Jet Propulsion Laboratory
California Institute of Technology

Advances in the Application of Unmanned Aerial Technologies to In Situ Airborne Observations at Active Volcanoes

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IAVCEI 2017 Scientific Assembly
Portland, Oregon USA—August 14-18

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Hawaii

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Christophe Kern (USGS)
Tamar Elias (USGS)
Christina Neal (USGS)
Rhonda Loh (NPS)
Greg Funderburk (NPS)
Lani and Bill Petrie (Kapapala Ranch)

Italy, Costa Rica, and Beyond

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Ira Leifer (Bubbleology Research International)

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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)-UCR-JPL Dragon Eye employment: Turrialba Volcano, 2013

• 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:

• NASA (Ames/GSFC-Wallops)-JPL-UCR-Bubbleology Inc. of SIERRA B and Dragon Eye to Salton Sea Volcanic Field 2017-2018.

• 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_2S 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

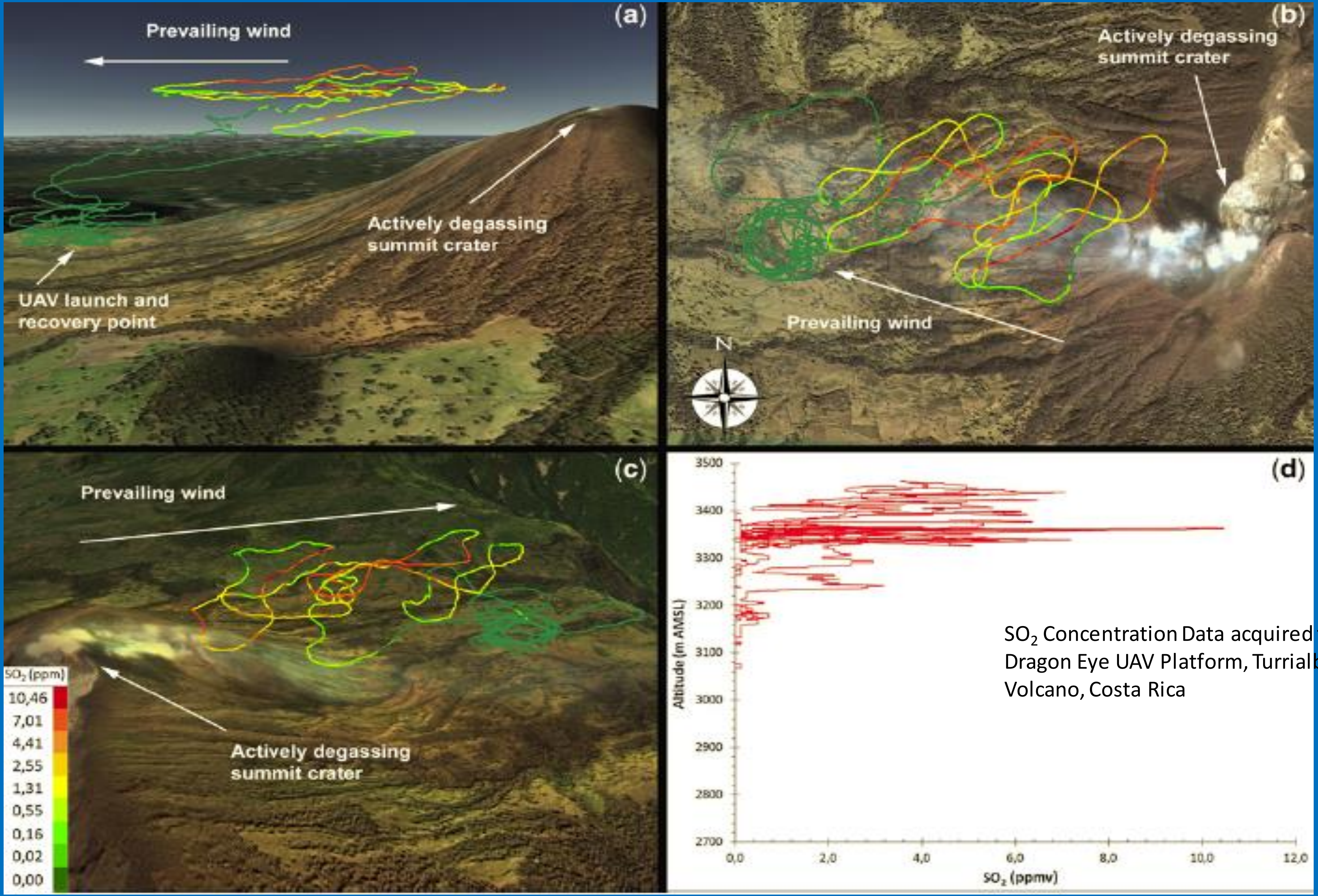
NASA DragonEye UAV

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

Turrialba, 08Feb13, Max. Alt.=3464m/11,258ftASL, Max. SO_2~10.5ppmv



SO_2 Concentration Data acquired from Dragon Eye UAV Platform, Turrialba Volcano, Costa Rica

Measuring the spatial/temporal rate of SO_2 Hydrolysis In Situ:

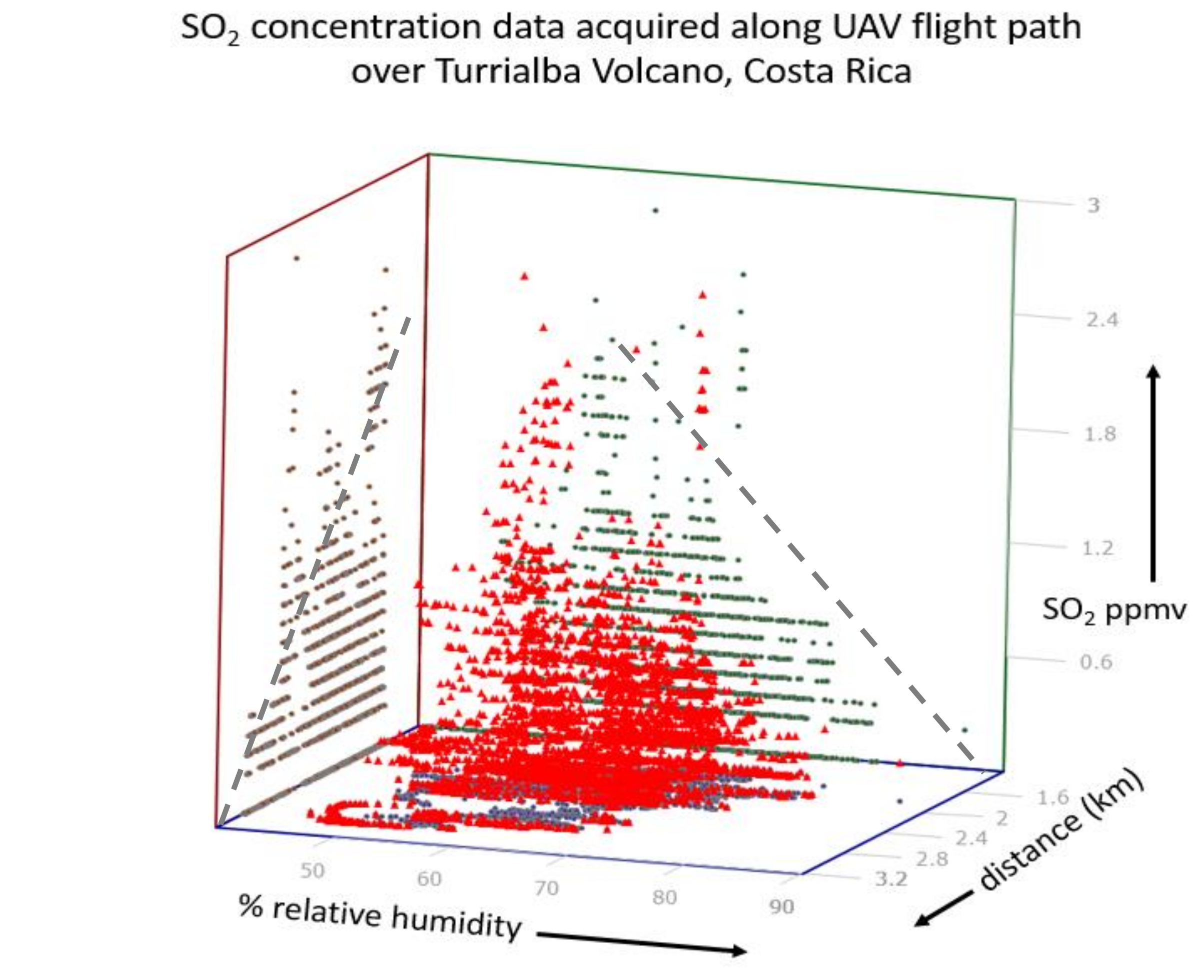
- An example of in situ data from a single UAV flight—40 deployments have been made over a 2 yr. period (
- Drop-off in SO_2 vs distance from vent is visible **(dotted line)**
- Drop-off in SO_2 vs relative humidity is visible **(dotted line)**
- Range of relative humidity with distance is mostly constant
- Dominant chemical pathway in clouds/fog:

  $(SO_2 \cdot H_2O)_{aq} \rightarrow HSO_3^-$

  $HSO_3^- + H_2O_2 \rightarrow H_2SO_4$

  [n.b., H_2SO_4 is possibly visible in HyTES data]

- Important problem for ecology and volcanology: what are the hydrolysis rate and production constants?



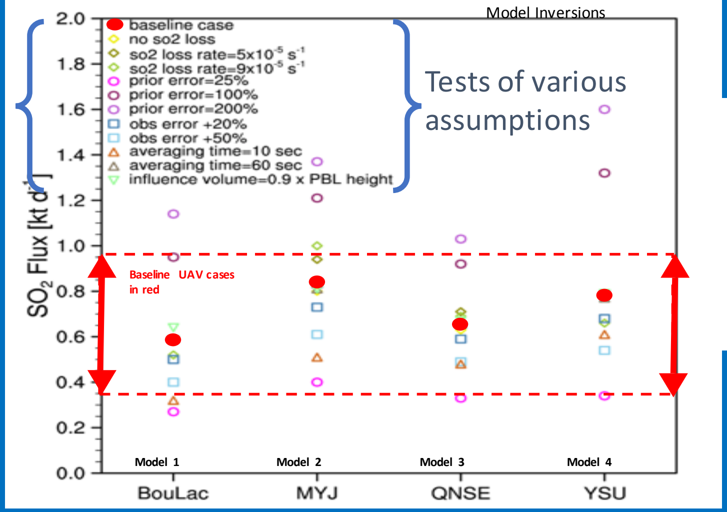
[SO_2] vs. distance from vent vs relative humidity

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

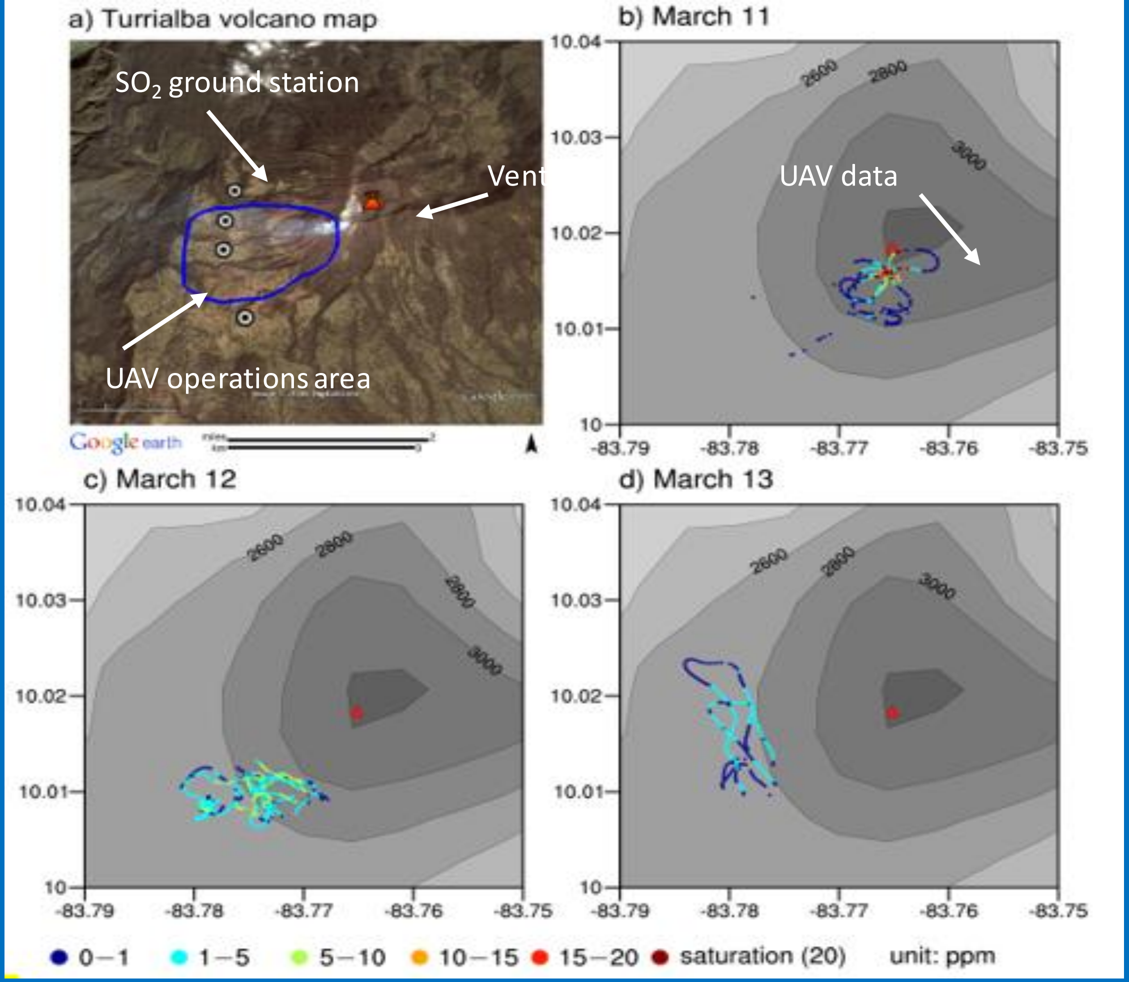
(*Journal of Volcanology & Geothermal Research, 2016*)

UAV data fed into reverse dispersion models generate SO_2 flux (kt/day); results consistent with observations.



Four reverse models

Measured flux range from ground stations since 2008—reasonable agreement



SO_2

~20ppmv max

La Solfatara Crater and Fumaroles, Greater Naples, Italy

UAV and Aerostat deployments

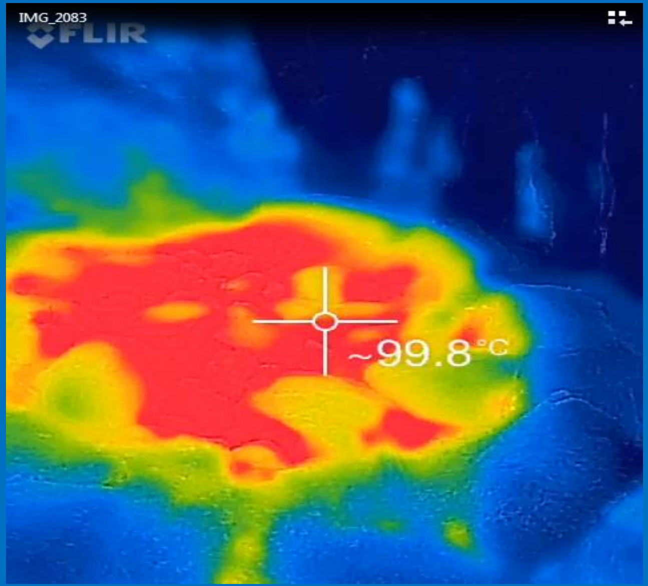
Low altitude (<500ft ASL)

INGV DJI Quadcopter—SO_2, CO_2, H_2S

UCR/JPL Mini-gas sensing package

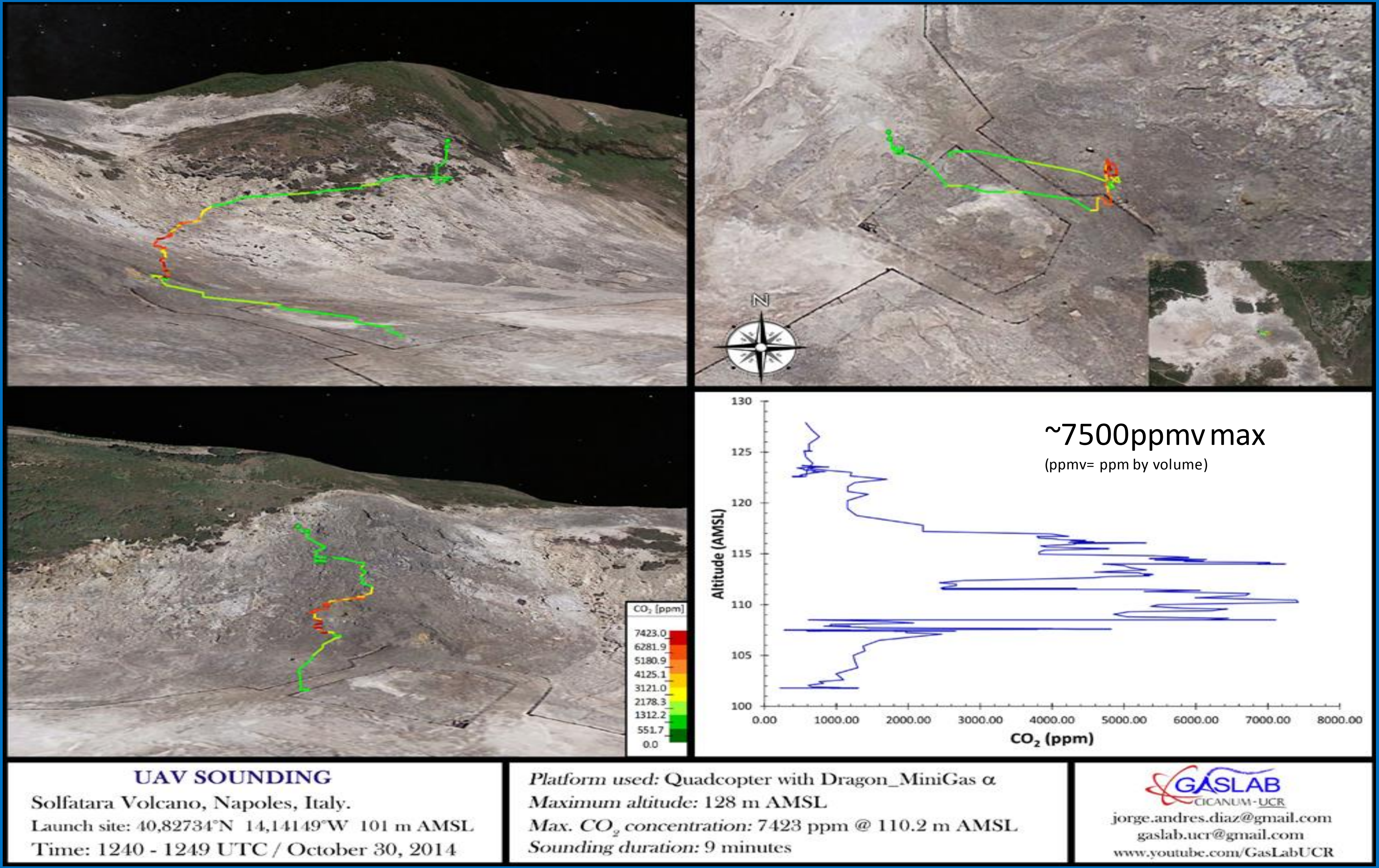
Field Area—La Solfatara: CO_2, H_2S, (SO_2, He?); "Resurgent Caldron"; now undergoing uplift and seismic activity (e.g., 31Oct14; Magnitude 2 earthquake)

Deployed a number of sensors at La Solfatara Crater, Italy on 30-31 Oct 2014

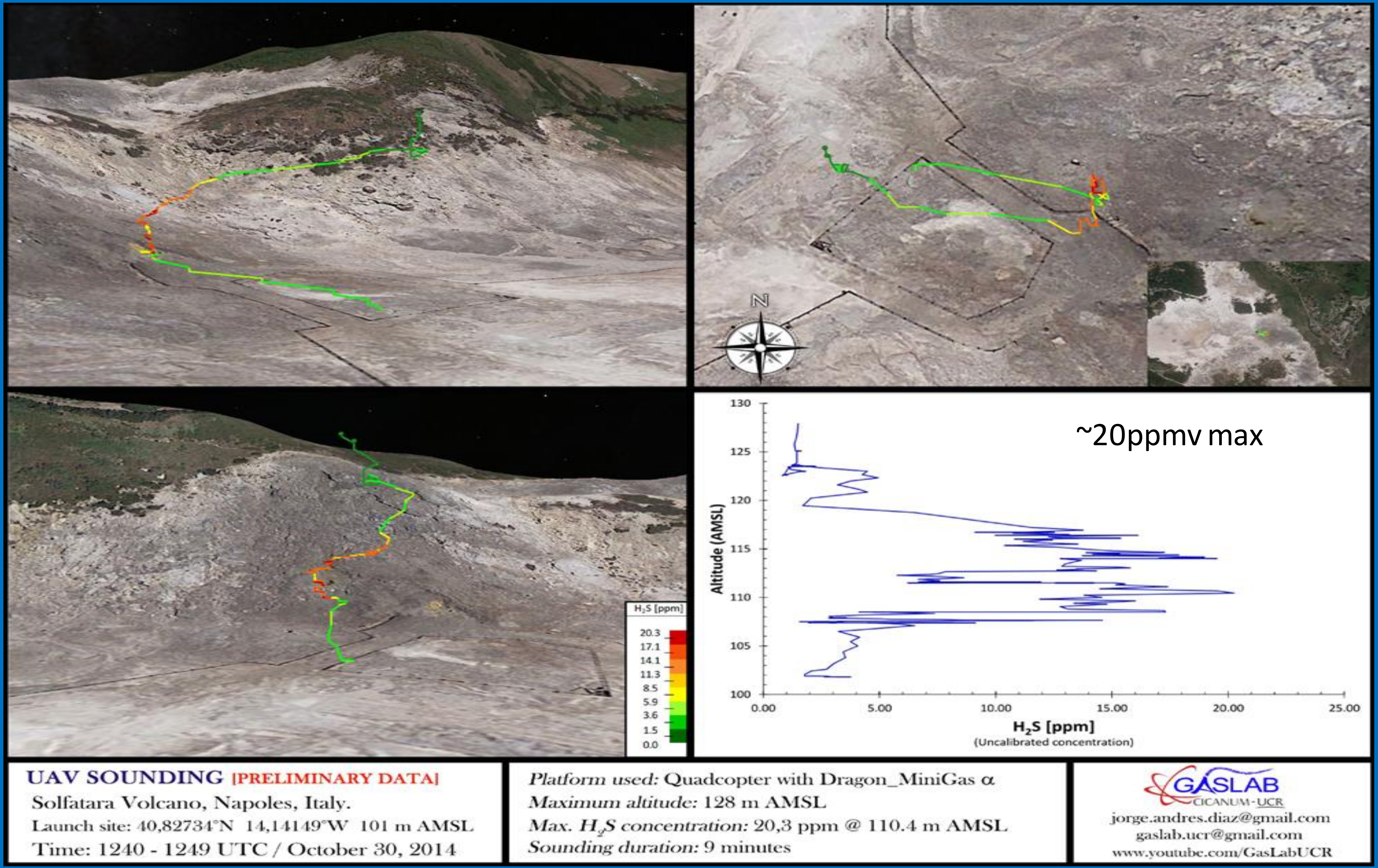


- Proof-of-concept test of new micro-miniaturization:
- Mini-gas sensor (SO_2, CO_2, H_2S, T, P, %H_2O, GPS, and telemetry)
- Mini-mass spectrometer (250amu mass range)
- FLIR ONE iPhone-based 8-14µm mini-imager
- Phantom Quad-copter UAV for Mini-gas lift into active fumarole.

Near Ground CO_2 Concentrations – La Solfatara, ITALY



Near Ground H_2S Concentrations – La Solfatara, ITALY



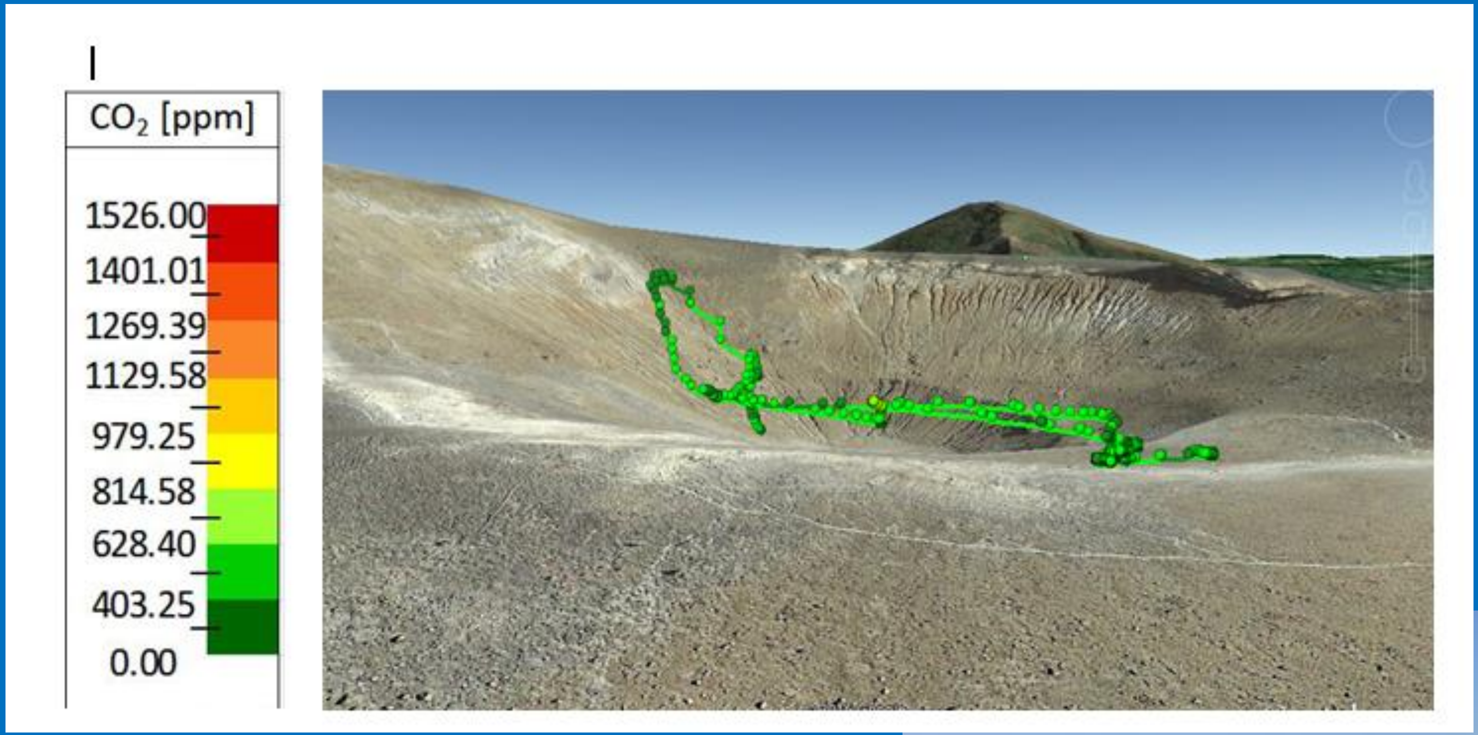
Vulcano Island, Tyrrhenian Sea, Italy

UAV and Aerostat deployments

Low altitude (<1000ft ASL)

UCR ItalDrone Octocopter

UCR/JPL Mini-gas package (SO_2, CO_2, H_2S)



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INGV

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

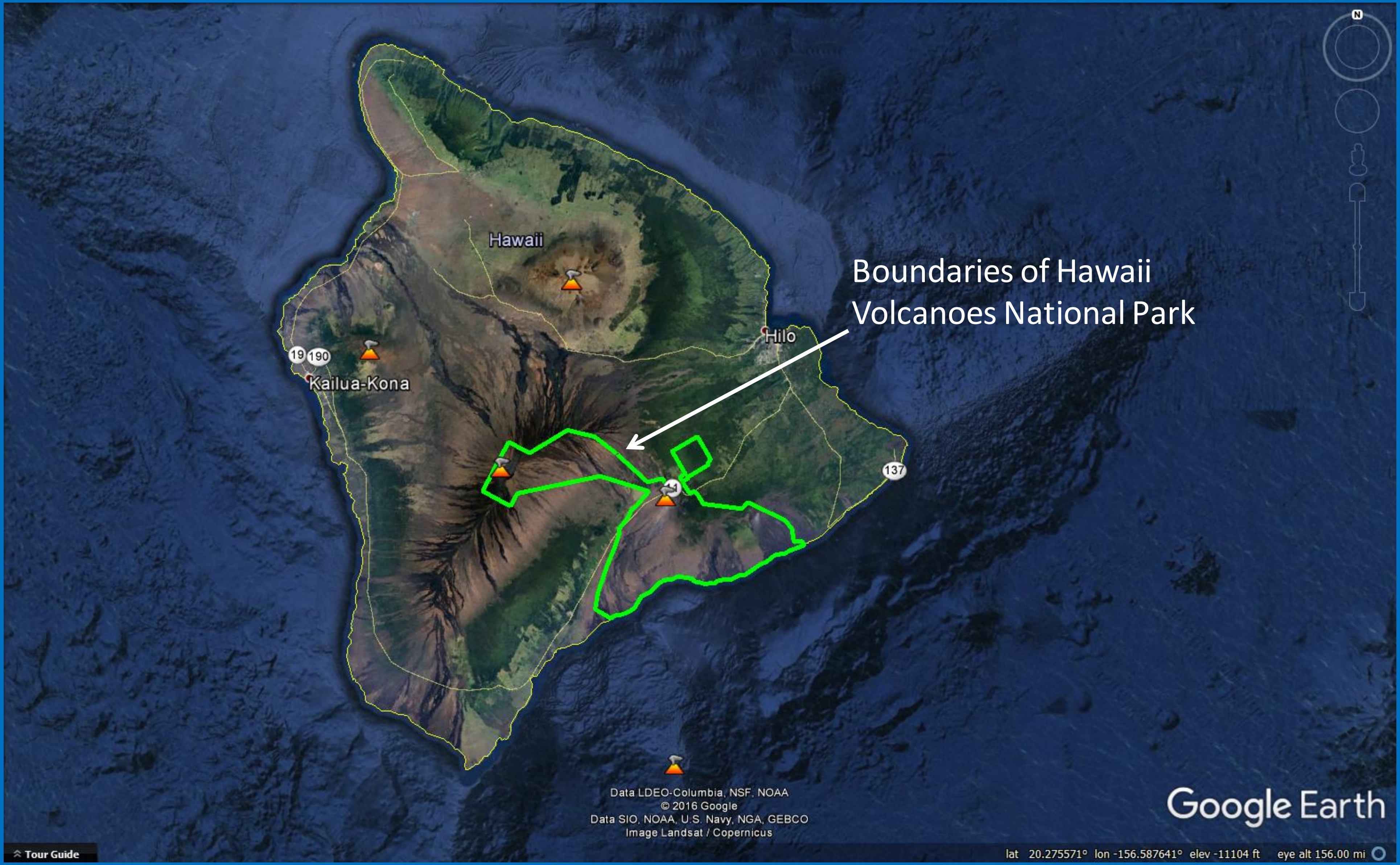
UAV and Aerostat deployments

Medium altitude (<5000ft ASL)

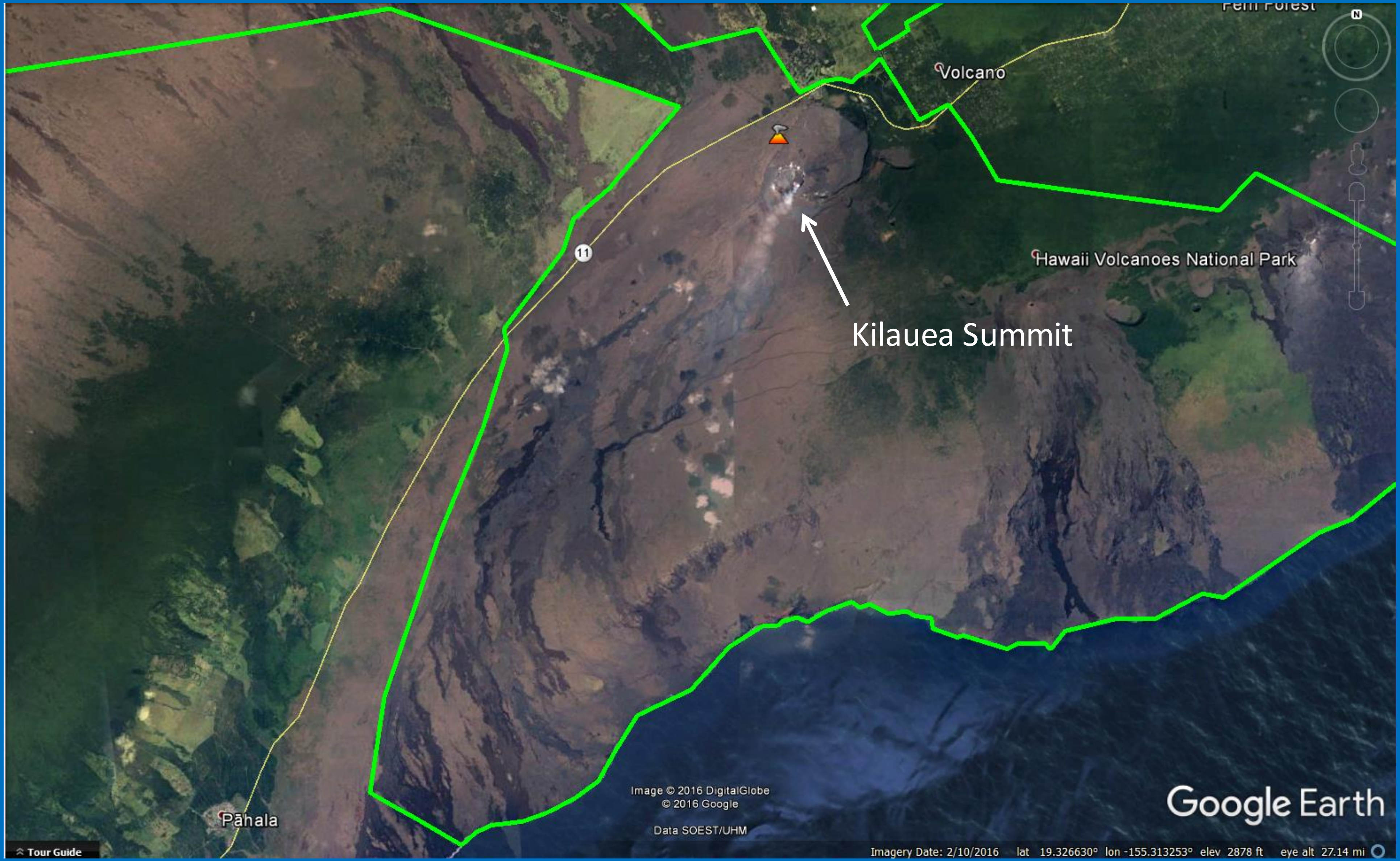
HyspIRI Prep Hawaii: Volcanoes and Coral Reefs

- 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

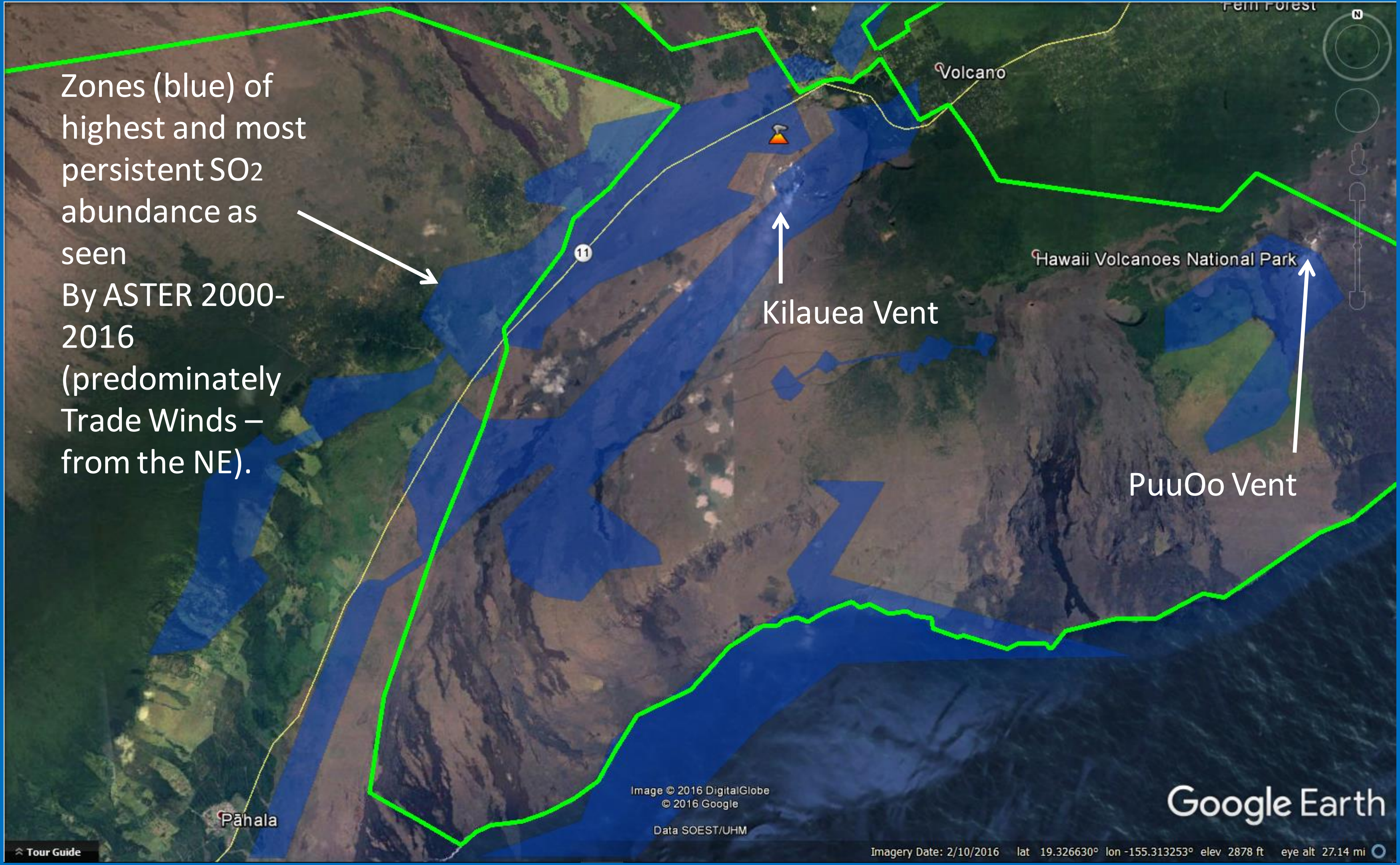

Kilauea Summit
Hawaii
Hilo
Kailua-Kona
19
190
137
Data LDEO-Columbia, NSF, NOAA
© 2016 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Google Earth
Tour Guide
lat 20.064736° lon -154.780297° elev -16849 ft eye alt 156.00 mi

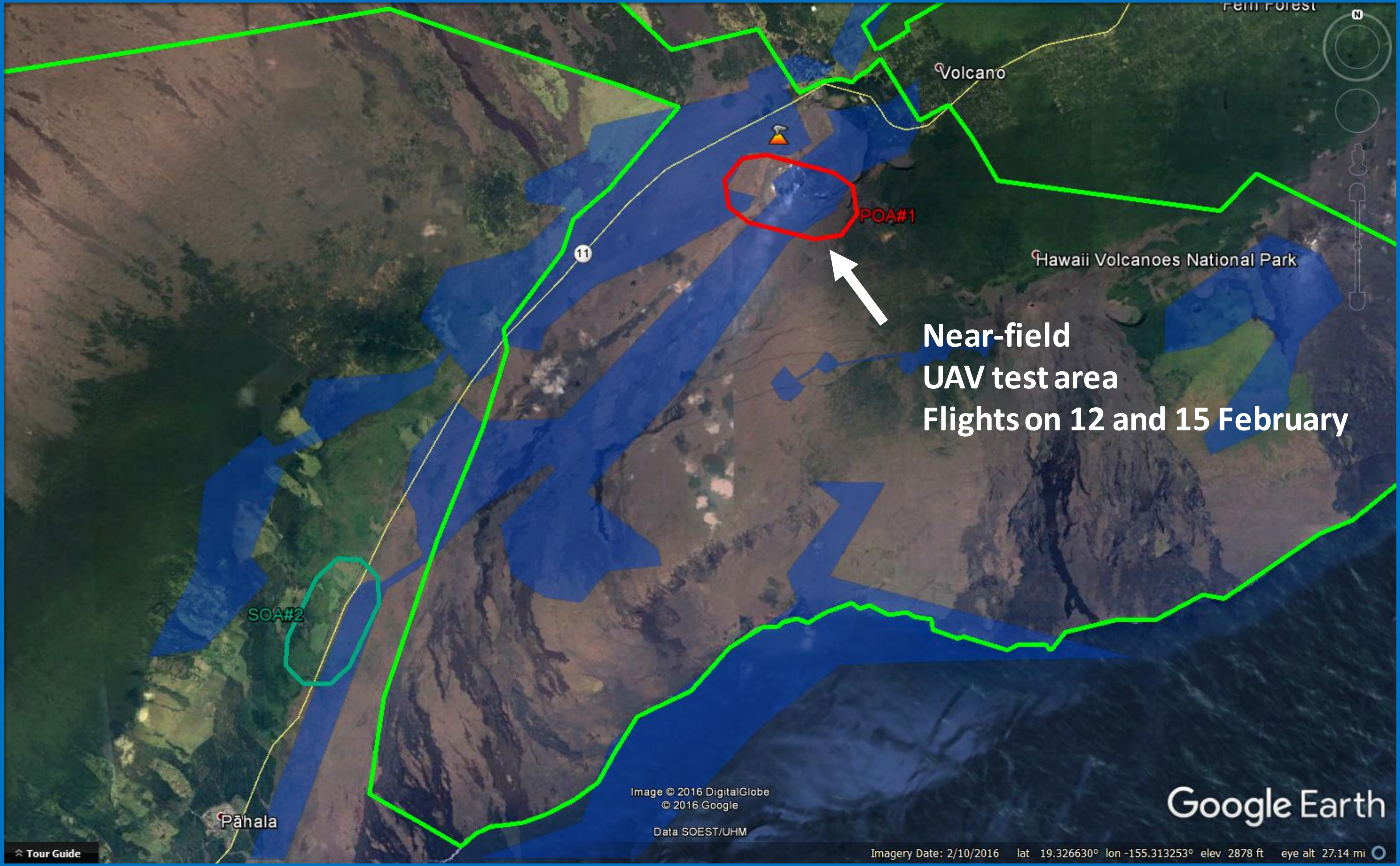


Boundaries of Hawaii
Volcanoes National Park
Hawaii
Hilo
Kailua-Kona
19
190
137
Data LDEO-Columbia, NSF, NOAA
© 2016 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Google Earth
Tour Guide
lat 20.275571° lon -156.587641° elev -11104 ft eye alt 156.00 mi

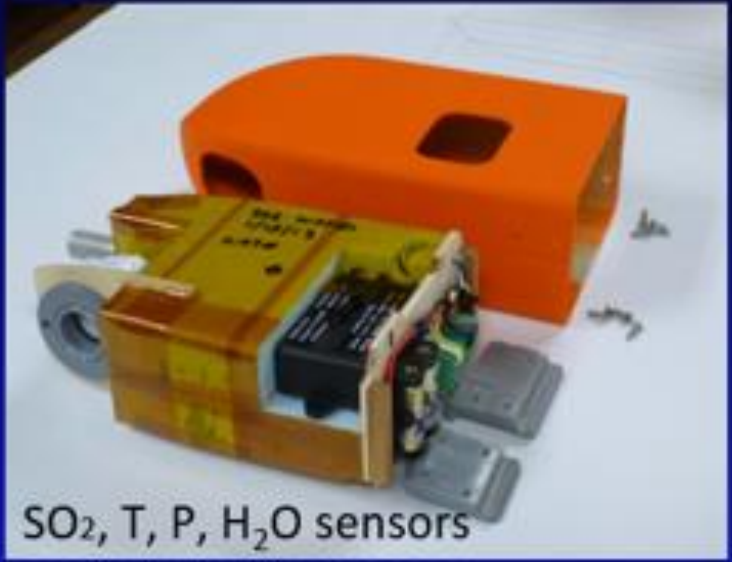


Fern Forest
Volcano
Hawaii Volcanoes National Park
Kilauea Summit
11
Pāhala
Image © 2016 DigitalGlobe
© 2016 Google
Data SOEST/UHM
Google Earth
Tour Guide
Imagery Date: 2/10/2016 lat 19.326630° lon -155.313253° elev 2878 ft eye alt 27.14 mi


Zones (blue) of highest and most persistent SO2 abundance as seen
By ASTER 2000-2016 (predominately Trade Winds – from the NE).
Kilauea Vent
PuuOo Vent
Volcano
Hawaii Volcanoes National Park
Pāhala
11
Image © 2016 DigitalGlobe
© 2016 Google
Data SOEST/UHM
Google Earth
Tour Guide
Imagery Date: 2/10/2016 lat 19.326630° lon -155.313253° elev 2878 ft eye alt 27.14 mi

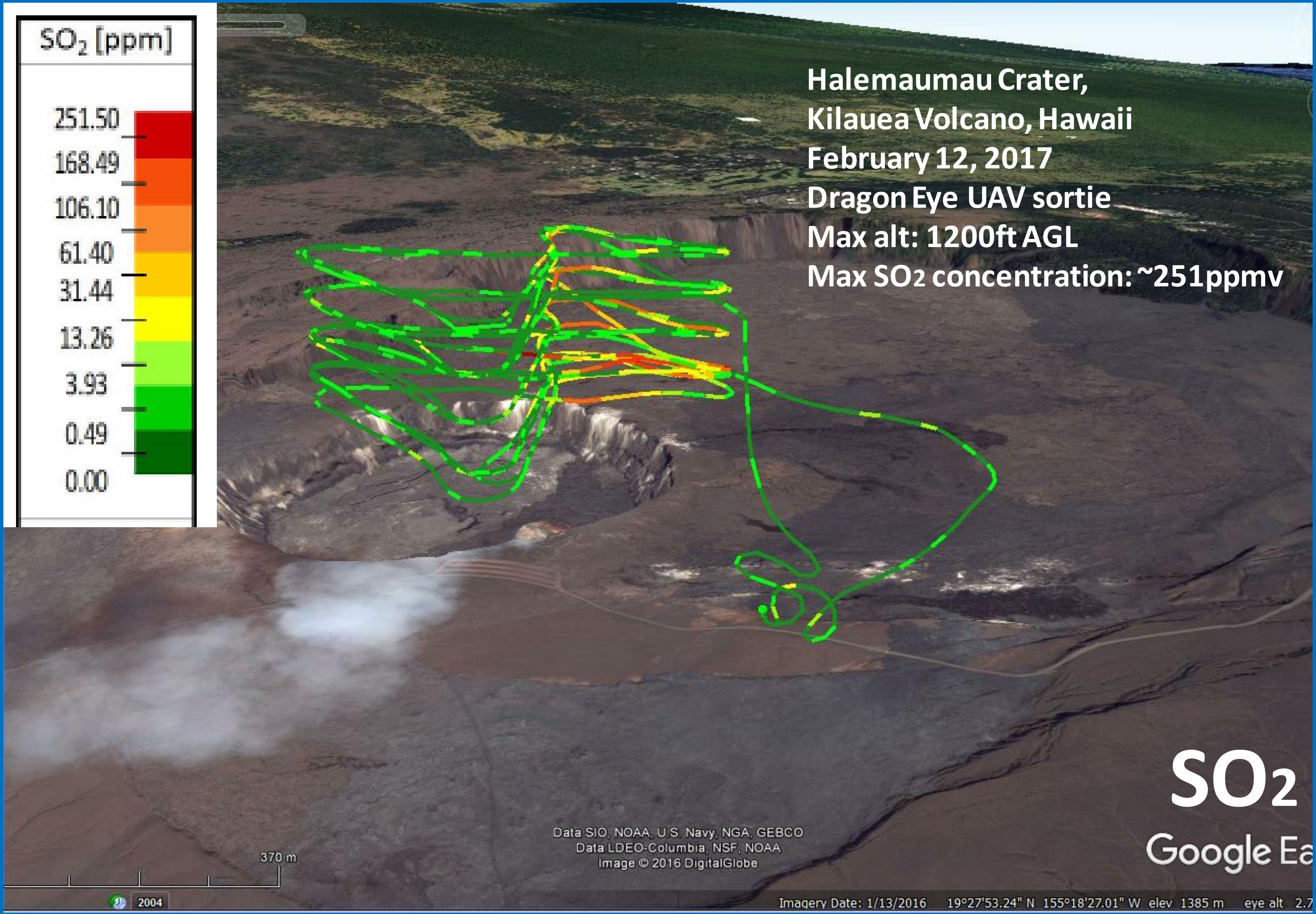

Fern Forest
Volcano
POA#1
11
Hawaii Volcanoes National Park
Near-field
UAV test area
Flights on 12 and 15 February
SOA#2
Pāhala
Image © 2016 DigitalGlobe
© 2016 Google
Data SOEST/UHM
Google Earth
Tour Guide
Imagery Date: 2/10/2016 lat 19.326630° lon -155.313253° elev 2878 ft eye alt 27.14 mi

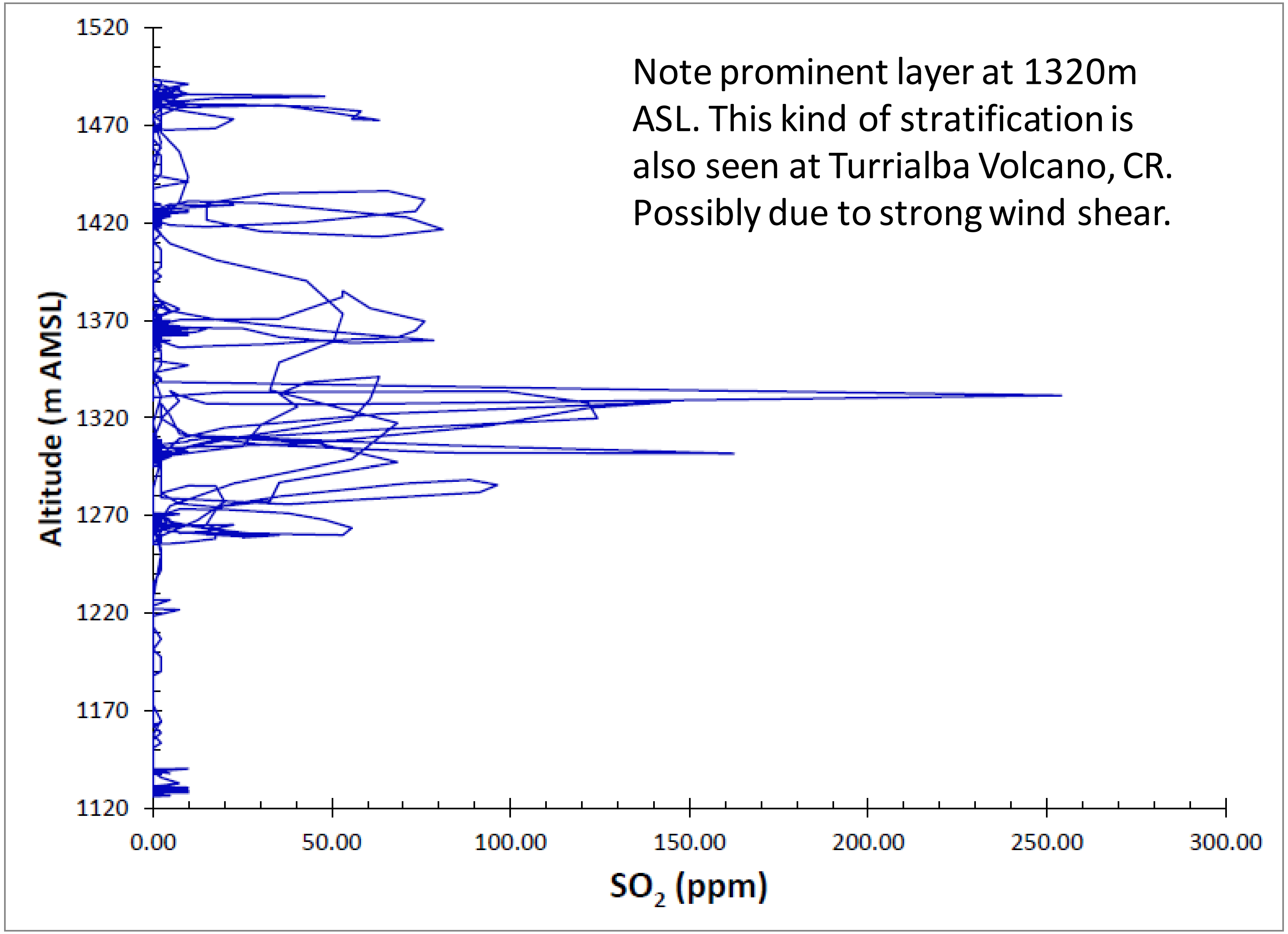
Volcanic gas and steam plume
Halemaumau Crater,
Kilauea Volcano, Hawaii
February 12, 2017

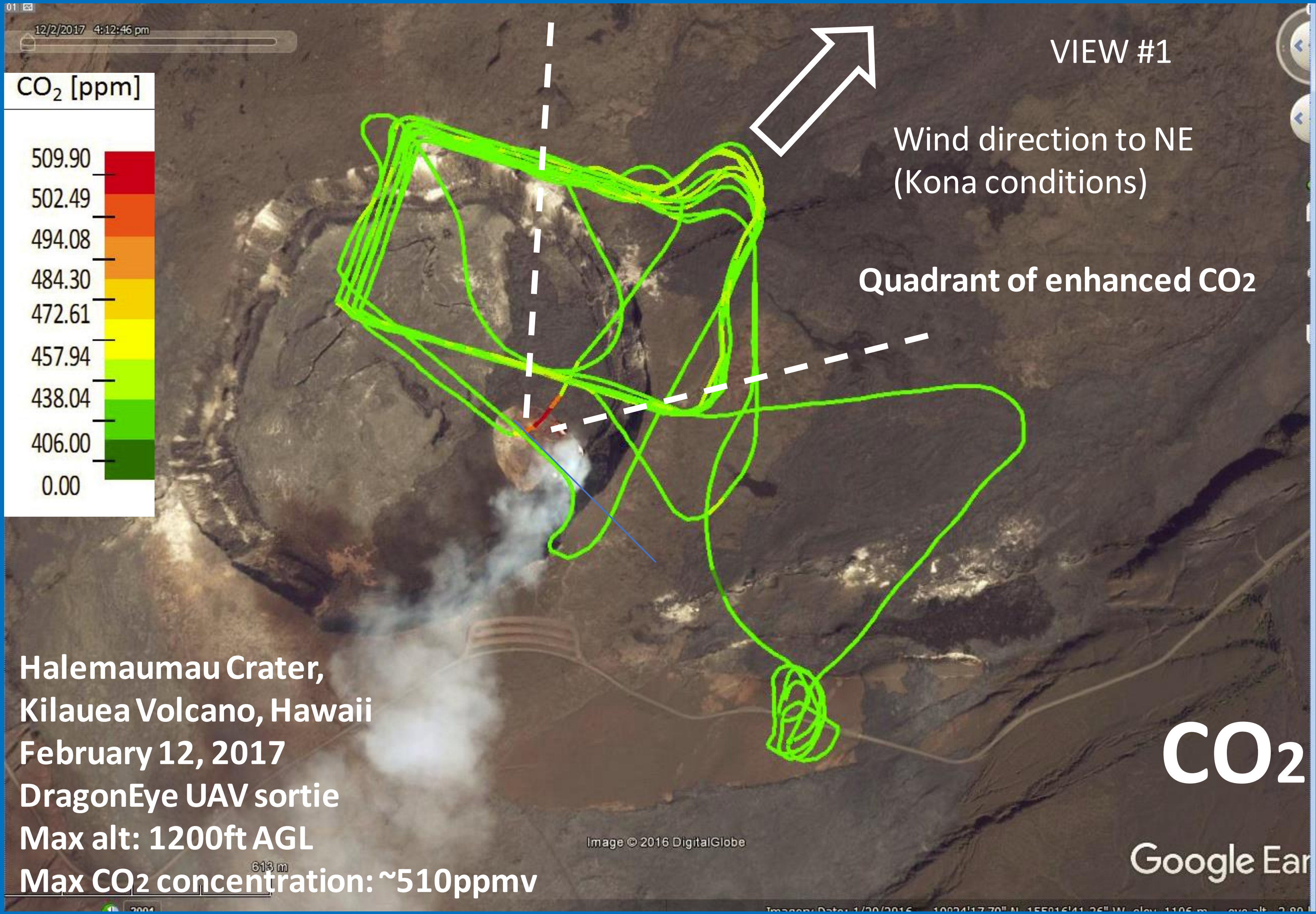


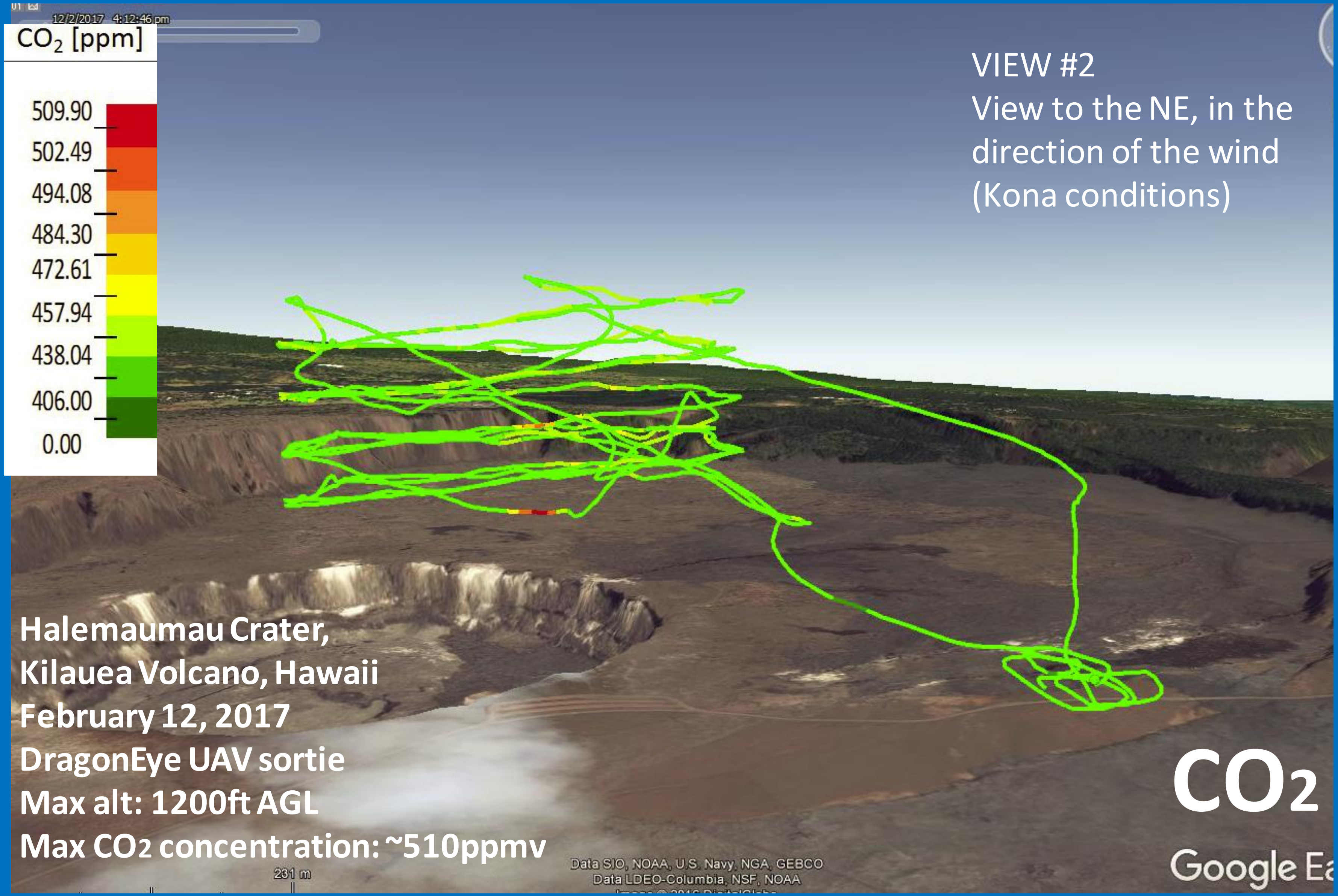
SO_2, T, P, H_2O sensors

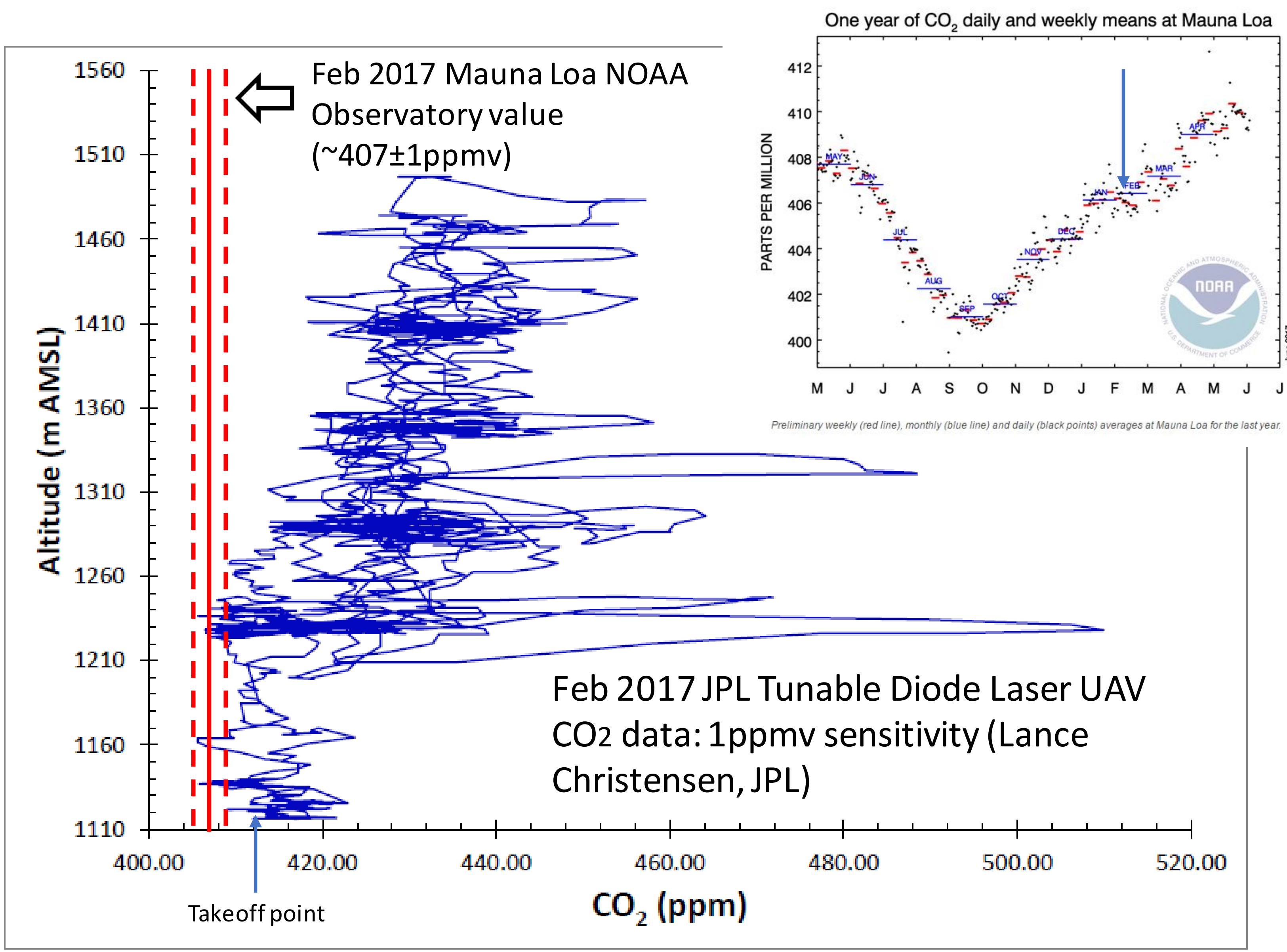
Dragon Eye in Flight

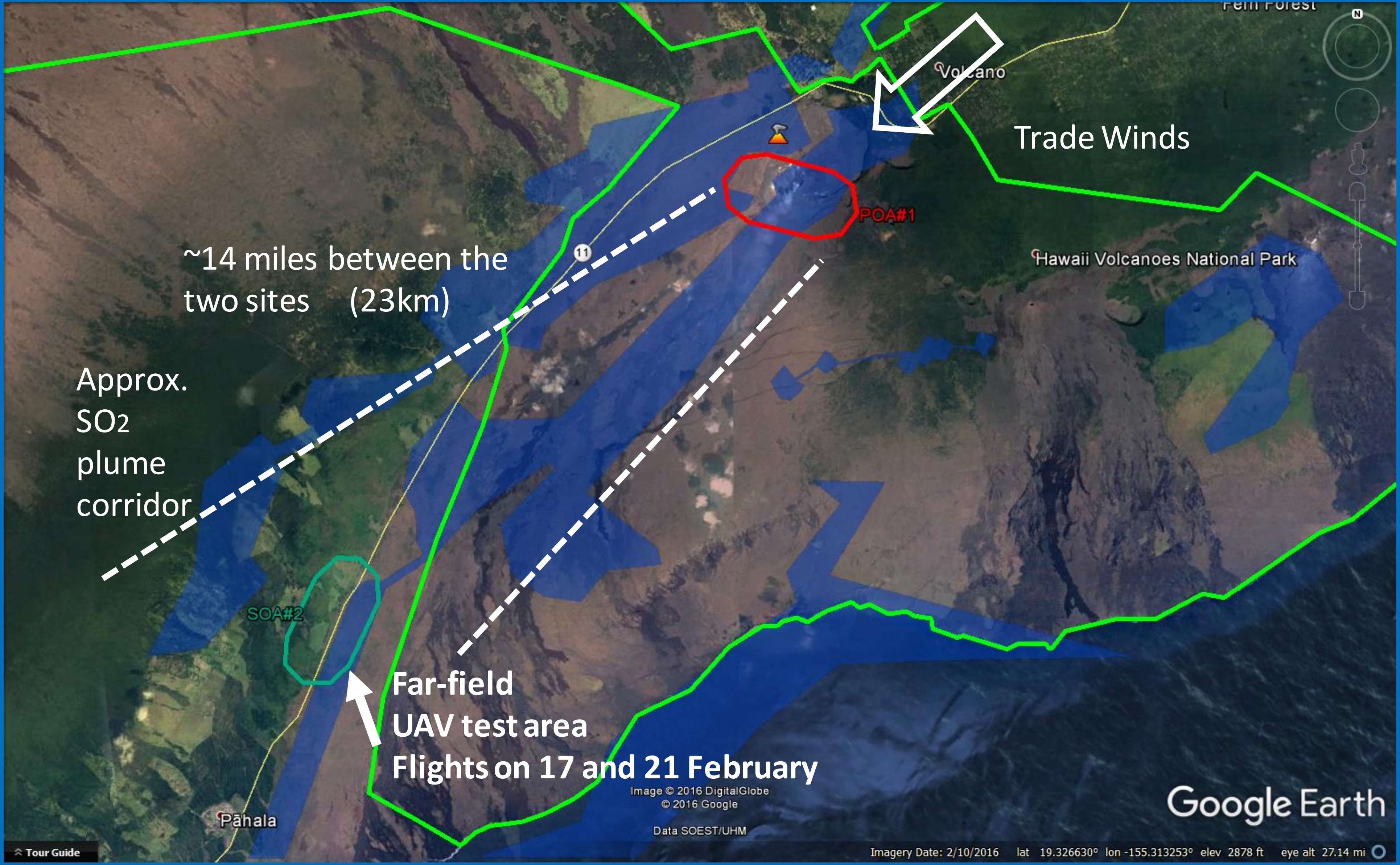

SO2 [ppm]
251.50
168.49
106.10
61.40
31.44
13.26
3.93
0.49
0.00
Halemaumau Crater,
Kilauea Volcano, Hawaii
February 12, 2017
Dragon Eye UAV sortie
Max alt: 1200ft AGL
Max SO2 concentration: ~251ppmv
SO2
Google Ea
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data LDEO-Columbia, NSF, NOAA
Image © 2016 DigitalGlobe
370 m
2004
Imagery Date: 1/13/2016 19°27'53.24" N 155°18'27.01" W elev 1385 m eye alt 2.7


Note prominent layer at 1320m ASL. This kind of stratification is also seen at Turrialba Volcano, CR. Possibly due to strong wind shear.
Altitude (m AMSL)
1520
1470
1420
1370
1320
1270
1220
1170
1120
0.00
50.00
100.00
150.00
200.00
250.00
300.00
SO2 (ppm)

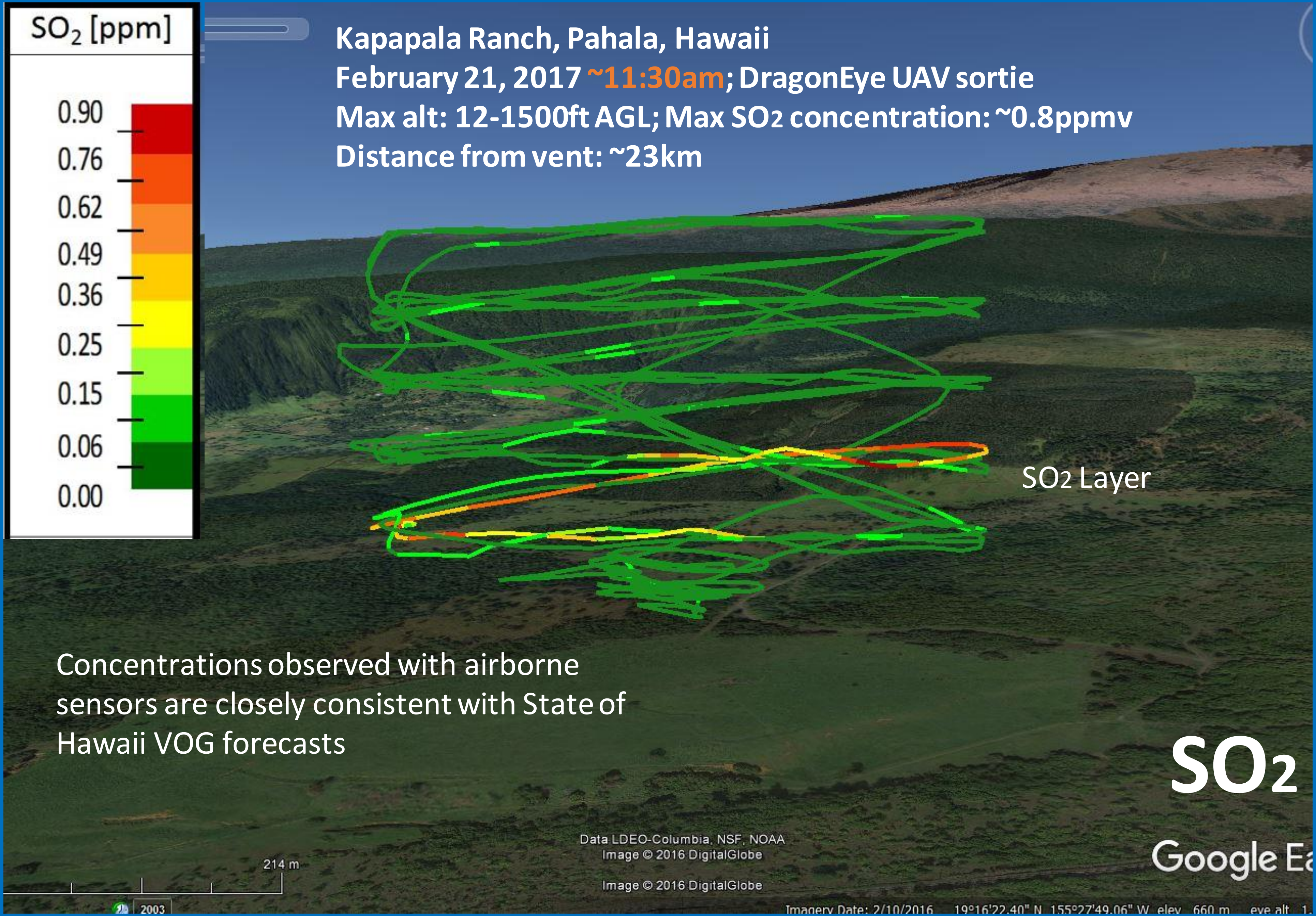

12/2/2017 4:12:46 pm
CO₂ [ppm]
509.90
502.49
494.08
484.30
472.61
457.94
438.04
406.00
0.00
VIEW #1
Wind direction to NE
(Kona conditions)
Quadrant of enhanced CO2
Halemaumau Crater,
Kilauea Volcano, Hawaii
February 12, 2017
DragonEye UAV sortie
Max alt: 1200ft AGL
Max CO2 concentration: ~510ppmv
613 m
Image © 2016 DigitalGlobe
Google Ear
CO2


12/2/2017 4:12:46 pm
CO2 [ppm]
509.90
502.49
494.08
484.30
472.61
457.94
438.04
406.00
0.00
VIEW #2
View to the NE, in the direction of the wind (Kona conditions)
Halemaumau Crater,
Kilauea Volcano, Hawaii
February 12, 2017
DragonEye UAV sortie
Max alt: 1200ft AGL
Max CO2 concentration: ~510ppmv
231 m
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data LDEO-Columbia, NSF, NOAA
CO2
Google Ea


Feb 2017 Mauna Loa NOAA
Observatory value
(~407±1ppmv)
Altitude (m AMSL)
1560
1510
1460
1410
1360
1310
1260
1210
1160
1110
400.00
420.00
440.00
460.00
480.00
500.00
520.00
Takeoff point
CO2 (ppm)
Feb 2017 JPL Tunable Diode Laser UAV
CO2 data: 1ppmv sensitivity (Lance
Christensen, JPL)
One year of CO2 daily and weekly means at Mauna Loa
PARTS PER MILLION
412
410
408
406
404
402
400
M J J A S O N D J F M A M J J
NOAA
June 2017
Preliminary weekly (red line), monthly (blue line) and daily (black points) averages at Mauna Loa for the last year.


Volcano
Trade Winds
POA#1
Hawaii Volcanoes National Park
~14 miles between the two sites (23km)
11
Approx. SO_2 plume corridor
SOA#2
Far-field UAV test area
Flights on 17 and 21 February
Image © 2016 DigitalGlobe
© 2016 Google
Data SOEST/UHM
Google Earth
Pāhala
Tour Guide
Imagery Date: 2/10/2016 lat 19.326630° lon -155.313253° elev 2878 ft eye alt 27.14 mi
N

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

SO_2

(From Vince Realmuto, JPL)

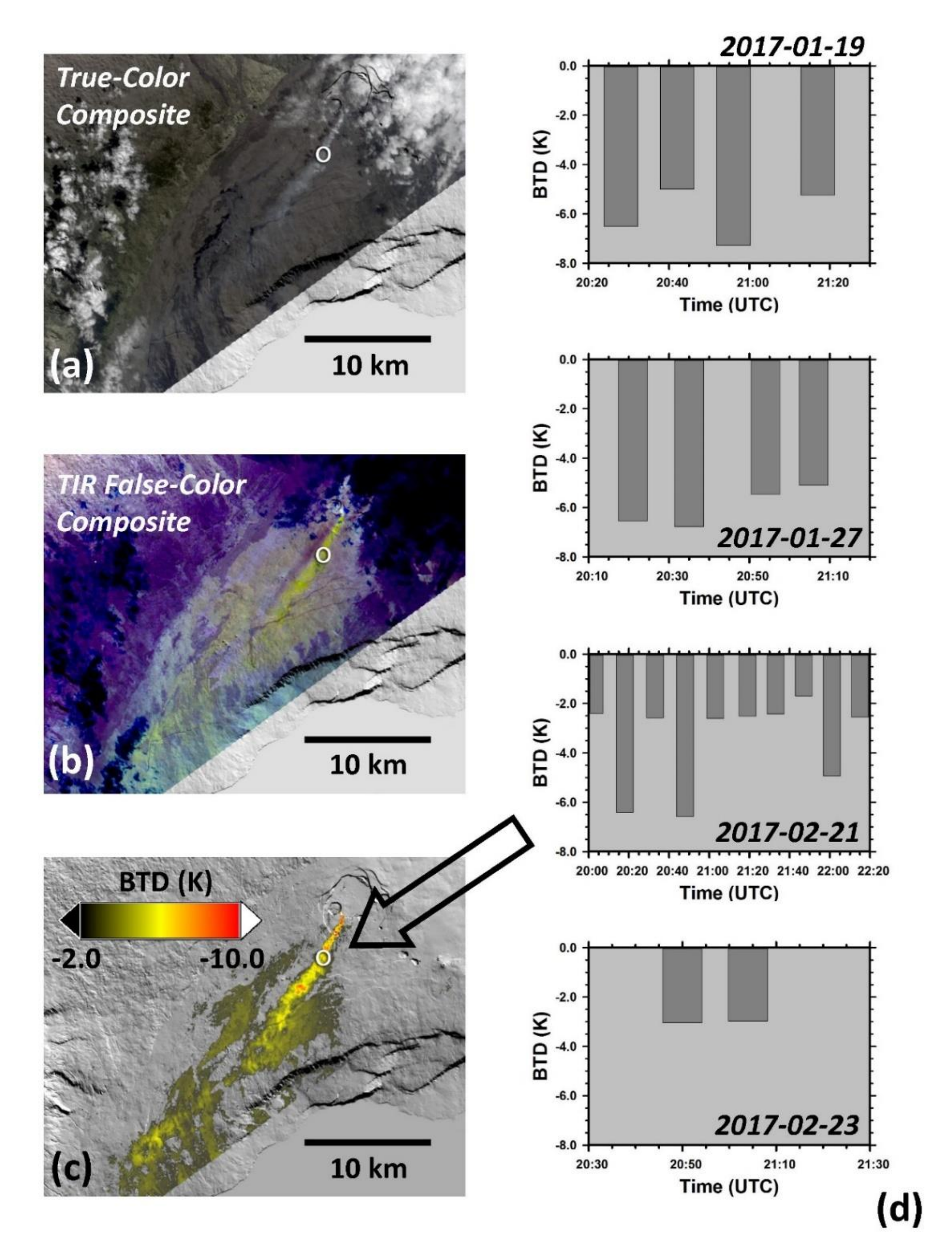
Brightness Temperature Difference (BTD) Time Series

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

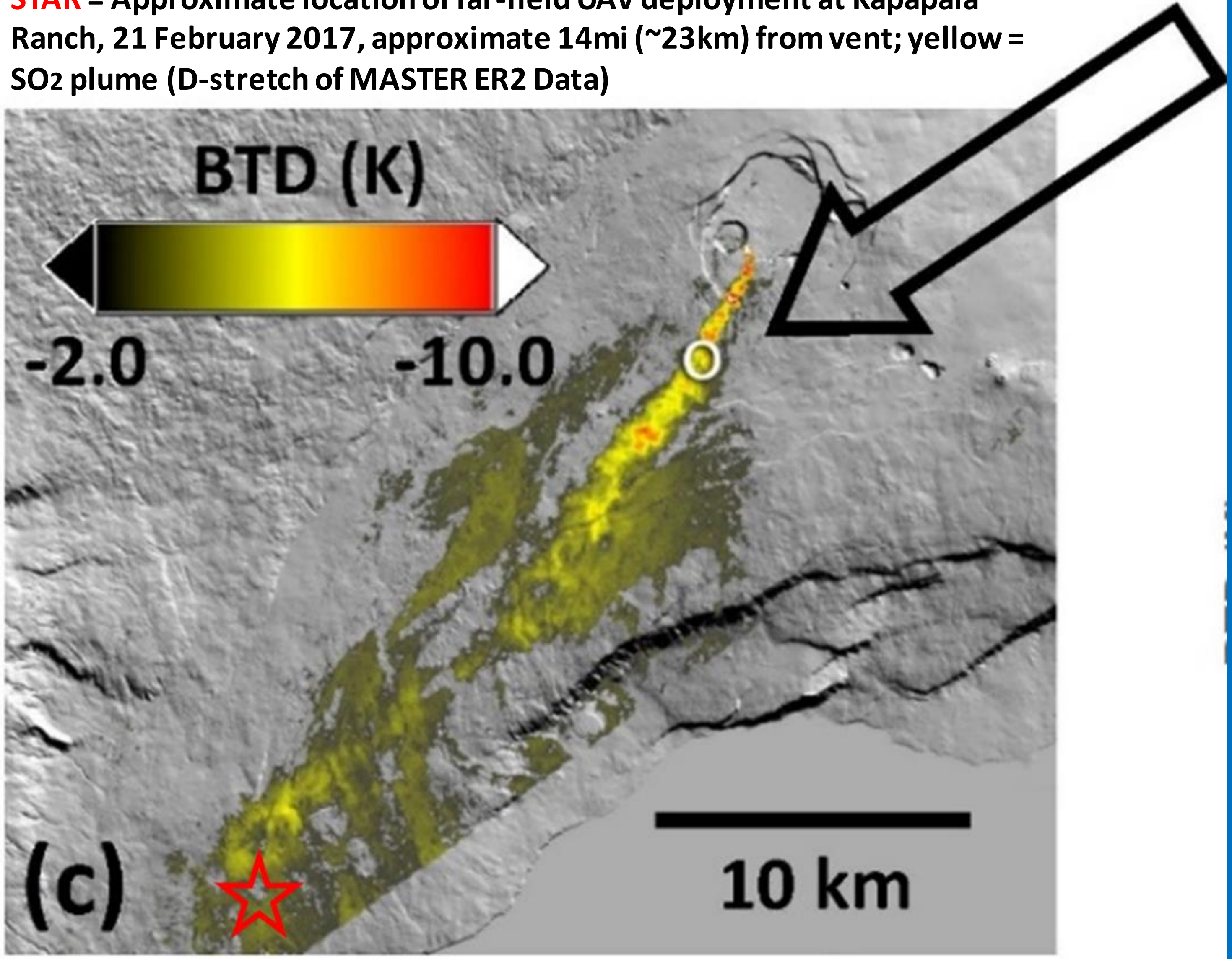
(b) False-Color composite of TIR data. SO_2 plume appears in yellow.

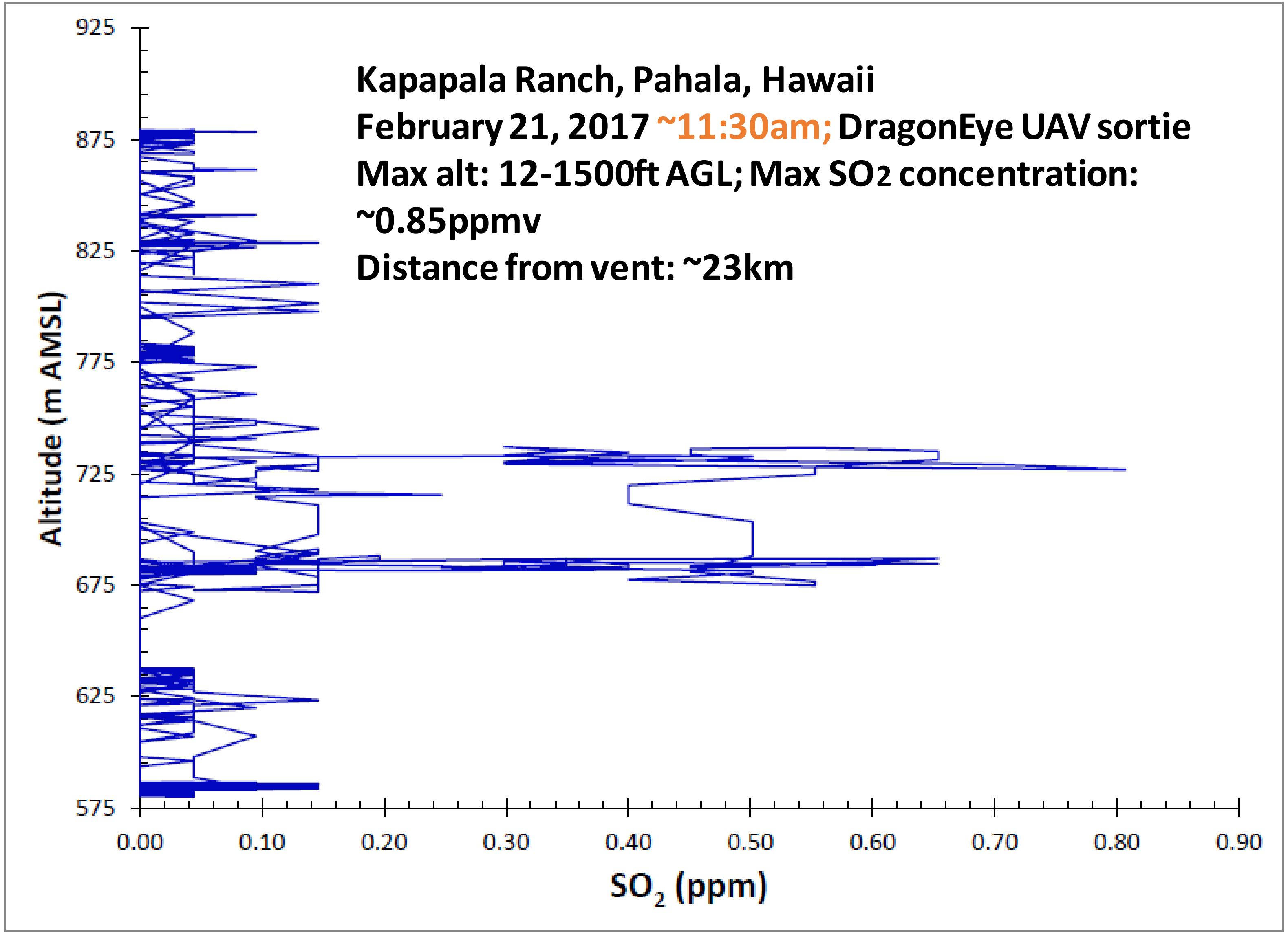
(c) Brightness Temperature Difference (BTD), calculated as difference between the BT in Channel 43 (8.7 μm) and the maximum BT over all of the MASTER TIR channels.

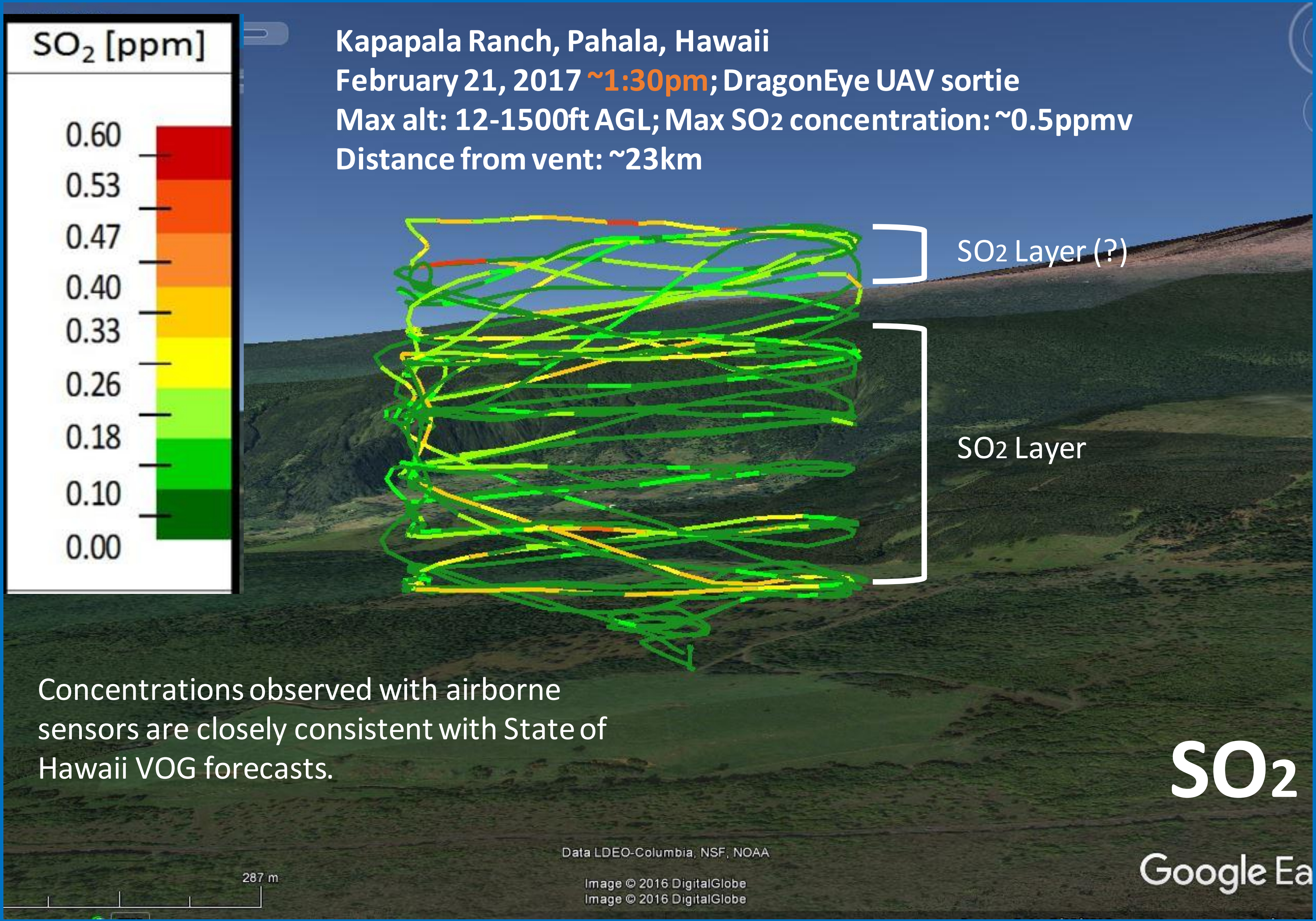
(d) BTD Values between 2017-01-19 and 2017-02-23, corresponding to the sample location marked by the white circle in Panels a – c. The decrease in (absolute) BTD for this location suggests a decrease in the concentration of SO_2 in the plume over this time interval.

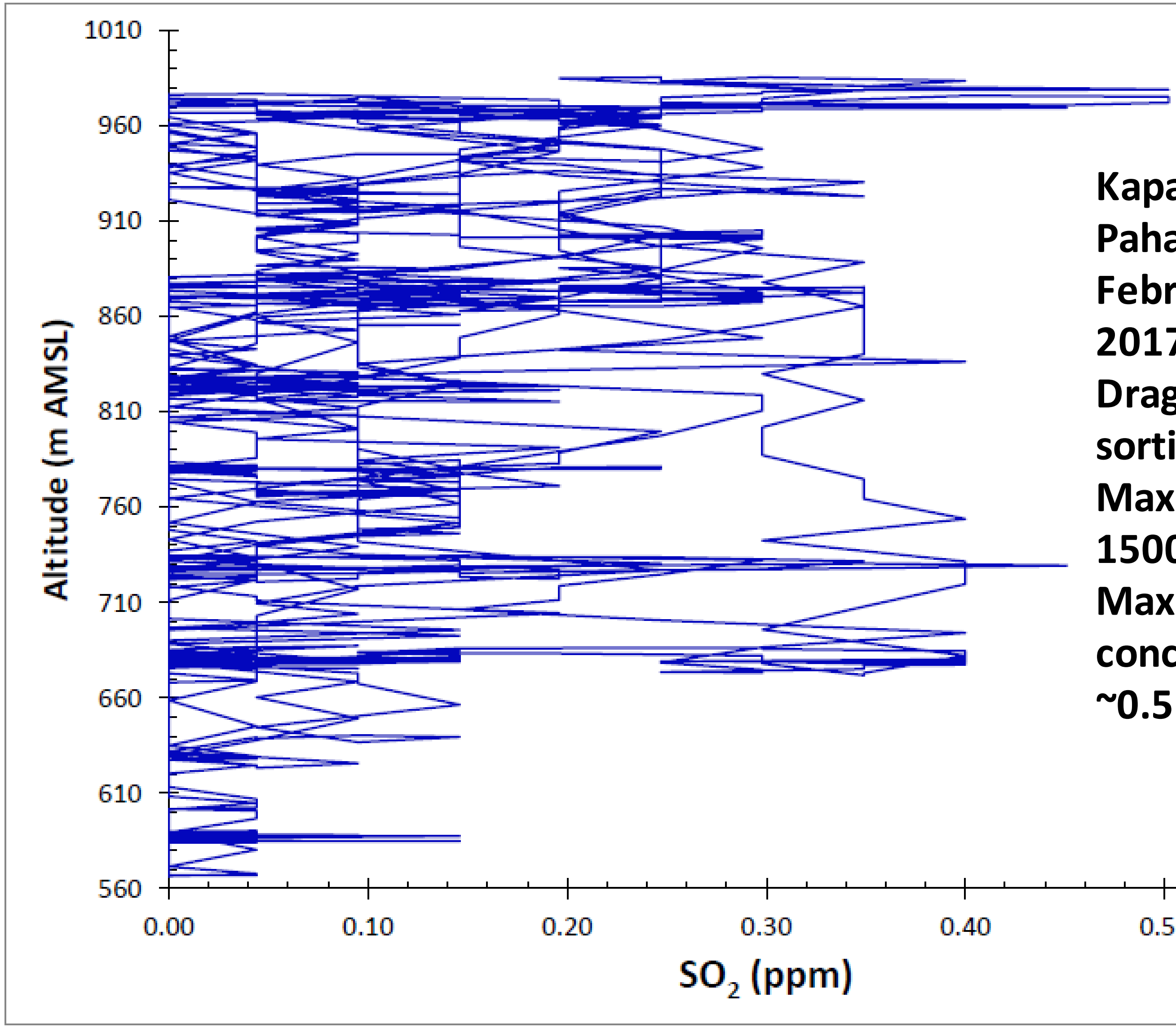


STAR = Approximate location of far-field UAV deployment at Kapapala Ranch, 21 February 2017, approximate 14mi (~23km) from vent; yellow = SO_2 plume (D-stretch of MASTER ER2 Data)




Kapapala Ranch, Pahala, Hawaii
February 21, 2017 ~11:30am; DragonEye UAV sortie
Max alt: 12-1500ft AGL; Max SO2 concentration: ~0.85ppmv
Distance from vent: ~23km
Altitude (m AMSL)
925
875
825
775
725
675
625
575
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
SO2 (ppm)


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
SO2 [ppm]
0.60
0.53
0.47
0.40
0.33
0.26
0.18
0.10
0.00
SO2 Layer (?)
SO2 Layer
Concentrations observed with airborne sensors are closely consistent with State of Hawaii VOG forecasts.
SO2
Data LDEO-Columbia, NSF, NOAA
Image © 2016 DigitalGlobe
Image © 2016 DigitalGlobe
287 m
Google Ea



Kapapala Ranch, Pahala, Hawaii February 21, 2017 ~1:30pm; DragonEye UAV sortie
Max alt: 1200-1500ft AGL;
Max SO_2 concentration: ~0.5ppmv

Results

1. NASA Dragon Eye UAVs successfully acquired airborne SO_2 and CO_2 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 SO_2 and CO_2 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 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 SO_2 levels ranged up to 250ppmv within the summit plume; CO_2 levels ranged up to 500ppmv within the summit plume (approximately 100ppmv above ambient background values). Ambient non-plume UAV CO_2 slightly elevated (+10ppm) vs NOAA values (diffuse volcano emissions?).

4. Far-field observations captured SO_2 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.

6. Small instrument development needs fostered/sustained.

7. VTOL /fixed-wing capabilities need development

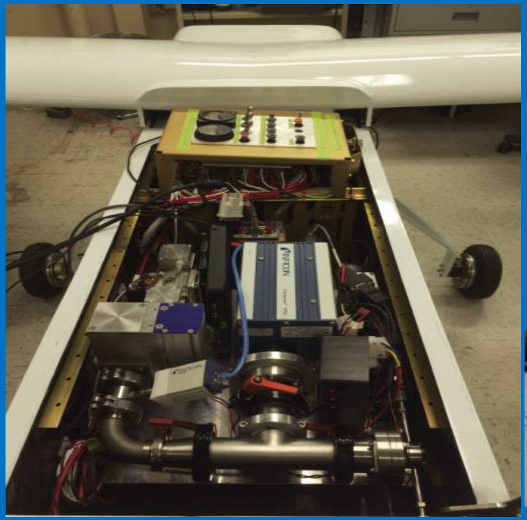
8. Aerostats should be included in the mix.

9. Science 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.

Future Activities

Future UAV Deployment to the Salton Sea, CA



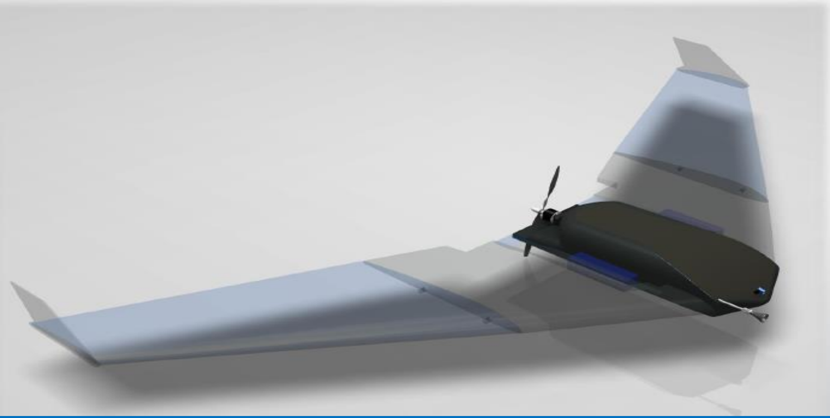
Salton Sea Geothermal Field Deployment with SIERRA-B & Dragon Eye UAVs (Sept 2018)

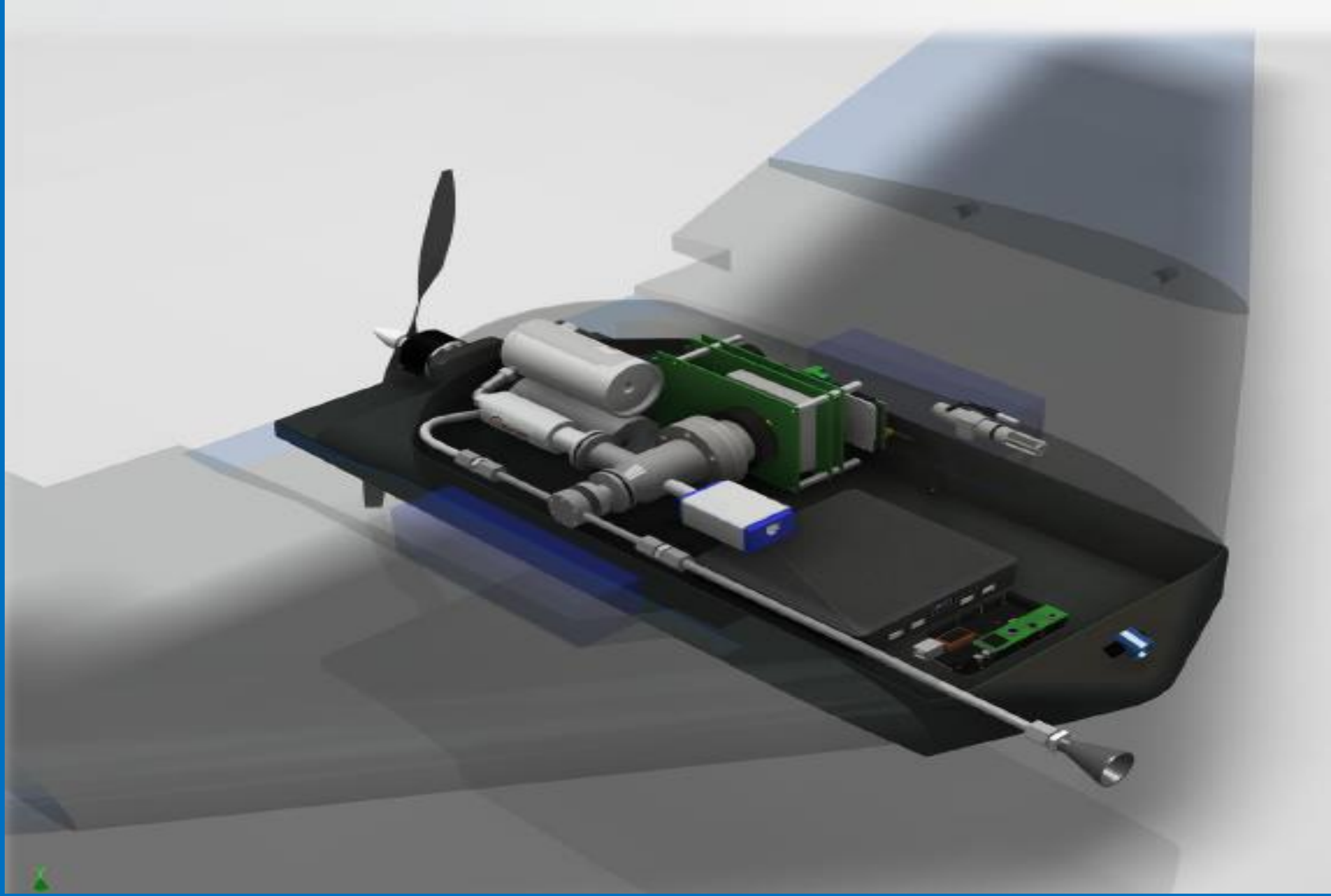
Two views of the UAV-MS XPF3 (UCR) integrated within the SIERRA_B UAV airframe at NASA ARC.

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

"Gryphons" or "mudpots" (small mud volcanoes) are ubiquitous in the Salton Sea Geothermal Field, most activel emitting a variety of gases: ***SO_2 CO_2 NO_x CH_4 H_2S OCS NH_3 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

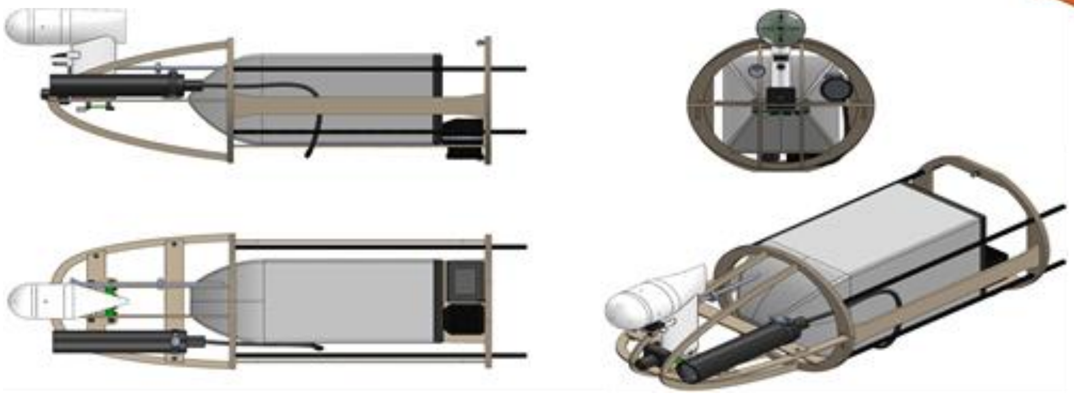
Future UAV, In development—USA

AIRCRAFT

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**

- Modular and field swappable payload.



- Catapult or hand launch and belly land

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?