In situ observations and sampling of volcanic emissions with unmanned aircraft: a NASA/UCR case study at Turrialba Volcano, Costa Rica

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1. OVERVIEW

Volcanoes and volcanic activity exist in infinite variety on this planet, and volcanic eruptions are among the most powerful and compact surface expressions of the earth's internal energy—and among the most dangerous. Thus, there is high societal importance in understanding the full range of volcanic activity, and in assessing the considerable risks volcanoes pose to human endeavors and lives. Our scientific knowledge of the effects of volcanic eruptions at the surface of the earth, particularly lava flows, pyroclastic flows, and associated gravity-driven flows, while far from complete, is vastly aided by the fact that activity and resultant deposits are at least *accessible* on the ground. In contrast, our scientific knowledge of, and experience with, more transient and *inaccessible* airborne volcanic emissions are far less, with access coming only from remote sensing observations, and few in situ data from sporadic heroic or inadvertent airborne encounters (e.g., Pieri et al., 2002; Carn et al., 2011). Yet airborne emissions, as the European experience during the 2010 airspace shutdown from airborne Icelandic ash well illustrated, can have devastating regional—even global—economic effects, and directly threaten human life.

Difficulties in predicting the trajectories and extents of drifting ash clouds have centrally contributed to inadvertent aircraft encounters with ash plumes. In December of 1989, a drifting ash cloud from the eruption of Redoubt Volcano caused perhaps the most serious and iconic incident to date, namely the near-fatal simultaneously all-engine shutdown of a Boeing 747-400 series aircraft northeast of Anchorage, Alaska (e.g., Casadevall, 1994). In early 2000, a drifting ash plume (probably having nucleated and having been masked by ice aerosols) several hundred miles northeast of Iceland caused severe engine damage to a Douglas Aircraft Company DC-8-72 research aircraft operated by the United States National Aeronautics and Space Administration (NASA) on a transit flight to measure ozone above Scandinavia and Russia (Pieri et al., 2002; Grindle and Burcham, 2003). Both unexpected encounters happened, in part, because of inadequate knowledge of the position and properties (e.g., ash injection altitude, concentration distributions) of these two volcanic clouds, thus calling into question our knowledge of boundary conditions and plume composition, as inputs to both mass retrieval models and predictive models for cloud trajectories (Casadevall, 1994; Pieri et al., 2002; Grindle and Burcham, 2003).

The current worldwide network of nine Volcanic Ash Advisory Centers (VAACs) was originally set up in the 1990s by the International Civil Aviation Organization (ICAO—agency of the United Nations), as part of the International Airways Volcano Watch (IAVW) to improve forecasts of the locations of ash clouds from volcanic eruptions in response to incidents like those mentioned above, where commercial aircraft had flown through volcanic ash resulting in partial or total loss of engine power. It became clear that volcanic ash was dangerous to aircraft and that to protect aircraft, pilots needed to be appraised in a timely manner, in order to divert their flight around the cloud, or to file flight plans that avoided contaminated airspace. The individual VAACs are run as part of national weather forecasting organizations of the country where they are based, e.g. the United States National Oceans and Atmospheres Administration (US NOAA) or the United Kingdom Met Office (UKMET). ICAO and its VAACs issue warnings to air traffic regarding the location and extent of ash-contaminated airspace after explosive eruptions. Their analyses are made public in the form of Volcanic Ash Advisories (VAAs) and often incorporate the results of computer simulation models called Volcanic Ash Transport and Dispersion (VATD) algorithms (Stunder et al., 2007).

Generally, speaking, in the years preceding and after the Alaska Redoubt 1989 ash encounter, ICAO best practices dictated a total avoidance of such airspace—a zero tolerance policy (e.g,. "…*pilots should plan to avoid known volcanic ash*." [Foreman, 1994]). Nearly all airlines followed this procedure, and since most ash warnings were for volcanoes around the Pacific Rim, this procedure worked reasonably well because, mostly, there was plenty of empty oceanic airspace through which to divert aircraft around drifting volcanic clouds.

The eruption of Eyjafjallajökull, beginning in March of 2010 (GVP, 2010), changed everything. Fine ash erupting from its Fimmvörðuháls vent drifted between Iceland, over the Faroe Islands, and into the airspace of the United Kingdom, as well as that of Scandinavia, and then on into continental Europe (e.g., Bursik et al., 2012). In the north Atlantic region and across the landmass of Europe, the luxury of "excess" airspace didn't exist. The London VAAC, with jurisdiction over the affected airspace, issued their first of many Volcanic Ash Advisories (VAAs; #2010/001, 14 April 1200Z) for the Icelandic eruption. This VAA then triggered a Significant Meteorological Information (SIGMET—meteorological information concerning aircraft safety) advisory from UKMET. As a result of this SIGMET, consistent with ICAO recommendations, the European Organization for the Safety of Air Navigation (EUROCONTROL) officially closed down controlled airspace to instrument flight rules (IFR) traffic throughout the UK and northern and central Europe continuously from 15-23 April 2010, and then intermittently for months afterward, much to the consternation of passengers and airline operators alike (Burgess, 2012).

As the days and weeks wore on, pressure from the public and airlines mounted to allow at least a limited number of flights (Brannigan, 2012). "Test flights" of empty passenger and research aircraft were conducted by airlines, manufacturers, and government agencies (e.g., Birnfield 2010, EUFAR 2010, Golding 2010, Jentink and Karwal 2010, Rauthe-Schöch 2010, Rindlisbacher 2010, Weinzierl, 2010).

Eventually, on 19 April 2011 the transport ministers of the European Commission approved a three-tiered risk-based classification of airspace to get stranded aircraft and passengers flying (Sorensen, 2010). They were (a) "*no fly zones or black zones*" (ash concentration > 4000μg/m^3; operations fully restricted); (b) "*enhanced procedures zones*" (grey zones: 2000-4000μg/m^3; red zones 200-2000μg/m^3; operations permitted with appropriate Member State oversight)"; and "*normal zones*" (white zones: <200μg/m^3; no flight restrictions).

Nevertheless, apocryphal reports surfaced, describing incidents where military aircraft in Belgium and Finland suffered serious internal engine damage after just a few minutes of flight within contaminated airspace (e.g., Bittooth, 2010; Flightglobal, 2010). In fact, "specific threshold values of concentration being used have not been rigorously explained in the open literature and no engine certification for ash exists (Guffanti, 2012)."

Thus, while previous to the Eyjafjallajökull 2010 eruption, it was generally accepted within the aviation community that zero ash tolerance (i.e., "zero risk") was the policy most appropriate for safe operation in the presence of drifting volcanic ash clouds or plumes emitting from active vents, economic (Oxford Economics 2012) and social pressures forced a revised policy in the European theater that accepts limited risk. This new policy has put enormous pressure on researchers to provide accurate and precise estimates of volcanic ash concentration and ash variability within airspace transited by commercial and general aviation, as well as by military aircraft (Guffanti 2010). Because of the nearly total lack of systematic in situ validation of operative models, both for deriving airborne ash concentrations from remote sensing data, and for prediction of ash cloud trajectories through the affected airspace, strong international impetus has developed to find ways to safely fly into ash plumes and clouds to measure their properties and to sample them. For instance Airbus and easyJet have mounted their own technical efforts in this area with Dr. Fred Prata of the Norwiegian Air Institute, to deploy the Airborne Volcanic Object Infrared Detector (AVOID) forward-looking infrared ash detection system, on their aircraft (Prata, 2011). At the time of the 2010 eruptions in Iceland, the ability to accomplish such tasks was essentially non-existent, except for a few small experimental efforts and a couple of chance airborne encounters.

Thus, the Eyjafjallajökull-Fimmvörðuháls 2010 eruption starkly illustrated the limitations of existing validation data, as airline operators vainly sought *confirmed* quantitative estimates of airborne ash concentrations in an attempt to estimate the hazard to turbine engines presented by ash contaminated airspace (Ian Davies, easyJet Ltd.—personal communication). Ash and gas concentrations derived from analysis of satellite remote sensing data (e.g. Geostationary Operational Environmental Satellite [GOES], Advanced Very High Resolution Radiometer [AVHRR], Advanced Spaceborne Thermal Emission and Reflection [ASTER] radiometer, and the Spinning Enhanced Visible and Infrared Imager [SEVIRI]), the main source of data on such phenomena, were then (and remain still) un-validated by in situ data.

In this paper, we describe how robotic **u**nmanned **a**erial **v**ehicles (herein called UAVs) can address a variety of measurements that are currently beyond the reach of manned aircraft, mainly for reasons of crew safety, but also because of the endurance required. The direct measurements and sampling that can be achieved in such UAV sorties address serious gaps in our present knowledge of the basic science of volcanic processes, as well as provide important validation data for estimations of volcanogenic ash and gas concentrations gleaned using remote sensing techniques. These data, in turn, constrain key proximal and distal boundary conditions for aerosol and gas transport models (e.g., Stunder et al., 2007; Webley et al., 2009, 2010), on which are based a number of decisions and evaluations by hazard responders and regulatory agencies. The current situation in which such estimates and models remain systematically un-validated is untenable.

At the present time, NASA Global Hawk (44 ft long, 116 ft wingspan, gross takeoff weight of 26,750 lb, ceiling 60,000 (or 60K) ft above sea level (ASL)—Figure 1a) and NASA Ikhana (36 ft long, 66 ft wingspan, gross takeoff weight of 10,500 lb, ceiling 25K ft ASL—Figure 1b; civilian version of the well-known Predator UAV) are among the most capable, sophisticated, and successful UAV platforms anywhere in terms of range and payload (e.g., Springer, 2013). For certain, well-posed eruption response missions, their long range and endurance, their ability to operate at high altitude, and their relatively large payload capabilities make them ideal platforms. They do, however, require substantial ground support because they are complicated, and are thus expensive to operate and have long preparation lead times. They also represent large capital investments by government agencies and the risk-benefit of operating them in ash contaminated airspace is somewhat problematic. Thus, it is most appropriate to deploy them at the distal margins of dilute volcanogenic plumes and clouds, or above volcanic plumes where possible, in zones that are of low risk to UAV health, for both down-looking remote sensing of volcanic plumes, as well as some limited in situ sampling, or as mother ships to small deployable micro-UAV glide-sondes for atmospheric profile and aerosol and gas sampling.

The medium sized **S**ensor **I**ntegrated **E**nvironmental **R**emote **R**esearch **A**ircraft—SIERRA, Figure 2, Figure 11a) operated by NASA Ames Research Center (ARC) with moderate endurance and payload capabilities, has demonstrated utility for scientific missions in harsh and remote environments (e.g., the 2009 NASA Characterization of Arctic Sea Ice Experiment [CASIE]). SIERRA would be appropriate for eruptions where very fast response is key, and where the theater of operations is relatively near the volcano at altitudes <12Kft.

Its much lower operating costs compared to NASA flagship UAVs make it less risk-averse, yet it can still carry substantial payloads (e.g., miniaturized mass spectrometer). When alternatively powered by batteries or fuel cells, and thus relatively insensitive to ash ingestion, SIERRA will be capable of extending the range of manned observations, both remote sensing and in situ, into the most ash-dense and gas-dense parts of eruption plumes, in all weather, and at night in proximity to hazardous terrain. Micro UAVs such as the Aerovironment Inc. Dragon Eye (Figure 3a,b,c) are even more flexible and can be more easily sacrificed, when necessary, yet may still be able to carry out useful scientific missions. Aerostats (e.g., tethered balloons and kites) are also appropriate platforms where measurements are desired over a particular place near a volcano for extended periods of time.

To illustrate how the current generation of small UAVs, aerostats, and available instruments can be used to investigate relatively low altitude (<12Kft ASL) plumes from passively emitting volcanoes, we briefly describe a case study from our ongoing field study at Turrialba Volcano in Costa Rica. Our goal at Turrialba is to undertake a systematic series of in situ measurements of volcanogenic SO_2 and other gases, as well as aerosols, in conjunction with over-flights by the NASA Terra earth orbital platform with the ASTER instrument onboard.

2. Remote Sensing Methods

Satellite remote sensing data has been used for many years to detect volcanic clouds, both volcanic ash (e.g., Prata 1989a; Schneider et al., 1995; Dean et al, 2004) and sulfur dioxide (e.g., Realmuto et al., 1994; Watson et al., 2004, Krotkov et al., 2010). To detect and track volcanic ash, AVHRR, GOES, ASTER, Moderate Resolution Imaging Spectroradiometer (MODIS) (e.g. Carn et al., 2009; Webley et al., 2009) and the Atmospheric Infrared Sounder (AIRS) (e.g. Prata et al., 2010) have all been used for clouds of varying magnitude and size. Data to use in scientific applications reductions from these sensors all exploit the reverse absorption effect (Prata 1989a, 1989b) of dry silicate ash within the thermal infrared portion (8-12μm) of the electromagnetic spectrum. A negative arithmetic difference between the radiance of two bands centered at 10.6 μm and 12 μm generally indicates dry, fine grained ash between 1–12 μm in effective radius (Rose et al., 2000a). As ash clouds become more diffuse, the ash cloud emitted radiance will fall below the detection limit of the retrieval methods (e.g., Schneider et al., 1995a). In situ data from volcanic ash clouds is very rare (Pieri et al., 2002; Schumann et al., 2010) and more in situ sampling is needed. Important in situ parameters include particle size distribution, ash cloud height, and ash cloud thickness including spatial (horizontal and vertical) and temporal variability of ash concentration.

Similarly, satellite imagery is routinely used for the detection and tracking of volcanic SO_2, particularly data from ASTER, MODIS, and AIRS in the infrared, and OMI in the ultraviolet. SO_2 and ash are most often emitted simultaneously by an erupting volcano, as happened during the Kasatochi Volcano in 2008 eruption (Prata et al., 2010; Krotov et al., 2010). However, this is not always the case, as seen during the El Chichon eruption in 1982 (Schneider et al., 1999). Nevertheless, SO_2, by virtue of its low ambient background concentration (e.g., 4-5 parts per billion by volume [ppbv]), is often relied on operationally as a proxy indicator for volcanic ash (e.g., Kreuger et al., 2009). Thus, understanding how solid aerosols (e.g., ash) and SO_2 are related, and under what conditions they are or are not spatially correlated, is key to understanding ambient chemical processes with the cloud (Rose et al., 2000a). For instance, do SO_2 and solid aerosols fractionate on the basis of altitude during some eruptions, and/or on the basis of chemical reactions within volcanic plumes? Is this phenomena somehow related to the observed post-eruption hydrolysis of SO_2? Sampling of volcanic ash clouds, across the full range of observed sizes, is very much needed to fully resolve and understand these processes. Thus manned and UAV-based in situ observations loom large in sorting the relevant variables for this problem, especially when used to validate correlated orbital data.

To determine the hazard to aviation from volcanic clouds, volcanic ash transport and dispersion models (VATD) are used by the operational agencies (Stunder et al., 2007) as well as for research and past event analyzes (D'Amours et al., 2010; Webley et al., 2010). PUFF, a trajectory volcanic ash tracking model developed by colleagues at the University of Alaska, Fairbanks (Searcy et al., 1998), and the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT—Stunder et al., 2007) are two Lagrangian trajectory volcanic ash tracking models that are used currently. [The latter is a new improved version of the previous Volcanic Ash Forecast Transport and Dispersion (VAFTAD) model (Hefter and Stunder, 1993).] Such models are sensitive to plume source conditions at the eruption vent. Parameters such as total eruption mass, eruption rate, particle size-frequency distribution, neutral buoyancy altitude (i.e., plume top altitude), vertical ash concentration distribution, and SO_2 flux are critical to accurate formulations of trajectories.

3. THE NEED FOR CALIBRATION AND VALIDATION OF REMOTE SENSING DATA AND MODELS

On the ground, gas/ash sampling at active vents is a difficult and dangerous gambit, for example, having cost the lives of six volcanologists during the 1993 Galeras eruption (Baxter and Gresham, 1997; Kerr, 1993). Airborne sampling with manned aircraft can also pose severe risks to aircraft engines and crews, even in dilute plumes (~1000-2000$\mu g/m^3$)(P. Allard, personal communication; W. Rose, personal communication), let alone in plumes with high ash concentrations that are opaque to upwelling TIR radiation.

UAV observations proximal to the eruption site provide a much more direct determination of critical VATD model input parameters than are available currently from near-field (i.e., ground-based) and orbital remote sensing. In addition, direct chemical sampling of volcanogenic gases (especially SO_2) provide important inputs for newer models that include atmospheric chemistry (e.g., WRF-Chem—Steensen et al., 2010, 2012; Webley et al., 2012).

In distal regions, where plumes are more dilute, it is of crucial importance to use in situ sampling to validate comparisons between VATD model predictions and satellite data, from which maps of the ash and SO_2 concentrations are generated, and to test satellite-based erupted mass airborne mass and concentration retrieval limits. Where airborne volcanic ash concentrations are within acceptable aircraft engine safety limits, it may be possible to use manned airborne laboratories for comprehensive sampling and near-field remote sensing observations (e.g., spectro-photometry, Laser Imaging Detection and Ranging (LIDAR) probes). Where ash concentrations are prohibitively high, the use of UAVs is indicated for accurate concentration data, especially regarding aircraft ash hazards (e.g., Prata and Tupper, 2009); in an early paper, Prata and Kerkmann (2007) point out that Wen and Rose (1994) suggest model mass loading estimation errors may be as high as 40–50%. Subsequent work by Pavolonis (2010) and Steensen et al. (2012) suggest that such retrievals are sensitive to determinations of plume brightness temperatures, and improved techniques in this area may result in lower mass loading estimation errors.

The second important aspect, the validation of transport model results, involves validating trajectory prediction models using remote sensing results. Once an explosive eruption is known to have occurred, the determination of whether and where an airborne volcanic hazard exists generally has two aspects, both of which are model dependent: (1) prediction of the position of the progressively expanding ash/gas plume utilizing Lagrangian, Eulerian, or hybrid transport models (e.g., HYSPLIT or PUFF), and (2) the verification and validation of the plume position and ash concentrations predicted by the transport models using a combination of remote sensing satellite observations, image processing techniques (i.e., de-correlation stretches, brightness temperature differences), and ash/gas retrieval models, as well pilot reports, and ground observations when they are available (Hufford et al., 2000; Dean et al., 2004). Often, the initial eruption conditions are unobserved or only poorly estimated, thus providing considerable uncertainty in predictions of even basic plume geographic extent. If a small flexible UAV system were deployed at a restless volcano in advance of an eruption, it could respond almost immediately to developing events, providing data within the first few minutes, if not within hours, after the onset of the eruption. Real time data streams are becoming the norm. Thus, data on the near-initial conditions of the activity could be in the hands of first responders, modelers, and those involved in tasking and analyzing data from remote sensing platforms almost immediately.

Currently, we have no comprehensive in situ validation data for ash and SO_2 loading models. For instance, currently, it is not possible to directly relate TIR and UV ash-loading retrieval models to actual in-plume concentrations, for either low altitude (<10,000ft) or high altitude (>10,000ft) volcanogenic plumes and clouds. To date all validation attempts have been vicarious (e.g., utilizing correlating spectrometers [COSPECs], or newer Flyspec [miniature COSPEC] or Differential Optical Absorption Spectrometer [DOAS] devices) which themselves rely on models of plume dynamics and line-of-sight atmospheric species absorption to derive SO_2 flux). Some preliminary attempts at such correlations with small SO_2 sensors, and one compact mass-spectrometer have been made by us (Diaz et al., 2010) and a few others (M. Watson and A. Durant-personal communication).

Ultimately, the overall goal among researchers and hazard responders is to implement hardware and methodologies that will enable routine in situ characterizations of volcanic plumes and clouds for the calibration and validation of remote sensing data (e.g., ASTER, OMI, SEVIRI, MODIS), and for future orbital instruments like the planned NASA Hyperspectral InfraRed

Spectrometer (HyspIRI). The success of current efforts in the North America and Europe along this line has three important prompt benefits:

- the provision of new basic scientific observational capabilities, including the improvement of our ability to detect, analyze, monitor, model, and predict aviation ash hazards;
- improvement in the accuracy and precision of our ability to detect, analyze, monitor, model emissions from quiescently emitted tropospheric plumes at restless volcanoes, changes in which often precede eruptions; and
- the definition of scientific and operational requirements for validating remote sensing observations of plumes at or above the tropopause—especially those from massive explosive eruptions that pose the most pressing hazard to aircraft.

4. In situ observations and sampling

4.1 The limits of manned airborne observations

One of the main scientific impacts of the Eyjafjallajökull eruption in 2010 has been the realization that in situ sampling is a critical necessity, not only for prompt assessments of local and regional airborne ash hazards, but also for important validation and calibration activities with respect to relevant remote sensing instruments. An impressive array of existing and new European manned aircraft have be specifically modified and/or adapted for sorties into, around, and over volcanic clouds and plumes is a direct result of the Icelandic 2010 eruption experience. For example during the Eyjafjallajökull crisis, the EUropean Facility for Airborne Research (EUFAR, a pan-European consortium) fielded an aggregate of 70 research flights, by a dozen participating operators from almost as many countries, flying over 10^5km, for about 250 flight hours. Notable aircraft used during this campaign, among others, are the UK Met Office/National Environment Research Council (NERC) Facility for Airborne Atmospheric Measurements (FAAM) British Aerospace BAe146 (transport aircraft—11 flights), and the German Aerospace Center (Deutsches Zentrum für Luft- and Raumfahrt—DLR) Falcon 20 (business jet—17flights), the Metair Dimona (Switzerland, powered glider—9 flights), and the Dutch National Aerospace Research Laboratory (Nationaal Lucht- en Ruimtevaartlaboratorium–NLR) Cessna Citation (business jet—7 flights). Instruments flown included imagers, LIDAR systems, gas analyzers (typically CO, CO_2, CH_4, O_3, SO_2, NO_x), in situ particle counters and particle size frequency-distribution samplers (0.1-960 um), aerosol counters (volatile and non-volatile), filter sampling devices, mass spectrometers, and radiometers (EUFAR, 2010). (In the U.S., NASA is currently investigating similar manned aircraft approaches [Paul Lundgren, JPL—personal communication; Tom Mace—NASA Dryden Flight Research Center, personal communication] that could produce "quick response" manned platforms within a few years.)

The EUFAR flight campaigns are significant because they represent the first dedicated systematic attempt to conduct airborne in situ measurements during a major volcanic ash cloud event at the regional scale. Equal in importance to the prodigious amount scientific data collected, are the lessons learned from the experience. A number of important conclusions benefiting the airborne ash hazard community can be drawn based on their experience (EUFAR, 2010):

- The uncertainty of remote sensing measurements can reach two orders of magnitude if the scattering index (real and imaginary) and the density of the particles are not correctly specified.
- Research aircraft can safely penetrate diffuse parts of plumes and collect particles in situ to precisely characterize important parameters. For reasons of crew safety, UAVs are necessary for penetration of the dense parts of the plume to measure representative values of the mass flux and particle size distribution (for dispersion model inputs). Emphases should be put on developing miniaturized instruments for small UAVs.
- Typical research aircraft latency (e.g., preflight preparation) was 1 to 2 days, when the aircraft were available. Procedures for recall from other less urgent field campaigns are key.
- Trajectory and concentration prediction vulnerabilities arise because of uncertainties in eruption models as inputs to dispersion models. In situ measurements of ash concentration, size distribution, scattering properties and density are necessary to improve plume models, and remote sensing retrieval techniques.
- There is an urgent need to develop instrumented UAVs with two main goals: (a) to improve boundary condition constraints on volcanological models of eruptions to improve inputs for meteorological ash dispersion and trajectory models; and (b) to provide crisis responders with routine measurements of important intrinsic plume parameters (e.g., ash concentration, particle size-frequency distribution, altitude profile of ash distribution, plume neutral buoyancy height).

4.2 Extending our reach: unmanned vehicles

Here, we briefly review some of the volcanological problems that UAVs can and will, address in the realm of volcanology, especially in the context of explosive eruptions. A catalog of available platforms is beyond our scope, and, in any case, is evolving rapidly, as are the available instrument complements. Instead, in the final sections, we describe some of the technology and applications that are known to us to perhaps inform the reader as to a few approaches, technologies and strategies for that may be of use.

UAV robots can dare to fly near and over restless volcanoes, taking risks that would be unwise for their human counterparts, either on the ground or in the air. Generally speaking, robotic aircraft will be most useful with respect to making in situ time-series concentration measurements, and sampling, gas (e.g., SO_2, CO_2, CH_4, H_2S, He) and aerosols (i.e., ash,

H_2SO_{4liq}, HCl_{liq}), while simultaneously taking important atmospheric altitudinal profile data of temperature, pressure, humidity, and wind velocity (Pieri et al., 2012). Such measurements and samples inform our understanding of basic volcanogenic processes in eruption plumes, as well as in more quiescent persistent passive outgassing. Changes in the rate of such steady emissions, either an increase *or* decrease, can herald increased volcano restlessness, and may be a relatively prompt eruption harbinger.

Another modern technology that has gained vastly in its application to volcanoes and eruptions is multispectral remote sensing, mostly from orbit (e.g., Pieri and Abrams, 2004, 2005), but also from aircraft (e.g., Realmuto et al., 1992. 1994; Abrams et al., 1996). Such data consist of both directly reflected solar energy at wavelengths shorter than about 2.5µm, and of re-emitted solar energy at wavelengths longer than about 7µm. Between those two values, at least during the day, upwelling radiation is a mixture of the two. Such radiation, either reflected or emitted contains valuable information about the composition and concentration of volcanogenic gases and aerosols, and is perceived and recorded by orbital instruments.

During and after eruptions, such data are the prime sources of information on the airborne concentrations and mass distributions of volcanic eruption products (e.g., gases and ash), as well as their location and progression through the troposphere and the stratosphere. Typically, instruments will acquire data from a nadir perspective, so upwelling radiation from the earth's surface is attenuated by the intervening volcanogenic material—models that relate the amount of radiation received to the degree of along-path absorption thus tend to estimate the erupted mass (aerosols or gas) in the atmosphere between the sensor and the surface, the so-called "column abundance" (i.e., mass/area). Ash or gas concentration (mass/volume) is then derived by estimating a plume or cloud thickness.

Often the altitude of such eruption *plumes* (emission cloud still "attached" to the source vent) and drifting volcanic *clouds* (cloud of erupted material that is no longer connected to the source vent) is only poorly estimated. This is usually accomplished by comparing perceived average temperature of the feature to meteorological atmospheric temperature vs. altitude profile estimates, under the assumption that the cloud is in radiative equilibrium with the surrounding atmosphere (it's often not)(e.g., Bursik et al., 2012; Tupper et al., 2009). Usually, the thickness of the plume or cloud is only poorly known. Still worse, Lagrangian models for predicting ash trajectories in the ensuing post-eruption hours and days, can depend critically on estimates of the altitude vs. ash concentration of the eruption column, and the so-called "injection altitude" of the ash particulates, as well as their size-frequency distribution (e.g., Bursik et al., 2012; Graf et al., 1999).

Predictions of volcanic cloud trajectories often depend crucially on the injection altitude of the major fraction of erupted ash (e.g., Bursik et al., 2012; Mastin et al., 2009), especially when winds are stratified, as is routinely observed (Bursik 2001; Bursik et al., 2009). Nevertheless, these parameters are often only poorly known, estimated on the basis of previous eruptions, or on samples of ash fallout underneath such plumes or clouds (e.g., Mastin et al., 2009). Such deposits are typically composed of the coarser fractions, thus leaving open the actual distribution of the fine fraction that is still airborne. Errors in estimating such parameters have contributed to inaccuracies in volcanic cloud position predictions, which resulted in aircraft ash encounters, and potential uncertainties in the errors associated with model predictions during the 2010 Eyjafjallajökull eruption episodes (Bursik et al., 2012).

Clearly, unmanned aircraft can be sent into the most ash-concentrated core areas of volcanic plumes and clouds, with no risk to crews, although with moderate to possibly high risk to the aircraft, and within areas that are typically put under temporary flight restriction (TRF) by civil air authorities. Thus UAVs, to be effective for volcanological investigations should be capable of conducting the measurements desired, but not so expensive as to deter their deployment because of perceived risk, given recognition that the device may be sacrificed. With that caveat, it's clear that technology exists to map the lateral and vertical extents of the plume, and within core zones of the plume or cloud. Concentration measurements and sampling of aerosol abundance, sizes, and compositions can be accomplished in this high hazard zone. UAVs in the small to medium size range can be pre-positioned near a restless volcano if it shows signs of awakening, or can be forward-deployed as air cargo to a potential eruption site on quick notice. Thus, as first-responders become more familiar with their capabilities and expert in their deployment, and when the platforms and instruments are able to provide data in real time, UAVs are likely to become vital, and immediately available operational tools during volcanic crises.

Potential disadvantages of such UAV systems are mainly those of logistics and bureaucracy. If a volcano of interest is remote, it can be difficult to deploy a UAV to that area (e.g., Aleutian Islands in Alaska, USA). For active volcanoes near populated areas (e.g., Sakurajima Volcano, near Kagoshima City, Japan; Mt. Etna near Catania, Sicily, Italy; Mt. Rainier, near Seattle, Washington, USA), there are often issues of getting flight clearances because of the presence of manned commercial, military, and general aviation aircraft, although during a volcanic crisis, that restriction would seem to be at least somewhat paradoxical. Nevertheless, desirable flight testing of UAVs in the flight environments around and above such areas before crises occur is generally problematic. Because some countries are sensitive to the exporting of their advanced potentially dual-use technology to international venues (currently, UAV systems often fall under such scrutiny), there may be issues in getting permission to use such technology outside the home country, even under crisis conditions.

Current UAV platforms exhibit a strong correlation between empty mass (e.g., size), performance, and instrumental capability. Thus, smaller UAVs may be less capable than required, though more expendable. Larger UAVs, though more capable, are probably viewed as less expendable because of program economics. One solution to this problem that we are pursuing is the leveraging of cutting-edge miniaturization of instrumentation and infrastructure (e.g., communications gear) for spacecraft applications for small-to-micro UAV applications. Thus, optical particle counters, aerosol impactors, aerosol optical absorption analyzers, UV-visible-infrared multispectral and hyperspectral imaging spectrometers, radiometers, LIDARS, and radars, are all possible.

Balloons, both free-flying and tethered, are relatively uncomplicated UAV platform choices and have been a standard tool for meteorological observations for many years. With respect to volcano studies, a pioneering effort by Belousov and Belousova (2004) involved the use of tethered balloons to conduct basic ash collection within the emission plume of Karymsky Volcano in Kamchatka. Most recently, in the UK, the University of Reading, the University of Herfordshire, and Oxford University (Harrison et al., 2010) collaborated on a free-flying instrumented weather balloon within an eruption cloud from Eyjafjallajökull in April 2010 over Scotland, reporting strong electrostatic charging. In 2008, a free-flying altitude-keeping balloon was flown over the Island of Hawaii in a collaboration between the University of Bristol (UK), Smith College (USA), and Michigan Tech University (USA) to conduct SO_2 and CO_2 measurements in the gas plume from Kilauea Volcano (M. Watson—personal communication). Comparable efforts by the authors are underway at Turrialba Volcano in Costa Rica to measure SO_2 concentrations in its steady eruption plume (see following section) using tethered weather balloons with small SO_2-sonde payloads, for the first time in coordination with ASTER and OMI observations.

The earliest efforts to use free flying fixed wing UAVs for volcanic gas sampling known to the authors was undertaken in 2002 within two independent projects. The first was a gas chromatograph suspended beneath a parafoil device (University of South Florida, the Southwest Research Institute, the University of Miami, Dr. Tim Dixon, Principal Investigator). The other was for an Aerosonde micro-UAV aircraft (Holland, 1992) with a miniaturized SO_2 sensor (JPL and the Aerosonde Corporation; Pieri, 2005), both of which encountered technical and regulatory difficulties. The JPL project, however, continued at a low level, eventually resulting in a miniaturized SO_2 sensor that was flown by co-authors Pieri and Abtahi on a micro-UAV (2m wingspan; 1kg payload), in collaboration with the NASA Wallops Flight Facility. At about that time in Japan (2000-2001), the Yamaha Corporation conducted surveillance imaging flights at Unzen Volcano and at Mt. Usu (Sato, 2003). McGonigle et al. (2008) reported on airborne CO_2 measurements at Vulcano Island in Italy using a small UAV helicopter, and Saggiani et al. (2007) described flights of the INGV Raven aircraft over Stromboli Volcano.

Also, during this time in the United States and Europe, as the popularity of small UAVs grew, the regulatory environment progressively stiffened, as regulators were increasingly hesitant to approve even scientific or disaster response UAV flights within mixed air traffic environments of national airspaces (e.g., Karp and Pasztor, 2006). Rule compliant test flights became more and more difficult near populated areas, and increased airspace clearance, pilot currency, and aircraft review requirements, applied to even the hobby-class radio-controlled UAVs, became prohibitive (personal communication—G. Bland, NASA). Currently, in the United States, the operation of small UAVs for scientific or business purposes, even though the identical aircraft can be operated legally as a recreational model by a radio-control hobbyists, now requires nearly the same piloting, airspace clearance, and aircraft safety reviews as a commercial aircraft (FAA, 2005, 2013; Aero News Network, 2011; Egan, 2012). The same situation exists in much of Europe (e.g., Wezeman, 2007).

Unsurprisingly, civil aviation authorities in more remote and less populated areas, with less air traffic, such as Central America, offer substantial relief from these high-traffic area requirements. As is happening elsewhere, however, authorities there are turning their attention to the challenges and advantages that UAVs represent to the use of their airspace (e.g., ICAO, 2011; Quesada, 2012). In areas, such as Costa Rica, where substantial volcanic hazards often exist, local populations stand to benefit from the use of UAVs and related technologies to mitigate serious local and regional hazards (e.g., Leff, 2011; Manrique, 2012). In that country, for instance, specific UAV airspace clearances are currently issued directly by the office of the Director General for Civil Aviation (DGAC) on a case-by-case basis (personal communication—A.V. Segura, Sub-Director General) and are monitored during operations by the Air Surveillance Service of Costa Rica (personal communication—Capt. A. Romaro).

5. Case study and technology roadmap: Turrialba Volcano, Costa Rica

The final section, a case study, briefly summarizes our efforts to develop and test small and relatively inexpensive lighter-than-air and fixed wing UAV platforms in Costa Rica at Turrialba Volcano (Diaz et al., 2011a,b; Diaz et al., 2012; Pieri et al., 2012). We view Turrialba as an appropriate natural laboratory where it is possible to test and prove platforms and instrumentation in low-level steady state volcanogenic gas and aerosol emissions at moderate altitudes (<12Kft ASL), where good technical infrastructure support exists, and where there is good physical access to the volcano. Being able to operate effectively in this relatively benign volcanic environment is a *sine qua non* with respect to approaching investigations within the much more difficult and demanding high altitude environment (>30Kft ASL) where emissions from large explosive eruptions often reside and range through, and where transiting aircraft face substantial danger from turbine engine ash ingestion (e.g., Casadevall, 1994; Pieri et al., 2002; Grindle and Burcham, 2003; Bursik et al., 2009; Carn et al., 2011).

5.1 Background

Volcán Turrialba, (Figures 4a,b; 5a,b,c,d) a massive basaltic-to-dacitic stratovolcano, is the most southeastern of Costa Rica's young volcanoes. It is the second tallest volcano in Central America (3340m ASL; 500km^2 plan area) next to Irazú on its western flank, both overlooking the city of

Cartago. These two large stratovolcanoes are only separated by about 10km, thus their combined volumes make up the most massive such complex in Central America (Carr et al., 1990, Reagan et al., 2006). Three craters make up its currently active summit complex (generally now continuously erupting SO_2, steam, and CO_2 from its south-westernmost vent), from which most activity from Turrialba has been sourced, however, there are two pyroclastic cones on its southwest flank (Smithsonian 2011). At least five major explosive eruptions have been documented at Turrialba over the past 3500 years, and a series of explosive eruptions in 1864 and 1866 produced summit pyroclastic flows and ash fallout in the Central Valley. Lahars extended into surrounding towns (Reagan et al., 2006). Because of its dense centripetal valley network, very limited vegetation coverage (now further compromised by sulfuric acid rain and CO_2 seepage causing extensive tree-kills as observed in the field in March 2012 by Pieri and Diaz) combined with frequent rainfall, Turrialba currently presents a serious hazard to people living on and near it (Duarte, 1990; Reagan et al., 2006). Currently, it has begun a new eruptive phase and recent in situ airborne mass spectrometer observations of increased helium output, reported by Diaz and Pieri, suggest that new magma has moved into the system (Diaz et al., 2010). Increased seismic activity and substantially increased fumarolic activity have been observed since 1998 (Barboza et al., 2000; Fernández et al., 2002; Barboza et al., 2003; Mora et al., 2004; Reagan et al., 2006). Given this recent history and current observations (e.g., Diaz et al., 2010; Martini et al., 2010; Campion et al., 2012) it is likely that Turrialba will again experience explosive eruptions.

5.2 Science and Operations

Given the current restless state of this large and threatening volcanic edifice, the understanding and monitoring of its persistent current atmospheric emissions are important and their systematic study may offer clues to future eruptive behavior of the volcano, especially in the near term. To monitor and further study its dynamic activity, we are taking a multiple-prong approach that could serve as a template for studying other volcanoes, and which takes advantage of new emerging technology to acquire data that are probably otherwise unobtainable. Aspects of our research program include (1) systematic monitoring of Turrialba from orbit, primarily with the ASTER instrument, and especially with its thermal infrared (TIR) camera; (2) in situ observations from aerostats and free-flying UAVs, designed as much as possible to be conducted during ASTER overpasses—so-called "sub-orbital" observations in typical NASA parlance; and (3) reconciliation of the orbital results with in situ data in order to validate mass retrieval and transport models. Since Turrialba is predominately a low altitude (10-12Kft ASL) SO_2 emitter, with light ash emissions, it offers a relatively benign airspace and ground environment, at least currently, and thus a good environment for testing and developing our hardware and software.

Our science objectives are comprehensive, and reflect the new opportunities that deployments of relatively small and economical airborne platforms potentially can offer. Overall, of course, we want to increase our fundamental knowledge of volcanic plume characteristics by intimately observing their dynamics and sampling their composition. Of particular interest is the determination of the primary injection altitude and concentrations of emissions at that altitude, a crucial boundary condition for many transport models, and difficult, if not impossible to do from orbit. The additional overall objective, clearly, will be to understand how remote sensing instrument response relates to physical and chemical properties of the eruption plume. Systematically achieving this objective will provide fundamentally new instrument and model calibration and validation data. We are trying to understand (a) what the ash and gas concentration thresholds are for existing and future instrumentation, (b) how well we can scale local, in-situ measurements to entire plumes, given that the distributions of materials within plumes are not uniform, and (d) how much ash and gas, while present outside the orbital instrument response envelope, is nevertheless still present. This is of particular relevance to air safety issues.

The basic measurements we are making are (1) concentration of SO_2, CO_2, and water vapor, as well as other volcanic gases at parts-per-billion by volume (ppbv) and parts-per-million by volume (ppmv) levels, as well as concentration (e.g., $\mu g/m^3$) and size-frequency distribution of any ash, with careful attention to their correspondence to the drop off in response function in ASTER at the edges of plumes; (2) measurement of the sub-plume ground temperature and evaluate the effect of plume-shadowing on the flux of upwelling TIR radiation in the context of SO_2 retrieval models; (3) measurement of ash and SO_2 properties near the eruption column to determine distribution with respect to altitude above the vent, for initialization of transport dispersion model simulations (e.g., PUFF, HYSPLIT), and finally (4) to measure loss of SO_2 as a function of downwind distance to compare with the dispersion models used for operational forecasts. All of these measurements are accessible to the aerostats and UAVs described below, and are currently underway.

As we undertake this work, we are acutely aware of the operational challenges of simultaneously operating several types of UAVs (e.g., multiple fixed-wing, multiple lighter-than-air craft, free-flying vs. aerostat) simultaneously within the airspace around Turrialba, and are benefitting from our previous work at this volcano (e.g., Diaz et al., 2001, 2002, 2010). Nevertheless, that complexity also yields synergistic benefits, and so part of our work is to evaluate our fleet of UAV platforms to assess their performance in meeting volcanological science goals. We are particularly interested in evaluating how our instrumentation and aircraft behave in harsh environments under autonomous operation in airspace close to volcanoes. Currently, we are in the first year of a three year NASA project to carry out in situ observations in the Turrialba plume. We are conducting our work three types of unmanned airborne platforms: (1) *aerostats* i.e., tethered balloons, and occasionally kites; (2) *micro-UAVs (µUAVs)*, i.e., which include the Dragon Eye UAV and the UCR-operated Vector Wing 100; and (3) the SIERRA *medium UAV* (Table 1).

5.3 AEROSTATS

To date (February 2013) we have tested our aerostat (tethered balloon and kite) and Vector Wing 100 UAV (Figure 3d, e) systems. With one meter diameter meteorological balloons, we have conducted multiple deployments of into the Turrialba plume up to approximately 13Kft ASL (6.5Kft AGL), with an SO_2-sonde payload consisting of an electrochemical SO_2 sensor (0-5ppmv and 0-20ppmv ranges), as well as the normal pressure, temperature, relative humidity, and GPS location sensors (Figure 6, Table 1). We have also field-tested "Aeropod" and "Super-Aeropod" enclosures (Figure 7) built by the NASA Wallops Island Flight Facility (WFF) of the Goddard Spaceflight Center (GSFC) at lower altitudes (up to 7.5Kft ASL, 0.5Kft AGL), suspended under tethered balloons and kites, with payloads that have included anemometers, particle counters, CO_2 detectors, temperature, pressure, relative humidity, and GPS sensors. Our SO_2-sonde deployments have encountered in-plume concentrations in the range of 2-20ppmv within about 3km of the Turrialba vent at altitudes up to 13Kft ASL (Fig 8).

At fixed locations, aerostats contribute important time series data on plume composition and dynamics. Such platforms are relatively simple and dependable. Kites, which have a rich history of being used for aeronomy (e.g., Franklin, 1752) have the added advantage of not requiring helium for lift. This can be an important advantage on remote volcanoes, where air or ground support is not available. In addition, kites tend to be more stable than simple tethered balloons at the higher end of the wind spectrum (up to about 20kts). In our experience with launching tethered weather balloons from the Turrialba summit, it is not uncommon to experience 20-40kt gusts, which are beyond the capability of our equipment to withstand and we have occasionally lost payloads. Above that velocity, however, robust relatively new kite-balloon hybrids, marketed commercially under the names of Helikite™ in the UK and SkyDoc™ in the US. Helikites™ have been used in the UK for meteorological observations and appear to be stable in winds up to hurricane force (≥73mph; Allsopp, 2013). In addition, volcanoes, most especially in tropical areas, often experience variable visibility conditions, and at Turrialba Volcano it has not been uncommon for us to launch in clear weather and recover tethered payloads through heavy clouds and fog in pouring rain. Still, despite some limitations, we feel strongly that aerostats are cost-effective for time-variable atmospheric profiling, monitoring and sampling at-a-station. They provide crucial time-series flight environment information (e.g., turbulence spectra, boundary layer and slope wind intensity and distribution) that can substantially reduce risk in planning UAV sorties.

Over the last year or more, as our in situ sampling technology has matured, we have more frequently been able to coordinate our SO_2 tethersonde launches with ASTER data acquisitions. The success of t

his endeavor is highly weather-dependent, with the dry season in the Central Valley of Costa Rica tending to occur between December and April. This year (2013), fortunately, we have been successful in having cloud-free days during ASTER overpasses, with coordinated tethersonde acquisitions on 07 Jan 2013, 16 Jan 2013, 08 Feb 2013—those data are currently being reduced and analyses will be forthcoming. In figure 8, however, we show the results of an earlier (2012) coordinated attempt at in situ SO_2 measurements with our tethersonde system. This deployment occurred on 01 February 2012, in clear weather, about 11 days after the ASTER overpass that occurred on 21 January 2012 (referenced in Figure 9). Winds were calm and weather was clear. Maximum SO_2 concentration recorded was 5ppmv at about 3300m ASL, maximum saturation concentration of this sensor. The actual maximum SO_2 concentration was likely to have been 6-7ppmv during this period, judging from Figure 8, and this compares favorably with the earlier ASTER-based estimate of 6ppmv. In Figure 8, ascent (blue) and descent (red) SO_2 vertical profiles are shown at lower right.

The estimation of plume composition from radiance measurements can be a complicated affair, based on the use of radiative transfer modeling to fit the observed spectra of upwelling thermal radiation. In the thermal IR, a number of factors affect radiative transfer retrievals, including the subjacent ground temperature, the emissivity of the ground beneath the plume, as well as the elevation of the ground surface underneath the plume, the plume altitude and thickness, and local atmospheric temperature and humidity. Thus, when we conduct in situ measurements of the SO_2 concentration within the plume, we also conduct atmospheric profile measurements, as well as ground temperature measurements. Of course, our knowledge of these parameters is imperfect, however, in situ measurements, along with interactive mapping and fitting of the image data and radiative transfer modeling results, greatly improve our ability to evaluate the impact of these uncertainties on our estimates of plume composition (e.g., Realmuto et al., 1994, 1997; Realmuto and Worden, 2000; Urai, 2004; Pugnahi et al., 2006; Campion et al., 2010, 2012; Henney et al., 2012).

Figure 9, shows the results of analysis of ASTER TIR bands located at or near the well-known sulfur dioxide absorption band centered on 8.5µm, acquired on 21 January 2012, under nearly perfectly clear sky conditions. For reference, panel (a) is an ASTER Very Near InfraRed (VNIR) false-color 3-band (Band 1: 0.52 - 0.60 µm; Band 2: 0.63 - 0.69 µm; Band 3: 0.76 - 0.86 µm) composite image showing the vegetation-free summits of both Turrialba and Irazú volcanoes. Panel (b) is a principal component decorrelation stretch image created from the five ASTER thermal infrared bands (Band 10: 8.125-8.475 µm; Band 11: 8.475-8.825 µm; Band 12: 8.925-9.275 µm; Band 13: 10.25-10.95 µm; Band 14: 10.95-11.65 µm), showing the SO_2 plume in yellow extending toward the west. Panel (c) shows the SO_2 concentration derived from the radiative transfer modeling of ASTER TIR radiance data, with a maximum of about 6ppmv. This agrees well with the later tethersonde measurement shown in Figure 8, and was characteristic of Turrialba for this time period (e.g., Campion et al., 2012).

5.4 THE DRAGON EYE µUAV

The RQ14 Dragon Eye μUAV (Figure 3a,b,c) was originally designed by the U.S. Naval Research Laboratory for reconnaissance applications of U.S. Marine Corps (USMC) combat platoons, and saw extensive use. The Aerovironment Corporation was awarded a 2003 contract to build over 1000 units, after which the USMC switched to the larger RQ-11 Raven UAV for the balance of the contract. Dragon Eye is a small delta-winged tailless aircraft that weighs 2.25 kg (5lb) with a wingspan of 1.14m (3ft 9in), and can carry a 500g payload. It can be launched by hand, or by bungee—with a bungee launch and full power it can climb vertically after release. It uses a GPS inertial navigation system, capable of completely automatic take-offs and landings, with computer way-point inputs. It is thus fully autonomous. It can be carried in a back pack and breaks apart on landing to absorb impact. It is then reassembled and relaunched, and can tolerate moderately rough landing zones.

The Dragon Eye comes equipped with three cameras: low light visible, daytime color visible and thermal infrared. It can carry two cameras at a time, or the camera pods can be replaced with reconfigured nose pods that snap on and snap off the airframe. We have adapted Dragon Eye to carry a small electrochemical SO_2 sensor, a small optical particle counter (0.5-5μm range), a small evacuated vacuum sampling bottle (0.1deci-liter) with an automatic actuator, and temperature-pressure-humidity sensors, as well as a GPS unit and data logger. The native Dragon Eye electronics send a continuous stream of video and housekeeping data out to a range of approximately 5km. It has a rated operational ceiling of 8,000ft ASL, however, we will be testing it to altitudes in excess of that and expect performance will be adequate.

In the fall of 2012, the Airborne Science Program at NASA Ames Research Center acquired 75 Dragon Eye aircraft and control systems as USMC surplus, in part on behalf of our volcanological in situ sampling program. We will be deploying about ten of these aircraft to Turrialba Volcano in March 2013 to flight test them in the airspace around the volcano at a variety of altitudes. We will be conducting SO_2 concentration measurements, as well as sampling solid aerosols. Initial flight testing that we've conducted in the U.S. demonstrated that Dragon Eye is a rugged, dependable, and flexible platform for volcanological research within the lower troposphere. Additionally, with Dragon Eye, we accept a higher deployment risk that comes with penetrating volcanic plumes and eruption columns, given the low cost of the airframe, the number of aircraft at our disposal, and the low cost of the very small Dragon Eye instrument payloads. Finally, we are exploring how to deploy a number of these aircraft in 2D and 3D meshes to gather unique simultaneous time-series data over extended areas (e.g., active lava flows) and volumes (e.g., volcanic plumes).

5.5 THE VECTORWING 100

In 2011, in San Jose, the Gas Lab of the Center for Investigations in Atomic, Nuclear, and Molecular Sciences (CICANUM) at the University of Costa Rica began operational tests of a VectorWing100 μUAV that it acquired from Maryland Aerospace, Inc. in the United States

(Figure 3d,e). The VectorWing100 is a tailless flying wing design with a 2.1m wingspan and a flight weight of 3.6kg. It can carry approximately 1kg payload and has been outfitted with a small electrochemical SO_2 sensor and temperature, pressure, humidity sensors and a data logger. It has an inertial navigation system and can be operated in autonomous mode. The aircraft is now routinely acquiring SO_2 data within the Turrialba plume under instrument flight rules (IFR) conditions (i.e., through clouds) at altitudes of up to 11,500ft (3500m) ASL, and has been deployed during ASTER overpasses. As of January 2013, we are deploying the VectorWing 100 in concert with our aerostats to collect in situ SO_2 data twice per month during ASTER overflights (16 day nadir repeat at the equator). The original Maryland Aerospace 400 watt electric motor has been refitted with an 1800 watt powerplant and that has provided a considerable margin of safety with respect to high winds and turbulence encountered near around the volcano. We expect to continue to collect in situ data around Turrialba with the VectorWing100 to support the March 2013 NASA Dragon Eye deployment and the March 2014 SIERRA/Dragon Eye deployment. (To our knowledge, this is the first time that a free flying UAV has been engaged in systematic *routine* operational sampling of emissions from an active volcano. Also, to the best of our knowledge, we are the first to *routinely* and systematically deploy aerostats in a similar capacity, and in concert with a free flying UAV.)

5.6 The SIERRA Medium UAV

An important component of our in situ observation and sampling activity at Turrialba Volcano in Costa Rica is the SIERRA UAV (Figure 3, Figure 11a), a medium class, medium duration UAV originally designed by the United States Naval Research Laboratory (NRL). We expect to deploy SIERRA to Turrialba Volcano in March 2014. Researchers at the NASA Ames Research Center developed a partnership with NRL to evaluate the utility of this class of aircraft to the NASA earth science community. The relatively large payload (~100lbs; gross takeoff weight 400lbs) coupled with a significant range (600 nautical miles (nmi) @ 60kts, depending on payload and weather), small size (20ft wingspan), and short runway requirement, makes it an attractive observational platform, especially for potential deployment to areas with minimally improved airstrips. This UAV typically conducts low altitude missions (up to 12Kft ASL) for tropospheric chemistry sampling and remote area surveys. Its payload capabilities are relatively robust. For instance, for an arctic ice survey above the Arctic Circle at Svalbard Island (CASIE, 2009) it carried two laser altimeters, a synthetic aperture radar (SAR), zenith- and nadir-pointing micro-spectrometers, digital still and video tracking cameras, a pyrometer, and a zenith pointing pyronometer. All instruments were contained in the SIERRA nose-cone with the exception of the SAR which was mounted on the side of the fuselage in a pod. SIERRA operates autonomously over-the-horizon, and maintains communications with its base via satellite, which allows data transfer and reprogramming of the mission during flight. The SIERRA UAV has also supported a number of other science data collection campaigns, such as a seagrass and coral reef biome survey in South Florida (F.Muller-Karger, et al. 2012), and an electromagnetic survey of buried faults in the California Sierra (Pandika, 2012).

5.7 Instruments

In addition to navigation, GPS and telemetry instrumentation for platform control, data transmission, and geo-location for SIERRA, we have several instrument packages for volcanic observations. We've adapted several commercial-off-the-shelf (COTS) instruments to address our science questions, that are available for deployment on SIERRA, including:

- TSI Inc. Model 3007 particle counter—minimum detectable particle (D_{50}) = 10 nm, maximum detectable particle > 1μm with ground (for small particles);
- TSI Inc. Model 3330 Optical Particle Spectrometer—continuous size distribution, 0.3-10 μm in up to 16 channels (for larger particles);
- Droplet Measurement Technologies, Inc. Cloud Droplet Probe—outside mount, 2-50 μm diameter;
- Mini-nephelometer—to obtain particulate scattering coefficients;
- Aerosol Drum Impactor—size-segregated composition, 0.9-35 μm; sample analyses will include beta-gauge (mass concentration), synchrotron x-ray fluorescence (elemental composition), optical absorption as ƒ(ë) (provided by University of Alaska Fairbanks, Dr. Cathy Cahill);
- Bolometer—TIR ground brightness temperature;
- Temperature, pressure, & relative humidity—SIERRA facility instruments;
- ULISSES (Figure 11b) is a miniaturized mass spectrometer built using COTS components (mass analyzer, vacuum pumps, chamber, valves); down-sized version of the Airborne Volcanic Emissions Mass Spectrometer (AVEMS) instrument flown onboard the NASA WB57 aircraft in previous deployments to Costa Rica (Arkin et. al., 2002, 2004, Griffin et. al., 2008) and for Space Shuttle support (Arkin et al., 2001); field tested previously at Costa Rican volcanoes (Diaz et al. 2010); multi-gas sensing (provided by the University of Costa Rica, Dr. Andres Diaz and NASA Kennedy Space Center, Mr. Eric Gore)
- Isokinetic inlet and data acquisition system.

We have two identical low-cost instruments light-weight that are carried on-board both SIERRA and Aeropod platforms, to provide additional range for aerosol and gas sampling. These are:

- Hal Technology (HalTech), LLC HPC-600 six-channel hybrid handheld particle counter (0.3-25μm)
- Electrochemical SO_2 sensor, 0-20ppmv, 10ppbv sensitivity, additional gases including H_2S, CO_2, CO, CH_4 (in collaboration with University of Costa Rica, Dr. Andres Diaz; Teledaq Corporation, Dr. Ali Abtahi; NASA GSFC/WFF, Mr. Ted Miles)

Although the current mission to Turrialba focuses on measurements of gas (e.g., primarily SO_2) emissions, we will be looking toward the challenges of sampling volcanic aerosols, such as compensation in uncertainty in refractive index of ash sample vs. normal aerosols, iso-kinetic sampling, compensation for aggregation, and non-spherical shape effects. SIERRA also carries its standard visible wavelength and TIR down-looking imagers (<1kg, VGA 640x480 pixels, with telemetry), and a micro-spectrometer for observations between 0.36 to 1.1 µm (<2kg). Relative humidity, pressure, temperature, wind direction and speed will be measured by another standard on-board package.

Turrialba Volcano is well-posed for our measurements, as it's been erupting steadily at levels detectable from ASTER and OMI observations in orbit (e.g., Fig 9). It is predominately a low altitude SO_2 emitter, with light ash emissions, and a relatively benign airspace and ground environment. Tethered aerostat gas observations are currently on-going in coordination with ASTER overpasses. Current plans call for deployment of SIERRA to Turrialba Volcano for a 15 day deployment in March of 2014. It will deploy from a commercial airport about 20km from the Turrialba summit vent (Fig 4b). The combination of SIERRA with aerostats provides "UAV volcano toolkit" appropriate for the relatively low altitude, steadily erupting plumes emitted by our target volcano in Costa Rica.

6. Summary

Burgeoning new technology in the design and development of robotic aircraft—unmanned aerial vehicles (UAVs)—presents unprecedented opportunities for the volcanology community to observe, measure, and sample eruption plumes and drifting volcanic clouds in situ. While manned aircraft can sample dilute parts of such emissions, demonstrated hazards to air breathing, and most particularly turbine, engines preclude penetration of the zones of highest ash concentrations. Such areas within plumes are often of highest interest with respect to boundary conditions of applicable mass-loading retrieval models, as well as Lagrangian, Eulerian, and hybrid transport models used by hazard responders to predict plume trajectories, particularly in the context of airborne hazards. Before the 2010 Ejyafyallajokull eruption in Iceland, ICAO zero-ash-tolerance rules were typically followed, particularly for relatively uncrowded Pacific Rim airspace, and over North and South America, where often diversion of aircraft around ash plumes and clouds was practical. The 2010 eruption in Iceland radically changed the paradigm, in that critical airspace over continental Europe and the United Kingdom were summarily shut by local civil aviation authorities and EURO CONTROL. A strong desire emerged for better real-time knowledge of ash cloud characteristics, particularly ash concentrations, and especially for validation of orbital multispectral imaging. UAV platforms appear to provide a viable adjunct, if not a primary source, of such in situ data for volcanic plumes and drifting volcanic clouds from explosive eruptions, with prompt and comprehensive application to aviation safety and to the basic science of volcanology.

Current work is underway in Costa Rica at Turrialba volcano by the authors, with the goal of developing and testing new small, economical UAV platforms, with miniaturized instrument payloads, within a volcanic plume. We are underway with bi-monthly deployments of tethered SO_2-sondes and are in the planning stages for the deployment of the SIERRA UAV to our site in March 2013. We will be conducting in situ observations simultaneously with ASTER orbital multispectral TIR data acquisitions, in order to compare in situ measurements with estimates of SO_2 mass loading and dispersion derived from ASTER data.

Though small UAVs are now being considered for use in active volcanic areas for in situ sampling of emissions (e.g., efforts by our group, and by our colleagues at the INGV in Italy and the Applied Science University in Dusseldorf, Germany, and others in the United Kingdom and Iceland), and also for remote sensing, much more needs to be done in the way of instrument development, and in developing small UAVs for both low altitude (tropospheric) and high altitude (stratospheric) applications. In particular, the development of all weather and day/night operational flight capabilities in close proximity to hazardous topography is crucial to a truly responsive volcano in situ measurement system.

Finally, it is imperative that national civil aviation authorities recognize the unique benefits of such platforms. It is important that authorities understand that severely restricting or not deploying such tools in airspace over restless volcanoes or within eruption plumes, ostensibly because of the perceived (small) risk that such unmanned aircraft pose to manned air operations, itself poses a bigger transcendental risk to proximal populations and particularly to the aviation community, itself.

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8. References

Abrams, M; Bianchi, R; Pieri, D, 1996, Revised mapping of lava flows on Mount Etna, Sicily, *Photogrammetric Engineering and Remote Sensing 62, **12**,* 1353-1359.

Aero News Network, 2011, AMA: FAA Seeks to restrict model aircraft flight, http://www.aero-news.net/index.cfm?do=main.textpost&id=80760875-a5a3-451e-b415-7c5248645401

Allsopp, 2013, Tactical Aerostats—Overview; Allsopp Helikites Ltd, Hampshire, UK; http://www.allsopphelikites.com/index.php?mod=page&id_pag=24

Arkin CR, Ottens AK, Diaz JA, Griffin TP, Follestein D, Adams F, Steinrock T, 2001, Evaluating Mass Analyzers as Candidates for Small, Portable, Rugged Single Point Mass Spectrometers for Analysis of Permanent Gases, NASA Technical Reports Server, Doc. ID 20010056289; http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20010056289_2001083781.pdf

Arkin CR, Griffin TP, Ottens,AK, Diaz JA, Follistein DW, Adams FW and Helms WR, 2002, "Evaluation of Small Mass Spectrometer Systems for Permanent Gas Analysis" *J. Am. Soc. Mass Spectrom., **3**,* 1004-1012.

Arkin CR,Griffin TP, Diaz JA, Follistein DW, Curley CH, Floyd DP, Naylor GR, Haskell WD, . Blalock M, Adams FW, 2004, "A small mass spectrometer system for in situ gas analysis" *Trends in Anal. Chem., **23**(4),* 322 – 330.

Barboza, V, Fernández, E, Martínez, M, Duarte, E, and Van der Laat, RE, Marino T, Hernández E, Valdés J, Sáenz R, and Malavassi E, 2000, Volcán Turrialba: Sismicidad, Geoquímica, Deformación y nuevas fumarolas indican incrementos en la actividad (abstract), in Los retos y propuestas de la investigación en el III milenio (CONINVES): *Memoria, Editorial UNED*, 78.

Barboza V, Fernández E., Duarte, E., Sáenz, W., Martínez, M., Moreno, N., Marino, T., van der Latt, R., Hernández, E., Malavassi, E., and Valdés, J., 2003, Changes in the activity of Turrialba Volcano; seismicity, geochemistry, and deformation, *Seismological Research Letters, **74**,* p. 215

Baxter, PJ, Gresham A, 1997, Deaths and injuries in the eruption of Galeras Volcano, Colombia, 14 January 1993, *J. Volc. Geotherm. Res., **77***, 325-338.

Belousov A., Belousova M., 2004, The first attempt of sampling a volcanic cloud, *Priroda 4,* 42-54 (in Russian).

Bittooth, 2010, http://bittooth.blogspot.com/2010_04_01_archive.html

Bone E and Bolkcom C, 2003, Unmanned Aerial Vehicles: Background and Issues for Congress, *Congressional Research Service Document RL31872*, 52pp; www.fas.org_irp_crs_RL31872.pdf

Brannigan VM, 2010, Alice's Adventures in Volcano Land: The Use and Abuse of Expert Knowledge in Safety Regulation, *European Journal of Risk Regulation* ***2***, 107-113.

Brock G, 2010, Role of the Volcanic Ash Advisory Centres, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud--Detection, Observation, Measurement, Modelling, The way forward,* 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

Burgess A., 2012, Media, Risk, and Absence of Blame for "Acts of God": Attenuation of the European Volcanic Ash Cloud of 2010, *Risk Analysis, **32**, 10*, 1693-1702.

Bursik M, 2001, Effect of wind on the rise height of volcanic plumes, *Geophys Res Lett* ***18**:*3621–3624

Bursik M.I., Kobs S.E., Burns A., Braitseva O.A., Bazanova L.I., Melekestsev I.V., Kurbatov A., Pieri D.C. 2009.Volcanic plumes and wind: jet stream interaction examples and implications for air traffic. *J Volcanol Geotherm Res ,* ***186***, 60-67.

Bursik M, Jones M, Carn S, Dean K, Patra A, Pavolonis M, Pitman EB, Singh T, Singla P, Webley P, Bjornsson H, Ripepe M, 2012, Estimation and propagation of volcanic source parameter uncertainty in an ash transport and dispersal model: application to the Eyjafjallajökull plume of 14–16 April 2010, *Bull. Volcanol.* Published online 06 Oct., DOI 10.1007/s00445-012-0665-2

Campion R, Martinez-Cruz M, Lecocq T, Caudron C, Pacheco J, Pinardi G, Hermans C, Carn S, Bernard A, 2012, Space- and ground-based measurements of sulphur dioxide emissions from Turrialba Volcano (Costa Rica), *Bull Volc, **74**, 7,* 1757-1770 DOI: 10.1007/s00445-012-0631-z

Campion R, Salerno GG, Coheur PF, Hurtmans D, Clarisse L, Kazahaya K, Burton M, Caltabiano T, Clerbaux C, Bernard A, 2010, Measuring volcanic degassing of SO2 in the lower troposphere with ASTER band ratios *J Volcanol Geotherm Res ,* ***194,*** 1-3, 42-54. DOI: 10.1016/j.jvolgeores.2010.04.010

Carr, M. J., M. D. Feigenson, L. C. Patino, and J. A. Walker (2003), Volcanism and geochemistry in Central America: Progress and problems, in Inside the Subduction Factory, *Geophys. Monogr. Ser.,* ***138,*** edited by J. Eiler, pp. 153–174, AGU, Washington, D. C., doi:10.1029/138GM09.

Carn SA, Pallister JS, Lara L, Ewert JW, Watt S, Prata AJ, Thomas RJ, and Villarosa G, 2009. The Unexpected Awakening of Chaitén Volcano, Chile, *Eos Trans. AGU, **90(24)***, 205–206.

Carn, S.A., Froyd, K.D., Anderson, B.E., Wennberg, P., Crounse, J., Spencer, K. , Dibb, J.E., Krotkov,N.A., Browell, E.V., Hair, J.W., Diskin,G., Sachse, G. , Vay S. A., 2011, In situ measurements of tropospheric volcanic plumes in Ecuador and Colombia during TC4, *J. Geophys Res, **116**,* D00J24, doi:10.1029/2010JD014718, 2011.

Casadevall, TJ, 1994, The 1989-1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations, *J Volcanol Geotherm Res* ***62***, 301-316.

CAA (Civil Aviation Authority, UK), 2011, *CAA issues update on Volcanic Ash Arrangements*, http://www.caa.co.uk/application.aspx?catid=14&pagetype=65&appid=7&mode=detail&nid=1996

CASIE, 2009, NASA Earth Science Project Office, *Characterization of Arctic Sea Ice Experiment, Home Page*; http://www.espo.nasa.gov/casie/

D'Amours R, Malo A, Servranckx R, Bensimon D, Trudel S, and Gauthier-Bilodeau JP, (2010). Application of the atmospheric Lagrangian particle dispersion model MLDP0 to the 2008 eruptions of Okmok and Kasatochi volcanoes, *J. Geophys. Res.,* ***115***, D00L11, doi:10.1029/2009JD013602.

Dean KG, Dehn J, Papp KR, Smith S, Izbekov P, Peterson R, Kearney C, Steffke A, 2004, Integrated satellite observations of the 2001eruption of Mt. Cleveland, Alaska, *J Volcanol Geotherm Res ,* ***135****,* 51– 73.

Diaz JA, Gentry WR, Giese DR, "Portable Double Focusing Sector Field Mass Spectrometer System for Field Gas Monitoring*". Field Analysis Chemistry and Technology.* ***5*** *(3)*, pp. 156-167, June 2001.

Diaz JA, Giese DF, Gentry WR, 2002, "Mass spectrometry for in situ volcanic gas monitoring," *Trends in Analytical Chemistry,* ***21*** *(8),* pp.498-514.

Diaz JA, Pieri D, Arkin CR, Gore E, Griffin T, Fladeland M, Bland G, Soto C, Madrigal Y, Castillo D, Rojas E, Achi S., 2010, "Utilization of in situ airborne MS-based instrumentation for the study of gaseous emissions at active volcanoes," *International Journal of Mass Spectrometry* ***295****,* pp.105–112.

Diaz J.A., Pieri D.C., Bland G., Fladeland M. 2012. Volcano Monitoring with small Unmanned Aerial Systems. Oral presentation and abstract. *Proc. AIAA Infotech@Aerospace 2012 Conference,* Garden Grove, CA, USA, 19-21 June.

Diaz J.A., Pieri D.C., Bland G., Fladeland M., Gore E., Arkin R.C., Soto C. 2011a. Utilization of Small In-Situ Airborne Platforms, Lightweight Sensors and Remote Sensing for Volcanic Plume Analysis. Abstract and oral presentation. *Proc. 34th International Symposium for Remote Sensing of Environment,* Sydney, Australia, 14 April.

Diaz J.A., Pieri D.C., Arkin R.C., Bland G., Fladeland M., Gore E., Castillo D., Corrales E., Madrigal Y. 2011b. Utilization of Lightweight MS based Instrumentation and Small UAV Platforms for In-Situ Volcanic Plume Analysis. Oral presentation and abstract. *Proc. 8th Harsh Environment Mass Spectrometry Workshop*, St. Petersburg, FL, USA, 22 September.

Duarte, E., 1990, *Algunos aspectos del riesgo volcanico en el Volcan Turrialba* [Licenciado en Geografi a thesis]: Costa Rica, Universidad Nacional, 123 p.

Egan P, 2012, The Law and Operating Unmanned Aircraft In the U.S. National Airspace System, *sUAS News*, http://www.suasnews.com/2012/03/13397/the-law-and-operating-unmanned-aircraft-in-the-u-s-national-airspace-system/

EUFAR, 2010, EUropean Facility for Airborne Research Integrating Activity of the EC FP7, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud--Detection, Observation, Measurement, Modelling, The way forward,* 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

FAA, 2005, Unmanned Aircraft Systems Operations in the U. S. National Airspace System - Interim Operational Approval Guidance, *AFS-400 UAS POLICY 05-01*; U.S. Federal Aviation Administration, http://www.eoss.org/faa/AFS_400_UAS_POLICY_05_01.pdf

FAA, 2013*, Fact Sheet – Unmanned Aircraft Systems (UAS),* US Federal Aviation Administration; http://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=14153

Fernández, E., Duarte, E., Sáenz, W., Malavassi, E., Martínez, M., Valdés, J., and Barboza, V., 2002, Cambios en la Geoquímica de las Fumarolas del Volcán Turrialba, Costa Rica: 1998–2001 (abstract), *Proc. Colima Volcano: Eighth International Meeting*, 84.

Franklin B, 1752, New Electrical Experiment by B. Franklin, letter to Peter Collinson, *Gentleman's Magazine*, Philadelphia, December.

Flightglobal, 2010, http://www.flightglobal.com/news/articles/pictures-finnish-f-18-engine-check-reveals-effects-of-volcanic-340727/

Foreman P, 1994, Warning Systems and Pilot Action, p. 163-168, in *Volcanic Ash and Aviation Safety, Proc. Of the First International Sympoisum on Volcanic Ash and Aviation Safety*, Seattle, WA, USA, 1991; *U.S. Geological Survey Bulletin **2047**,* US Government Printing Office, Washington, D.C., 450pp.

Golding B, 2010, Observations made by UK aircraft, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud--Detection, Observation, Measurement, Modelling, The way forward*, 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

Graf HF, Herzog M, Oberhuber JM, Textor C (1999) Effect of environmental conditions on volcanic plume rise. *J Geophys Res. 104, **24***, 309–320.

Griffin TP, Diaz JA, Arkin CR, Soto C, Curley CH, and Gomez O, "Three-Dimensional Concentration Mapping of Gases using a Portable Mass Spectrometer System" J. *Am. Soc. Mass Spectrom., **19***, pp. 1411-1418, 2008.

Grindle TJ, Burcham FW, 2003, Engine Damage to a NASA DC-8-72 Eyjafjallayökull Airplane from a High-Altitude Encounter With a Diffuse Volcanic Ash Cloud, *NASA/TM-2003-212030,* US Government Printing Office, 22pp.

Guffanti M, 2012, Volcanic-Ash Hazards to Aviation in the Post- World: a Status Report, in *Proc. of the Turbine Engine Technology Symposium 2012*, Dayton, Ohio; http://www.meetingdata.utcdayton.com/agenda/Agenda.asp?ID=tets201234570302&sid=1780,1774,1775.

GVP, 2010, Eyjafjallajökull 03/2010 Fissure eruption and lava flows from E flank on 20 March, Smithsonian Global Volcanism Program, *BGVN* ***35****:03*; http://www.volcano.si.edu/world/volcano.cfm?vnum=1702-02=&volpage=var#bgvn_3503

Harrison RG, Nicoll KA, Ulanowski Z, Mather TA, 2010, Self-charging of the Eyjafjallajökull volcanic ash plume, *Environ. Res. Lett.* ***5*** *(April-June 2010)* doi:10.1088/1748-9326/5/2/024004

Heffter, J.L. and B.J.B. Stunder, 1993: Volcanic Ash Forecast Transport And Dispersion (VAFTAD) Model. *Weather Forecasting,* ***8***, 534-541.

Henney LA, Rodriguez LA, Watson IM, 2012, A comparison of SO2 retrieval techniques using mini-UV spectrometers and ASTER imagery at Lascar volcano, Chile*, Bull Volc,* ***74***, 2, 589-594. DOI: 10.1007/s00445-011-0552-2

Holland, Greg J., Tad McGeer, Harold Youngren, 1992: Autonomous Aerosondes for Economical Atmospheric Soundings Anywhere on the Globe. *Bull. Amer. Meteor. Soc.,* ***73,*** 1987–1998, doi: http://dx.doi.org/10.1175/1520-0477(1992)073<1987:AAFEAS>2.0.CO;2

Hufford, G., JJ Simpson, L Salinas, E Barske, and Pieri, D.C., 2000, Operational considerations of volcanic ash for airlines, *Bull. Amer. Met. Soc.,* ***8****, 4,* 745-755.Kerr, 1993.

ICAO, 2011, *Unmanned Aircraft Systems (UAS)*, International Civil Aviation Organization Cirular 328 (AN/190), 38pp. http://www.icao.int/Meetings/UAS/Documents/Circular%20328_en.pdf

Jentink H, Karwal A, 2010, NLR Cessna Citation II observation flights during the Eyjafjallajökull event, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud--Detection, Observation, Measurement, Modelling, The way forward,* 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

Karp J, Pasztor A, 2006, Drones in Domestic Skies? They're in Demand for Rescue And Surveillance Missions, But Critics Question Safety, *Wall Street Journal*, August 7, 2006; page B1; http://www.mail-archive.com/medianews@twiar.org/msg12701.html

Kreuger A, Yang K, Krotkov N, 2009, Enhanced monitoring of sulfur dioxide sources with hyperspectral UV sensors, in Remote Sensing of Clouds and the Atmosphere XIV, edited by RH Picard, K Schäfer, A Comeron, E Kassianov, CJ Mertens, *Proc. of SPIE,* ***7475***, doi: 10.1117/12.830142

Krotkov NA, Schoeberl MR, Morris GA, Carn S, and Yang K, 2010. Dispersion and lifetime of the SO2 cloud from the August 2008 Kasatochi eruption, *J. Geophys. Res.,**115***, D00L20, doi:10.1029/2010JD013984.

Leff A, 2011, Drones hunt data on volcanic eruptions in Costa Rica, *Reuters Alert Net*, 22 Nov 2011; http://www.trust.org/alertnet/news/drones-hunt-data-on-volcanic-eruptions-in-costa-rica.

Martini F, Tassi F, Vaselli O, Del Potro R, Martinez M, Van del Laat R, Fernandez E, 2010, Geophysical, geochemical and geodetical signals of reawakening at Turrialba volcano (Costa Rica) after almost 150 years of quiescence, *J Volcanol Geotherm Res* , ***198**, 3-4,* 416-432 DOI: 10.1016/j.jvolgeores.2010.09.021

Manrique SV, 2012, Studying volcanic emanations unmanned aircraft and high-tech, *Girasol*, *Jan-Dec 2011, **14**, 44*, University of Costa Rica, San Jose.

Mastin L, Guffanti M, Servanckx R, Webley P, Barostti S, Dean K, Denlinger R, Durant A, Ewert J, Gardner C, Holliday A, Neri A, Rose W, Schneider D, Siebert L, Stunder B, Swanson G, Tupper A, Volentik A, Waythomas A (2009) A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions, *J Volcanol Geotherm Res **186,** 10–21*, special issue on Volcanic Ash Clouds; L. Mastin and P.W. Webley (eds.)

McGonigle, A. J. S. , Aiuppa, A., Giudice, G., Tamburello, G., Hodson, A.J., Gurrieri S., 2008, Unmanned aerial vehicle measurements of volcanic carbon dioxide fluxes, *Geophysical Research Letters, **35***, L06303, doi:10.1029/2007GL032508

Mora, R., Ramírez, C., and Fernández, M., 2004, La actividad de los volcanes de la Cordillera Central, Costa Rica, entre 1998–2002, in Soto, G.J. and Alvarado, G.E., eds., La Vulcanología y su entorno geoambiental: *Revista Geológica de América Central*, ***30***, 189–197.

Muller-Karger F, Herwitz S, Hu C, Yates K, Carlson P, Ramsewak D, Toro-Farmer G, Vega-Rodríguez M, Melo N, Berthold R, Guild L, McGillis W, Turk D, 2012, UAS High Resolution Assessment of Carbon Dynamics in Seagrass and Coral Reefs Biomes, presentation, 2012 HyspIRI Science Workshop, NASA Decadal Survey Mission, 16-18 October, Washington, DC. http://hyspiri.jpl.nasa.gov/downloads/2012_Workshop/day2/18_FMuller-Karger-HyspIRI_OCT2012_UAS_HyspIRI_FL_Keys_In%20Situ_Optics_Component%E2%80%93IMaRS.pdf

Oxford Economics, 2012, *Airbus- Volcanic Ash Impact on Air Travel*, report for Airbus Industries; Oxford, UK; http://www.oxfordeconomics.com/my-oxford/projects/128815.

Pandika, M, 2012, Problem Solving on the Fly, *NASA Ask Magazine*, NASA Academy of Program/Project & Engineering Leadership, Washington, D.C. http://www.nasa.gov/pdf/703235main_48s_problem_solving.pdf

Pavolonis MJ, 2010, Advances in Extracting Cloud Composition Information from Spaceborne Infrared Radiances-A Robust Alternative to Brightness Temperatures. Part I: Theory, *Journal of Applied Meteorology and Climatology, **49**, 9,* 1992-2012, DOI: 10.1175/2010JAMC2433.1

Pieri, D, 2005, In-situ observations of volcanic plumes for applications and research, *NASA Technical Report 20060022664*, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060022664_2006156292.pdf

Pieri, DC, Ma C, Simpson JJ, Hufford GL, Grove G, and Grindle T, "Analyses of In situ Airborne Volcanic Ash from the Feb 2000 Eruption of Hekla", *Geophys. Res. Lett* ***29***, *16*, 19-1 to 19-4.

Pieri D.C., Diaz J.A., Bland G., Fladeland M. 2012. Airborne Ash Hazards: In Situ Calibration and Validation of Remotely Sensed Data and Models. Oral presentation, poster presentation, abstract. *Proc. AGU Chapman Conference Volcanism and the Atmosphere*, Selfoss, Iceland, 10-15 June.

Pieri D.C., Diaz J.A., Bland G., Fladeland M. 2012, Unmanned Airborne Platforms for Validation of Volcanic Emission, Composition, and Transport Models, poster, *Proceedings of the Fall AGU, **V21-B-2785**,* American Geophysical Union, Washington, D.C.

Pieri D, Abrams M, 2004, ASTER watches the world's volcanoes: a new paradigm for volcanological observations from orbit, *J Volcanol Geotherm Res , **135**, 1-2,* 13-28, DOI: 10.1016/j.jvoleores.2003.12.018

Pieri D, Abrams M, 2005, ASTER observations of thermal anomalies preceding the April 2003 eruption of Chikurachki volcano, Kurile Islands, Russia, *Remote Sensing of Environment, **99**, 1-2,* 84-94, DOI: 10.1016/j.rse.2005.06.012

Prata AJ, 1989a, Infrared radiative transfer calculations for volcanic ash clouds. *Geophysical Research Letters **16**,* 1293-1296.

Prata AJ, 1989b, Observations of volcanic ash clouds in the 10-12 μm window using AVHRR/2 data, *International Journal of Remote Sensing **10**,* 751-761.

Prata, 2011, *AVOID—Airborne Volcanic Object Infrared Detector*, http:// www.nicarnicaaviation.com/ Portals/90/ media/ AVOID.pdf, Nicarnica Aviation and Norweigian Institute for Air Research, Kjeller, Norway.

Prata AJ. Gangale G, Clarisse L, and Karagulian F, 2010, Ash and sulfur dioxide in the 2008 eruptions of Okmok and Kasatochi: Insights from high spectral resolution satellite measurements, *J. Geophys. Res., **115**,* D00L18, doi:10.1029/2009JD013556.

Prata, A. J., and Tupper, A., 2009, Aviation hazards from volcanoes: the state of the science, *Natural Hazards,* DOI 10.1007/s11069-009-9415-y

Prata AJ and Kerkmann J, 2007, Simultaneous retrieval of volcanic ash and SO2 using MSG-SEVIRI measurements, *Geophys. Res. Lett,* ***34*** *(5),* L05813Quesada OC, 2012, Roadmap on UAS for the SAM Region, *ICAO & LACAC UAS Seminar For Caribbean + South America Regions*, abstract; Lima, Peru - 18-20 April 2012, p.1; http://www.icao.int/Meetings/UAS/Documents/ICAO-UAS-Seminar_Lima-Peru_Program_120331.pdf

Pugnaghi S,Gangale G, Corradini S, Buongiorno MF, 2006, Mt. Etna sulfur dioxide flux monitoring using ASTER-TIR data and atmospheric observations, *J Volcanol Geotherm Res ,* ***152*****,** 1-2, 74-90   DOI: 10.1016/j.jvolgeores.2005.10.004

Rauthe-Schöch A, 2010, CARIBIC--Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrumented Container, Brief on 3 volcanic missions without passengers, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud--Detection, Observation, Measurement, Modelling, The way forward*, 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

Reagan M, Duarte E, Soto GJ, Fernández E, 2006, The eruptive history of Turrialba volcano, Costa Rica, and potential hazards from future eruptions, pp 235–257, in Rose WI, Bluth, GJS, Carr MJ, Ewert JW, Patino LC, Vallance JW, Volcanic hazards in Central America: *Geological Society of America Special Paper* ***412***, 286 pp.

Realmuto VJ, Hon K, Kahle AB, Abbott EA, Pieri, DC, 1992, Multispectral Thermal Infrared Mapping of the 1 October 1988 Kupaianaha Flow Field, Kilauea Volcano, Hawaii, *Bull Volc,* ***55****, 1-2,* 33-44; DOI: 10.1007/BF00301118

Realmuto, V.J., M.J. Abrams, M.F. Boungiorno, and Pieri, D.C., 1994, The use of multispectral thermal infrared image data to estimate the sulfur-dioxide flux from volcanoes--A case study from Mount Etna, Sicily, July 29, 1986", *J. Geophys. Res. Sol. Earth,* ***99***, 481-488.

Realmuto VJ, Sutton AJ, Elias T, 1997, Multispectral thermal infrared mapping of sulfur dioxide plumes: A case study from the East Rift Zone of Kilauea Volcano, Hawaii, *J. Geophys Res-Solid Earth,* ***102,*** *B7,* 15057-15072.   DOI: 10.1029/96JB03916

Realmuto VJ, Worden HM, 2000, Impact of atmospheric water vapor on the thermal infrared remote sensing of volcanic sulfur dioxide emissions: A case study from the Pu'u 'O'o vent of Kilauea Volcano, Hawaii, *J. Geophys Res-Solid Earth,* ***105****, B9*, 21497-21507.   DOI: 10.1029/2000JB900172

Rindlisbacher T, 2010, Measurements and Forecast of Volcanic Ash: A FOCA Input, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud-*

-Detection, Observation, Measurement, Modelling, The way forward, 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

Rose WI, Bluth GJS, Ernst GGJ, 2000a, Integrating retrievals of volcanic cloud characteristics from satellite remote sensors: a summary. *Philosophical Transactions of the Royal Society of London: A Mathematical, Physical and Engineering Sciences* ***358,*** 1585 – 1606.

Rose, W.I., G. J. Bluth, C. M. Riley, I. M. Watson, T. Yu, and G. J. Ernst, 2000b, Potential Mitigation of Volcanic Cloud Hazards using Satellite Data—a Case Study of the February 2000 Hekla Event and an Unexpected NASA DC8 encounter, *Eos Trans. AGU, 81(48),* Fall Meet. Suppl. Abst. V61B-09.

Saggiani G, Persiani F, Ceruti A, Tortora P, Troiani E, Giuletti F, Amici S, Buongiorno M, DiStefano G, Bentini G, Bianconi M, Cerutti A, Nubile A, Sugliani S, Chiarini M, Pennestri G, Petrini S, Pieri D, 2007, A UAV System for Observing Volcanoes and Natural Hazards, *Eos Trans. AGU,* ***88****(52),* Fall Meet. Suppl., Abstract GC11B-05.

Sato A, 2003, Civil UAV Applications in Japan and Related Safety & Certification—RMAX Helicoper UAV, *Yamaha Aeronautic Operations Report 02 Sep 2003*, Shizuoka, Japan, 10pgs, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA427393

Schumann U, Weinzierl B, Reitebuch O, Schlager H, Minikin A, Forster C, Baumann R, Sailer T, Graf K, Mannstein H, Voigt C, Rahm S, Simmet R, Scheibe M, Lichtenstern M, Stock P, Rüba H, Schäuble D, Tafferner A, Rautenhaus M, Gerz T, Ziereis H, Krautstrunk M, Mallaun C, Gayet J.-F, Lieke K, Kandler K, Ebert M, Weinbruch S, Stohl A, Gasteiger J, Olafsson H, and Sturm K, 2010. Airborne observations of the Eyjafjallajökull volcano ash cloud over Europe during air space closure in April and May 2010. *Atmospheric Chemistry and Physics Discussions,* ***10*** *(9),* 22131-22218

Schneider DJ, Rose WI, Kelley L, 1995a, Tracking of 1992 eruption clouds from Crater Peak vent of Mount Spurr Volcano, Alaska, using AVHRR: in Keith, T. E. C., (ed.), The 1992 eruptions of Crater Peak vent, Mount Spurr Volcano, Alaska*, U.S. Geological Survey Bulletin 2139*: 27-36

Schneider, D. J., and Rose, W. I., 1995b, *Tracking of the 1992 Crater Peak/Spurr eruption clouds using AVHRR. U.S. Geol. Surv. Bull.* ***2139***, 27–36.

Searcy C, Dean KG, and Stringer W, 1998. PUFF: A volcanic ash tracking and prediction model, *Journal of Volcanology and. Geothermal Research,* ***80***, 1-16.

Sorensen P, 2010, The EU's response to the Ash crisis, in *Proceedings of the European Aviation Safety Agency (EASA) Workshop: Volcanic Ash Cloud--Detection, Observation, Measurement, Modelling, The way forward*, 21 June 2010, Cologne; http://www.easa.europa.eu/events/docs/2010/21-06/presentations.zip

Springer PJ, 2013, *Military Robots and Drones*, ABC-CLIO LLC, Santa Barbara, CA, 299pp.

Steensen TS, Stuefer M, Webley PW, Grell GA, and Freitas SR, 2010, Analysis of the Eyjafjallajökull Eruption using the WRF-Chem Model compared to Satellite-Based Ash Retrieval Algorithms. *Abstract **V41E-2320***, presented at 2010 AGU Fall Meeting.

Steensen, T, Stuefer M, Webley PW, Grell G, Freitas S, 2012, Qualitative comparison of Mount Redoubt 2009 volcanic clouds using the PUFF and WRF-Chem dispersion models and satellite remote sensing data, *J. Volcanol. Geotherm. Res.,* doi:10.1016/j.jvolgeores.2012.02.018, in press.

Smithsonian Institution, Global Volcanism Program, 2011, "*Turrialba, summary*" http://www.volcano.si.edu/world/volcano.cfm?vnum=1405-07=.

Stunder BJB, Heffter JL, and Draxler RR, 2007, Airborne Volcanic Ash Forecast Area Reliability, *Weather and Forecasting, **22***, 1132-1139, DOI: 10.1175/WAF1042.1

Tupper A, Textor C, Herzog M, Graf HF, Richards MS (2009) Tall clouds from small eruptions: the sensitivity of eruption height and fine ash content to tropospheric instability, *Nat Hazard **51**,* 375–401. doi:10.1007/s11069-009-9433-9

Watson IM, Realmuto VJ, Rose WI, Prata AJ, Bluth GJS, Gu Y, Basder CE, Yu T, 2004, Thermal infrared remote sensing of volcanic emissions using the Moderate Resolution Imaging Spectroradiometer (MODIS), *J Volcanol Geotherm Res* ***135*****,** 75-89.

Urai M, 2004, Sulfur dioxide flux estimation from volcanoes using Advanced Spaceborne Thermal Emission and Reflection Radiometer - a case study of Miyakejima volcano, Japan, *J Volcanol Geotherm Res **, 134***, 1-2, 1-13. DOI: 10.1016/j.jvolgeores.2003.11.008

Webley PW, Dehn J, Lovick J, Dean KG, Bailey JE and Valcic L, 2009, Near Real Time Volcanic Ash Cloud Detection: Experiences from the Alaska Volcano Observatory, Special Issue on Volcanic Ash Clouds, eds. Larry Mastin and Peter Webley, *J Volcanol Geotherm Res , **186** (1–2),* 79-90.

Webley PW, Dean KG, Dehn J, Bailey JE, and Peterson R, 2010, Volcanic-ash dispersion modeling of the 2006 eruption of Augustine Volcano Using the Puff Model, chapter 21 of Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., *The 2006 eruption of Augustine Volcano, Alaska: USGS Professional Paper **1769***, 507 – 526.

Webley PW, Steensen T, Stuefer M, Grell G, Freitas F, Pavolonis M, 2012, Analyzing the Eyjafjallajökull 2010 eruption using satellite remote sensing, lidar and WRF-Chem dispersion and tracking model*, J., Geophys. Res, **117***, D00U26, doi:10.1029/2011JD016817

Weinzierl B, Schumann U, Minikin A, Reitebuch O, Schlager H, Rahm S, Scheibe M, Lichtenstern M, Stock P, Forster C, Baumann R, Wirth M, Sailer T, Graf K, Mannstein H, Freudenthaler V, Groß S, Lieke K, Weinbruch S, 2010, *Proceedings of the 53rd session of the United Nations Committee on the Peaceful Uses of Outer Space (9-18 June),* Vienna, Austria, http://www.oosa.unvienna.org/pdf/pres/copuos2010/tech-23E.pdf

Wen, S., and W. I. Rose, Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR bands 4 and 5, *J. Geophys. Res.,* ***99****,* 5421–5431.

Wezeman S, 2007, *UAVS and UCAVS: Developments in the European Union*, European Parliment/EC Communities, Brussels, BE, 24pp; EP/EXPO/B/SEDE/FWC/2006-10/Lot4/05; http://www.europarl.europa.eu/committees/en/sede/studiesdownload.html?languageDocument=EN&file=19483

9. Table 1. UAVs and Characteristics

UAV Platform Type	UAV Name	Payload mass	Instruments	Operating Ceilings (estimate)	Propulsion or Lift	Endurance & Range	UAV Operator
Aerostat	Tether-sonde (balloon)	<1kg	SO_2, T, P, %H_2O, GPS, telemetry	12-13Kft ASL	Helium	24hrs+/ tethered	UCR
Aerostat	AeroPod (kite)	<1kg	SO_2, T, P, %H_2O, GPS, pan-camera	10-15Kft ASL	Dynamic wind pressure	8hrs+/ tethered	NASA GSFC/WFF
µUAV	Dragon Eye	<0.5kg	SO_2, T, P, %H_2O, GPS, OPC, nanoPC, Color VIS, Lo light VIS, Thermal IR, evacuated sampling bottle	12K+ft ASL	Electric	1hr/ 10km	NASA ARC
µUAV	Vector Wing 100	<1kg	SO_2, T, P, %H_2O, GPS, color VIS	15K ft ASL	Electric	30min/5km	UCR
Medium UAV	SIERRA	<45kg	ULISSES mass Spectrometer, SO_2, T, P, %H_2O, GPS, multi-spectral imaging, bolometer, optical particle counters, Liquid aerosol probe, mini-nephelometer, aerosol drum impactor,	15K ft ASL	Gas	10hrs/500km	NASA ARC

10. Figure Captions

Figure 1 a—NASA Global Hawk

NASA's Dryden Flight Research Center operates two developmental Northrop Grumman Global Hawk aircraft for use in high-altitude, long-duration Earth science missions. Global Hawk measures 44 feet in length, with a wingspan of 116 feet. NASA operates the Global Hawk with payloads up to 2000 pounds and at altitudes up to 65, 000 feet. Its range is greater than 10,000 nautical miles and its endurance is greater than 31 hours. Dropsondes for nadir deployment into volcanic clouds would be a possibility from Global Hawk, if the aircraft can fly above the ash layer. Since the neutral buoyancy heights of most explosive eruption plumes are generally below the operational ceiling of this aircraft, dropsondes or glidesondes deployment could be possible in well-posed situations. (Photo: NASA).

Figure 1 b—NASA Ikhana

Ikhana is a Choctaw Native American word for “intelligent, conscious, or aware.” NASA uses this airborne platform for a variety of long duration earth science missions and to demonstrate and validate electronic sensor technologies. This aircraft is a low-wing monoplane with a narrow fuselage and high-aspect-ratio wing, large V-shaped tail with ventral fin, rear-mounted turboprop engine, and retractable tricycle landing gear. The enlarged fuselage nose accommodates various payloads, including imaging systems, lidars and radars. (Photo: NASA)

Figure 2—Medium Sized UAV—NASA SIERRA

SIERRA medium UAV at NASA Ames Research Center, Moffett Field, California. (Photo: NASA)

Figure 3 a—Micro-UAV—NASA Dragon Eye

The RQ-14 Dragon Eye, originally designed by the U.S. Naval Research Laboratory in 2001 for the U.S. Marine Corps and built by Aerovironment, Inc. is shown in a typical hand-launch configuration with engines at takeoff power. This small (e.g., 0.9m length, 1.1m wingspan, 2.7kg weight) is a rugged and versatile platform for deployment of small COTS sensors into volcanic plumes. It cruises at 65kph over a 5-10km range, and flies completely autonomously, with automatic takeoffs and landings. It comes equipped with two visible wavelength cameras and a thermal IR imager. The current NASA ARC Dragon Eye fleet consists of 75 aircraft plus spares, operated under the auspices of the NASA Airborne Science Program, currently for NASA investigators at JPL and ARC.(Photo: Justin Linick, JPL).

Figure 3 b—Micro-UAV—NASA Dragon Eye in flight

The NASA Dragon Eye in level flight in U.S. government-controlled airspace near Jolon, California on 28 January 2013 during one of its first NASA test flights. The orange nose compartment contains a small SO_2 sensor, temperature, pressure and humidity sensors, and onboard data storage (shown below in Figure 3c). One of the main goals of this flight testing was to verify center-of-balance configurations for a variety of small sensors for Dragon Eye, including an Optical Particle Counter and a 0.1deci-liter evacuated gas/aerosol sample bottle. (Photo: Justin Linick, JPL).

FIGURE 3 C—MICRO-UAV—NASA DRAGON EYE INSTRUMENT PACKAGE

Shown is a disassembled Dragon Eye nose (shown in flight configuration in Figure 3b). The sensor package was configured by co-authors Bland and Miles at NASA GSFC/WFF, incorporating an SO_2 sensor design evolved from an original design by co-author Abtahi. In the field, Dragon Eye nose pods with different instrument configurations can be easily swapped thanks to a convenient unique snap attachment.

FIGURE 3 D,E—MICRO-UAV—UCR VECTOR WING 100

Figure 3d. The VectorWing 100 UAV, built by Maryland Aerospace, Inc. and operated by the CICANUM Gas Lab at the University of Costa Rica, is shown undergoing preflight checks in the field at Turrialba Volcano by coauthors Corrales (left) and Alan (right). It has a 2.1m wingspan, an in-flight weight of 3.6kg, and an approximate payload weight of about 1kg. Its range is 10-15km with 30-45min endurance at a cruise speed of about 50km/hr. At Turrialba Volcano, in autonomous flight, it has achieved an altitude of 11,500 feet, in order to undertake SO_2 concentration measurements within the Turrialba steam and gas plume, in conjunction with near-simultaneous ASTER TIR data acquisitions.
Figure 3e. Screen capture of the VectorWing 100 after takeoff from 8900ft ASL over the southwest slopes of Turrialba Volcano (from http://www.youtube.com/watch?v=-g9wewHEvtU&feature=plcp *Vuelo de reconocimiento en Volcán con UAV*).

FIGURE 4 A,B—TURRIALBA VOLCANO FROM ABOVE

Index maps of Turrialba Volcano and surrounding terrain (Google Earth™). Ground-based photos of Turrialba (Figures 5 and 6) were taken from the vicinity of the Turrialba Lodge, indicated in the lower figure 4b.

FIGURE 5 A,B,C,D—TURRIALBA VOLCANO FROM THE GROUND

5a. Turrialba Volcano in morning from about 3km away. Visible light. (Pictures were taken in March 2012 from the vicinity of the Turrialba Lodge [Fig. 4])

5b. Turrialba Volcano in morning from about 3km away. Thermal infrared MikroShot camera image with plume temperature indicated in scale bar.
5c. View of stream valley on lower slopes of Turrialba Volcano from 500ftAGL from kite-borne digital camera—image is about 200m across. Note the poor condition of the trees, most likely from volcanogenic CO_2 suffocation of root systems, while surface grasses are thriving. Small animals are reported to have died within the ravine.
5d. Ground level view of dead trees visible in upper left corner of figure 5c. Generally all vegetation on the upper slopes of Turrialba below the summit have been devastated during the last several years from SO_2-engendered acid rain, as well as poisoned by CO_2 rising along fractures. While in this area, Pieri and Diaz measured 100ppm fluctuations in background CO2 when winds blew downslope from the summit, indicating an active source nearby.

Figure 6 a,b.—SO_2 Sonde and Balloon at Turrialba Volcano

Figure 6a. Closeup of SO_2 tethersonde payload at Turrialba Volcano. Styrofoam housing supports an electrochemical SO_2 sensor, a GPS location and altitude sensor, and standard sensors for temperature, pressure, and relative humidity.
Figure 6b. SO_2 tethersonde payload suspended under a standard 1m diameter meteo-balloon, at Turrialba Volcano. ready for launch at Turrialba Volcano. Upslope and near-field vegetation have been heavily damaged by SO_2 acid rain and CO_2 inundation. Picture was taken in March 2012.

Figure 7—Kites and Aeropods

Figure 7a. Kite-borne instrumentation. The 9 ft Delta kite was built by Into-the-Wind, Inc. and is deploying an Ocean Optics 4000 imaging system.
Figure 7b. Closeup of Aeropod with JPL electrochemical SO2 sensor attached, designed and built at NASA Wallops Flight Facility. Device is approximately 1m in length.
Figure 7c. Close-up of Aeropod with mini-recording anemometer attached.

Figure 8—Turrialba Tethered Balloon Deployment, 01 February 2012

This deployment was accomplished 11 days after the ASTER deployment referenced in Figure 9. Winds were calm and weather was clear. Maximum SO_2 concentration recorded was 5ppmv (sensor saturation) at about 3300m ASL. Actual max SO_2 concentration was likely to be 6-7ppmv during this period. This measurement compares favorably with the earlier ASTER-based estimate of 6ppmv. Ascent (blue) and descent (red) SO_2 vertical profiles are shown at lower right. Trajectories in Google Earth™ images are color-coded according to the legend at left. [Background image was projected in Google Earth™, and trajectories were plotted using the GPS Visualizer™ software created by Adam Schneider]).

FIGURE 9—TURRIALBA ASTER SO_2 MEASUREMENT, 21 JANUARY 2012

The results of analysis of ASTER TIR bands located at or near the well-known sulfur dioxide absorption band centered on 8.5um, acquired on 21 January 2012, under nearly perfectly clear sky conditions (see text for details on ASTER bands). For reference, panel (a) is an ASTER VNIR false-color composite image Turrialba and Irazu volcanoes. Panel (b) shows the SO_2 plume in yellow extending toward the west in a principal component image using the five ASTER TIR bands. Panel (c) shows SO_2 concentration derived from ASTER TIR data, with a maximum of about 6ppmv. This agrees with the later tethersonde measurement shown in Figure 8.

FIGURE 10—TURRIALBA UAV SO_2 MEASUREMENT, 08 FEB 2013

VectorWing 100 UAV SO_2 sensor data are plotted over Turrialba Volcano using Google Earth™ and GPS Visualizer™. The aircraft was launched from approximately 8800ft (2700m) ASL and achieved a maximum altitude of 11,258ft (3464m) ASL. Flight duration was 22min and the maximum SO_2 concentration observed was 10.46ppmv at about 10,871ft (3345m) ASL, about the altitude of the Turrialba summit. The color coding legend for the flight path can be seen at lower left. ASTER data were acquired at approximately the same time and the data analysis will be forthcoming.

FIGURE 11 A,B—SIERRA IN FLIGHT AND THE ULISSES MASS SPECTROMETER

Figure 11a. SIERRA in flight.(Photo: NASA)
Figure 11b. ULISSES Mass Spectrometer for SIERRA UAS - Nose with integrated 3D engineering concept (left), and beta prototype (right).

Figure 1a. Large UAV--NASA Global Hawk

Figure 1b. Large UAV--NASA Ikhana

FIGURE 2. Medium Sized UAV—NASA SIERRA

FIGURE 3a. Micro-UAV—NASA Dragon Eye

FIGURE 3b. Micro-UAV—NASA Dragon Eye in flight

FIGURE 3c. Micro-UAV—NASA Dragon Eye Instrumented Nose Pod

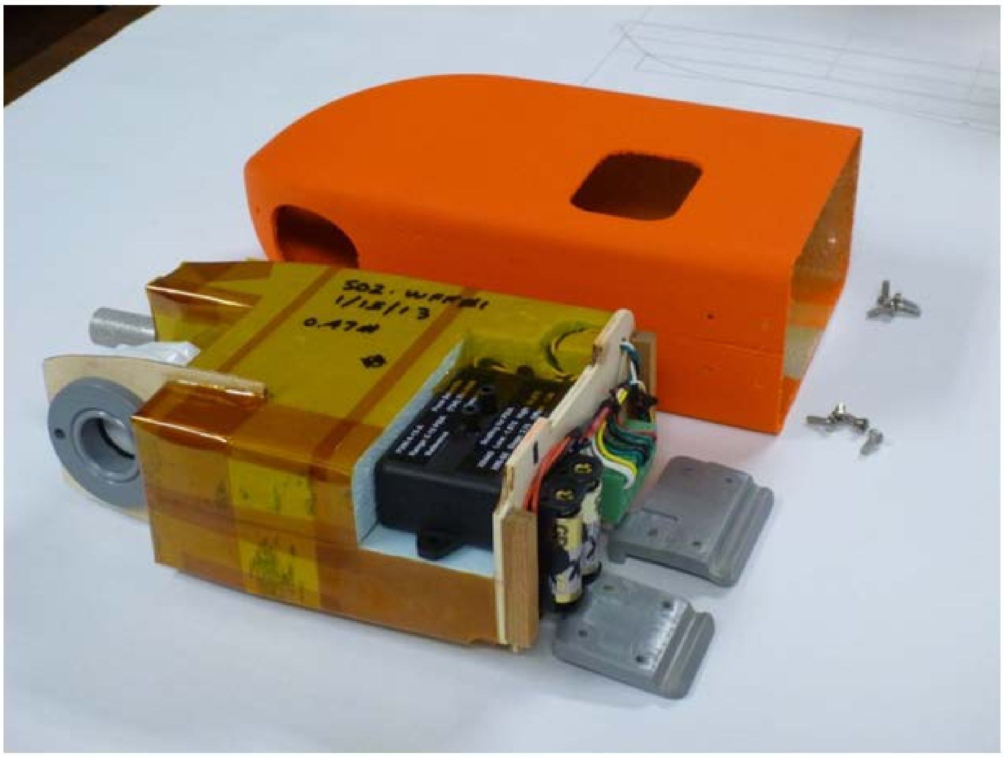

FIGURE 3d,e. Micro-UAV—UCR Vector Wing 100

Figure 3d.

Figure 3e.

FIGURE 4a,b. Turrialba Volcano from Above

Figure 4a.

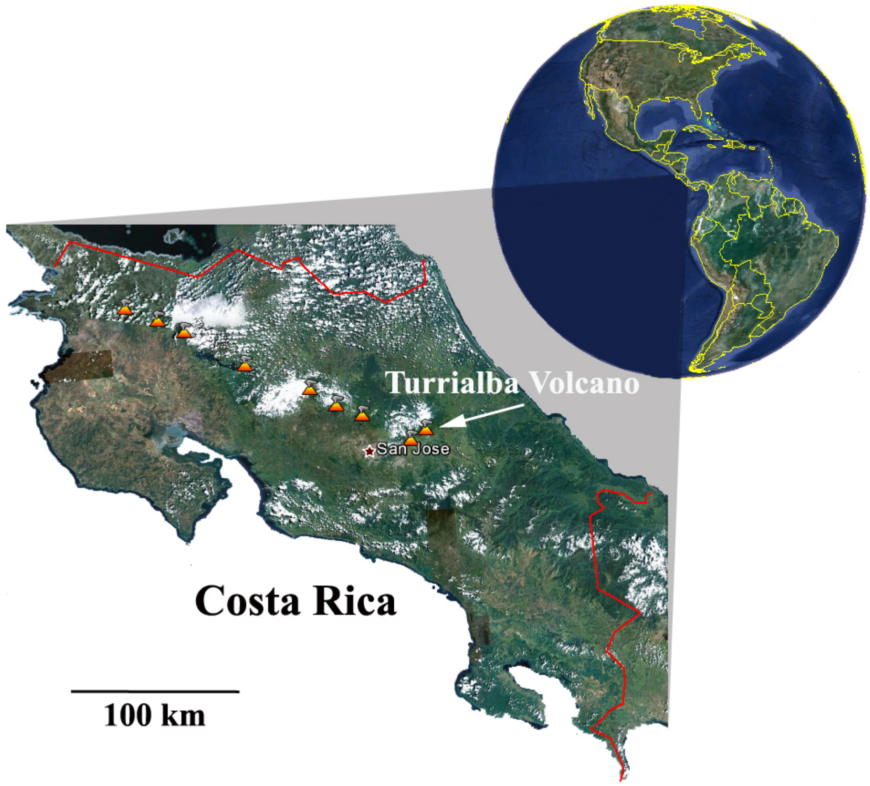

Figure 4b.

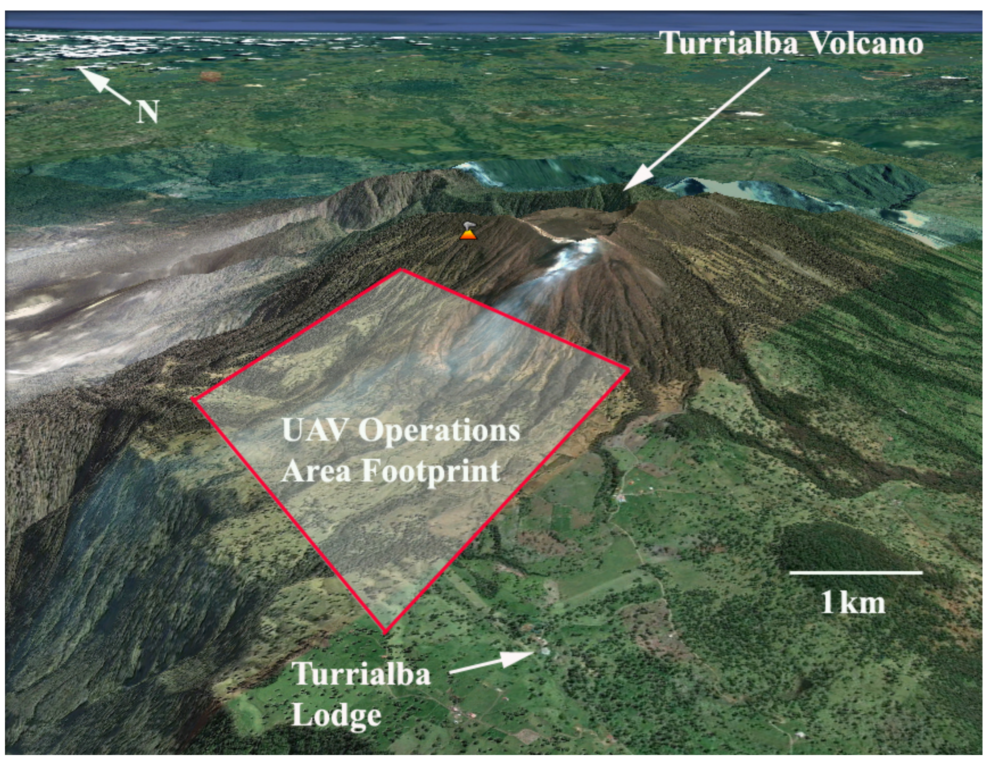

Figure 5a,b,c,d. Turrialba Volcano from the Ground

Figure 5a.

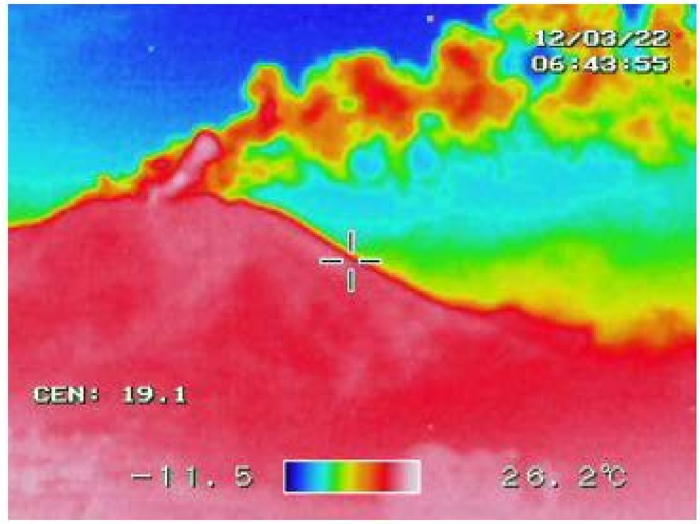

Figure 5b.

Figure 5d.

Figure 6a,b. Sulfur Dioxide Tethersonde and Balloon at Turrialba Volcano

Figure 6a.

Figure 6b.

Figure 7a,b,c. Kites and Aeropods

Figure 7a.

Figure 7b.

Figure 7c.

Figure 8—Turrialba Tethered Balloon Deployment—01 February 2012

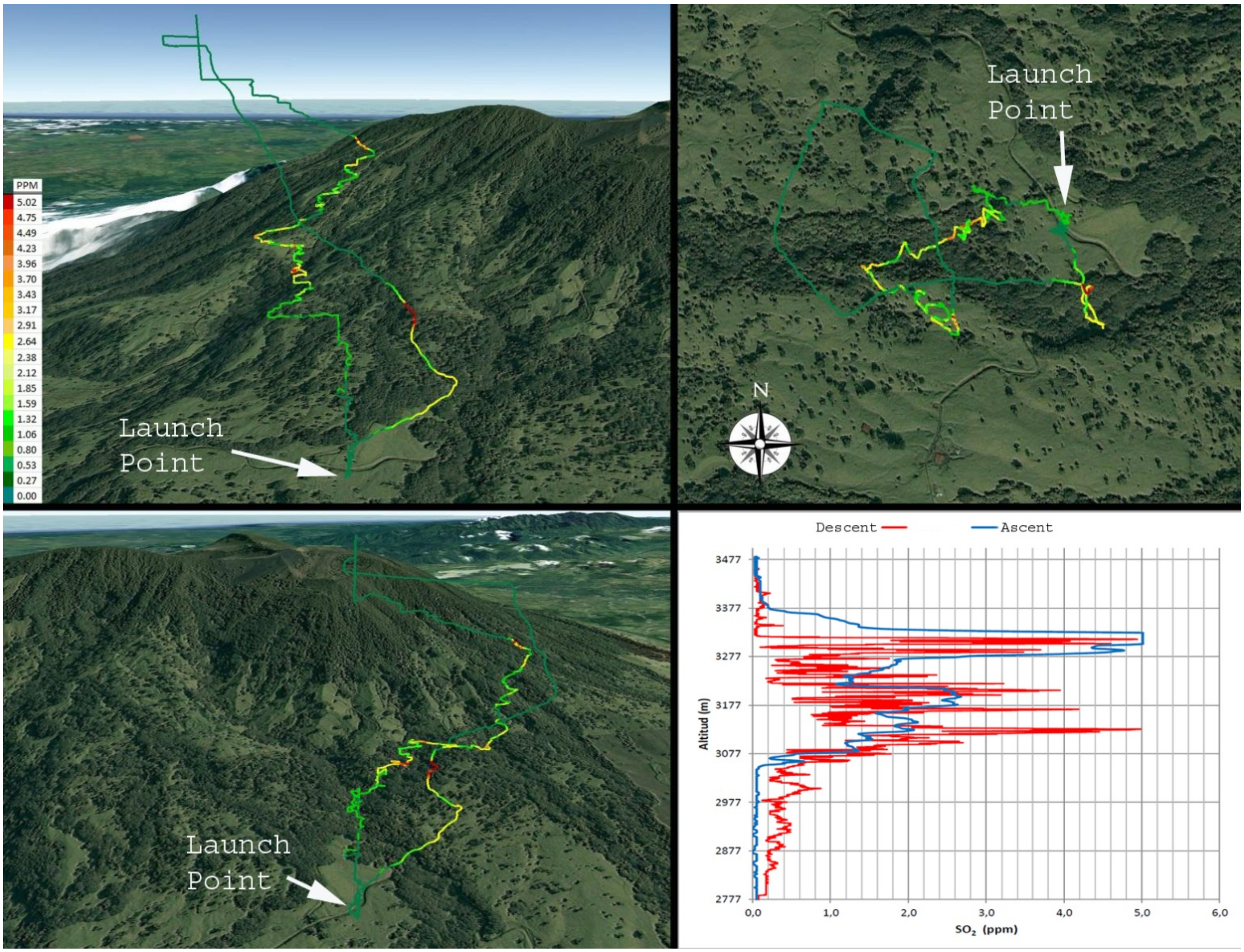

Figure 9—Turrialba ASTER Sulfur Dioxide Measurement, 21 January 2012

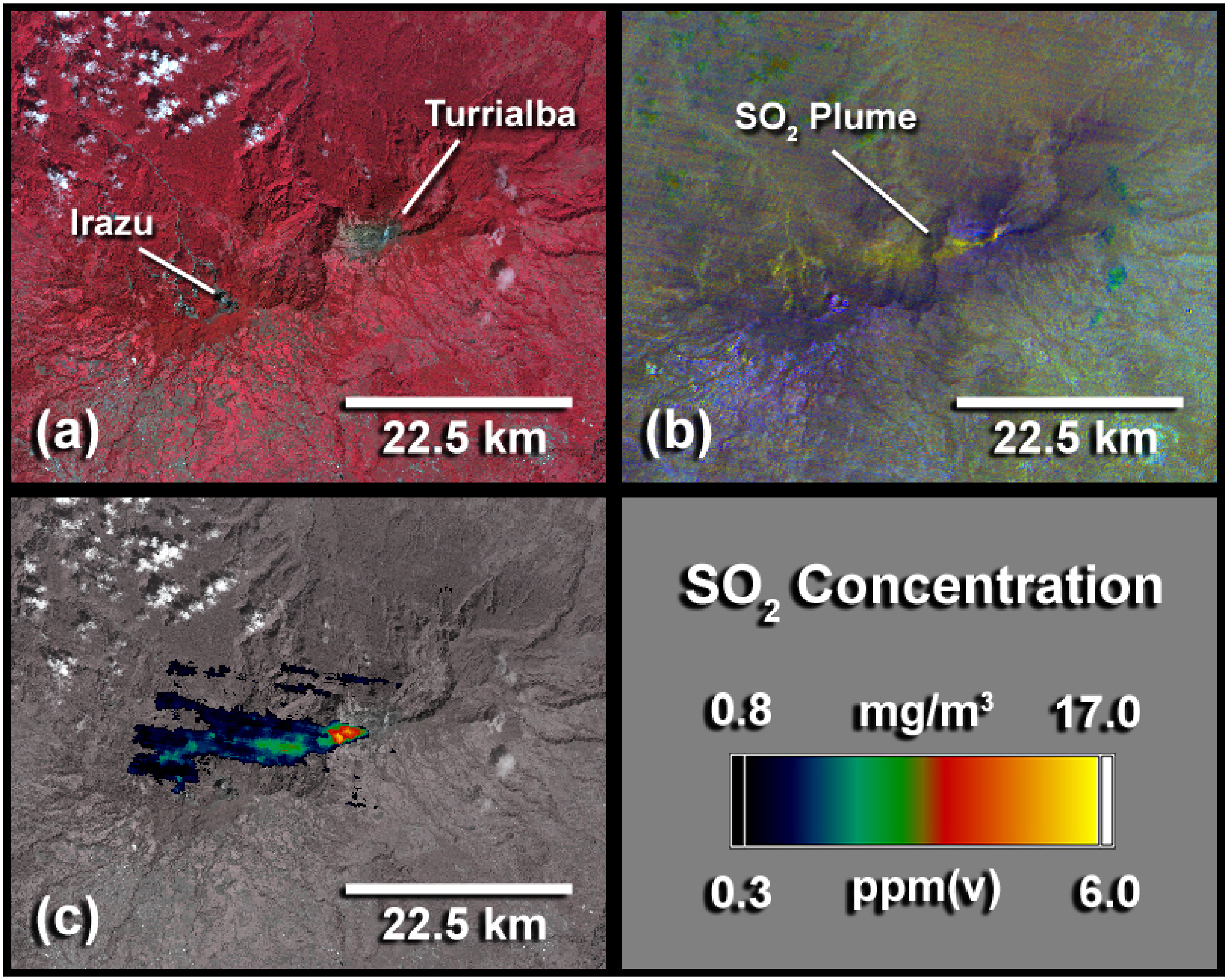

Figure 10—Turrialba UAV Sulfur Dioxide Measurement, 08 Feb 2013

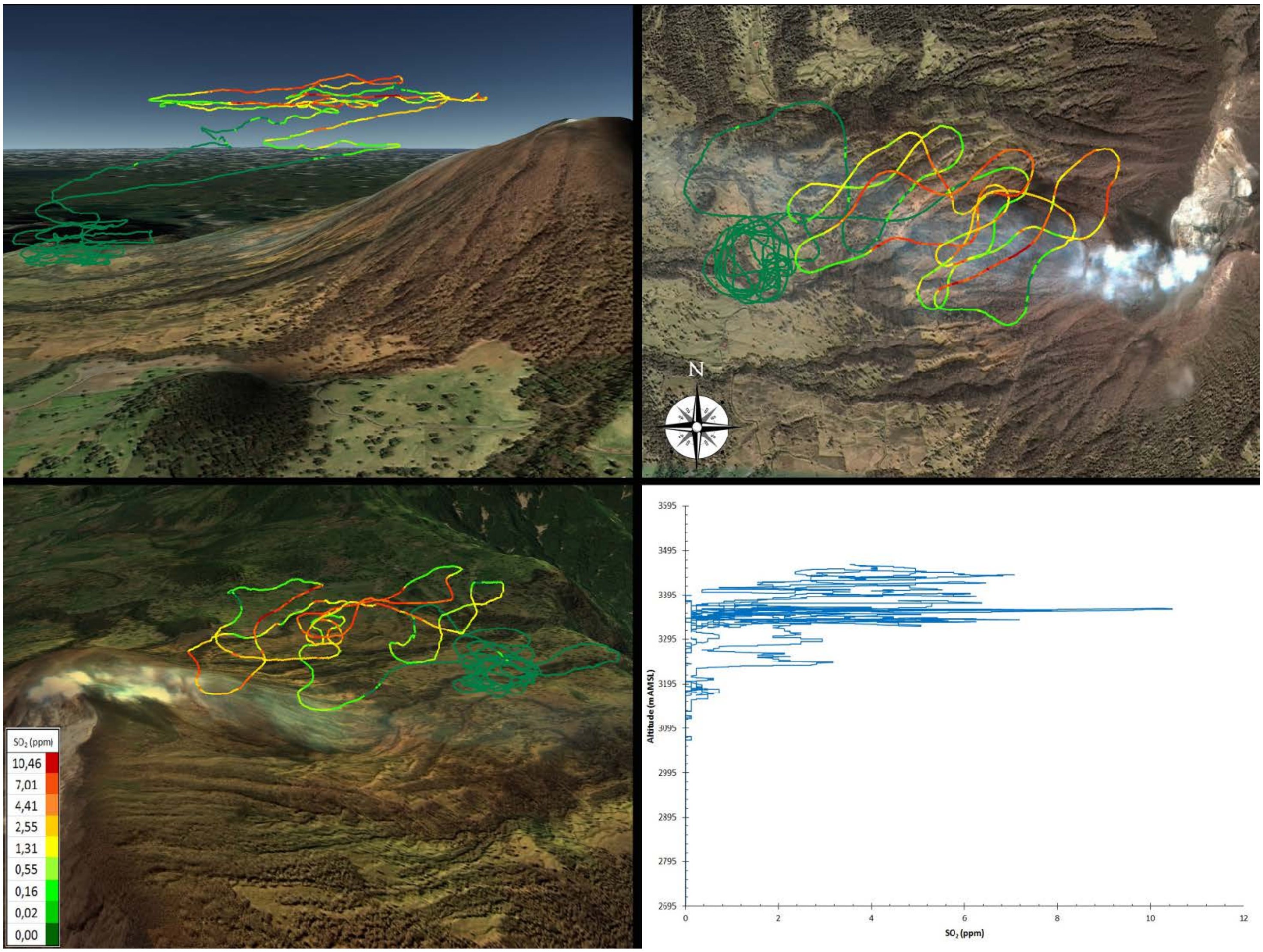

Figure 11a,b. SIERRA and ULISSES

Figure 11a.

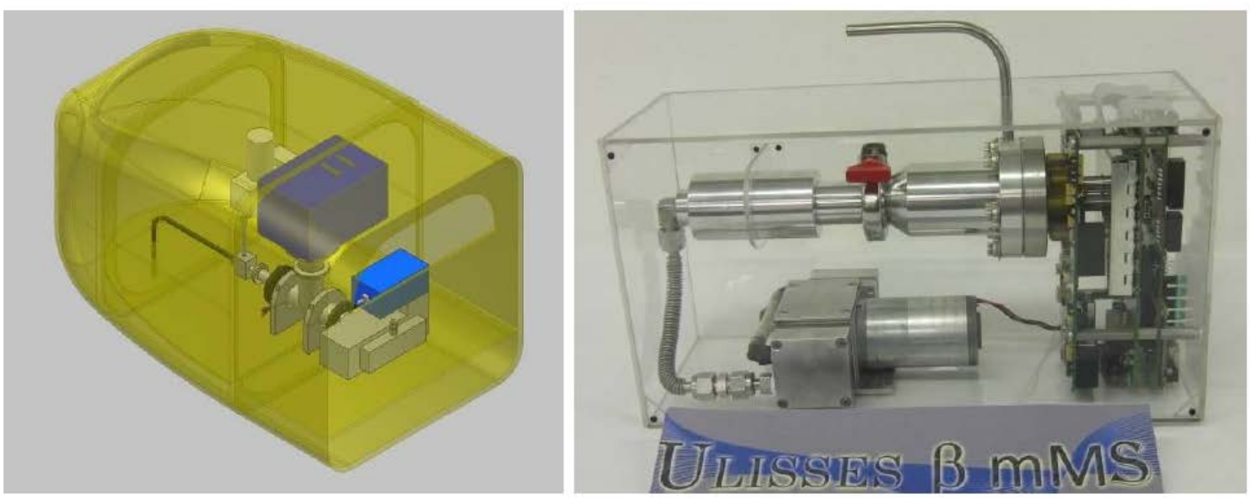

Figure 11b.