Unmanned Aerial Technologies for In Situ Validation of Remote Sensing Data and Retrievals at Active Volcanoes

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Outline of Talk

• History of NASA Volcano UAV-based efforts
  • Science objectives
    • Case studies
      ➢ Costa Rica
      ➢ Italy
      ➢ Hawaii
  • Results
• Future Activities
**Small UAV Volcanology Activities supported by NASA SMD Earth Surface and Interior Focus Area, NASA SBIR Program, INGV, UCR**

*David Pieri (JPL) and Andres Diaz (University of Costa Rica) and Government, University, and Industry Team*

**Scope of Activities:**
- Genesis: NASA (ARC-GSFC/WFF), JPL, UCR, INGV collaboration; ISRSE Congress, Stresa, Italy, 2009

**Past Deployments:**
- UCR-JPL Systematic deployments of aerostats/UAVs: Turrialba Volcano 2011-2016
- NASA (Ames/GSFC-Wallops)-JPL-UCR/NTCR deployment of Sierra A to Costa Rica planned for 2014; deferred with loss of a/c into Arctic Ocean
- INGV-UCR-JPL deployment to La Solfatara, Italy 2015
- INGV-UCR-JPL deployment to La Solfatara/Vulcano Island 2016

**Most Recent:**
- NASA (Ames/GSFC-Wallops)-JPL-UCR-USGS-NPS (UofH) deployment to Kilauea Volcano 2017

**Future:**
- JPL-Black Swift Technology-NTCR/UCR/OVSICORI deployments in Costa Rica 2017-2018
- JPL-Makel Engineering Inc-deployment of VTOL UAV to lava sites (TBD) for NASA HOTTech Program
- JPL-NASA GRC-Black Swift Technology-USGS-NPS UAV deployment to Hawaii—TBD
Objectives

- **In situ validation** of remote sensing derived (e.g., ASTER, ER2-based MASTER/HyTES and AVIRIS-ng) gas and aerosol retrievals using free-flying UAV-based, aerostat-based, and ground instrumentation.
- Characterize the near surface extent, distribution, constituents, and dispersion characteristics of gas and aerosol emissions, especially SO\(_2\) hydrolysis (e.g., Kilauea Volcano, Hawaii; Volcan Turrialba, CR).
- Improve accuracy of local SO\(_2\) and CO\(_2\) flux estimates using in situ airborne data (also H\(_2\)S as appropriate).
- Improve approaches to statistical representation of UAV data.
- Improve knowledge of local volcanic phenomena to mitigate hazards to local residents.
- **Validate and improve transport models** (applications to mitigation of airborne volcanic hazards to aviation).
- Facilitate instrument development, especially miniaturization (planetary mission testbeds).
Turrialba Volcano, Costa Rica

UAV and Aerostat deployments
High Altitude (9-13Kft ASL)
Tethered balloons
UCR VANTAR UAV
NASA DragonEye UAV
JPL/UCR SO$_2$ and CO$_2$ sensors
Dragon Eye and Aerostat Deployment to Turrialba Volcano in Costa Rica in Support of ASTER SO$_2$ Data Product Validation

Compact Sulfur Dioxide sensor package for Dragon Eye small UAVs and Aerostats
SO$_2$ Concentration Data acquired from Dragon Eye UAV Platform, Turrialba Volcano, Costa Rica.
Measuring the spatial/temporal rate of SO₂ Hydrolysis In Situ:

- An example of in situ data from a single UAV flight—40 deployments have been made over a 2 yr. period.

- Drop-off in SO₂ vs distance from vent is visible (dotted line).

- Drop-off in SO₂ vs relative humidity is visible (dotted line).

- Range of relative humidity with distance is mostly constant.

- Dominant chemical pathway in clouds/fog:

  \[(\text{SO}_2 \cdot \text{H}_2\text{O})_{\text{aq}} \rightarrow \text{HSO}_3^–\]

  \[\text{HSO}_3^– + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4\]

  [n.b., \(\text{H}_2\text{SO}_4\) is possibly visible in HyTES data]

- Important problem for ecology and volcanology: what are the hydrolysis rate and production constants?
Constraining the sulfur dioxide degassing flux from Turrialba volcano, Costa Rica using unmanned aerial system measurements

Xin Xi, Matthew S. Johnson, Seongeun Jeong, Matthew Fladeland, David Pieri, Jorge Andres Diaz, and Geoff Bland

(Journal of Volcanology & Geothermal Research, 2016)

UAV data fed into reverse dispersion models generate SO₂ flux (kt/day); results consistent with observations.

Tests of various assumptions

Measured flux range from ground stations since 2008—reasonable agreement

~20ppmv max
La Solfatara Crater and Fumaroles, Greater Naples, Italy

UAV and Aerostat deployments
Low altitude (<500ft ASL)
INGV DJI Quadcopter—SO$_2$, CO$_2$, H$_2$S
UCR/JPL Mini-gas sensing package
Field Area—La Solfatara: CO$_2$, H$_2$S, (SO$_2$, He?); "Resurgent Caldron"; now undergoing uplift and seismic activity (e.g., 31Oct14; Magnitude 2 earthquake)
Deployed a number of sensors at La Solfatara Crater, Italy on 30-31 Oct 2014

- Proof-of-concept test of new micro-miniaturization:
- Mini-gas sensor (SO$_2$, CO$_2$, H$_2$S, T, P, %H$_2$O, GPS, and telemetry)
- Mini-mass spectrometer (250amu mass range)
- FLIR ONE iPhone-based 8-14µm mini-imager
- Phantom Quad-copter UAV for Mini-gas lift into active fumarole.
Near Ground CO$_2$ Concentrations – La Solfatara, ITALY

~7500 ppmv max

(ppmv = ppm by volume)

UAV SOUNDING
Solfatara Volcano, Napoles, Italy.
Launch site: 40°88’34”N 14°14’19”W 101 m AMSL
Time: 1240 - 1249 UTC / October 30, 2014

Platform used: Quadcopter with Dragon_MiniGas α
Maximum altitude: 128 m AMSL
Max. CO$_2$ concentration: 7423 ppm @ 110.2 m AMSL
Sounding duration: 9 minutes
Near Ground H₂S Concentrations – La Solfatara, ITALY

~20ppmv max

UAV SOUNDING [PRELIMINARY DATA]
Solfatara Volcano, Napoles, Italy.
Launch site: 40.82734°N 14.14149°W 101 m AMSL.
Time: 1240 - 1249 UTC / October 30, 2014

Platform used: Quadcopter with Dragon_MiniGas α
Maximum altitude: 128 m AMSL.
Max. H₂S concentration: 20.3 ppm @ 110.4 m AMSL.
Sounding duration: 9 minutes

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gaslab.ucr@gmail.com
www.youtube.com/GasLabUCR
Vulcano Island, Tyrrhenian Sea, Italy

UAV and Aerostat deployments
Low altitude (<1000ft ASL)
UCR ItalDrone Octocopter
UCR/JPL Mini-gas package (SO₂, CO₂, H₂S)
ItalDrone
10kg payload
With Mini-Gas sensor
Vulcano Island
Italy
September 2015
(with Andres Diaz, UCR)
Kilauea Volcano, Hawaii, USA

HyspIRI, MASTER and ASTER support

UAV and Aerostat deployments
Medium altitude (<5000ft ASL)
HyspIRI Prep Hawaii: Volcanoes and Coral Reefs

- ER-2: MASTER (HyTES) & AVIRIS-ng
- ASTER – VIS/TIR day/night orbital data
- Dragon Eye UAVs – in situ sampling SO$_2$/CO$_2$
- Aerostats (kites) – in situ sampling SO$_2$/CO$_2$
- Ground measurements – in situ sampling SO$_2$/CO$_2$
- Modeling – source flux and transport SO$_2$

(Your Hawaiian vacation location and our deployment site 😊)

(You are ~Here 😊)
Boundaries of Hawaii Volcanoes National Park
Zones (blue) of highest and most persistent SO$_2$ abundance as seen by ASTER 2000-2016 (predominately Trade Winds – from the NE).
Near-field UAV test area
Flights on 12 and 15 February
Volcanic gas and steam plume
Halemaumau Crater,
Kilauea Volcano, Hawaii
February 12, 2017
Halemaumau Crater, Kilauea Volcano, Hawaii
February 12, 2017
Dragon Eye UAV sortie
Max alt: 1200ft AGL
Max SO2 concentration: ~251ppmv
Note prominent layer at 1320m ASL. This kind of stratification is also seen at Turrialba Volcano, CR. Possibly due to strong wind shear.
Kilauea Panorama
Dragon Eye UAV
Takeoff at Kilauea
Halemaumau Crater, Kilauea Volcano, Hawaii
February 12, 2017
DragonEye UAV sortie
Max alt: 1200ft AGL
Max CO₂ concentration: ~510ppmv
Halemaumau Crater, Kilauea Volcano, Hawaii
February 12, 2017
DragonEye UAV sortie
Max alt: 1200ft AGL
Max CO2 concentration: ~510ppmv

VIEW #2
View to the NE, in the direction of the wind (Kona conditions)
Feb 2017 Mauna Loa NOAA Observatory value (~407±1ppmv)

Feb 2017 JPL Tunable Diode Laser UAV CO2 data: 1ppmv sensitivity (Lance Christensen, JPL)
Feb 2017 Mauna Loa NOAA Observatory value (~407±1ppmv)

Feb 2017 JPL Tunable Diode Laser UAV CO₂ data: 1ppmv sensitivity (Lance Christensen, JPL)

<SO₂ peak
Far-field UAV test area

Flights on 17 and 21 February

~14 miles between the two sites (23km)

Approx. SO₂ plume corridor

Hawaii Volcanoes National Park

Trade Winds

Panana
Kapapala Ranch, Pahala, Hawaii
February 21, 2017 ~11:30am; DragonEye UAV sortie
Max alt: 12-1500ft AGL; Max SO$_2$ concentration: ~0.8ppmv
Distance from vent: ~23km

Concentrations observed with airborne sensors are closely consistent with State of Hawaii VOG forecasts
(From Vince Realmuto, JPL)

**Brightness Temperature Difference (BTD) Time Series**

(a) True-Color composite of visible (RGB) data. MASTER data from 2017-02-21, collected between 20:18 - 20:29 UTC.

(b) False-Color composite of TIR data. \( \text{SO}_2 \) plume appears in yellow.

(c) Brightness Temperature Difference (BTD), calculated as difference between the BT in Channel 43 (8.7 \( \mu \text{m} \)) and the maximum BT over all of the MASTER TIR channels.

(d) BTD Values between 2017-01-19 and 2017-02-23, corresponding to the sample location marked by the white circle in Panels a – c. The decrease in (absolute) BTD for this location suggests a decrease in the concentration of \( \text{SO}_2 \) in the plume over this time interval.
**STAR** = Approximate location of far-field UAV deployment at Kapapala Ranch, 21 February 2017, approximate 14mi (~23km) from vent; yellow = SO2 plume (D-stretch of MASTER ER2 Data)
Kapapala Ranch, Pahala, Hawaii
February 21, 2017 ~11:30am; DragonEye UAV sortie
Max alt: 12-1500ft AGL; Max SO$_2$ concentration:
~0.85ppmv
Distance from vent: ~23km
Kapapala Ranch, Pahala, Hawaii
February 21, 2017 ~1:30pm; DragonEye UAV sortie
Max alt: 12-1500ft AGL; Max SO₂ concentration: ~0.5ppmv
Distance from vent: ~23km

Concentrations observed with airborne sensors are closely consistent with State of Hawaii VOG forecasts.
Kapapala Ranch, Pahala, Hawaii
February 21, 2017 ~1:30pm;
DragonEye UAV sortie
Max alt: 1200-1500ft AGL; Max SO\textsubscript{2} concentration: \sim 0.5ppmv
Kapapala Ranch UAV test site near Pahala, HI
Panorama
Dragon Eye UAV
Takeoff at
Kapapala Ranch
Dragon Eye UAV
Landing at
Kapapala Ranch
Results

1. **NASA Dragon Eye UAVs successfully acquired airborne SO₂ and CO₂ concentration data**, and ambient atmospheric profile data between the ground and approximately 1200ft AGL for emissions from the active Kilauea summit vent during the period 12-21 Feb 2017. Ground-based SO₂ and CO₂ data were also acquired along the rim of Halemaumau Crater.

2. **Nine successful flights were accomplished.** One flight terminated with the total destruction of the aircraft and payload estimated to be within the active Kilauea lava lake. Four flights were accomplished at Kilauea Summit; five flights were accomplished over Kapapala Ranch, 23km distant from the summit, along the lower slopes of Mauna Loa.

3. **Near-field SO₂ levels ranged up to 250ppmv within the summit plume; CO₂ levels ranged up to 500ppmv within the summit plume** (approximately 100ppmv above ambient background values). Ambient non-plume UAV CO₂ slightly elevated (+10ppm) vs NOAA values (diffuse volcano emissions?).

4. **Far-field observations captured SO₂ concentrations in the range of 0.1-1.0ppmv at altitudes up to 1500ft AGL with ambient atmospheric profile data.** These values are closely consistent with Hawaii State air quality predictions for the operational area.

5. **Comparisons with ASTER and MASTER data are ongoing.** Due to operational restrictions, only one MASTER-UAV simultaneous data set was acquired in the far-field. UAV-based data were acquired during the ASTER overpass on 12 February.

6. Analysis is ongoing, especially **comparisons of UAV in situ data to the remote sensing data, as well as reverse flux modeling** (e.g., Xi et al., 2016, JVGR—Turrialba Volcano, CR)
Lessons learned from our team activities

1. Expect losses--PLAN for them! (1 of 6 DragonEyes lost to lava lake)

2. Small UAV deployments are often less expensive and more flexible than manned a/c deployments.

3. ALWAYS have telemetry with sUAVs.

4. Need all weather, day/night IFR (beyond line-of-sight) capabilities and permissions for hazard response.

5. Cutting edged government sUAV programs need to be sustainable, for advanced applications beyond the marketplace.


7. VTOL /fixed-wing capabilities need development

8. Aerostats should be included in the mix.

9. **Science UAV uses need advocacy!**
Our JPL, NASA, USGS, US National Park Service, Univ. of Costa Rica deployment team at Kilauea, with an Aerovironment Dragon Eye unmanned vehicle with SO$_2$ sensor on-board:

*Volcanic Emissions Retrieval Experiment (VEREX)*
Future Activities
Two views of the UAV-MS XPF3 (UCR) integrated within the SIERRA_B UAV airframe at NASA ARC.

Future UAV Deployment to the Salton Sea, CA

Salton Sea Geothermal Field Deployment with SIERRA-B & Dragon Eye UAVs (Sept 2018)

Area (inside orange polygon) within which we plan to conduct flight operations with both the SIERRA and Dragon Eye UAVs.

ASTER VNIR Images

Gas vents (CO₂, H₂S, SO₂, CH₄, NH₃, etc.)

“Gryphons” or “mudpots” (small mud volcanoes) are ubiquitous in the Salton Sea Geothermal Field, most actively emitting a variety of gases: SO₂, CO₂, NOₓ, CH₄, H₂S, OCS, NH₃, wow!
Mini-mass spectrometers
(University of Costa Rica—GasLab)

- 100amu mass range, 3kg instrument mass;
- NASA SIERRA, UCR VANTAR (shown), or INGV RAVEN UAV implementations
- Good for lighter gases
- Prof. Andres Diaz, UCR
SUPERSWIFT XT

• Fully autonomous operations
• Modular field swappable payload
• Electric Propulsion
• 120 minute flight time
• Up to 2.3kg payload
• NASA SBIR Project
• Flight ceiling over 20,000ft
• 40 mph cruise speed
• Sealed against outside particulates
• Laser altimeter for precision landing system and low altitude terrain following
• Certified under multiple NASA flight safety reviews
Future UAV, In development—USA

JPL (Pieri) Concept for Gas Chromatograph-Mass Spectrometer on UAV tether over lava lake

FY17-19 NASA HOTTech funding for ambient **Hi-Temp (500°C) electronics & sensors** (Makel Engineering, Inc.; NASA GRC; JPL)—Hawaii? Venus?
Many Thanks!

¡Muchas Gracias!

Mille Grazie!

Mahalo nui loa!