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Volcano Monitoring with small Unmanned Aerial Systems

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The development of small unmanned aerial systems (sUAS) with a variety of sensor packages enables in situ and proximal remote sensing measurements of volcanic plumes. Using Costa Rican volcanoes as Natural Laboratories, we describe an initiative to develop low-cost, field-deployable airborne platforms to perform volcanic ash plume research and in situ volcanic monitoring in general, in conjunction with orbital assets and state-of-the-art models of plume transport and composition. Several gas sensors including a miniature mass spectrometer, and an electrochemical SO_2 sensor, combined with temperature, pressure, relative humidity, and GPS sensors, were deployed into the active plume of Turrialba Volcano. Several different airborne platforms such as manned research aircraft, unmanned aerial vehicles (UAVs), tethered balloons, as well as man-portable in situ ground truth systems were used during these this research. Remote sensing data was also collected from the ASTER and OMI spaceborne instruments. The deployments demonstrated a path to study and visualize gaseous volcanic emissions using mass spectrometer and gas sensor based instrumentation in harsh environmental conditions to correlate in situ ground/airborne data with remote sensing satellite data for calibration and validation purposes. The deployment of such technology improves on our current capabilities to detect, analyze, monitor, model, and predict hazards presented to aircraft by volcanogenic ash clouds from active and impending volcanic eruptions .

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I. Introduction

WE describe an on-going research initiative to study, measure and visualize volcanic gaseous emissions using small unmanned aircraft vehicles (UAVs), tethered balloons and ground portable equipment, using both in situ gas sensing instrumentation and remote sensing data, targeted to correlate ground data with satellite remote sensing data for calibration and validation purposes.

Three NASA centers — the NASA Ames Research Center (ARC), NASA Goddard Space Flight Center / Wallops Flight Facility (WFF), and the Jet Propulsion Laboratory (JPL) — together with the main research institution in Costa Rica, the University of Costa Rica, established a focus group targeting small airborne platforms and lightweight sensors such as miniature mass spectrometry instrumentation including complementary electrochemical sensors, VIS, UV, IR cameras and meteorological parameters to create an integrated single low altitude, harsh environment, system for in situ volcanic plume gas analysis,.

The active Costa Rica volcanoes are an ideal natural research laboratory environment. The current active volcanic condition on different volcanoes such as Turrilaba, Poás, Irazú, Arenal, Rincón de la Vieja and Miravalles and the national logistics and infrastructure make these study sites easily reachable and available to probe the environment and test new instrumentation. Also, the local UAV-friendly government policies allows Costa Rica to serve as a test bed for different UAV-based earth science research applications in collaboration with the local universities.

Figure 1. Two of Costa Rica's most active volcanoes: Arenal (Top) and Turrialba (Bellow). The active conditions which are visible from space, easy access and logistics allow the use of each of these sites as a Natural Laboratory for Calibration and Validation of Satellite Remote Sensing Observations.

Figure 2. University of Costa Rica's WING-100 UAS. System includes autopilot, VIS and IR cameras, SO_2, humidity, pressure, temperature and GPS sensors.

II. System Description

A. Airborne Platforms

In the past a manned CESSNA 206 aircraft from the Costa Rica Civil Aviation authority with external POD capabilities was used (Griffin et al., 2008, Diaz et al., 2010) to perform in situ gas plume analysis. Due to the increasing activity of the volcano and the risky ash content of the volcanic plume, however, the authorities suspended the in situ airborne missions.

Therefore, a series of unmanned airborne platforms are now being used to continue with the gathering of in situ volcanic plume data. These include a small electric UAV

Figure 3. Tethered balloon launches for in–situ volcanic plume measurements

(WING 100 manufactured by Maryland Aerospace Inc. and acquired by the University of Costa Rica) with 1 kg payload and 30 min endurance capabilities (Fig. 2), and a tethered balloon system with 1kg payload and 5 km maximum altitude capabilities (Fig 3).

UAVs have been selected for this effort, given the dangerous and often remote nature of volcanic plumes that pose a non-trivial risk to aircrews and high value assets such as the WB-57, DC-8 or P-3 aircraft which have been used before in Costa Rican missions.

The team is now expanding the payload capabilities by using the NASA Sensor Integrated Environmental Remote Research Aircraft (SIERRA) UAV, which is a medium class, medium duration, unmanned aircraft designed and tested at the NASA Ames Research Center to support earth science experiments in harsh environments or remote regions. UAVs have been selected for this effort, given the dangerous and often remote nature of volcanic plumes that pose a non-trivial risk to aircrews and high value assets such as the WB-57, DC-8 or P-3 aircraft which have been used before in Costa Rican missions. The SIERRA UAV was designed to conduct relatively low altitude missions for tropospheric chemistry sampling and remote area surveys.

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Figure 4. NASA Sierra UAV: multi-payload (up to 100lb) and long endurance capabilities (up to 11hrs).

sampling and remote area surveys. The aircraft has a range of 600nm, a ceiling of 10,000ft and can carry 80lbs for 10 hours. The pusher configuration and front payload nose make it ideal for atmospheric measurements. The SIERRA will be used initially to carry a mass spectrometer, SO_2 sensors, and meteorological instruments for measuring the margins of the plume. The team is also partnering with several companies through the NASA SBIR program to develop dropsondes and glidesondes to deploy from SIERRA into volcanic plumes. In addition, to enable more dangerous, in-plume sampling the SIERRA team is conducting studies on converting the A/C to a hybrid electric version to reduce risk associated with ash intake and combustion engines.

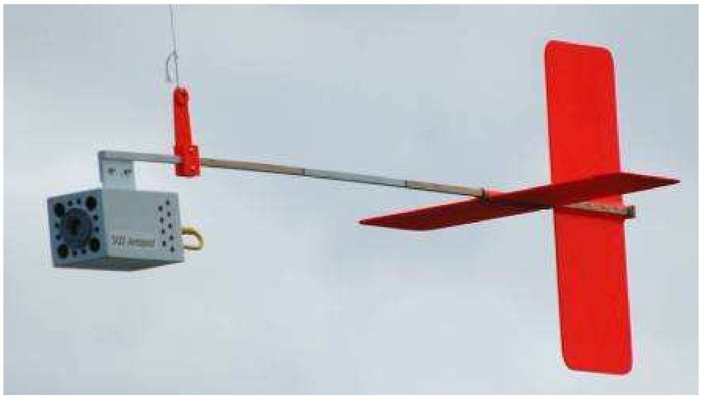

Figure 5. SO_2 Aeropod package (above) and Profiler Aeropod package (below) for kite and balloon-borne measurements

B. Sensor Instruments

Two main sensor instruments have been tested so far: the Aeropod system (Figure 5) and the ULISSES mass spectrometer based instrument (Figure 6). Several other sensor packages are planned to be use in the different airborne platforms.

The Aeropod is an aerodynamically stabilized small compact box device used for carrying small instruments on kites and tethered balloons. Several packages are in development for this work, including a system which contains an SO_2 electrochemical cell sensor combined with GPS, temperature pressure and relative humidity data with data logging capabilities. It is designed for balloon-borne measurement and it is been adapted for the WING-100 UAV platform.

Other Aeropod packages include: a profiling system for wind, temperature, and humidity measurements; several camera packages including visible, near-infrared, and thermal infrared imaging capabilities; atmospheric particle counters; and a carbon dioxide sensor. These systems have been developed as part of NASA's Advancing Earth Research Observation Kites and Tethered Systems (AEROKATS) effort. This development work is also aimed at kite development specifically for research uses, and line handling methods to ease field deployments. To date, the maximum routine operational altitude capability of kite-based observations is approximately 1500 ft AGL, and work continues to significantly expand the envelope.

The ULISSES (Utilization of Lightweight In situ Sensors and remote Sensing to study active volcanic Emissions Sites) is a small in situ harsh environment mass spectrometer- based system developed to demonstrate a path for its integration into UAV. It has been flight tested onboard the CESSNA 206 manned aircraft and a newer version is being designed for the SIERRA UAV. (Figure 6)

Other envisioned sensor instrument ensembles to be used with the airborne platforms are: a gas sensing package, an imaging sensor package, a meteorological data package, a remote sensing package and a particle analysis package.

C. Calibration and Validation Challenges with Respect to Remote Sensing Data

Current remote sensing retrieval and transport modeling efforts to detect, characterize, and track volcanic emissions suffer from very sparse in situ validation data. This has been a chronic and pervasive problem, and the Eyjafjallajökull 2010 eruption starkly highlighted this deficiency as experts failed to provide crucial accuracy and precision in predicting locations, trajectories, and ash concentrations for volcanic plumes causing significant negative economic impact worldwide. Ash and gas concentrations from analysis of satellite remote sensing data (e.g., SEVIRI, GOES, AVHRR and, ASTER) were typically unvalidated by in situ data. Such insufficiencies have centrally contributed to inadvertent aircraft encounters with ash plumes (e.g., 1989 Redoubt Volcano, near-fatal AK 747 ash encounter; 2000 Hekla Volcano, NASA DC-8 encounter, severe four engine damage).

The goal of our efforts to conduct in situ sampling of volcanic airborne emissions (e.g., Diaz et al., 2001, 2002, 2010; Pieri et al., 2002), has been to improve quality and range of data in proximal and distal volcanogenic environments (e.g., plumes and ash clouds) accessible to in situ techniques, for the calibration and validation of remote sensing data and derivative models, as well as for proximal and distal hazard evaluations.

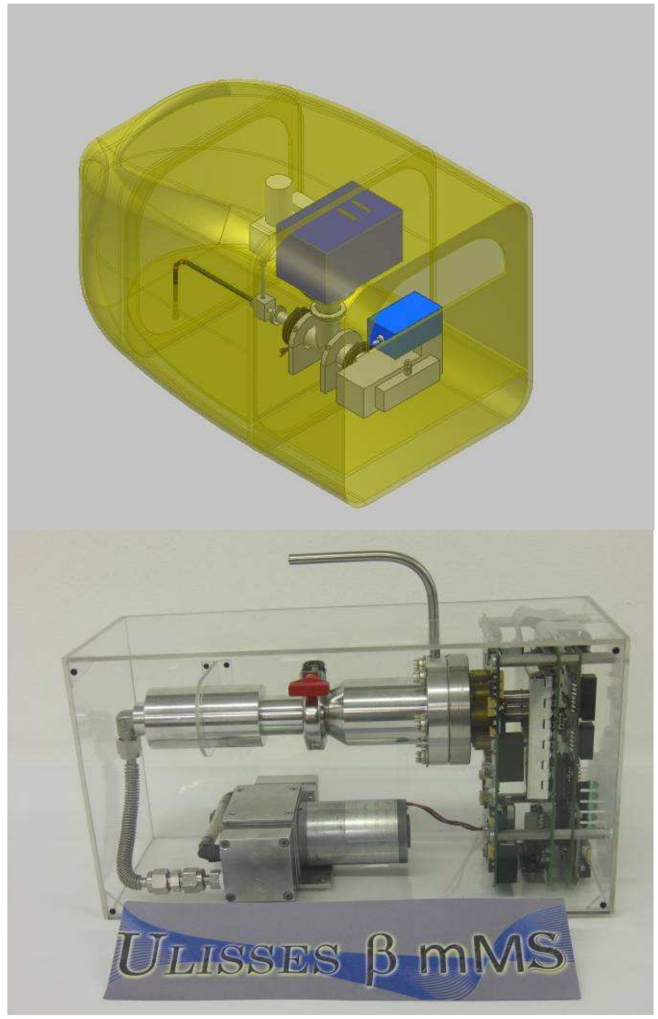

Figure 6. ULISSES-Sierra MS System UAV Nose with integrated miniature mass spectrometer 3D engineering concept (above) and beta prototype (below)

In situ sampling of airborne ash and gas at altitude is operationally difficult, but is of high scientific importance for understanding the dynamics and chemistry of volcanic plume aerosols, and for validation of existing ash plume detection, retrieval, and transport algorithms. In situ validation of orbital ash and gas retrievals is crucial in the context of hazards to aircraft (e.g., Prata et al., 2009), especially in the European theater where airspace alternatives to ash-contaminated airspace are limited (e.g., Eyjafjallajökull 2010 eruption and aftermath). For instance (a) sensitivity analyses ash plume mass retrieval algorithms (e.g., Wen and Rose, 1994) suggest mass loading errors of 40–50% (Prata and Kerkmann, 2007); (b) conservative estimated error for SEVIRI is ±10 D.U. on a single pixel basis, yielding a mass loading retrieval error of of approximately ±0.01 Tg (S) for the SO_2 clouds discussed in the same paper by Prata and Kerkmann, in the absence of correlative in situ validation.

Thus, given the dependency on assumptions for predictive ash/gas transport models, as well as for radiative transfer models that allow interpretation of TIR remote sensing signatures, and because the volcanologic and meteorologic conditions can vary considerably in an area of interest, remote sensing-based estimates the masses of drifting eruption clouds and plumes will benefit as in situ sampling capability becomes more easily and cheaply accessible. This is especially true as currently, to our knowledge, there is no systematic in situ validation program in place within operational eruption response agencies. Thus, our goal is to contribute to the development of a robust and flexible in situ capability, both for low altitude (<10Kft) and high altitude (>10Kft) volcanogenic plumes and clouds. We hope that our work reported on here is a first step in developing a variety of small economic and flexible platforms, including a mix of free-flying UAVs and tethered devices that can penetrate ash and gas-laden plumes and drifting clouds, in order to make the necessary in situ measurements for routine in situ characterizations.

III. Results

Several sets of satellite remote sensing and in situ data have been taken before and after the awakening of the Turrialba volcano which had an eruption on January 5th, 2010. Figures 7 and 8 show the visible plume from space collected by the ASTER and OMI instruments onboard the Terra and AURA satellites.

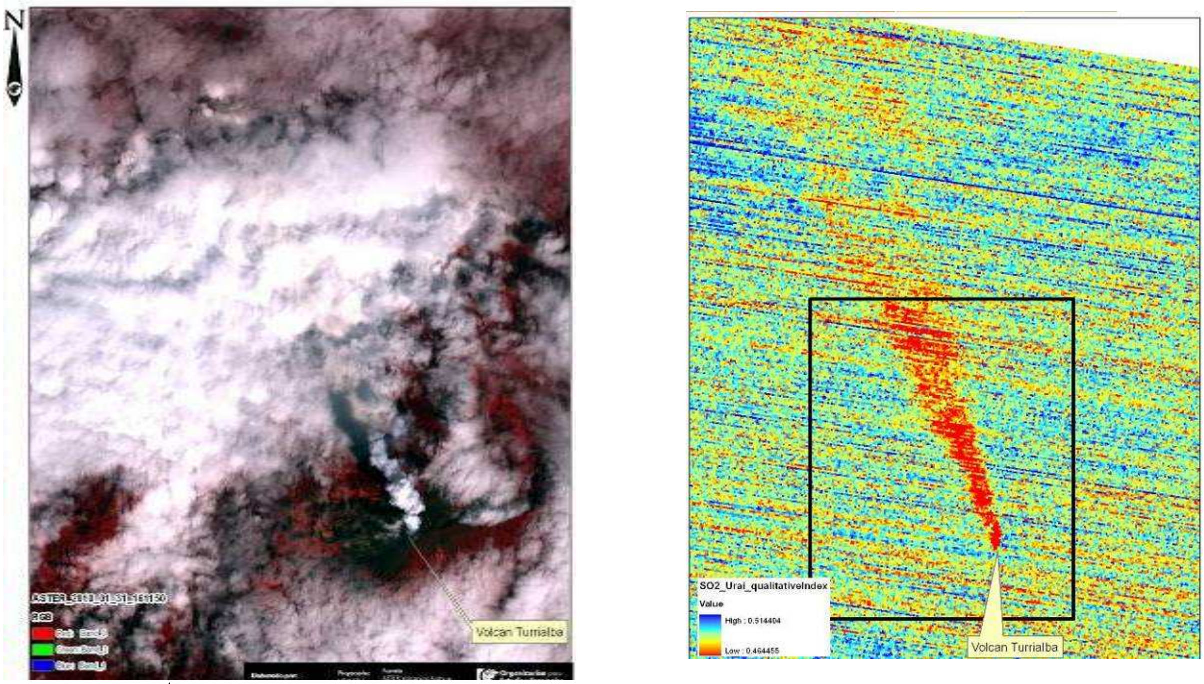

Figure 7. 31st Jan, 2010 ASTER images of Turrialba Volcano. Left: ASTER VIS image.* Right: *Corresponding ASTER TIR data with URAI-TIR_SO2 Plume Index

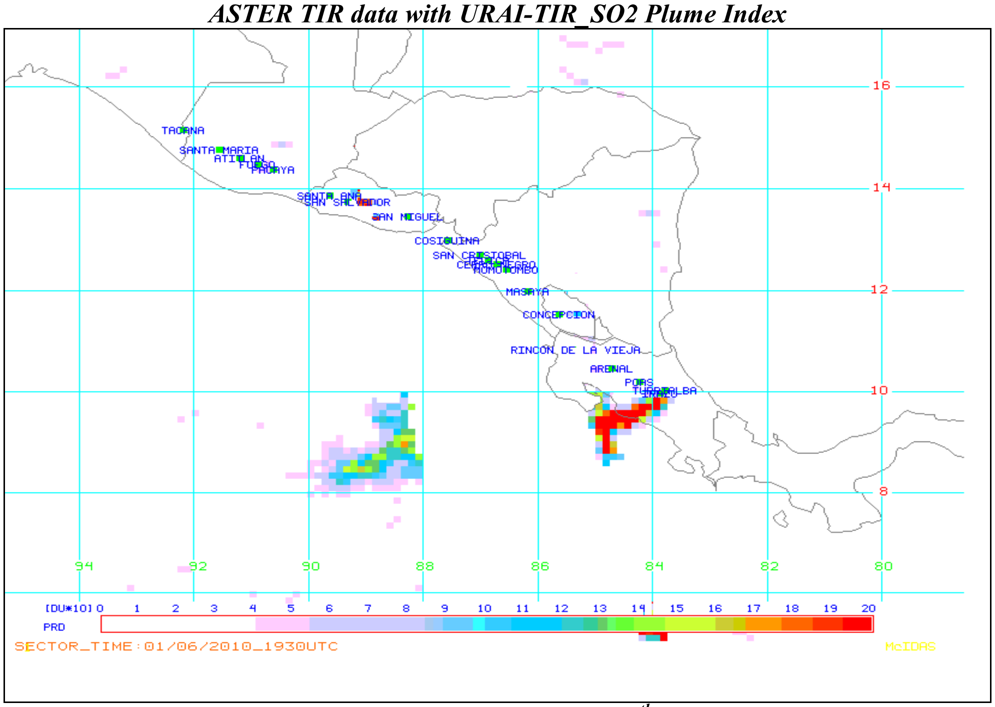

Figure 8. OMI_SO2 data for Turrialba Volcano eruption on Jan 5th 2010. Large plume visible drifting over Pacific Ocean (mid image pixels lost due to OMI sensor anomaly).

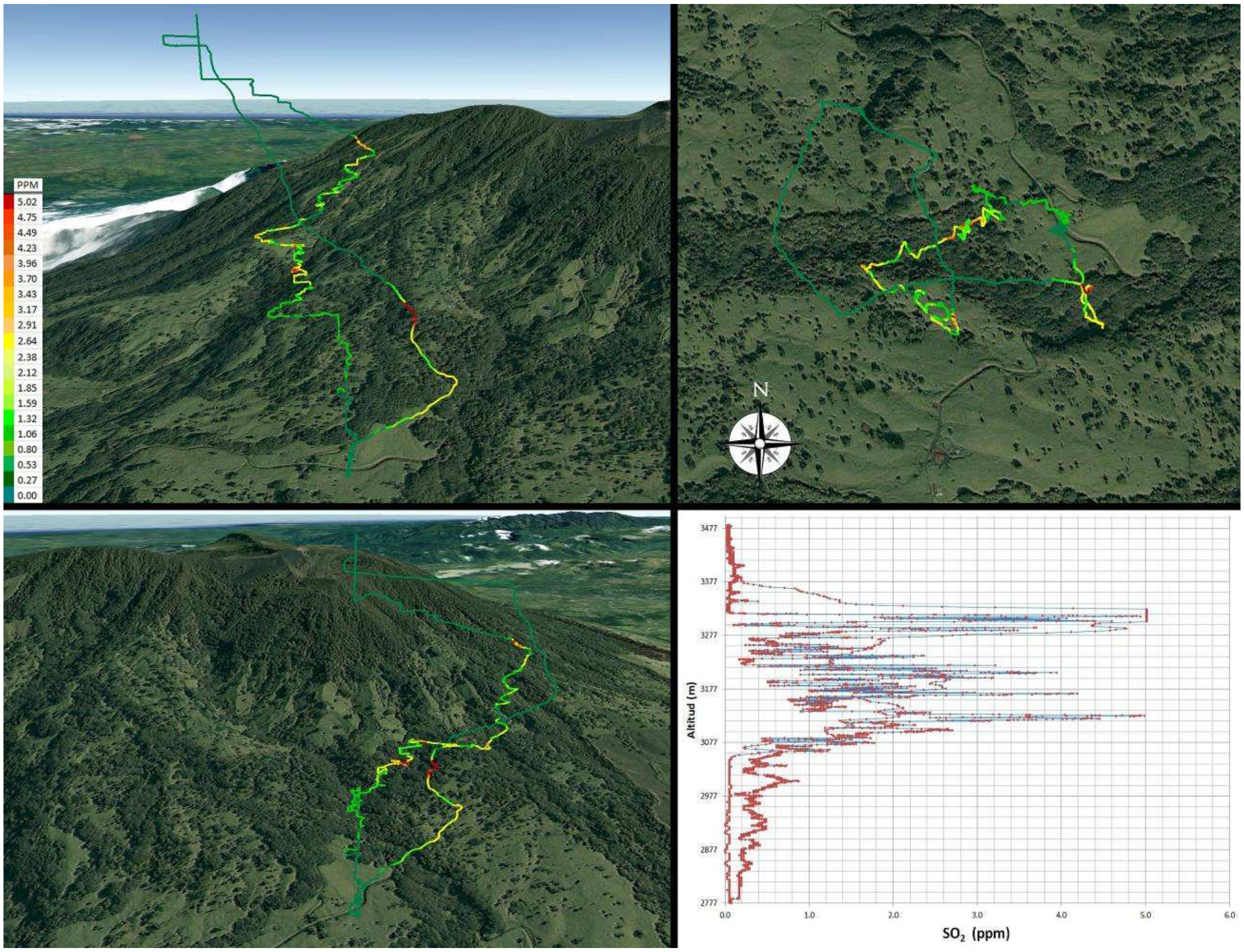

Figure 9. Balloon-borne 3D in situ volcanic plume SO_2 concentration data for Turrialba Volcano Feb 1st 2012 (red in the GPS traces indicates the highest SO_2 concentrations--around 5ppmv).

Coincident in situ data collection, small SO_2 sensors on-board kites and tethered balloons are used to produce 3D chemical concentration visualizations of the Turrialba Volcano plume (Figure 9) and compared to the satellite data for validation and calibration purposes.

IV. Conclusions

The deployments demonstrated a path to study and visualize gaseous volcanic emissions using mass spectrometer and gas sensor-based instrumentation in harsh environmental conditions for the correlation of in situ ground/airborne data with satellite remote sensing data, for calibration and validation purposes The deployment of such technology improves on our current capabilities to detect, analyze, monitor, model, and predict hazards presented to aircraft by volcanogenic ash clouds from active and impending volcanic eruptions. More work needs to be done in the utilization of in situ data to validate or correct retrieval algorithms, as well as those that predict plume dynamics.

V. Acknowledgments

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