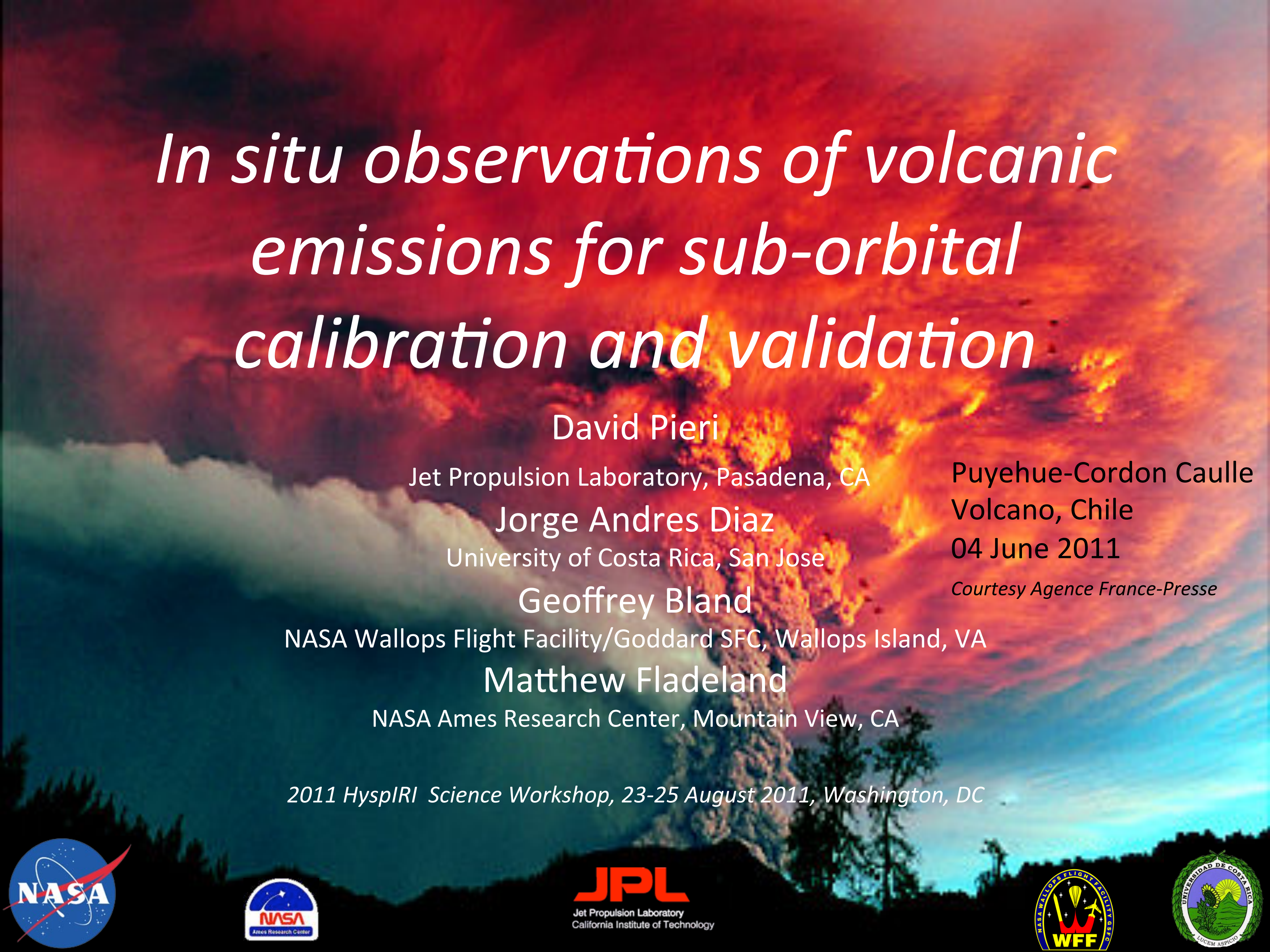


In situ observations of volcanic emissions for sub-orbital calibration and validation

David Pieri

Jet Propulsion Laboratory, Pasadena, CA

Jorge Andres Diaz

University of Costa Rica, San Jose

Geoffrey Bland

NASA Wallops Flight Facility/Goddard SFC, Wallops Island, VA

Matthew Fladeland

NASA Ames Research Center, Mountain View, CA

Puyehue-Cordon Caulle Volcano, Chile
04 June 2011

Courtesy Agence France-Presse

2011 HyspIRI Science Workshop, 23-25 August 2011, Washington, DC

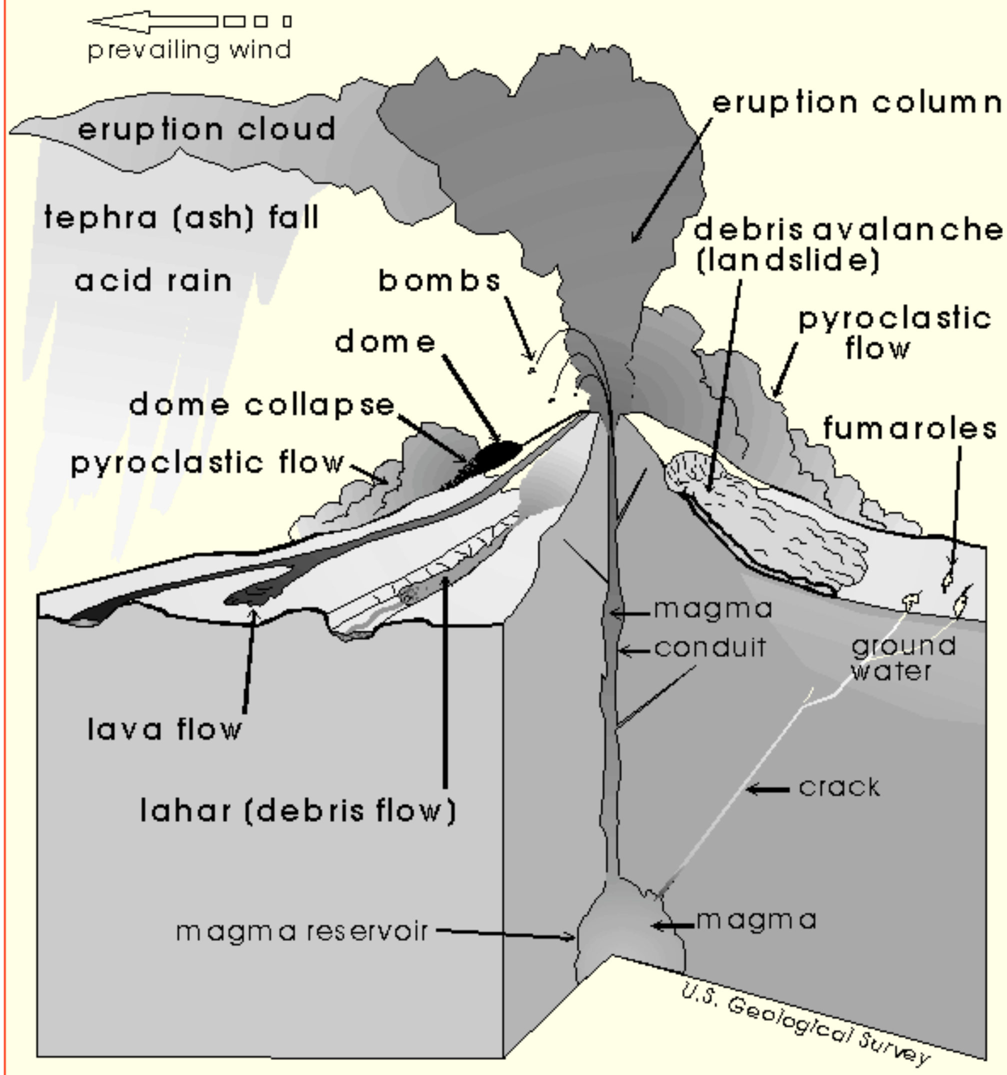
Jet Propulsion Laboratory
California Institute of Technology

Outline

1. The problem:
How can we conveniently, accurately, responsively, and relatively cheaply, sample volcanic ash and gas emissions in situ?

2. One solution: Use small unmanned aerial vehicles (UAVs).

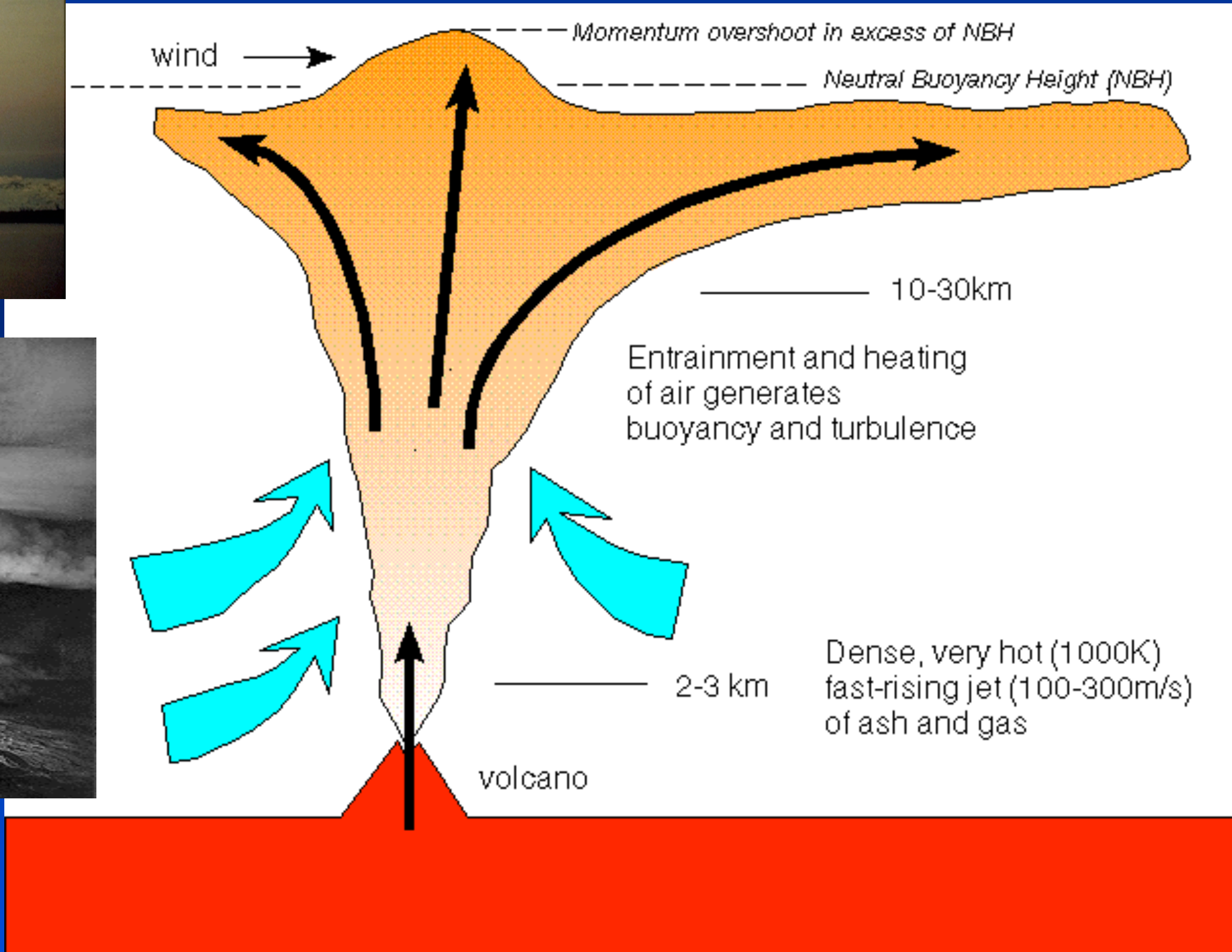
Volcano Hazards



USGS

Topinka, USGS/CVO, 1998, Modifief from: Myers and Brantley, 1995, USGS Open-File Report 95-231

Eruption column processes



Importance of In Situ Sampling of Volcanic Plumes?

- Basic science

  Better knowledge of instrument response

  How well are detection, mass-loading, and trajectory prediction models doing in characterizing volcanic airborne emissions, both gases and aerosols?

- Applied Science (Emphasis of this talk)

  ☠ Understand the physical properties of airborne volcanogenic emissions in the context of airborne hazards to aviation.

Ash is a serious regional to global threat to aircraft

"…the 2010 eruptions of Eyjafjallajökull in Iceland have highlighted the frailties of global aviation…"

"…today it is recognized that one of the more serious direct threats of airborne ash clouds is to aircraft in flight…"

"…the threat of volcanic ash clouds to aviation is significant in thinking about the multidimensional hazards of large eruptions in the future…"

excerpts from new book by Clive Oppenheimer, 2011, *Eruptions that Shook the World,* Cambridge University Press

The collision between volcanic eruptions and aviation: stimulus and response

- **The Stimulus: Airborne Hazards**
  - Eruption effects—injection of large amounts of volcanic gas, particulate ash, water vapor, and ice into the troposphere and stratosphere.
  - Volcanic plumes and clouds—drifting over major sections of the globe, disruptive, dangerous.
  - Effects on Aircraft—obvious prompt and more subtle delayed engine and airframe problems.

- **The Operational Response—Airlines, VAACs, First responders**
  - Where is the stuff? Where's it going?
  - Aviation—go around! OK for North America, parts of Asia, and maybe Australia/New Zealand but can't easily do it in Europe or Central/South America, for instance.
  - What concentration levels are safe to fly through and for how long?

The collision between volcanic eruptions and aviation: stimulus and response

- **The Observational Response—National weather and science agencies**
  - Remote sensing—get data!
  - Mainly satellite observations—from LEO and GEO. (HyspIRI will vastly help).
  - How do we interpret our data?
  - How much is there?
  - Could we have seen it coming--precursors? (HyspIRI will vastly help here, too.)
- ***The Critique (the role of in situ observations—focus of this talk)***
  - ***How good are our remote sensing data?***
  - ***What do our data mean in terms of "tangible" physical properties of volcanic clouds?***
  - ***How well can we validate our results and how can we improve them?***

Emergent Airborne Ash Issues 2009 and now

Jet Propulsion Laboratory
California Institute of Technology

The challenges:

Historical context: Pre-Eyjafyallajokull
In situ validation of ash-cloud models—R&D
First *Support to Aviation for Volcanic Ash Avoidance (SAVAA) Workshop* - Rome – Italy, 6-7 April, 2009

- **Rapidly dispersing ash clouds present an aviation threat that widens minute by minute during and after an eruption.**
- **First, at local scale—then rapidly becomes regional, and large eruptions can become continental to global in effect.**
- ****Physical characteristics of the eruption clouds are inferred from remote sensing data with few validation measurements.**
- ****Ash concentration, trajectory, altitude, and lateral extent estimates are highly dependent on**
  - **Dispersion models**
  - **Radiative transfer models**
  - **Remote sensing data reduction models**

An Inventory of handicaps-1

"…there are **no standard data products** specifically designed for volcanic ash and volcanic gases…" (Prata et al., IEEE, 2009)

"…There are also no internationally agreed satellite-based volcanic product standards and no protocols or procedures in place to permit specification of safe limits for aviation encountering airborne volcanic substances. Part of this problem lies with **the lack of sufficient information regarding what constitutes safe operating limits when flying near to volcanic clouds. Part of the solution lies in being able to provide quantitative satellite information and some means for validation."** (Prata et al., IEEE, 2009)

"…Currently, there is **no objective means for determining the injection height** of a volcanic eruption, and usually multiple dispersion simulations must be run and matched "by eye" to current or prior satellite imagery." (Prata et al., IEEE, 2009)

An Inventory of handicaps-2

"…Sensitivity analyses by Wen and Rose [1994] suggest **mass loading errors of 40–50%**." (Prata and Kerkmann, GRL, 2007)

"…We emphasize here that **neither of these SEVIRI retrieval schemes have been properly validated against independent measurements.** Based on an error budget for the TOVS/HIRS SO_2 retrieval scheme [Prata et al., 2003], a conservative error for SEVIRI is ±10 D.U. on a single pixel basis. This gives a mass loading retrieval error of approximately ±0.01 Tg(S), for the SO_2 clouds discussed here. (Prata and Kerkmann, GRL, 2007)

Questions :

- **How crucial are the validations of models and data reduction techniques? Is just knowing the ash is there "enough" to manage safety concerns?**

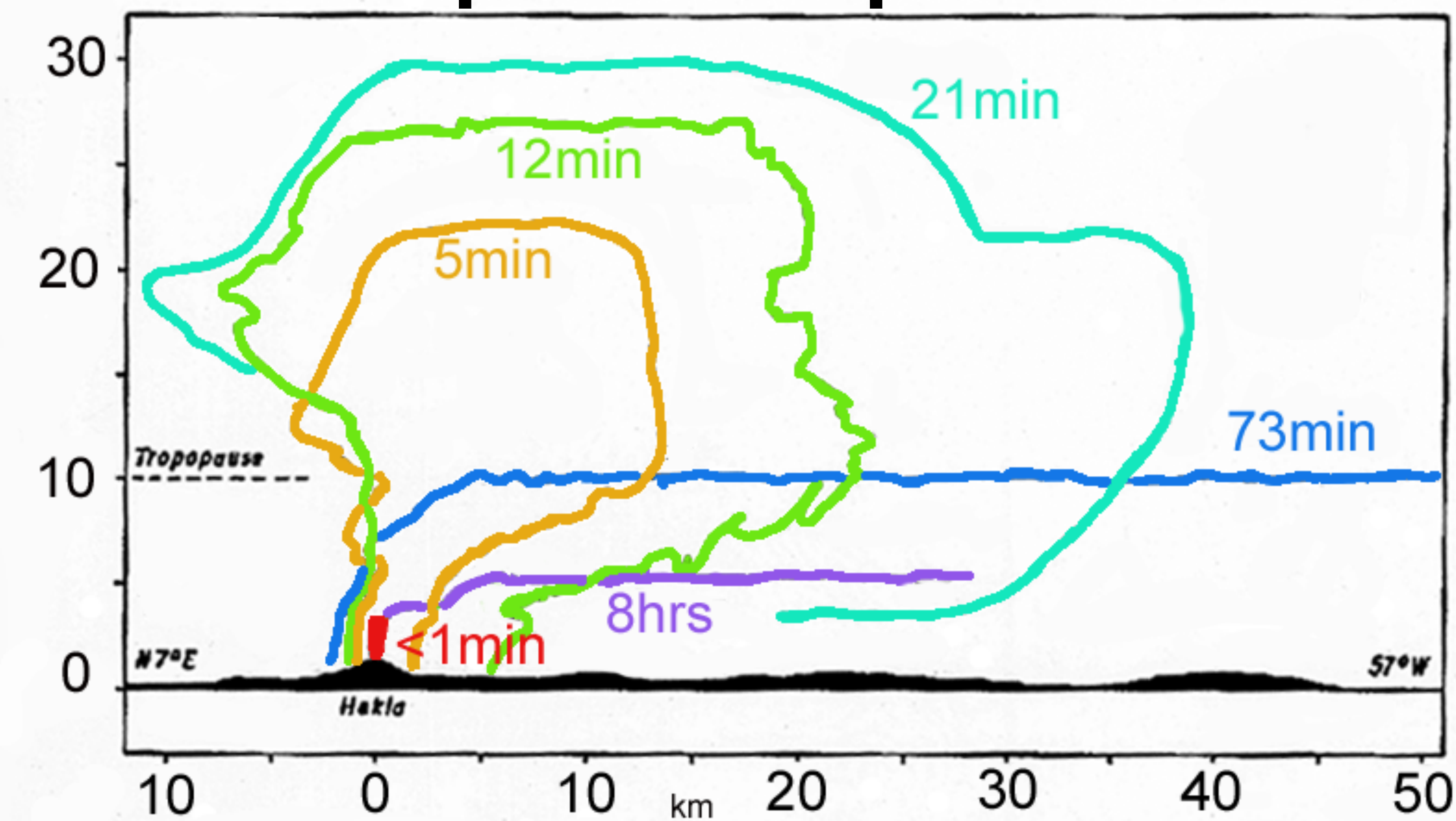
- **What are the consequences of establishing better confidence on knowledge of ash concentrations? Will this propagate to smaller safety margins as air carriers make more finely tuned risk-benefit analyses? "Don't ask, don't tell?"**

- *****How strongly are we willing to advocate for possibly heroic or expensive efforts to collect high altitude in situ validation data?**

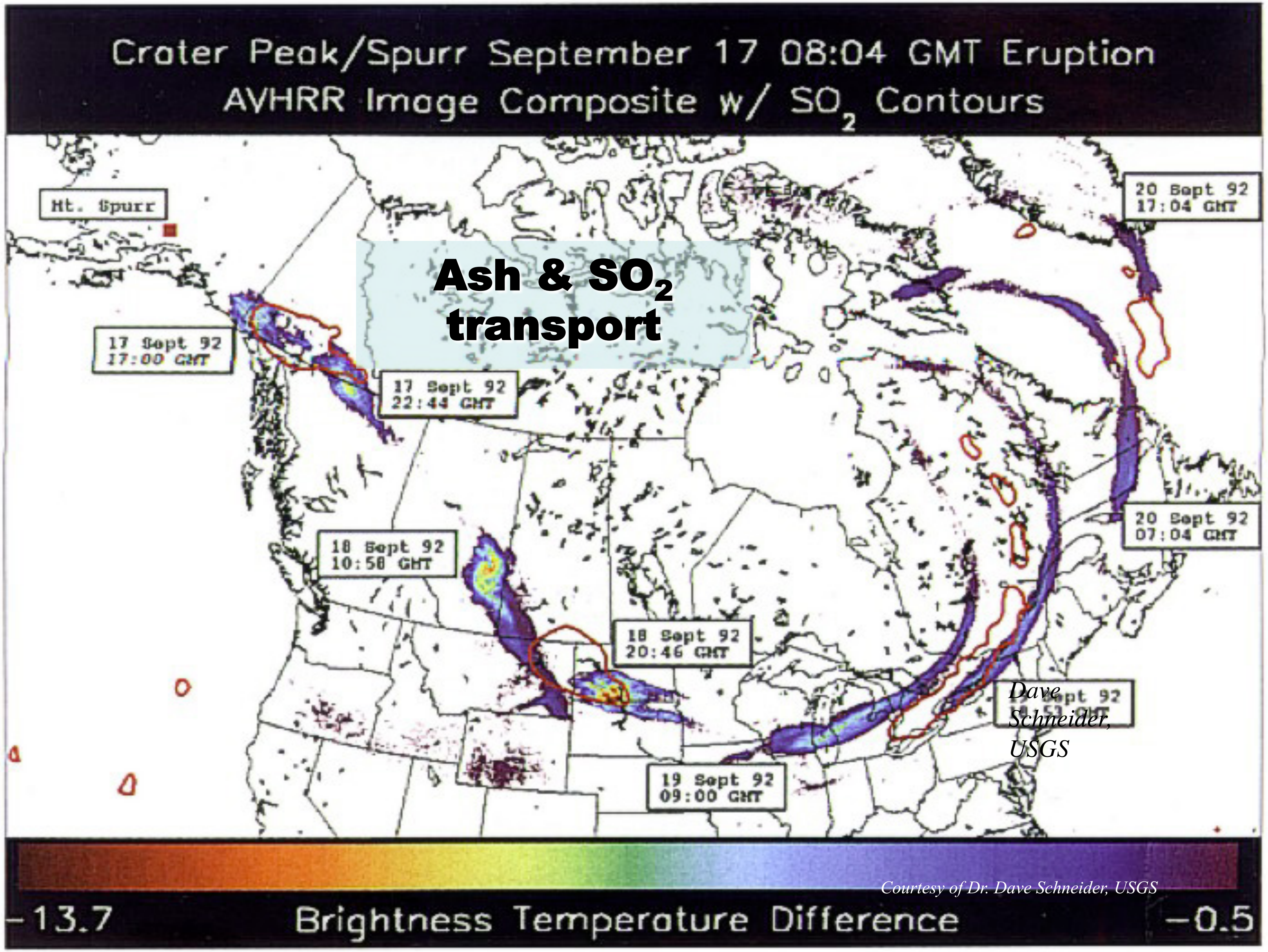
===

- **Ad hoc Airborne In Situ Sampling Working Group was to start in 2011 at Melbourne IAVCEI Congress—now planned for 2012 in Costa Rica**

Eruption column processes



Growth of the 1947 Hekla Plume
(after Thorarinsson, 1954)



Crater Peak/Spurr September 17 08:04 GMT Eruption
AVHRR Image Composite w/ SO_2 Contours
Ash & SO_2 transport
Mt. Spurr
17 Sept 92 17:00 GMT
17 Sept 92 22:44 GMT
18 Sept 92 10:58 GMT
18 Sept 92 20:46 GMT
19 Sept 92 09:00 GMT
20 Sept 92 07:04 GMT
20 Sept 92 17:04 GMT
Dave Schneider, USGS
Courtesy of Dr. Dave Schneider, USGS
-13.7
Brightness Temperature Difference
-0.5

Ash effects on aircraft

The effect of volcanic ash on aircraft--
Exterior

Manilla Intl. Airport,
After 1991 Mt. Pinatubo Eruption

PILOT KLM B-747 – "KLM 867 HEAVY IS REACHING {FLIGHT} LEVEL 250 HEADING 140"

ANCHORAGE CENTER - "OKAY, DO YOU HAVE GOOD SIGHT ON THE ASH PLUME AT THIS TIME?"

PILOT KLM B-747 – "YEA, IT'S JUST CLOUDY IT COULD BE ASHES. IT'S JUST A LITTLE BROWNER THAN THE NORMAL CLOUD."

PILOT KLM B-747 – "WE HAVE TO GO LEFT NOW... IT'S SMOKY IN THE COCKPIT AT THE MOMENT SIR."

ANCHORAGE CENTER – "KLM 867 HEAVY, ROGER, LEFT AT YOUR DISCRETION."

An Inciting incident
Redoubt Volcano, Dec 1989

PILOT KLM B-747 – "CLIMBING TO {FLIGHT} LEVEL 390, WE'RE IN A BLACK CLOUD, HEADING 130."

PILOT KLM B-747 – "KLM 867 WE HAVE FLAME OUT ALL ENGINES AND WE ARE DESCENDING NOW!"

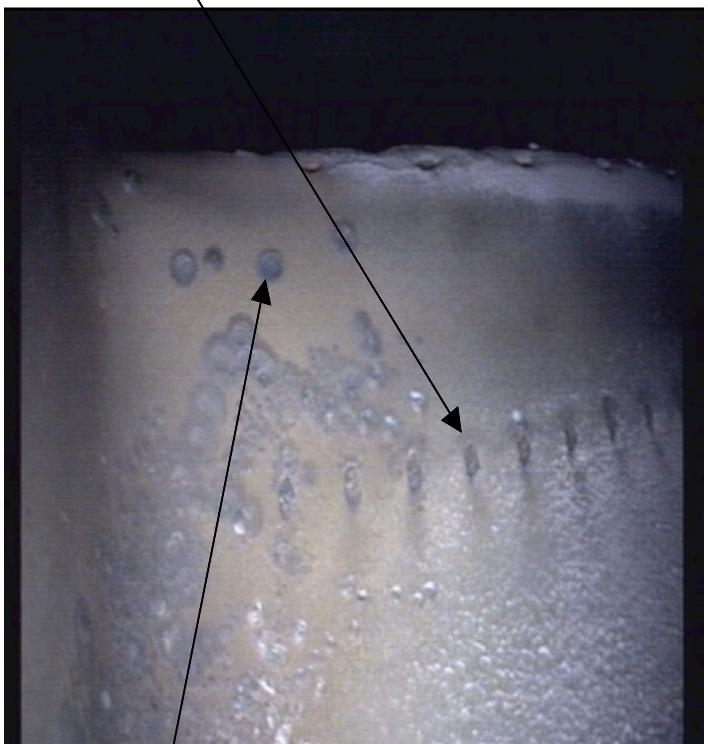
ANCHORAGE CENTER – "KLM 867 HEAVY ANCHORAGE?"

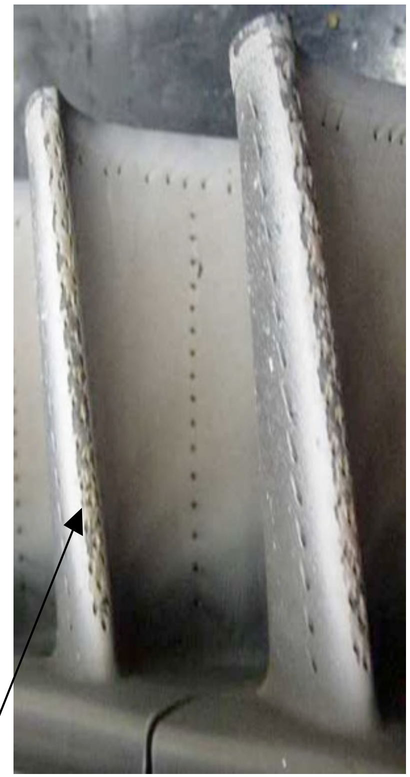
PILOT KLM B747 – "KLM 867 HEAVY WE ARE DESCENDING NOW … WE ARE IN A FALL!"

PILOT KLM B-747 – "KLM 867 WE NEED ALL THE ASSISTANCE YOU HAVE SIR. GIVE US RADAR VECTORS PLEASE!"

NASA DC-8 Research Aircraft Engine Parts after disassembly upon return from the SOLVE experiment (Courtesy NASA Dryden FRC)

Plugged Cooling Holes

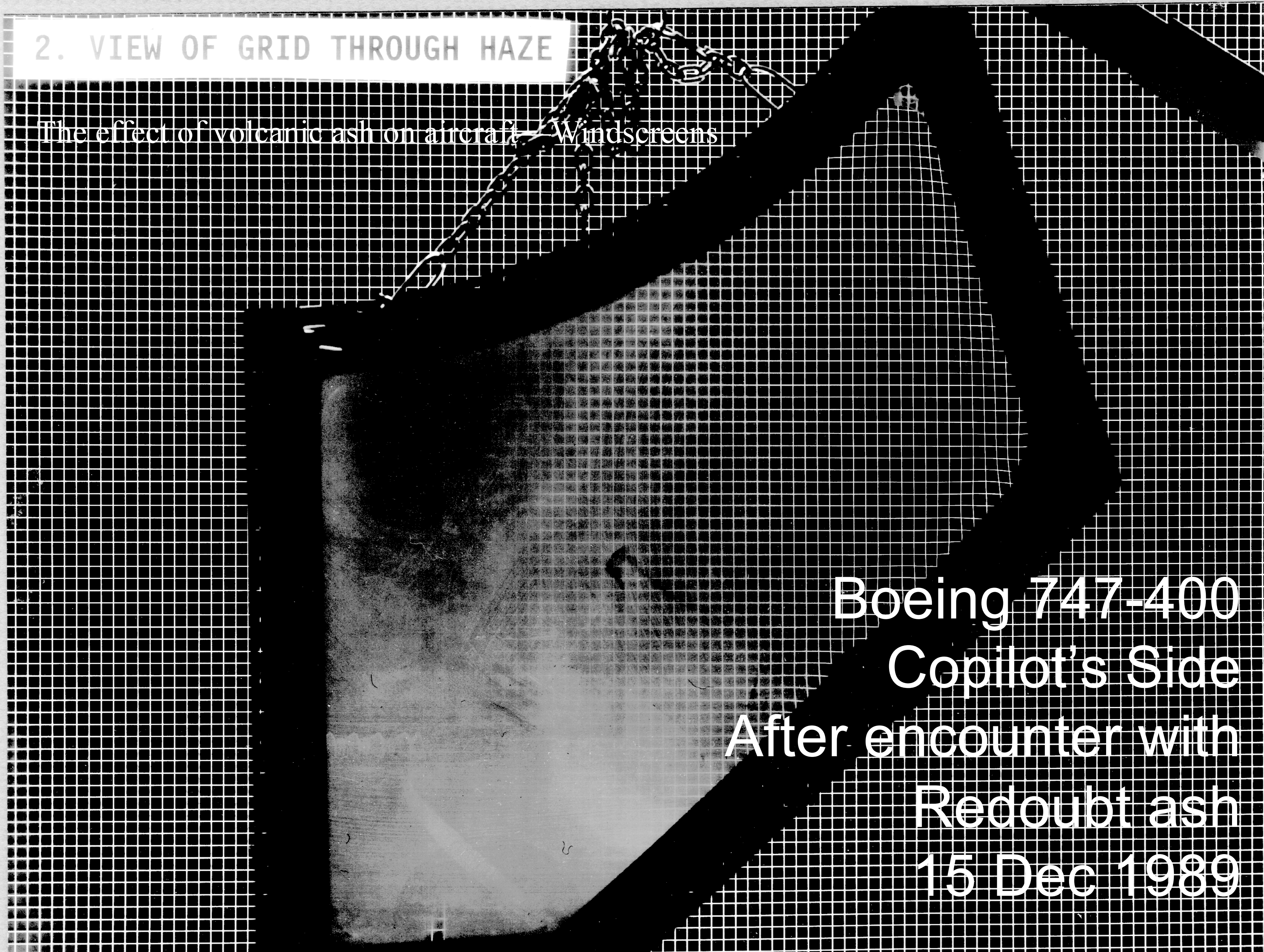


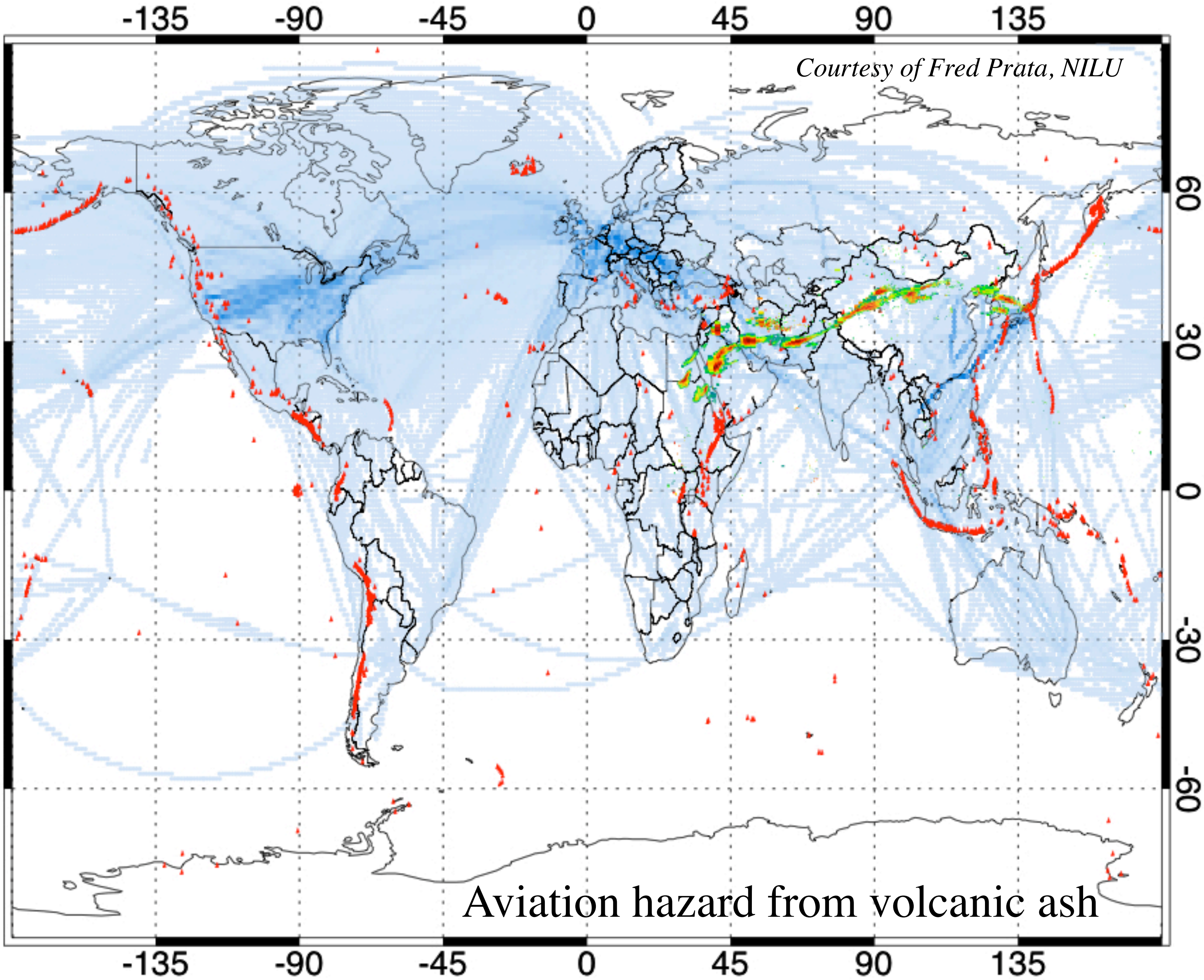


Blistered thermal coating

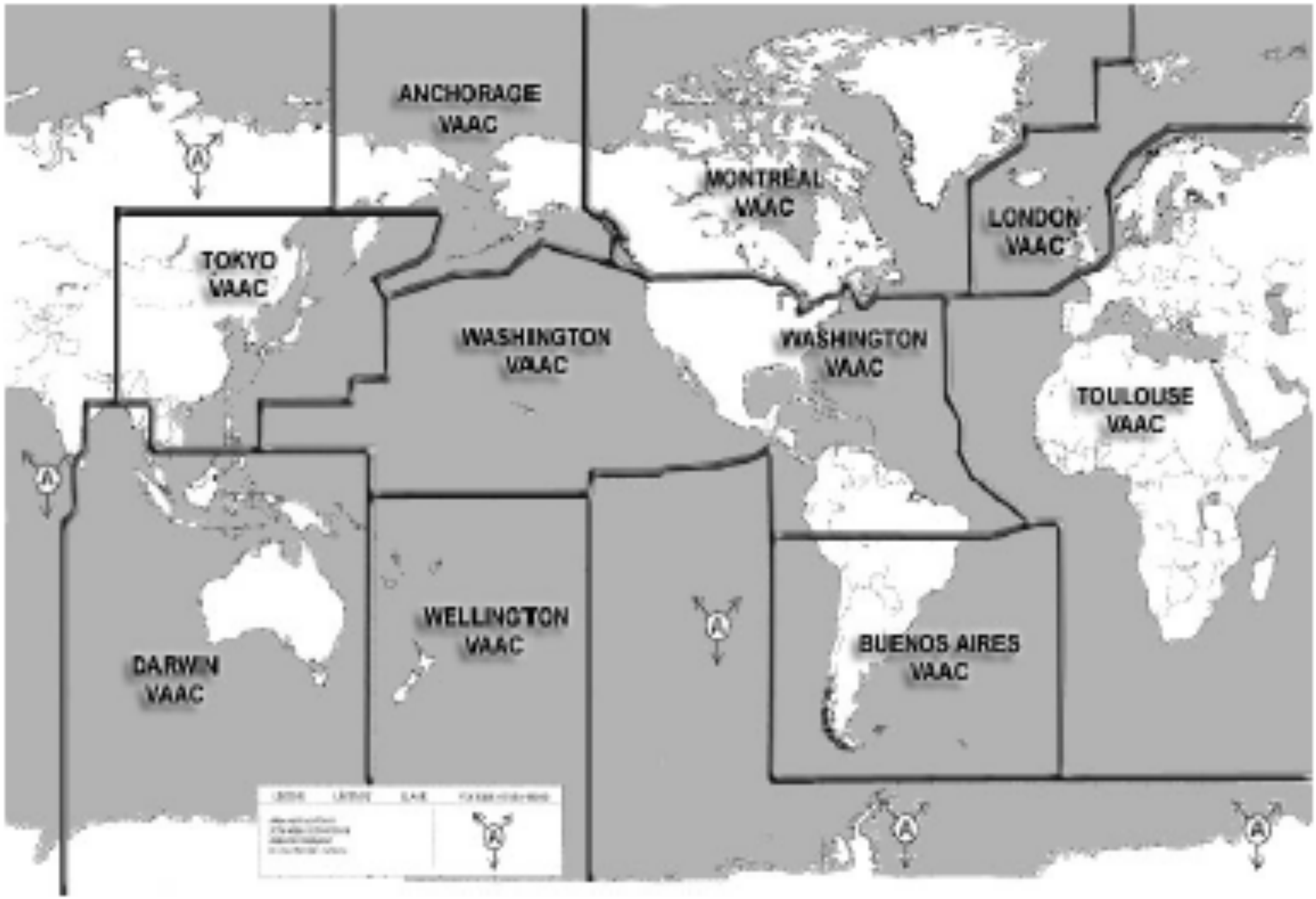
Erosion of Leading Edge

Build-up of Ash
Inside Passages


2. VIEW OF GRID THROUGH HAZE
The effect of volcanic ash on aircraft – Windscreens
Boeing 747-400
Copilot's Side
After encounter with
Redoubt ash
15 Dec 1989



Aviation hazard from volcanic ash



Chris Newhall, USGS

Properties of Volcanic Clouds

What do we know about ash particles?


Atmospheric and Environmental Impacts of Volcanic Particulates

Adam J. Durant[1], Costanza Bonadonna[2], and Claire J. Horwell[3]

1811-5209/10/0006-0235$2.50 DOI: 10.2113/gselements.6.4.235

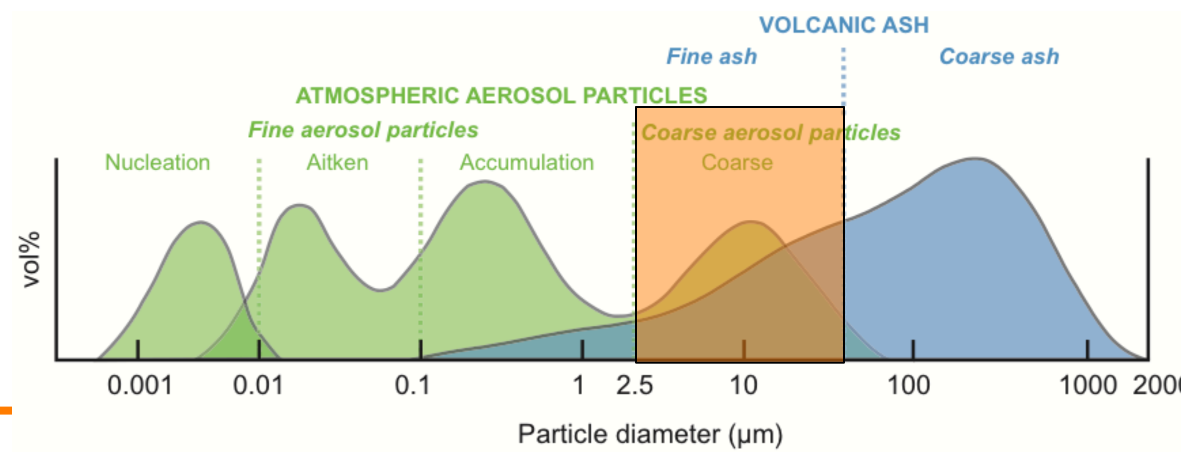
A single ash particle erupted during the 18 May 1980 eruption of Mount St. Helens, USA. The dark voids are vesicles formed as gases escaped. Image width is about 75 μm. USGS IMAGE BY A. SARNA-WOJCICKI

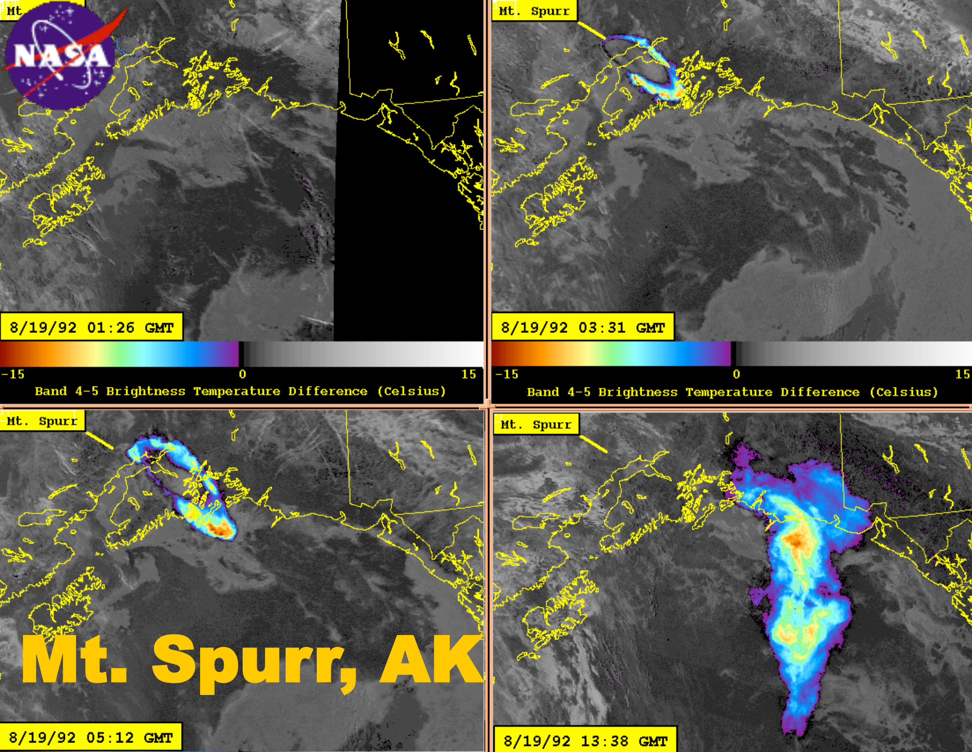
High silicate content

Particle size (radius) ranges from 0.01–500 μm (typically)

Irregular shape

Melting point ~1100 ºC (800–1200 ºC).





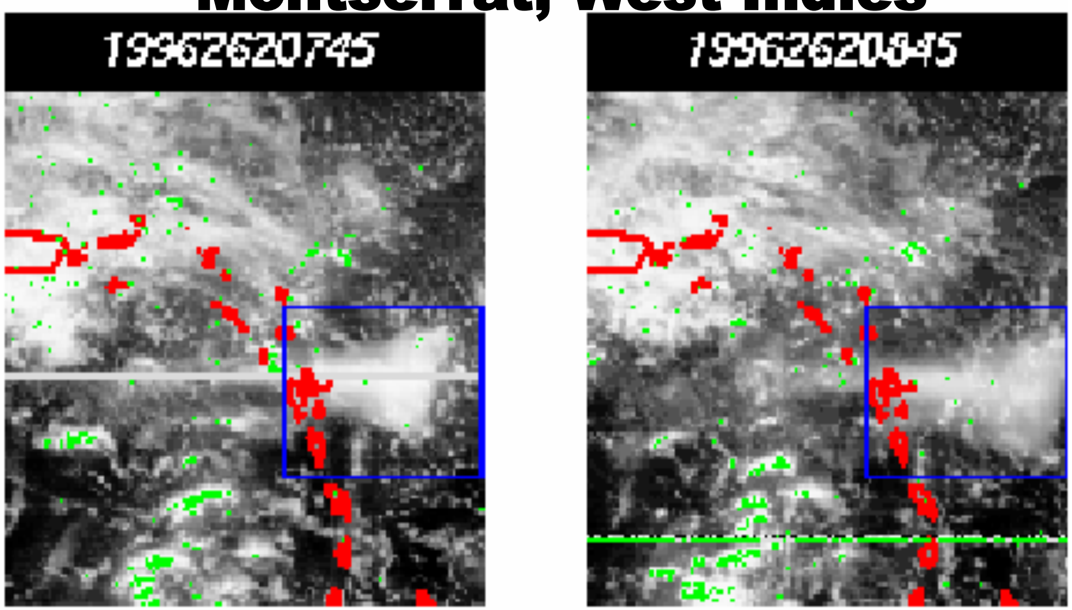
Seeing Ash with TIR Split Window

- **Comparison of Mt. Spurr '92 (polar dry) plume detection with La Soufriere (Montserrat) '96 (tropical wet) –**
- **Band 4 (10μm) minus 5 (12 μm) "subtraction technique" or "split window technique."**

- **Split Window technique only works after plume has become translucent to upwelling TIR radiation.**
- **Water vapor is confounding.**
- **Use of shorter TIR bands (e.g., 7-9 μm) could improve things.**

- ***HyspIRI may improve this***

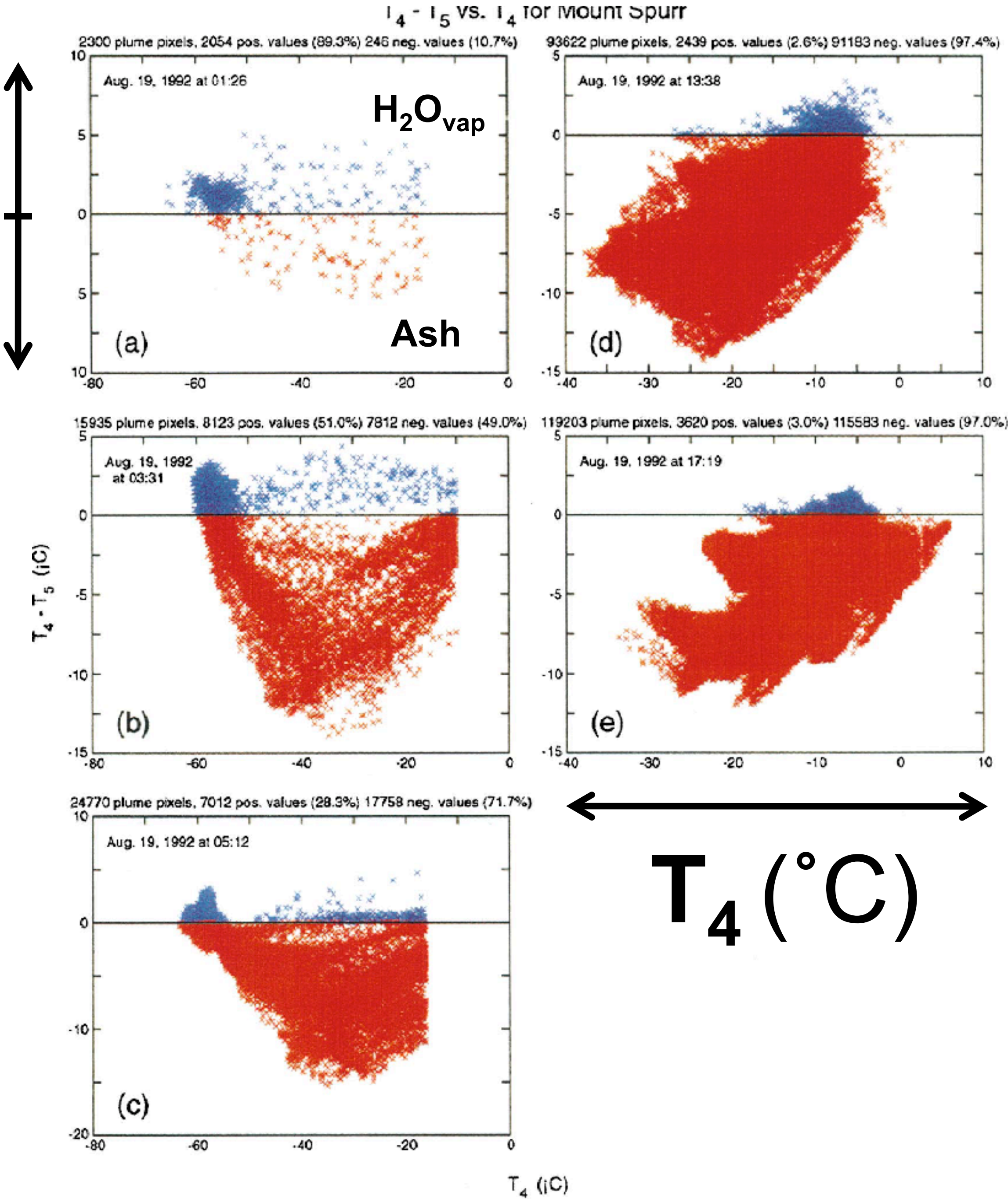
Montserrat, West Indies



ΔT_{4-5}

Positive

Negative



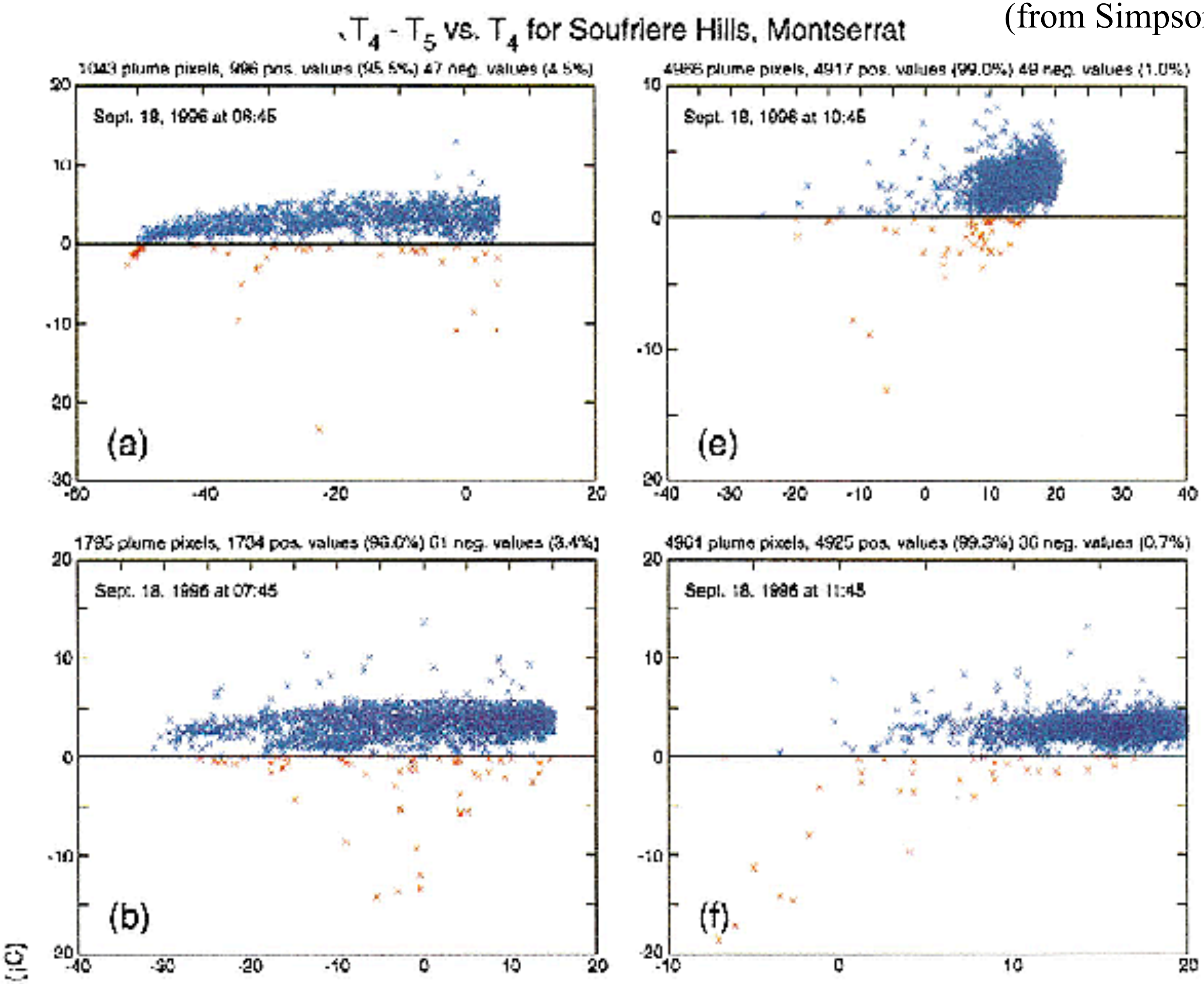
T_4 (˚C)

Statistics for Mt. Spurr Ash Plume

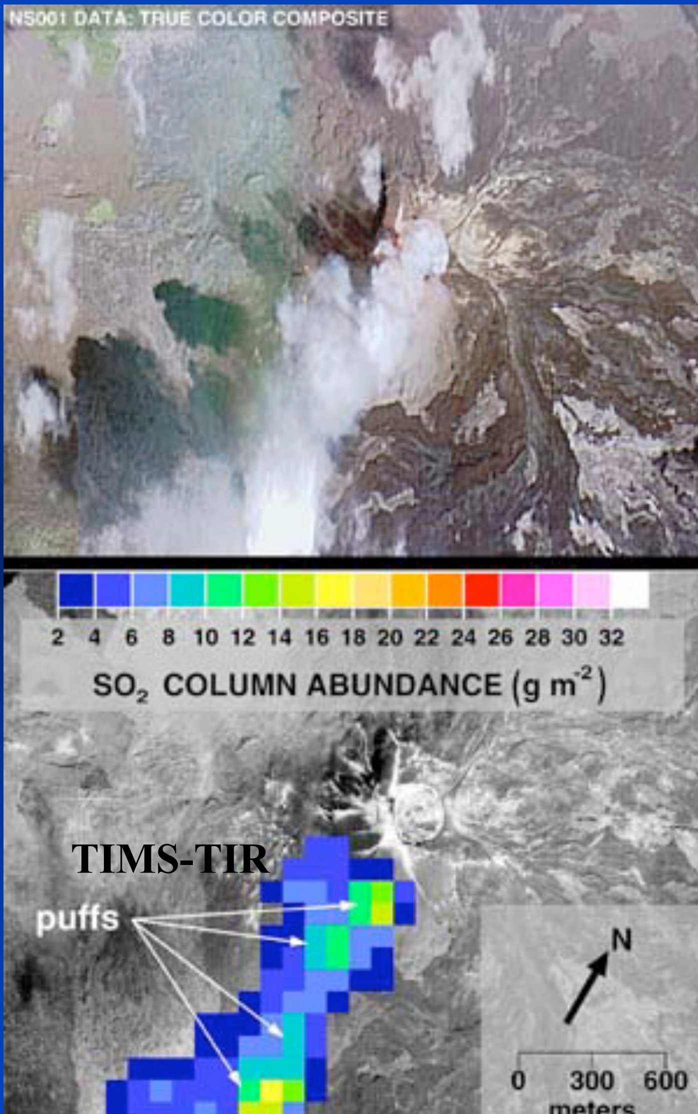
(from Simpson *et al*., 2000)

Statistics for Monserrat Ash Plume

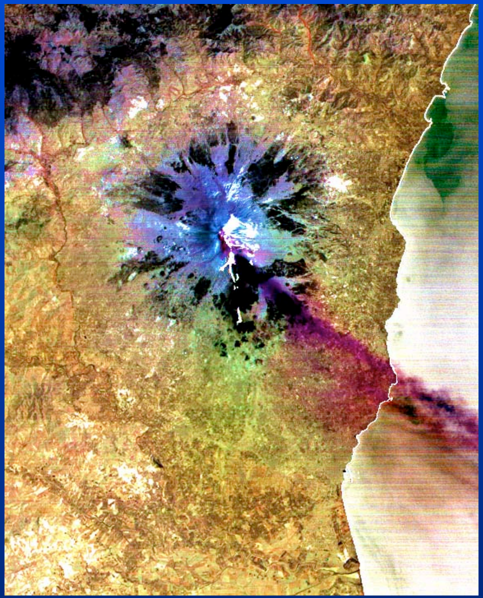
(from Simpson *et al.*, 2000)



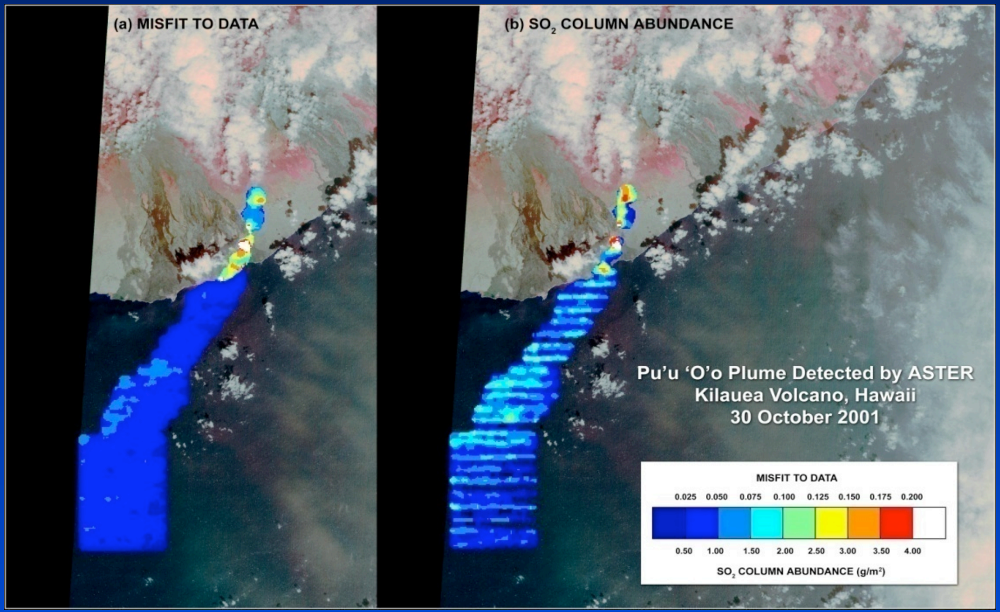
SO_2 Detection and Tracking Passive emission precursors: *HyspIRI Targets*



Airborne Detection from NASA C130 in over PuuOo Vent, Kilauea (left)



Orbital Detection of Tropospheric SO_2
ASTER over Hawaii (below) and Mt. Etna, Italy (above)



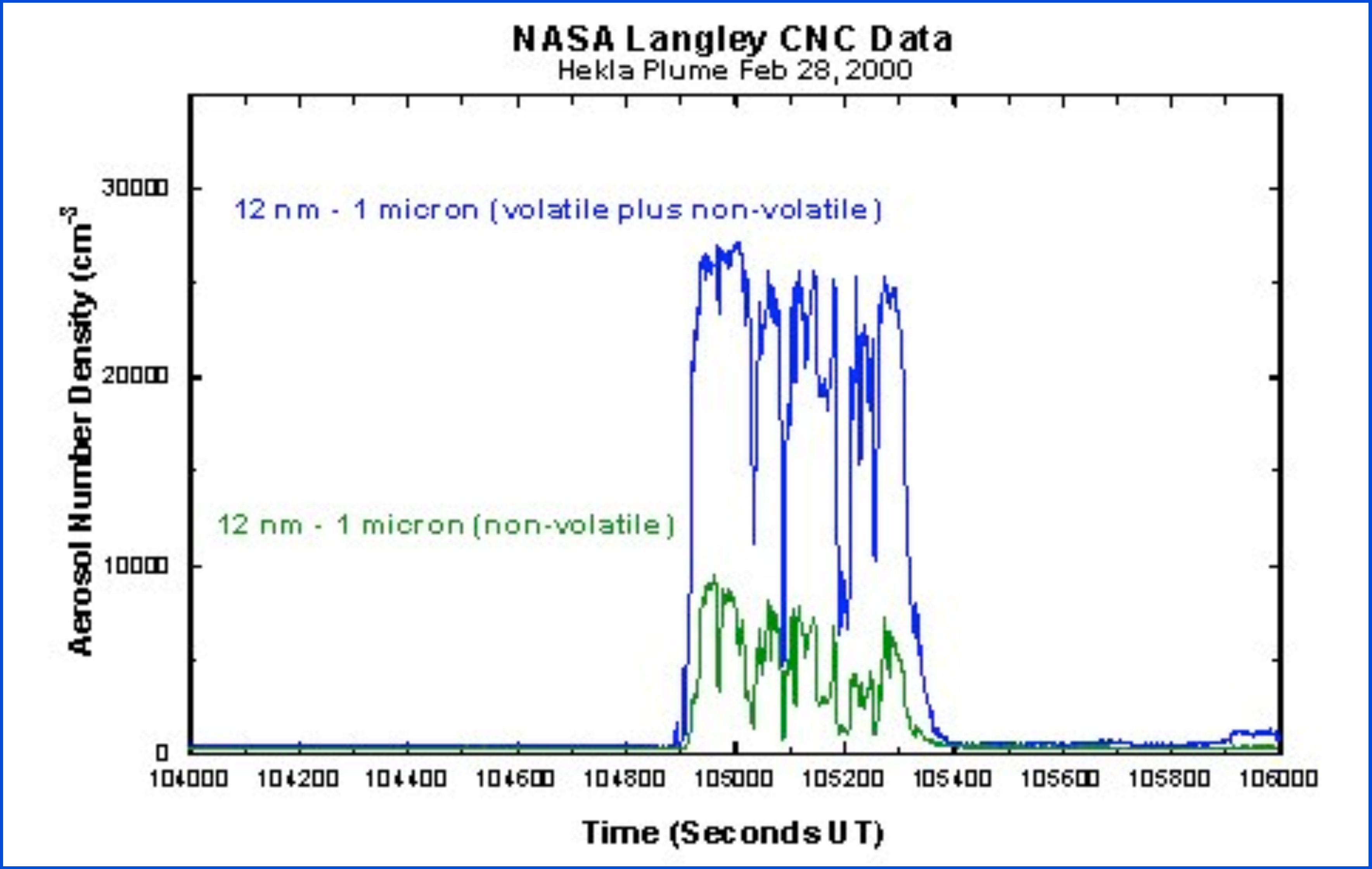
Courtesy Vince Realmuto, JPL

Case Study—NASA DC-8 Ash Encounter The Hekla February 2000 Eruption

- An ash encounter with a very dilute ash plume-- fine grained (<1-10μm diameter solid aerosols), ice-coated ash particles.
- A minimum "economic damage" encounter.
- Significant because of "silent damage"

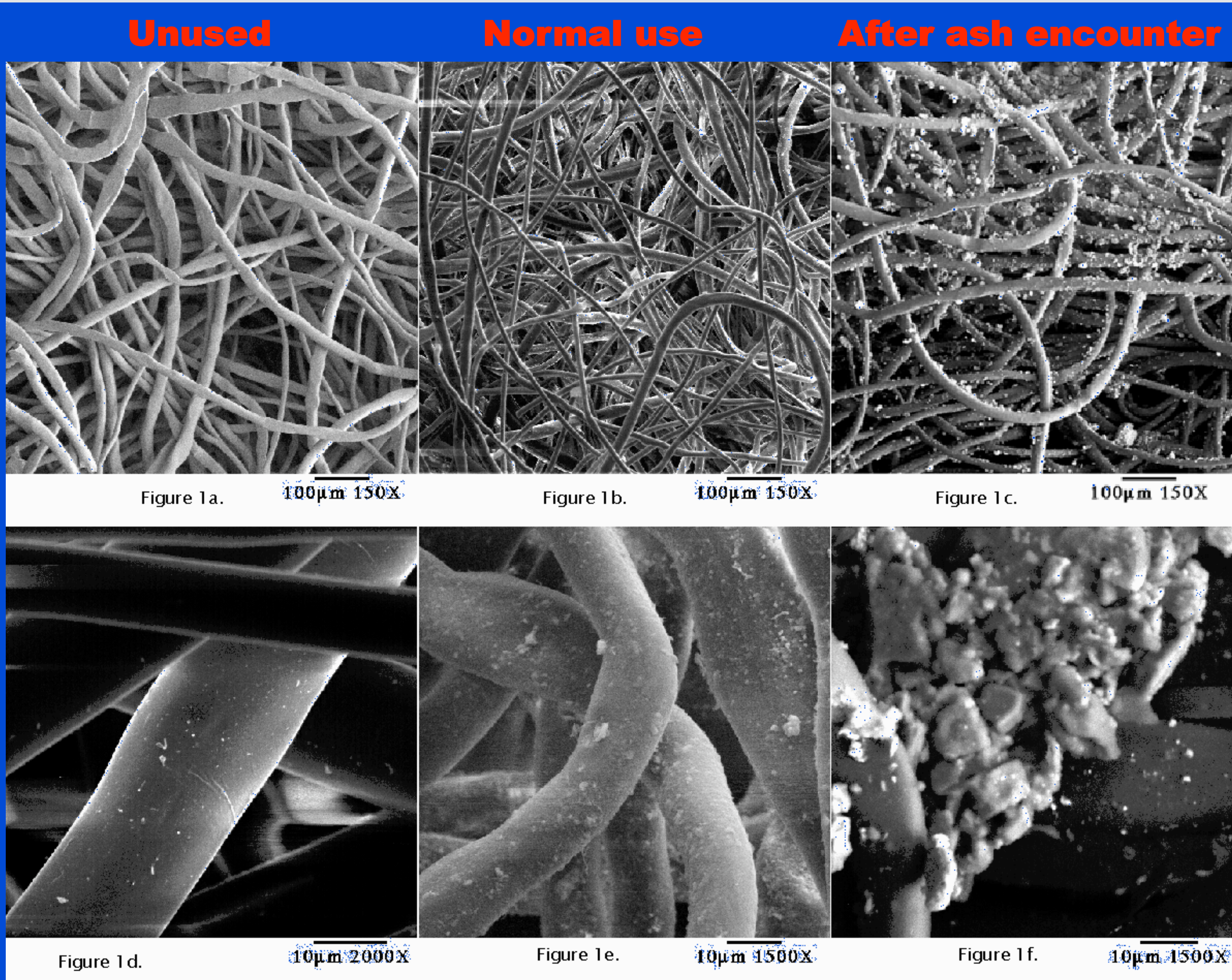
Jet Propulsion Laboratory
California Institute of Technology

Onboard solid aerosol collection data from the NASA DC-8 Research Aircraft engaged in the Kiruna SOLVE experiment (Courtesy NASA Langley RC)

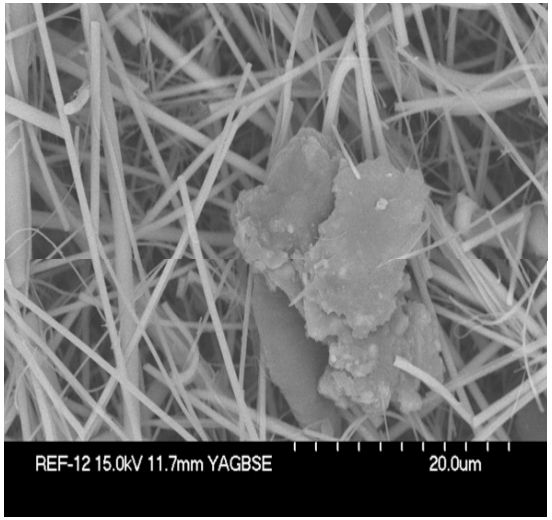


Jet Propulsion Laboratory
California Institute of Technology

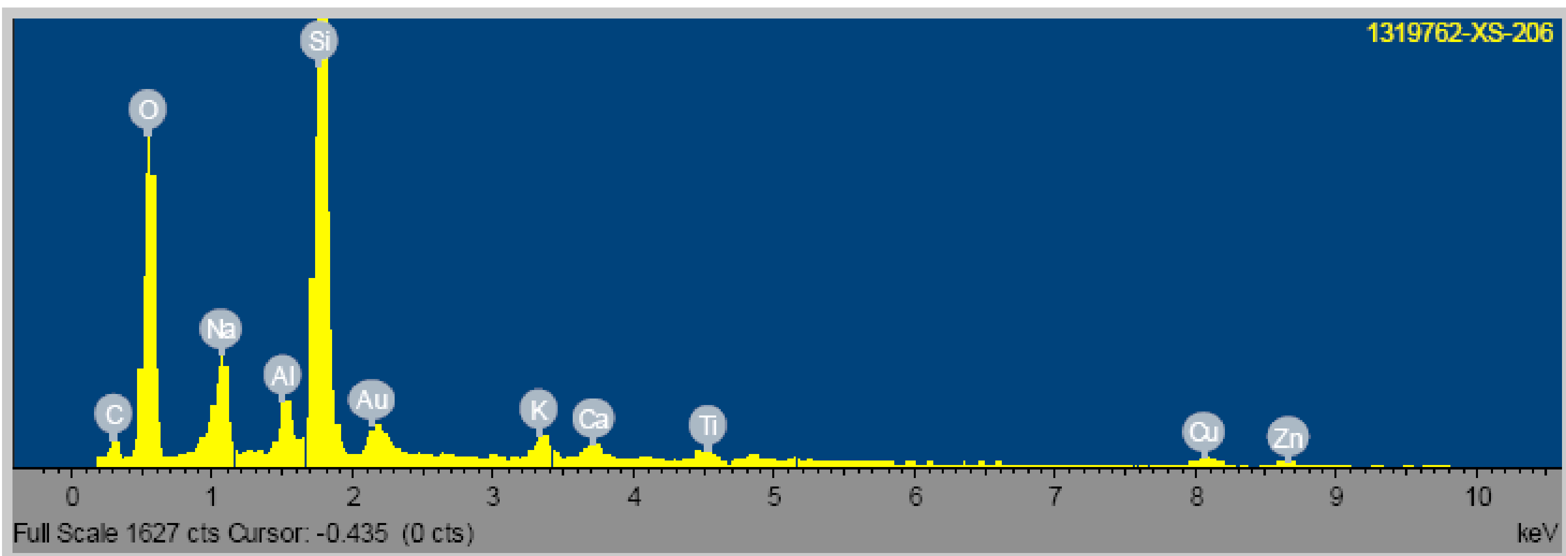
Caltech Scanning Electron Microscope imaging of the Keddeg Air Conditioning Filters from NASA DC-8 Research Aircraft
(from Pieri et al., 2002; GRL)



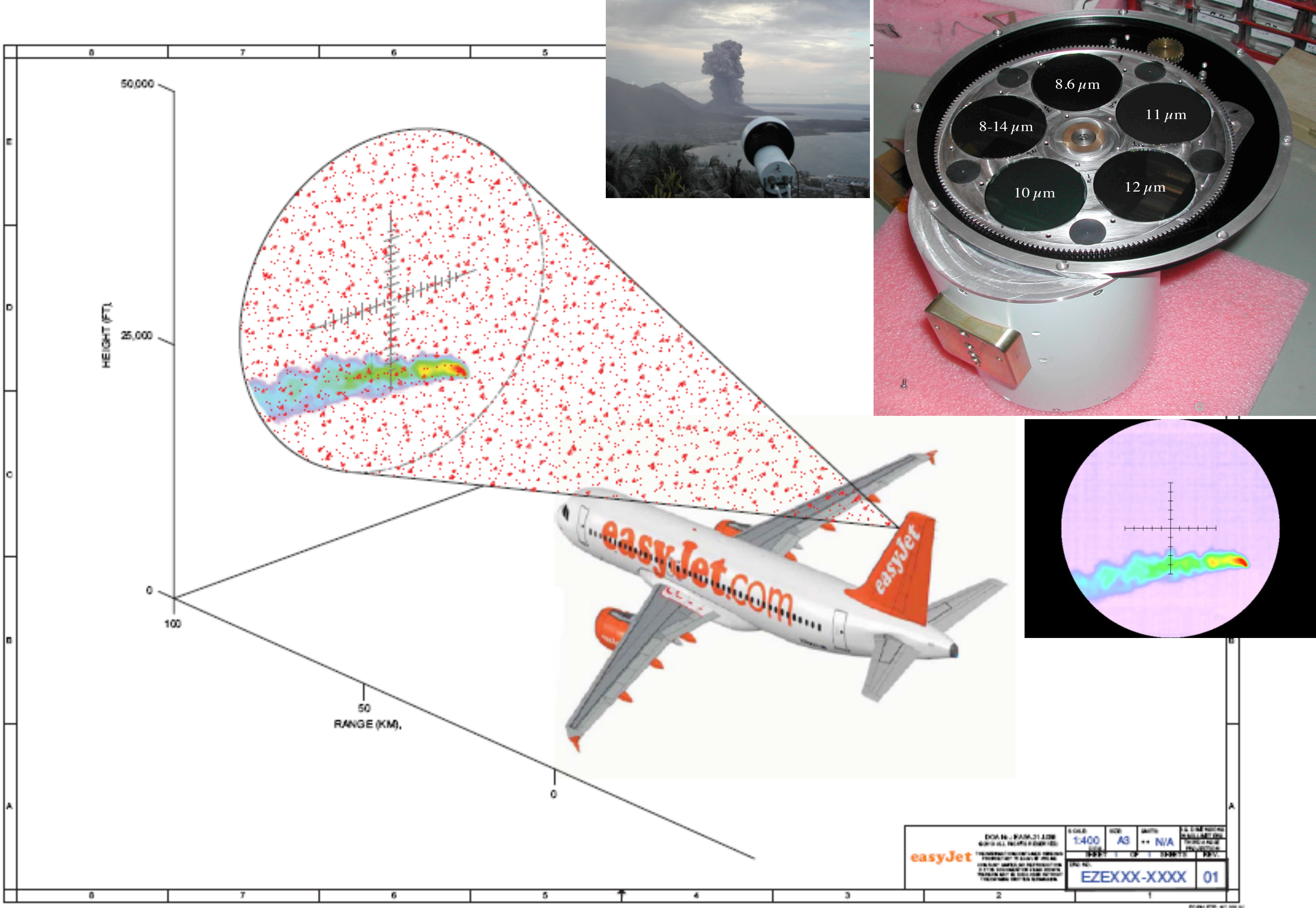
Recirculation Filter



SEM & EDX results from easyJet filters, Eyjafyallajokull 2010



Courtesy: Ian Davies



easyJet plc

NILU

Small UAV approach to sampling volcanic plumes:

1. Relatively cheap and less complicated
2. Quick response to dynamic events
3. Risk-appropriate tools for hazardous missions
4. Humble start (troposphere), aiming to evolve to larger (tropopause & stratosphere)

UAVs over volcanoes in Costa Rica

Project Scope : In-Situ + remote sensing integration of active volcanic plumes data for CAL/VAL of satellite remote sensing information

Approach:

- Simultaneous fixed-wing, blimp, and tethered aerostats UAS airborne observations, integrated with in-situ instrumentation with simultaneous orbital and ground-based remote sensing
- Operate in airspace too dangerous for manned aircraft—over and around actively erupting volcanoes.

Measurements:

- *In situ ash, SO2, H2S, CO2, He, and other gas concentration;*
- *Temperature + pressure + humidity;*
- *GPS location and altitude;*
- *Particle count by size*
- *Solid aerosol (ash) sampling for post-flight SEM analysis*

Instruments:

- *Electro-chem MEMS based SO2, CO2, H2S sensors; radiometers; particle drum-impactors, laser diode/optical particle counters, size-frequency analyzer, samplers; <u>mini-mass spectrometer</u>*

Where:

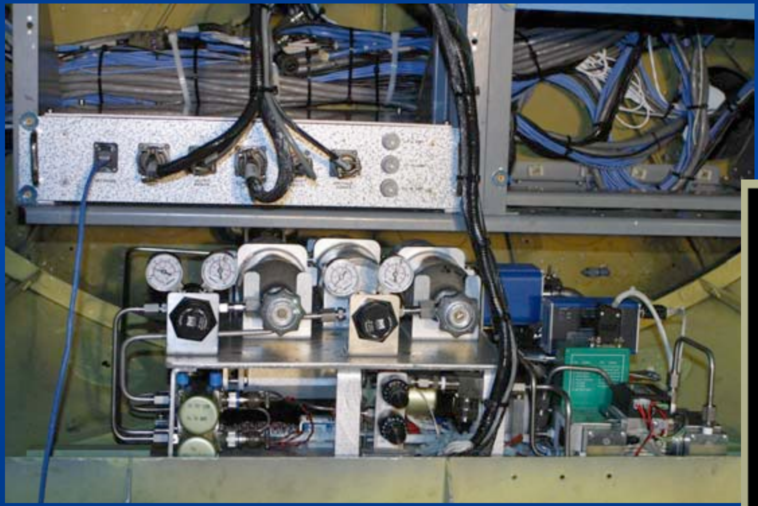
- *Turrialba and Arenal Volcanoes*

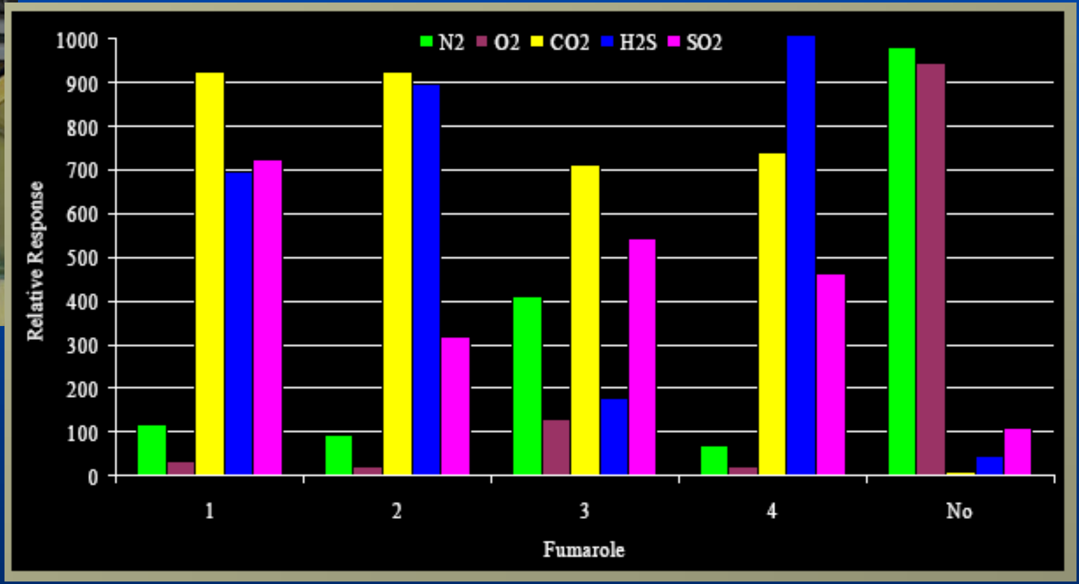
Why Costa Rica

- Active and stable volcanic plume conditions visible from space
- Easy access and logistics to sites
- UAV friendly environment
- Local scientific collaborators
- National Airborne Research Hangar

=▶ Natural Laboratory for Calibration and Validation of Satellite Remote Sensing Observations

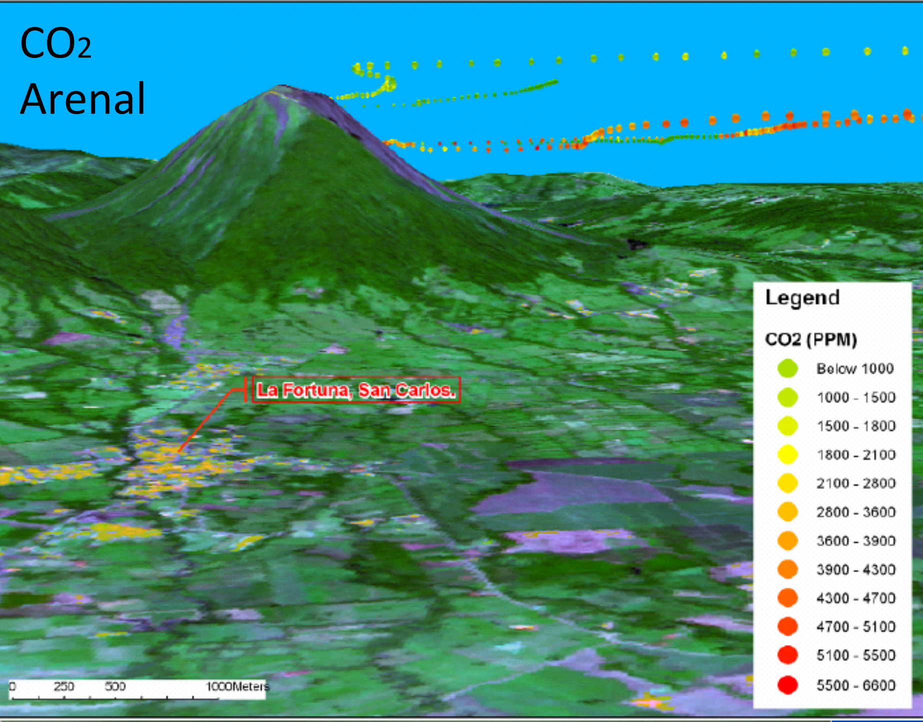
In situ Compact Airborne Mass Spectrometer in Costa Rica--NASA WB-57 and Cessna 206 (CARTA I & II)

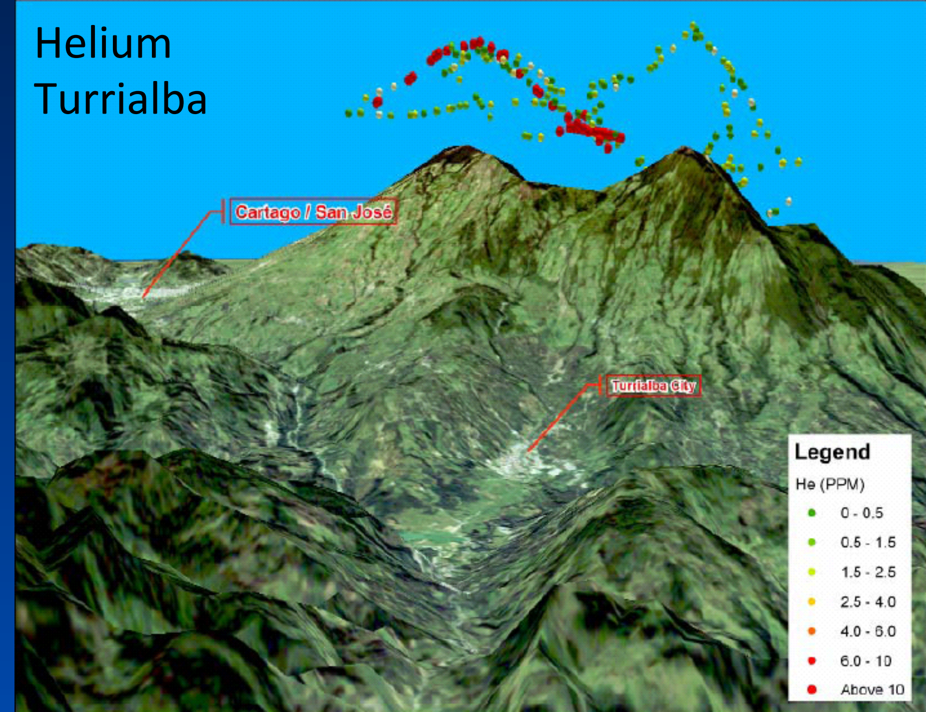


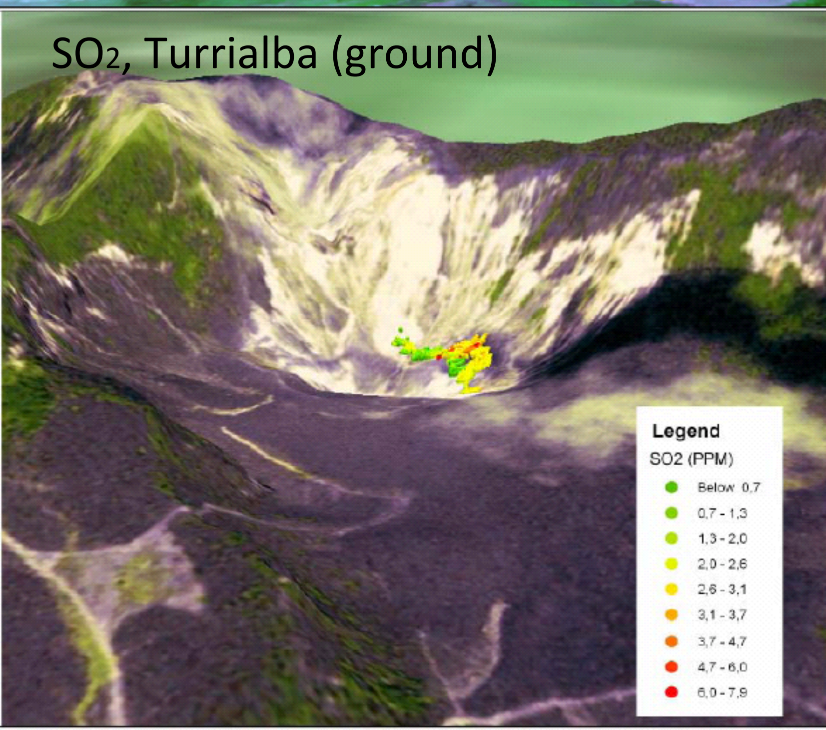


From Griffin et al., 2008 & Arkin, et al., 2009

Sampling at Turrialba fumarole in main crater



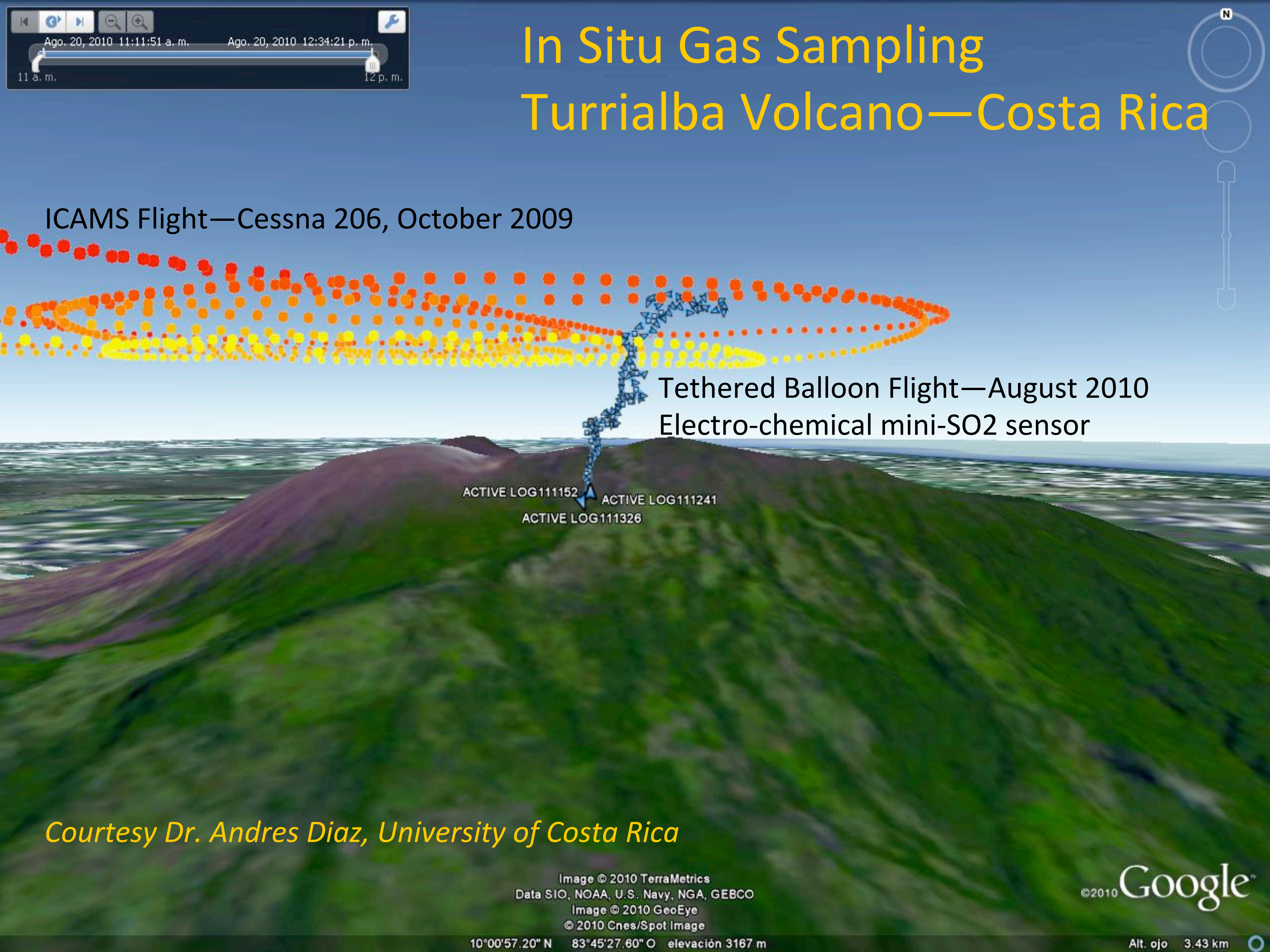




3-D Concentration Mapping with Portable Mass Spectrometer Systems in Costa Rica—airborne and ground

Courtesy of Andres Diaz, UCR

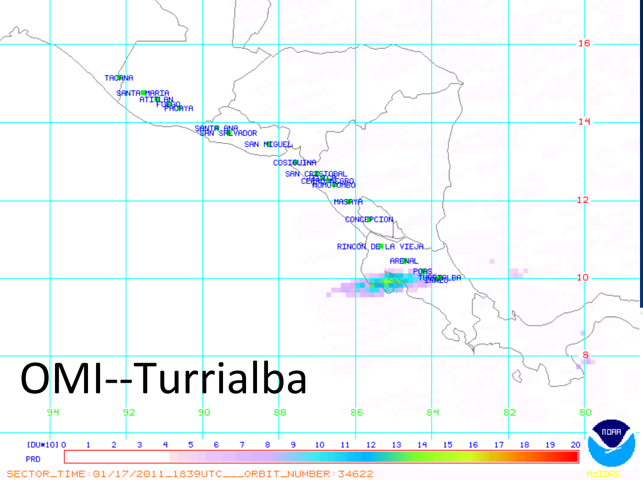
In Situ Gas Sampling
Turrialba Volcano—Costa Rica

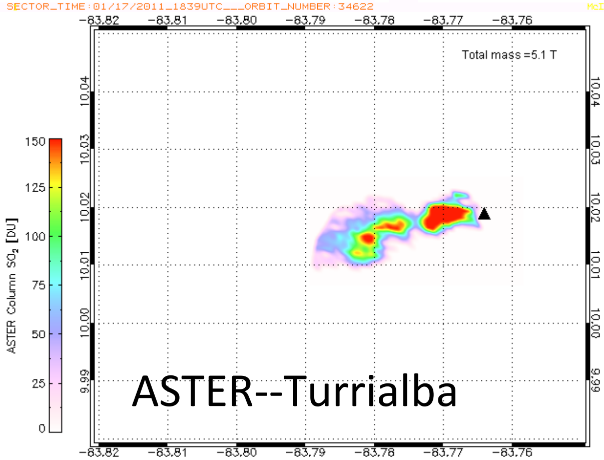


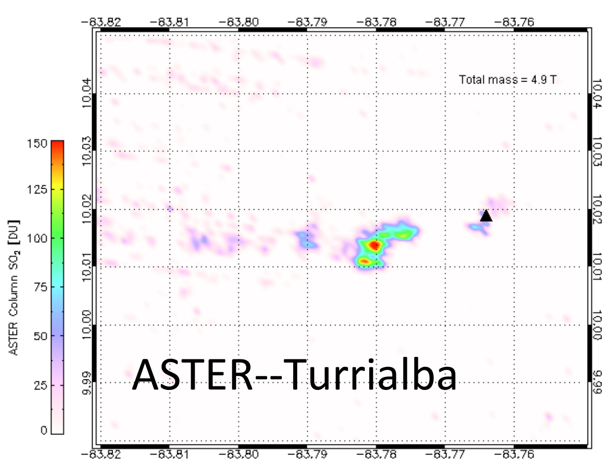
Courtesy Dr. Andres Diaz, University of Costa Rica

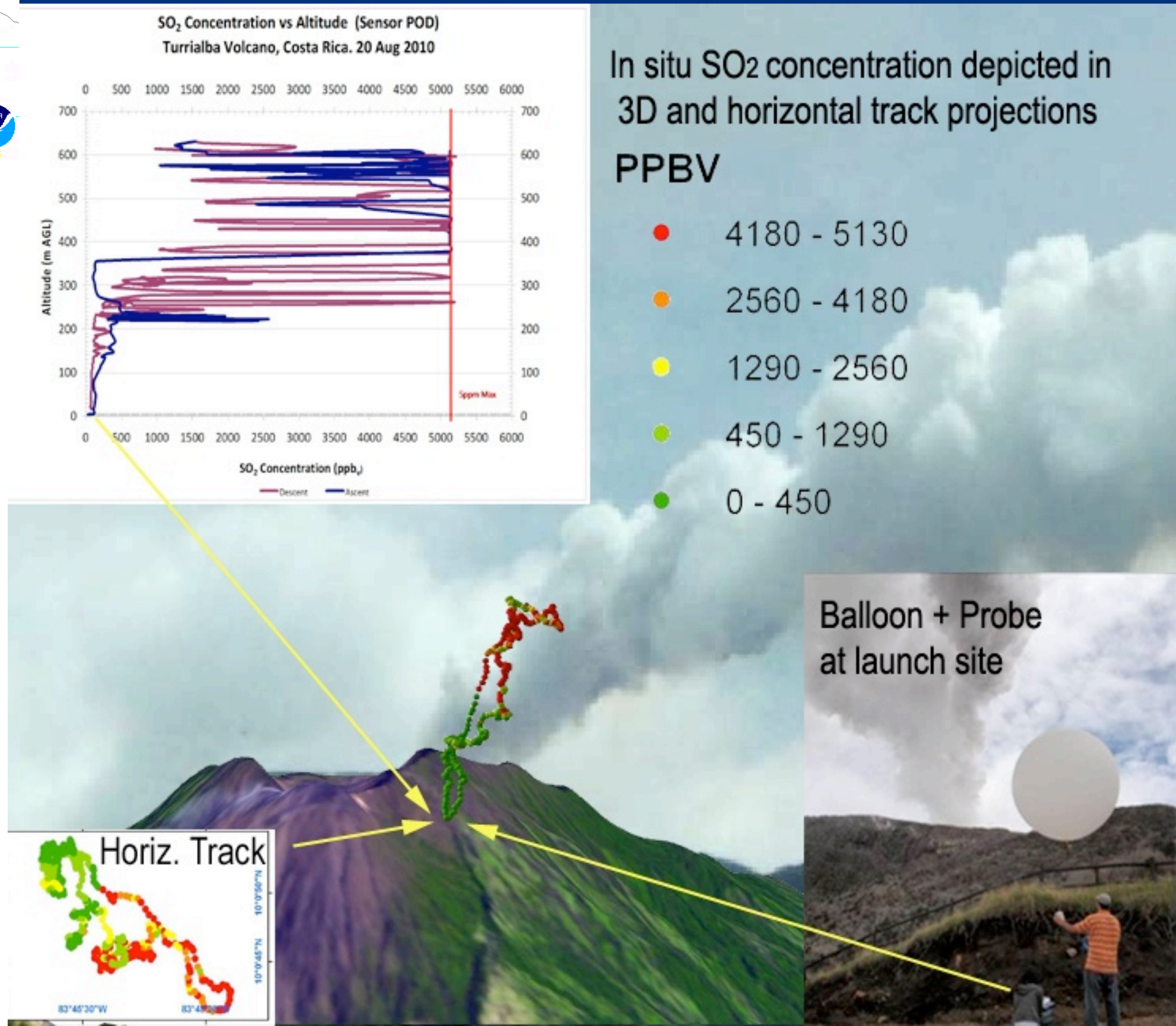
Turrialba Volcano, Costa Rica
Hard working UCR graduate student, January 2011

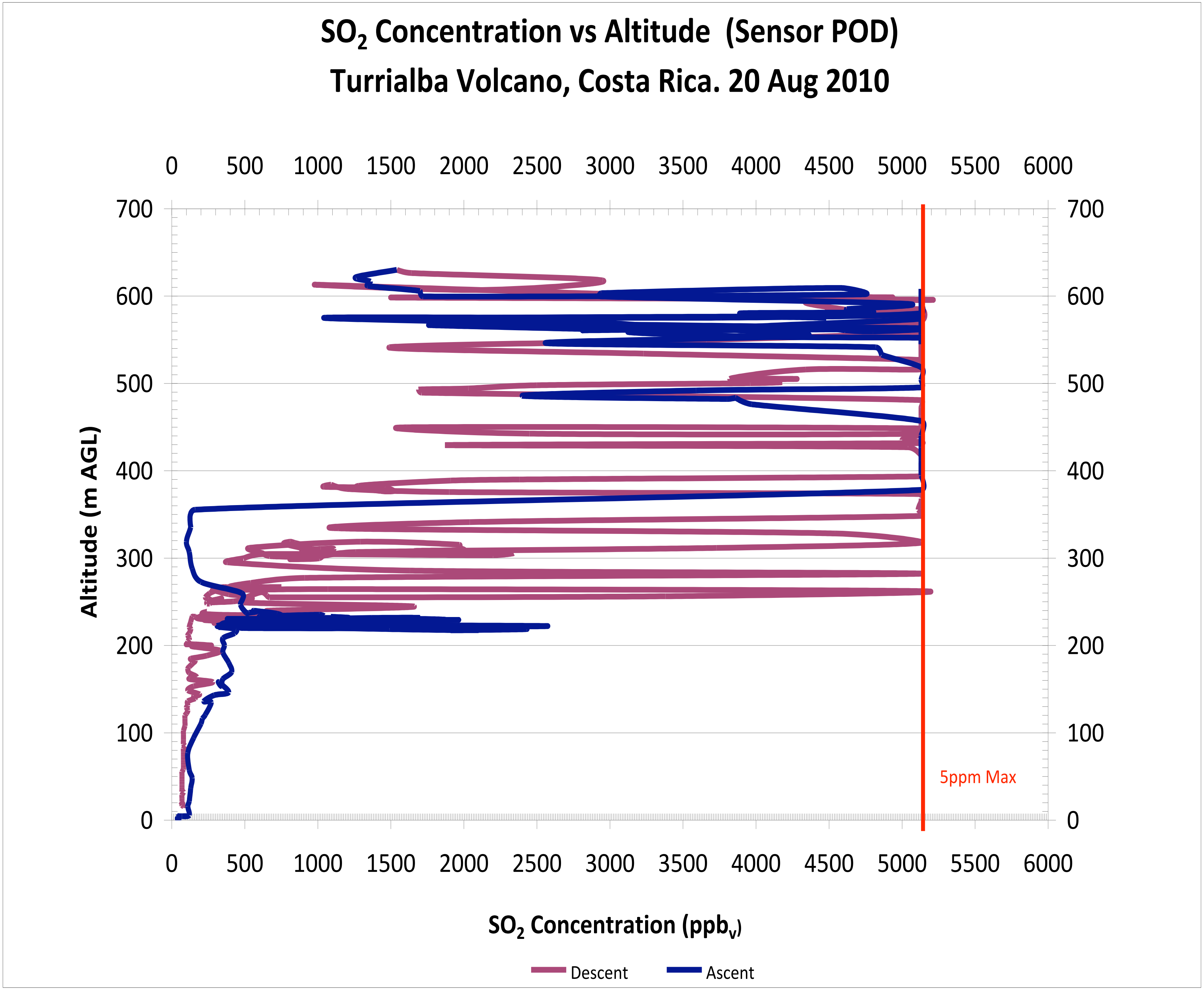
Satellite and Balloon-Based Measurements of Turrialba Volcano, Costa Rica—2010 & 2011



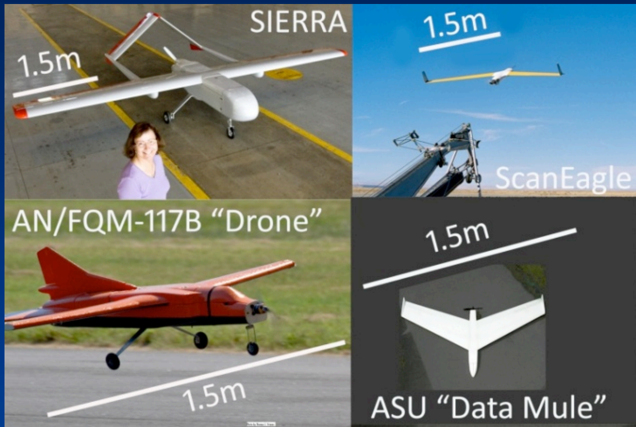


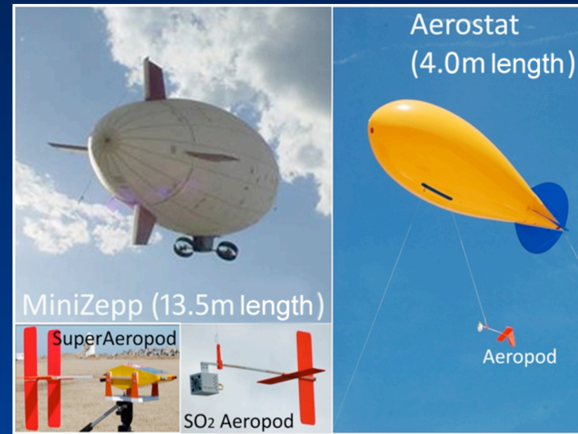





SO2 Concentration vs Altitude (Sensor POD)
Turrialba Volcano, Costa Rica. 20 Aug 2010
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000
700 600 500 400 300 200 100 0
Altitude (m AGL)
5ppm Max
SO2 Concentration (ppbv)
Descent
Ascent


Turrialba Volcano, Costa Rica
Intrepid International Field Team
January 2011

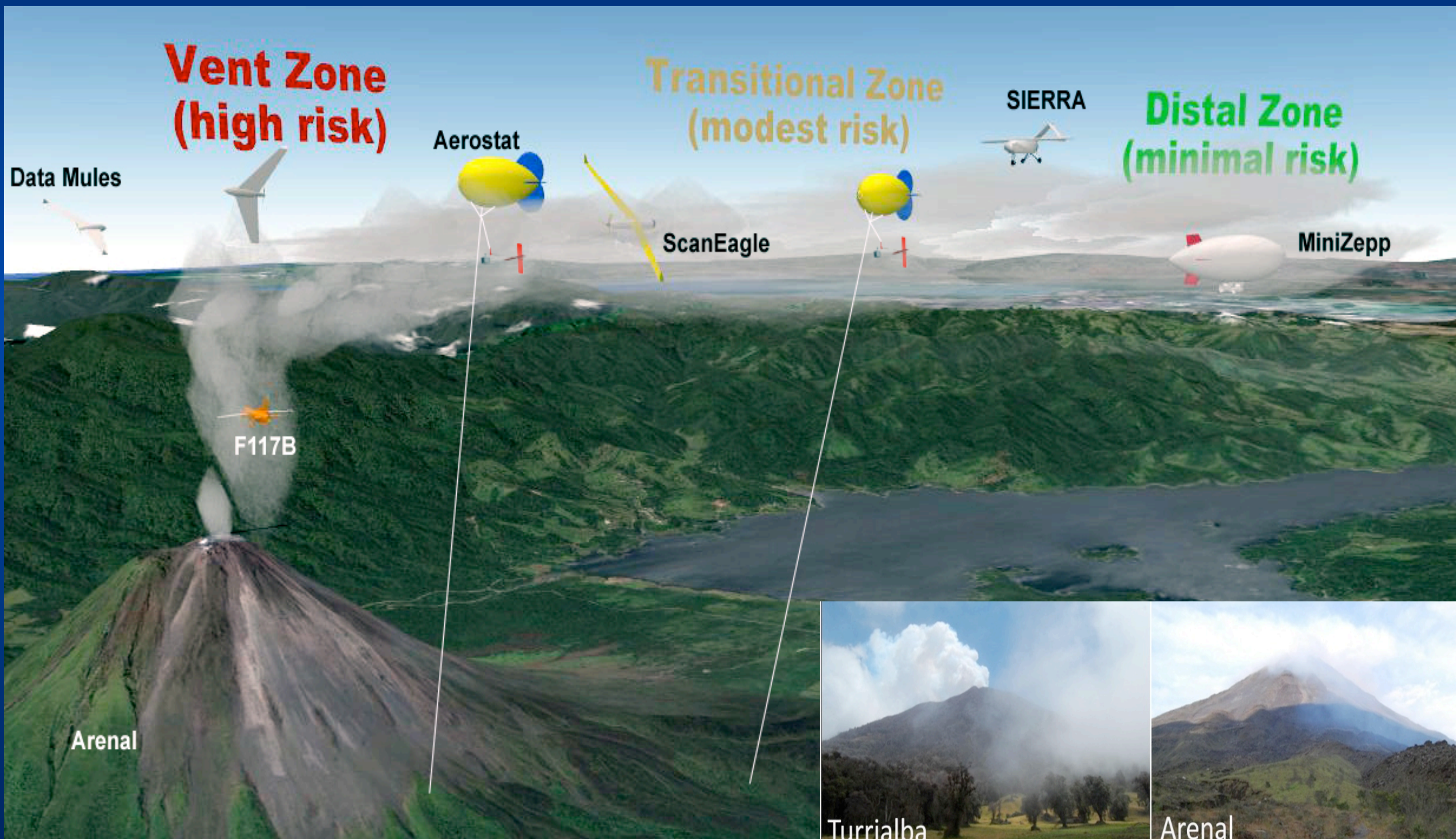




Allocation of instruments to CARTA 2012-2013 UAS platforms

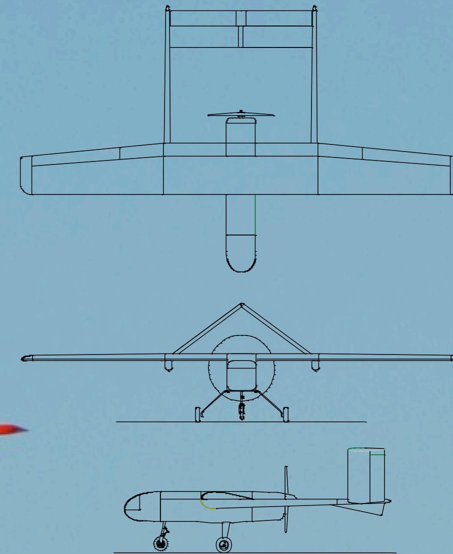
UAS	Type (FW-Fixed Wing)	Load (kg)	Instruments	Radius & Endurance (km)&(hrs)	Each UAS has a Unique Mission
SIERRA	**Gas, FW**	**45**	**ULISSES; Ames Particle Suite; T,P,%H_2O,SO_2,Aerosol size-freq., sampler; drum sampler.**	**100 & 8**	**Accurately define plume physical vs. photometric edges (e.g., in ASTER)**
ScanEagle	**Gas/Elec, FW Wing**	**6**	**Drum sampler, T,P,%H_2O,SO_2, Aerosol size-freq., sampler.**	**100 & 20+**	**Fast longitudinal, lateral and vertical profiles**
AN/ FQM-117B	**Elec, FW**	**1-2**	**T,P,%H_2O,SO_2, Aerosol size-freq., sampler.**	**10 & 2**	**Penetrate the eruption column—risky.**
Data Mules	**Elec FW**	**1**	**Digital stereo cameras (1 on ea.)**	**2 & 0.5**	**Plume topograhy**
MiniZepp	**Gas, Blimp**	**100**	**T,P,%H_2O,SO_2, Aerosol size-freq., sampler; real-time video**	**5 & 2**	**Slow Lagrangian temporal samples**
Aerostats	**Tethered Balloon**	**1**	**T,P,%H_2O,SO_2, Aerosol size-frequency, sampler.**	**2km vert & indef.**	**Static temporal sampling**

Notional diagram of the CARTA deployment strategy at Arenal Volcano:
*Vent Zone: Data Mules circle above eruption column, while F117B flies through it;
*Transitional Zone: ScanEagle profiles through it and Aerostats monitor within plume;
*Distal Zone: MiniZepp drifts with an air parcel--SIERRA prowls plume edges.

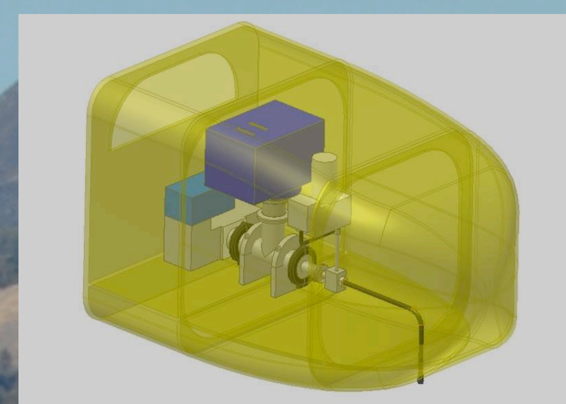


SIERRA, NASA Ames Research Center

Wing Span	20 ft.
Length	11.8 ft.
Height	4.6 ft.
Wing Area	42.4 sq. ft.
Empty Weight	215 lbs.
Gross Weight	445 lbs.
Max Speed	79 kts.
Cruise Speed	55 kts.
Stall Speed	30 kts.
(clean)	9.43
Aspect ratio	545 ft./min.
Rate of Climb	29-32% Chord
CG Position	~100lbs
Payload weight	28V DC
Payload power	8-10 hours
Duration	



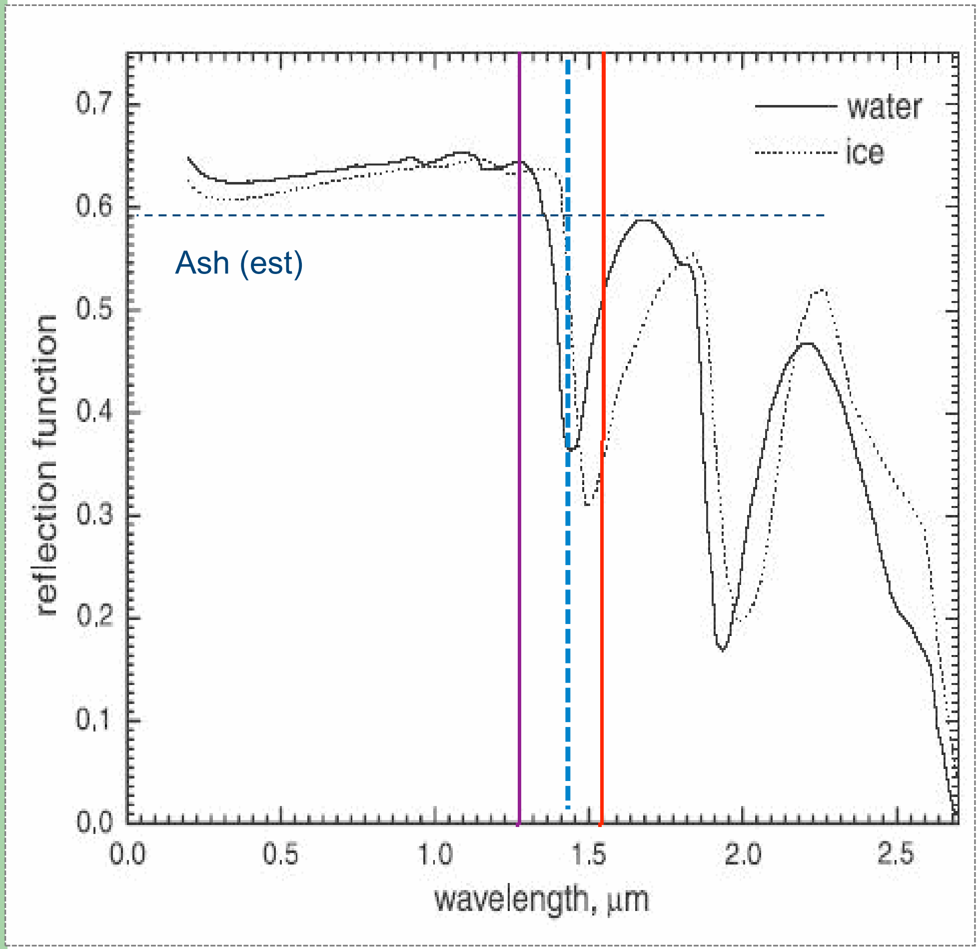
CAD model of ULISSES mini-mass spec gas analyzer integrated into the SIERRA nosecone



Maryland Aerospace Wing-100 UAV, University of Costa Rica

Small UAV Instrument and Platform Development under the *NASA Small Business Innovative Research* (SBIR) Program

ICE-WATER-ASH DISCRIMINATION



Laser probing wavelengths:
1310 nm
1550 nm
1430 nm (Phase 2)

Reflectivity relationships for discrimination:
@ 1310 nm: Ice ≈ Water ≈ SiO2
@ 1430 nm: Water < Ice < SiO2
@ 1550 nm: Ice < Water < SiO2

Ash reflectivity approximately the same for all wavelengths

Courtesy of Joe Gerardi

PROTOTYPE NEPHELOMETER

- Prototype dual wavelength active IR sensor used for tests at the NASA Glenn Icing Research Tunnel as well as tests in IDI’s cloud chamber
- Plastic embodiment – light weight

Courtesy of Joe Gerardi

IDI CLOUD CHAMBER

Sonaer nozzles for water generation:
- three calibrated water particle sizes
- range of flow rates

Vibrating sifter for ash generation:

-calibrated size and mass

Liquid nitrogen for ice crystal generation:

-insulated, double walled

-can cool chamber to below -40°C

Long path length:
- 16ft long fall distance
- high signal return
- averaging over many particles

Courtesy of Joe Gerardi

Vanilla Aircraft VA02-experimental, Fort Pickett, VA; 26 Jul 2011; SBIR Phase I

Vanilla Aircraft VA02-experimental—pre-launch.

Vanilla Aircraft VA02-experimental—launch!

Conclusions

• Validation and calibration of models of volcanogenic cloud transport and composition are important for basic volcanological science and application to air safety issues in the context of volcanic hazards.

• Low-cost field deployable airborne platforms and miniaturized instrumentation to sample and analyze volcanic ash and gas emissions, both during eruptions and as eruption precursors, can provide important correlative data to support other airborne and orbital observations.

• **In situ observations can materially enhance the utility and applicability of HyspIRI observations for the detection and monitoring of volcanic phenomena.**

• It is important to carry out proof-of-concept activities at relatively benign, low altitude active volcanoes, such as is the current situation in Costa Rica, in order to minimize risk to equipment and researchers.

• Such preliminary confidence-building and risk-reduction activities are part of a strategy to develop economical, quick-reaction high altitude in situ measurement capabilities in response to large explosive eruptions.

Attainable? Perhaps.