirely new set of capabilities at our fingertips. Although the eruption of White Island has delayed the final deployment of our UAS system, we are poised and ready to react to any and all volcanic unrest in the future.

Future work

The recent tragedy at White Island highlighted the importance of monitoring unrest, assessing risk, and mitigating hazards at New Zealand's volcanoes. For this, we must leverage all available technology to improve monitoring, and establish symbiotic collaboration between key stakeholders. Volcanology stands to benefit immensely from UAS, which now allow the safe in situ collection and analysis of volcanic plumes (gases + particulate aerosols) from previously inaccessible areas. This heralds a step-change in volcano monitoring, because volcanic plume chemistry is a direct indicator of magmatic versus hydrothermal dominance in a sub-volcanic system, and changes in plume chemistry can be key indicators of impending eruptions.

Our capacity for UAS volcanic plume analysis has been progressing, but we are not yet taking advantage of all available technologies and efforts of different groups have been relatively siloed. Development has focused on multirotor that are effective for short-range deployments (e.g., at places like White Island), but we still lack fixed-wing UAS capability for long-range deployments at NZ's larger edifices (e.g., Ruapehu). Furthermore, techniques developed in the academic community have yet to be implemented in regular volcano monitoring community. The best outcomes for New Zealanders who live and work in an inherently dynamic volcanic landscape will be gained through development of the best available tools for monitoring volcanic unrest, and coordinated use of these tools by all branches of the NZ and global volcanological community.

Future work should focus on two areas:

(1) Technology. We will expand the multirotor fleet and diversify the plume imaging and monitoring tools it carries. We will also develop and implement fixed-wing UAVs, to permit long-range and long-duration instrument deployments. The outcome will be the capacity to measure all types of plumes – whether magmatic or hydrothermal; from all of NZ's volcanoes – whether currently accessible or not.

(2) Partnership. We will establish a partnership between VUW and GNS Science to formalize the UAV systems as integral parts of the volcanic monitoring toolkit used by GeoNet. The outcome will be improved data streams that allow the research community to produce robust models of volcanic system evolution, and the monitoring community with additional types of data with which to assess volcanic hazards. We will also build an enduring collaboration with international UAV experts, to ensure that our work is at the global cutting edge.

Acknowledgements

Many collaborators contributed directly to the work:

Cynthia Werner (USGS), Santiago Arellano (Chalmers University, Stockholm), Christoph Kern (USGS), Brendan McCormick-Kilbride (U. Manchester, UK), Emma J. Liu (U. College London, U.K.), Kieran Wood (U. Bristol, U.K.), Alessandro Aiuppa (Universita di Palermo, Italy), Gaetano Giudice (INGV, Italy), Marcello Bitetto (Universita di Palermo, Italy), Nicole Bobrowski (Uni Heidelberg, Germany), Céline Mandon (Yachay Tech University, Ecuador)

In particular, I would like to thank Emma J. Liu (U. College London). Emma recognized the work I was doing in NZ and invited me to join her Deep Carbon Observatory project A.B.O.V.E. in Papua New Guinea. This was an invaluable experience, both for development of design principles, and for establishing research connections in PNG.

I would also like to thank Chuck Getter of the Coastal Drone Academy (Or, USA). Chuck's enthusiasm for drones as teaching tools is inspiring, and he welcomed me and my family to collaborate with him in the USA.

References

Aiuppa, A., Moretti, R., Federico, C., Giuidice, G., Gurrieri, S., Liuzzo, M., Papale, P., Shinohara, H., Valenza, M., 2007. Forecasting Etna eruptions by real-time observation of volcanic gas composition. Geology 35, 1115-1118.

Allard, P., Aiuppa, A., Bani, P., Métrich, N., Bertagnini, A., Gauthier, P.-J., Shinohara, H., Sawyer, G.M., Parello, F., Bagnato, E., Pelletier, B., Garabiti, E., 2016. Prodigious emission rates and magma degassing budget of major, trace and radioactive volatile species from Ambrym basaltic volcano, Vanuatu island Arc. J Volcanol Geotherm Res 322, 119-143.

Baker, D.R., Moretti, R., 2011. Modeling the solubility of sulfur in magmas: A 50-year old geochemical challenge, in: Behrens, H., Webster, J.D. (Eds.), Sulfur in Magmas and Melts: Its Importance for Natural and Technical Processes. Mineralogical Society of America, Chantilly, pp. 167-213.

Fischer, T.P., Chiodini, G., 2015. Volcanic, Magmatic and Hydrothermal Gases, in: Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H., Stix, J. (Eds.), The Encyclopedia of Volcanoes (2nd Edition). Elsevier, Amsterdam, pp. 779-797.

Ilyinskaya, E., Schmidt, A., Mather, T.A., Pope, F.D., Witham, C., Baxter, P., Jóhannsson, T., Pfeffer, M., Barsotti, S., Singh, A., Sanderson, P., Bergsson, B., McCormick Kilbride, B., Donovan, A., Peters, N., Oppenheimer, C., Edmonds, M., 2017. Understanding the environmental impacts of large fissure eruptions: Aerosol and gas emissions from the 2014-2015 Holuhraun eruption (Iceland). Earth Planet Sci Lett 472, 309-322.

Lowenstern, J.B., Bleick, H., Vazquez, J.A., Castro, J.M., Larson, P.B., 2012. Degassing of Cl, F, Li, and Be during extrusion and crystallization of the rhyolite dome at Volcán Chaitén, Chile during 2008 and 2009. Bull Volcanol 74, 2303-2319.

Mandon, C.L., Christenson, B.W., Schipper, C.I., Seward, T.M., Garaebiti, E., 2019. Metal transport in volcanic plumes: A case study at White Island and Yasur volcanoes. J Volcanol Geotherm Res 369, 155-171.

McCormick-Kilbride, B., Liu, E.J., Wood, K., Wilkes, T., Schipper, C.I., Mulina, K., Richardson, T., Werner, C., McGonigle, A.J.S., Pering, T., Aiuppa, A., Bitetto, M., Giudice, G., Itakarai, I., 2020. First measurements of volcanic gas composition at Bagana volcano, Papua New Guinea, EGU General Assembly, Vienna.

Reich, M., Zúñiga, A., Amigo, Á., Vargas, G., Morata, D., Palacios, C., Parada, M.Á., Garreaud, R.D., 2009. Formation of cristobalite nanofibers during explosive volcanic eruptions. Geology 37, 435-438.

Sano, Y., Williams, S.N., 1996. Fluxes of mantle and subducted carbon along convergent plate boundaries. Geophys Res Lett 23, 2749-2752.

Schipper, C.I., Moussallam, Y., Curtis, A., Peters, N., Barnie, T., Bani, P., Jost, H.J., Hamilton, D., Aiuppa, A., Tamburello, G., Giudice, G., 2017. Isotopically ($\delta^{13}C$ and $\delta^{18}O$) heavy volcanic plumes from Central Andean volcanoes: A field study. Bull Volcanol 79, 65.

Outputs and Dissemination -

This project led to me being invited to participate in the Deep Carbon Observatory project A.B.O.V.E. project in Papua New Guinea. (https://deepcarbon.net/project/above#Overview). This is a high-profile international project for which an online documentary was made (https://www.youtube.com/watch?v=H6xMlCrRJyc).

Following the A.B.O.V.E. project, I was then invited back to PNG to conduct drone work on Bagana Volcano. This work was featured twice on TVNZ:

https://www.tvnz.co.nz/one-news/new-zealand/kiwi-scientist-returns-world-first-mission-flying-drone-over-volcano?auto=6092790851001

https://www.newshub.co.nz/home/world/2019/10/stunning-footage-shows-papua-new-guinea-s-bagana-volcano-leaking-toxic-gases.html

Links to publications/theses

This manuscript is currently in peer-review. It is a direct outcome of the EQC-funded work, that led to me being invited to participate in this international consortium:

Liu EJ, … Schipper CI, ... (in review) Aerial Strategies advance volcanic gas measurements at inaccessible, strongly degassing volcanoes. Science Advances.

The work on Bagana volcano (PNG) has been presented at the European Geophysical Union annual meeting:

McCormick-Kilbride, B., Liu, E.J., Wood, K., Wilkes, T., Schipper, C.I., Mulina, K., Richardson, T., Werner, C., McGonigle, A.J.S., Pering, T., Aiuppa, A., Bitetto, M., Giudice, G., Itakarai, I., 2020. First measurements of volcanic gas composition at Bagana volcano, Papua New Guinea, EGU General Assembly, Vienna.

I have accepted an invitation to write a UAV/drone-based paper for a 2021 special issue of Geosciences. This will be the summary of the EQC-funded work. The technical parts of the paper are written, but final manuscript preparation requires deployment at White Island (or an analogue volcano) once Covid-19 restictions are lifted.

List of key end users

- Academic volcanologists
- Volcano monitoring personnel (GNS/GeoNET)
- Other Earth Scientists requiring UAS for different (non-volcanological) applications
- Civil Defense Authorities