# Integrating MODTRAN6 into the Plume Tracker Data Analysis Toolkit: A Progress Report

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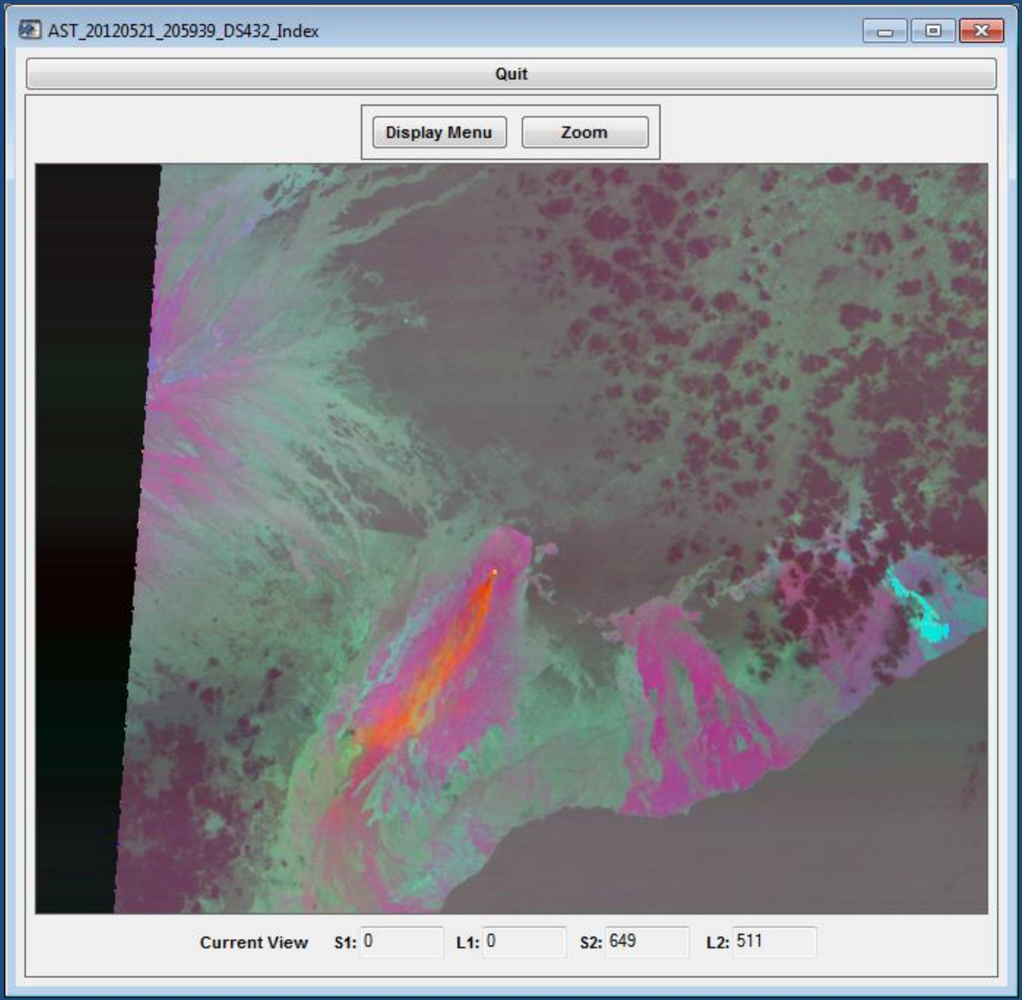
# Plume Tracker: Interactive Toolkit for Deep Analysis of TIR Image Data

**Facilitates Analysis of Data from Multiple Instruments, with Ancillary Data from Multiple Sources**

## A. Graphic User Interface

- Import Image and Ancillary Data
- Identify Regions-of-Interest for Mapping
- Visualize Input Data and Retrieval Results

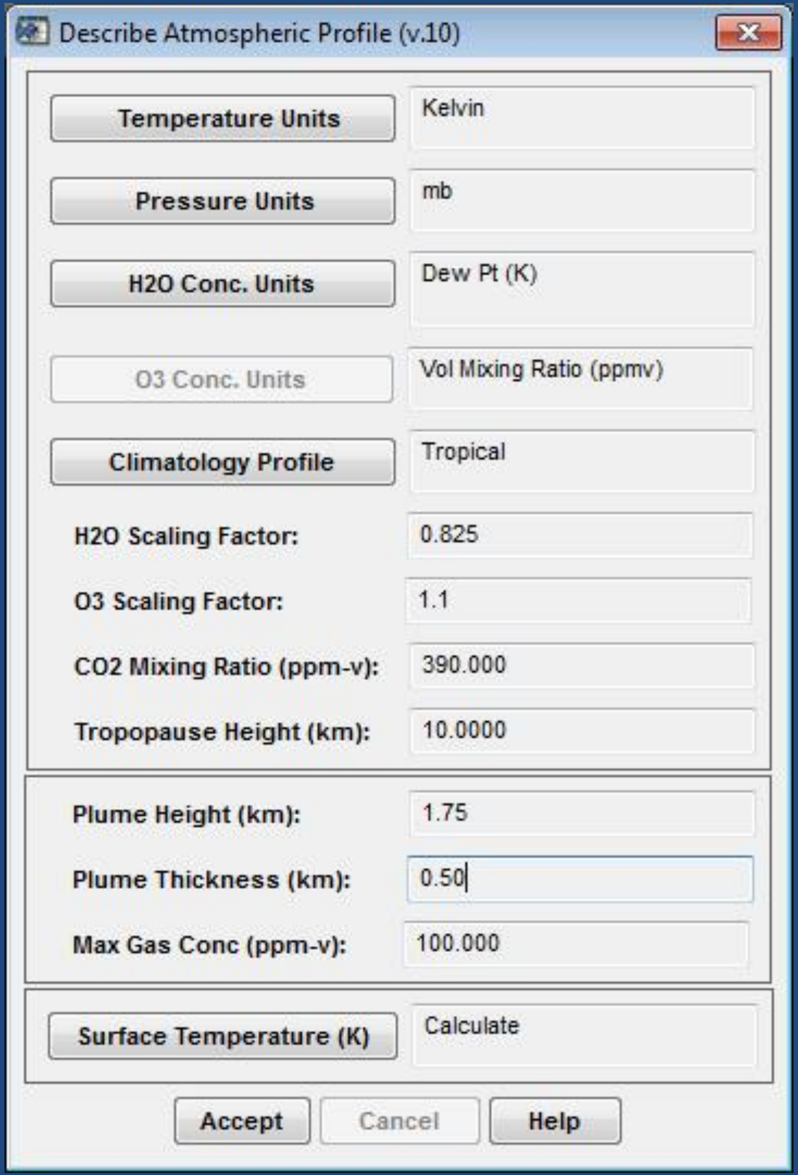



*Display Tool Widget*

# Plume Tracker: Interactive Toolkit for Deep Analysis of TIR Image Data

## B. Radiative Transfer Model Based on MODTRAN

- Component Architecture
- Communication via Standard COM Interface
- Custom Management and Formatting of Input Parameters for RT Model

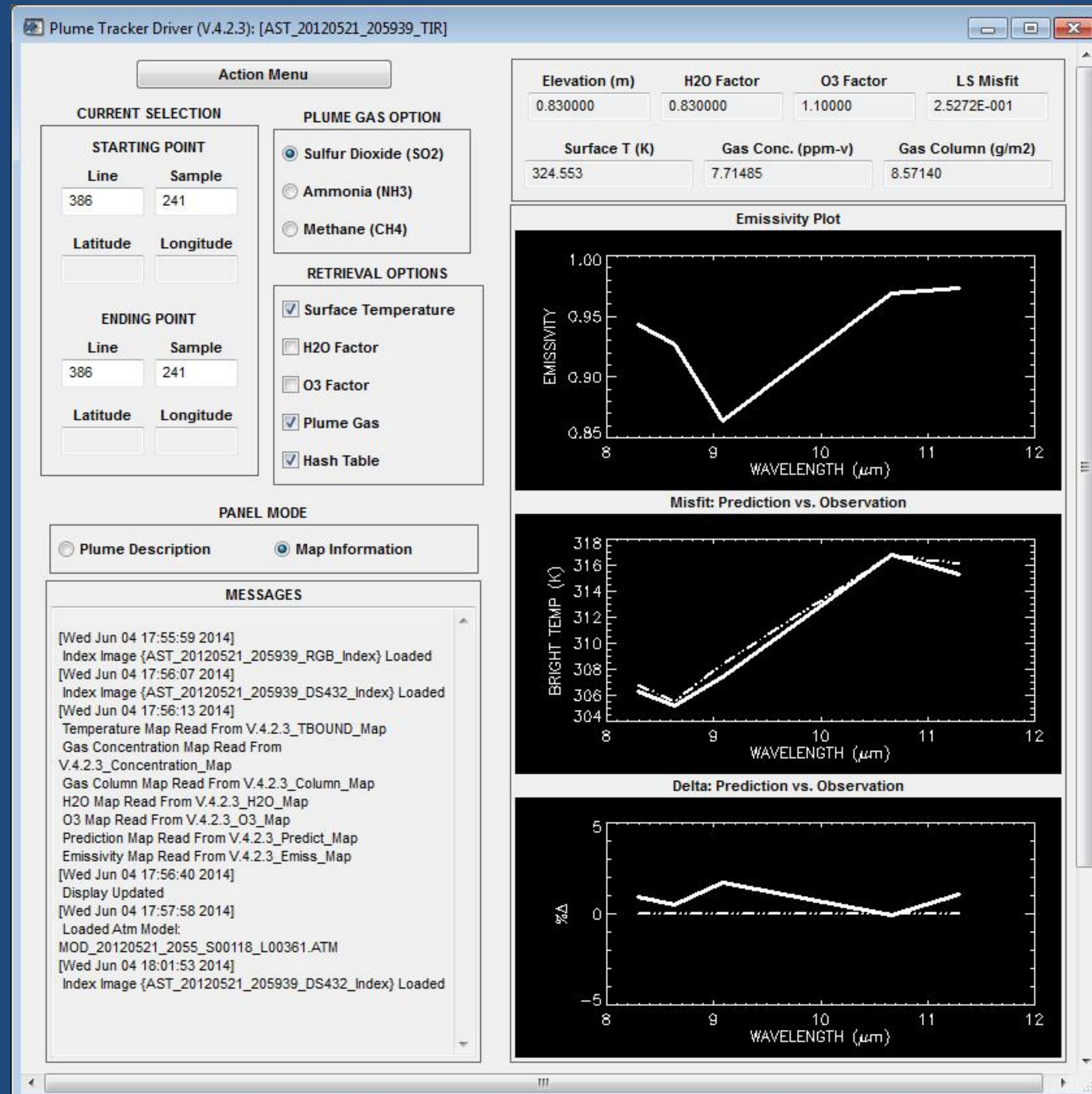



*Atmosphere Profile Widget*

# Plume Tracker: Interactive Toolkit for Deep Analysis of TIR Image Data

## C. Retrieval Procedures

- Surface Temperature and Emissivity
- $SO_2$, $NH_3$, and $CH_4$ Concentrations
- $H_2O$ Vapor and $O_3$ Scaling Factors
- Total Column Retrievals
- Optimized for 2-Component Retrievals (Temperature + Gas Concentration)




*Plume Tracker Driver Widget*

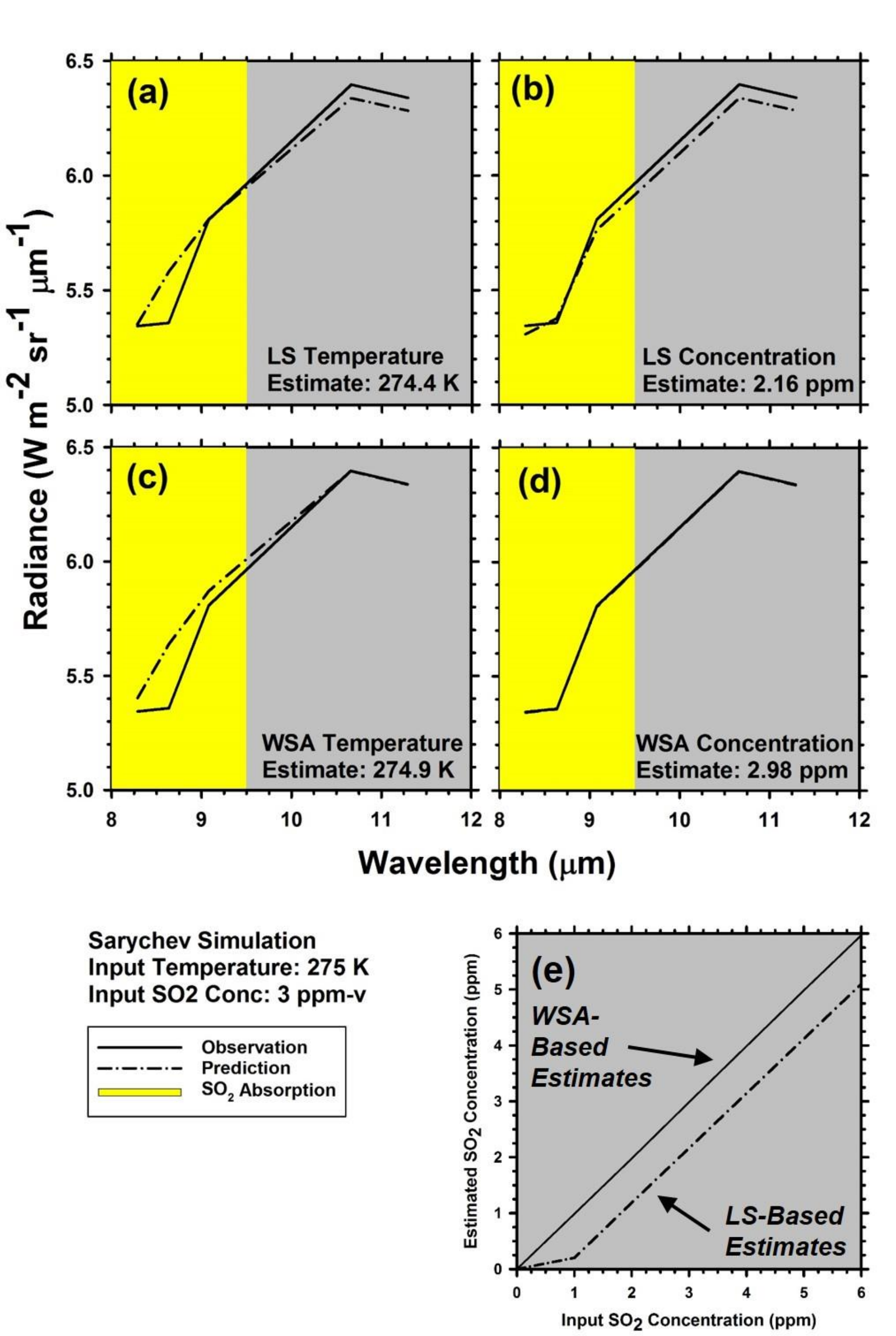
# Misfit Calculation: Least Squares vs. Weighted Spectral Angle

**Least Squares (LS):**

- Designed to Fit Noisy Data
- Equal Weight to Outliers
- Not Ideal for Temperature Estimation

**Weighted Spectral Angle (WSA):**

- Observed and Model Radiance Spectra Represented as Vectors in Data Space
- Minimize Angle Between Vectors (*Spectral Angle*)
- Minimization Weighted to Favor Solutions with Model Spectrum > Observed Spectrum
- Optimum Temperature Estimate Given Imperfect Knowledge of Atmospheric Composition



# Hash Table (Associative Array): Acceleration of Retrieval Algorithm

| | |
|---|---|
| *Key(1)* | *MODTRAN Spectrum(1)* |
| *Key(2)* | *MODTRAN Spectrum(2)* |
| *Key(3)* | *MODTRAN Spectrum(3)* |
| *Key(4)* | *MODTRAN Spectrum(4)* |
| … | … |

**Key(i) = [*zenith angle*][*surface elevation*][*surface temp*][*$H_2O$ factor*][*$O_3$ factor*][*$SO_2$ factor*]**

**Scan Key List for Matches to Existing Keys**

**Associated Spectrum used for Matching Keys;**
**New Table Entry for Unique Keys**

**More Efficient/Flexible than Table Look-Up**

- **Hold Tables Store Values Encountered in Scene, Not Every Possible Value**
- **Hash Tables Augmented or Purged Dynamically**

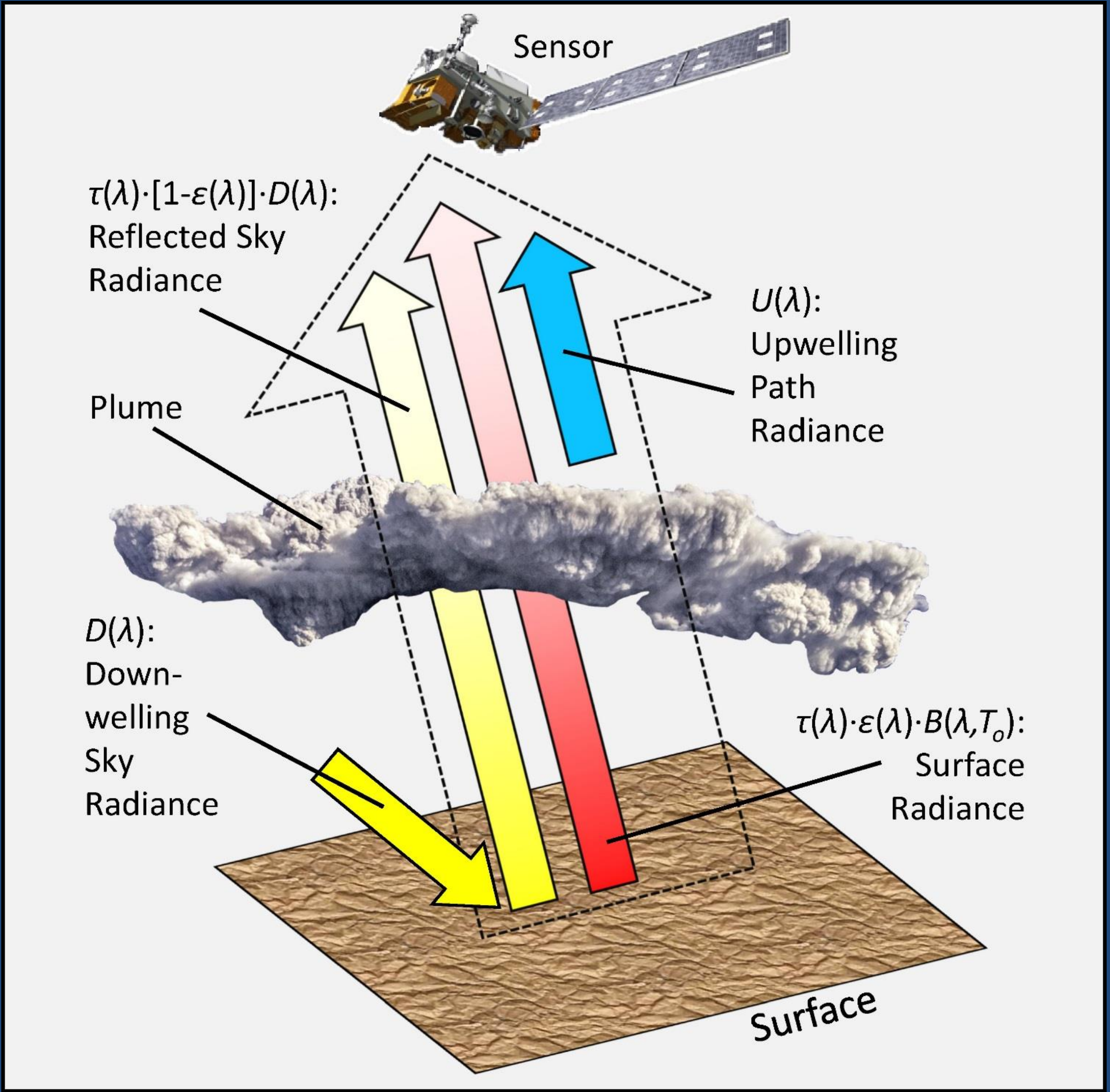
# Radiance Reconstruction

The observed radiance (outlined arrow) includes the surface radiance (red arrow), reflected sky radiance (yellow arrow), and upwelling path radiance (blue arrow)

The presence of a volcanic plume is expressed primarily through transmission [$\tau(\lambda)$]

Transmission, sky radiance [$D(\lambda)$], and path radiance [$U(\lambda)$] are independent of surface temperature [$T_o$] and emissivity [$\varepsilon(\lambda)$]

Cache $\tau(\lambda)$, $D(\lambda)$, and $U(\lambda)$, and reconstruct observed radiance for variable $T_o$ and $\varepsilon(\lambda)$



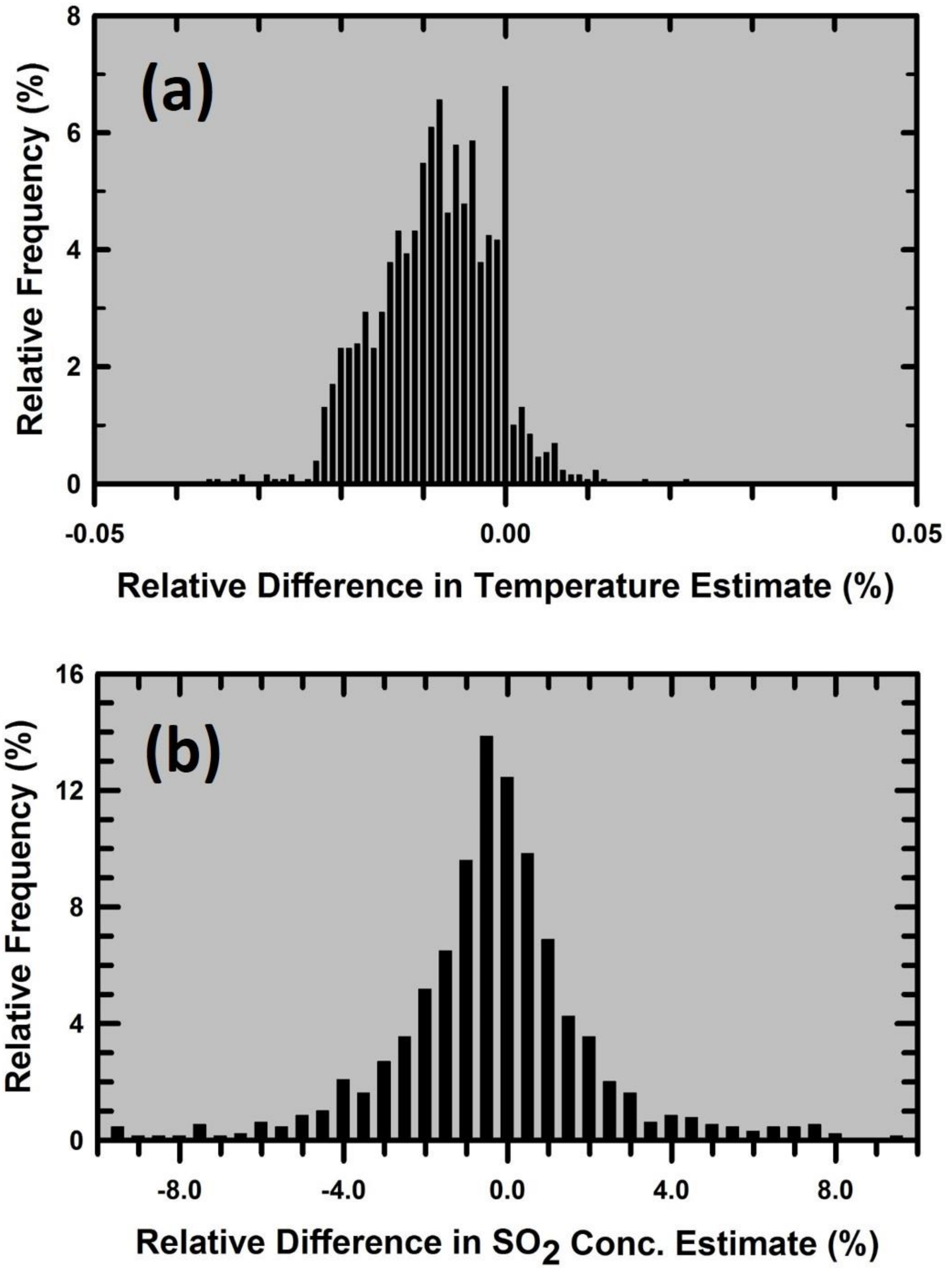
# Summary of Performance Gains (AIST-11 Project)

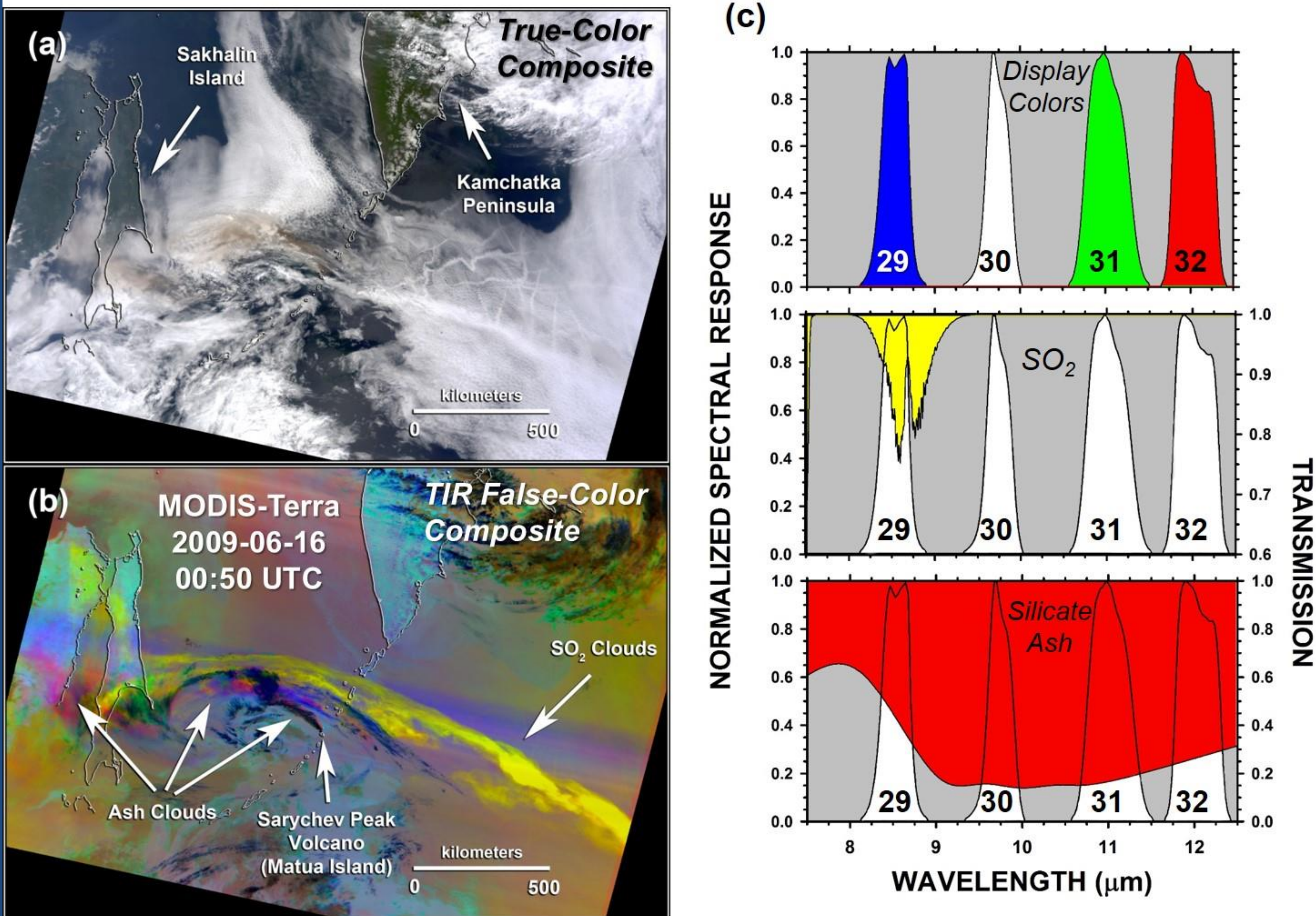
| | Domain Refinement *(V.2.2.9)* | Multi-Pass Brent Minimization *(V.3.0)* | Single-Pass Brent Minimization *(V.3.2)* | Reconstructed Radiance *(V.4.2b)* |
|---|---|---|---|---|
| **Calls to RT Model** *ROI = 1296 pixels* | *264,398 (204 calls/pix)* | *144,508 (112 calls/pix)* | *58,361 (45 calls/pix)* | *29,485 (23 calls/pix)* |
| **No Hash Table** | *6.4 sec/pix* | *3.2 sec/pix* | *1.26 sec/pix* | *0.61 sec/pix* |
| **Hash Table** | *1.6 sec/pix* | *0.8 sec/pix* | *0.16 sec/pix* | *0.019 sec/pix* |
| **Success Rate** *Hash Table Utilization* | *77.4 %* | *77.0%* | *88.0%* | *97.8%* |

# Investigation of Errors Introduced Through Use of the Hash Table Procedures, Relative to Native Radiative Transfer (RT) Calculations

a) The relative difference in temperature estimates shows a negligible negative bias, with 94% of the differences falling between -0.025 and 0.00%

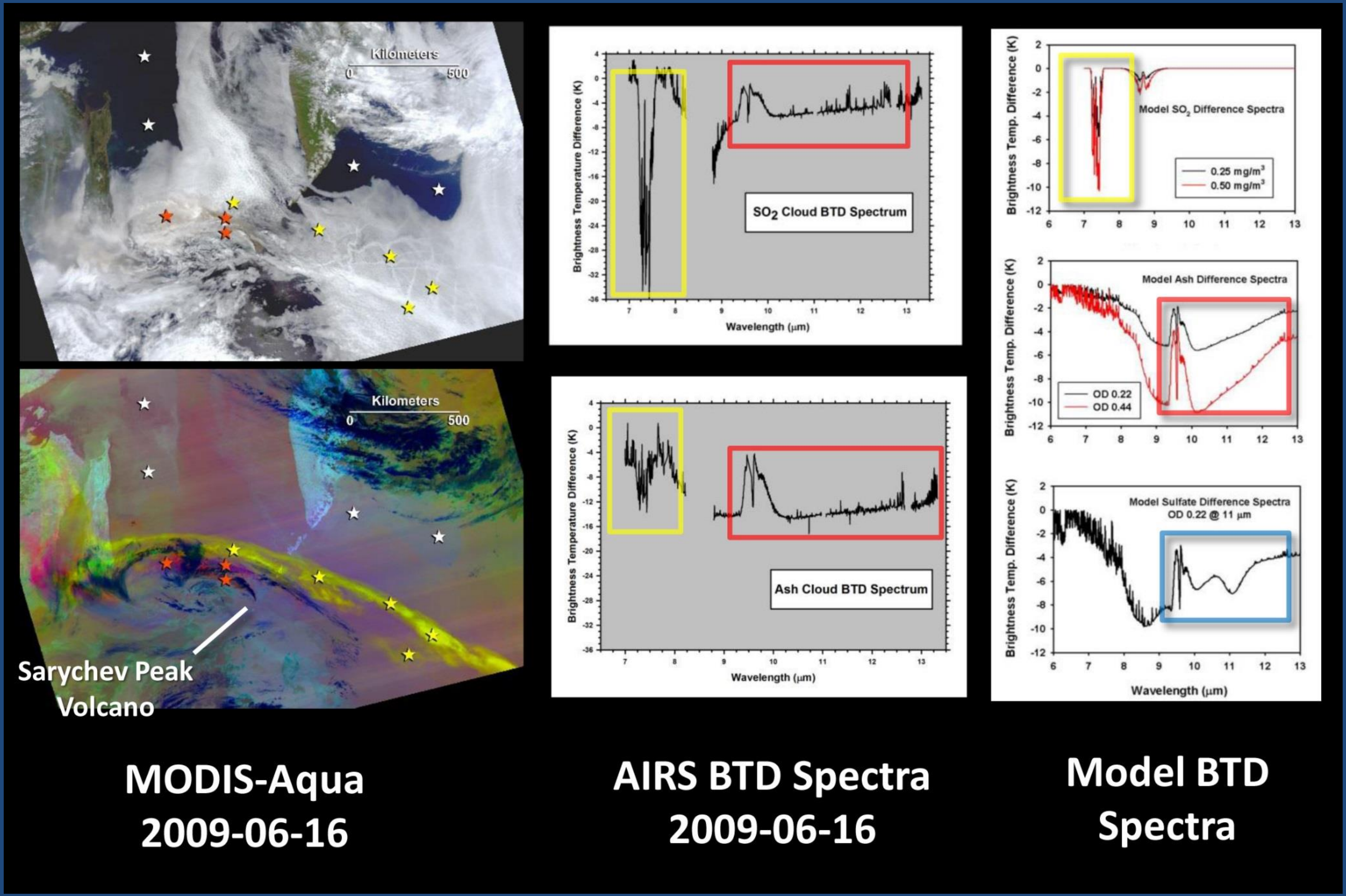
b) The relative difference in $SO_2$ concentration estimates shows no bias, and 94% of the differences fall between ±5%





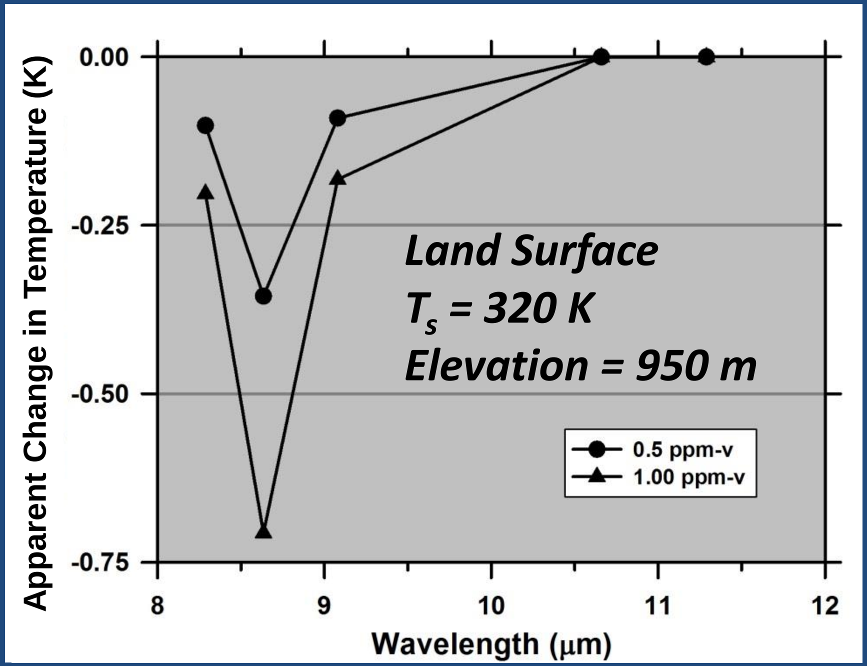
(a)
True-Color Composite
Sakhalin Island
Kamchatka Peninsula
kilometers
0
500
(b)
MODIS-Terra
2009-06-16
00:50 UTC
TIR False-Color Composite
SO2 Clouds
Ash Clouds
Sarychev Peak Volcano (Matua Island)
kilometers
0
500
(c)
Display Colors
29
30
31
32
SO2
Silicate Ash
NORMALIZED SPECTRAL RESPONSE
TRANSMISSION
WAVELENGTH (μm)
8
9
10
11
12
0.0
0.2
0.4
0.6
0.8
1.0
0.6
0.7
0.8
0.9
1.0

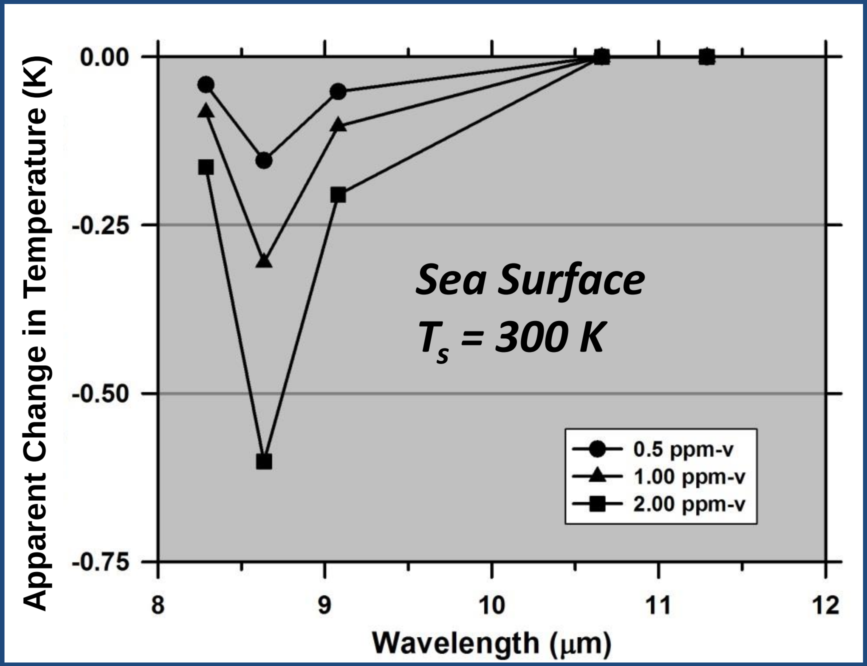
# AIRS High-Resolution (2138 Channels) Spectra: Unique Identification of Plume Constituents

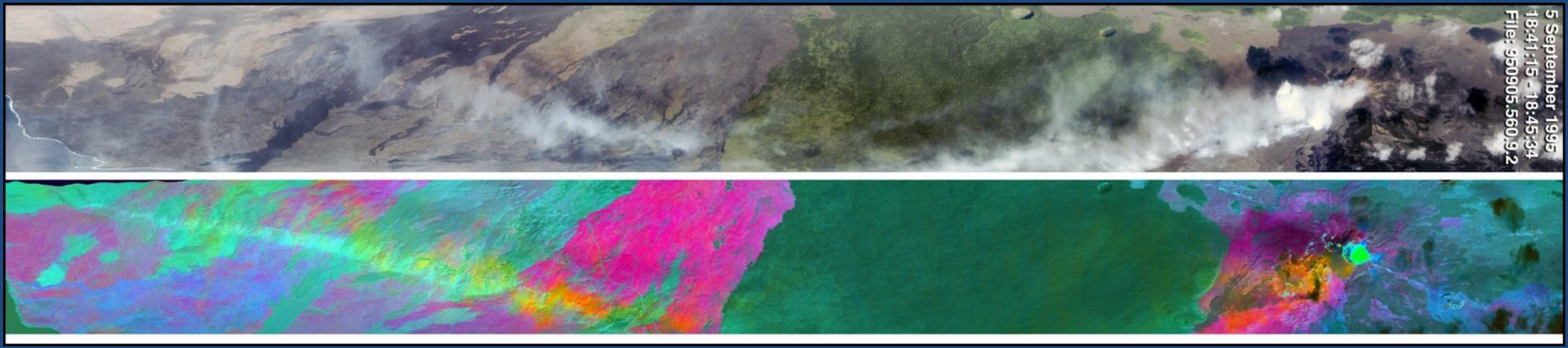


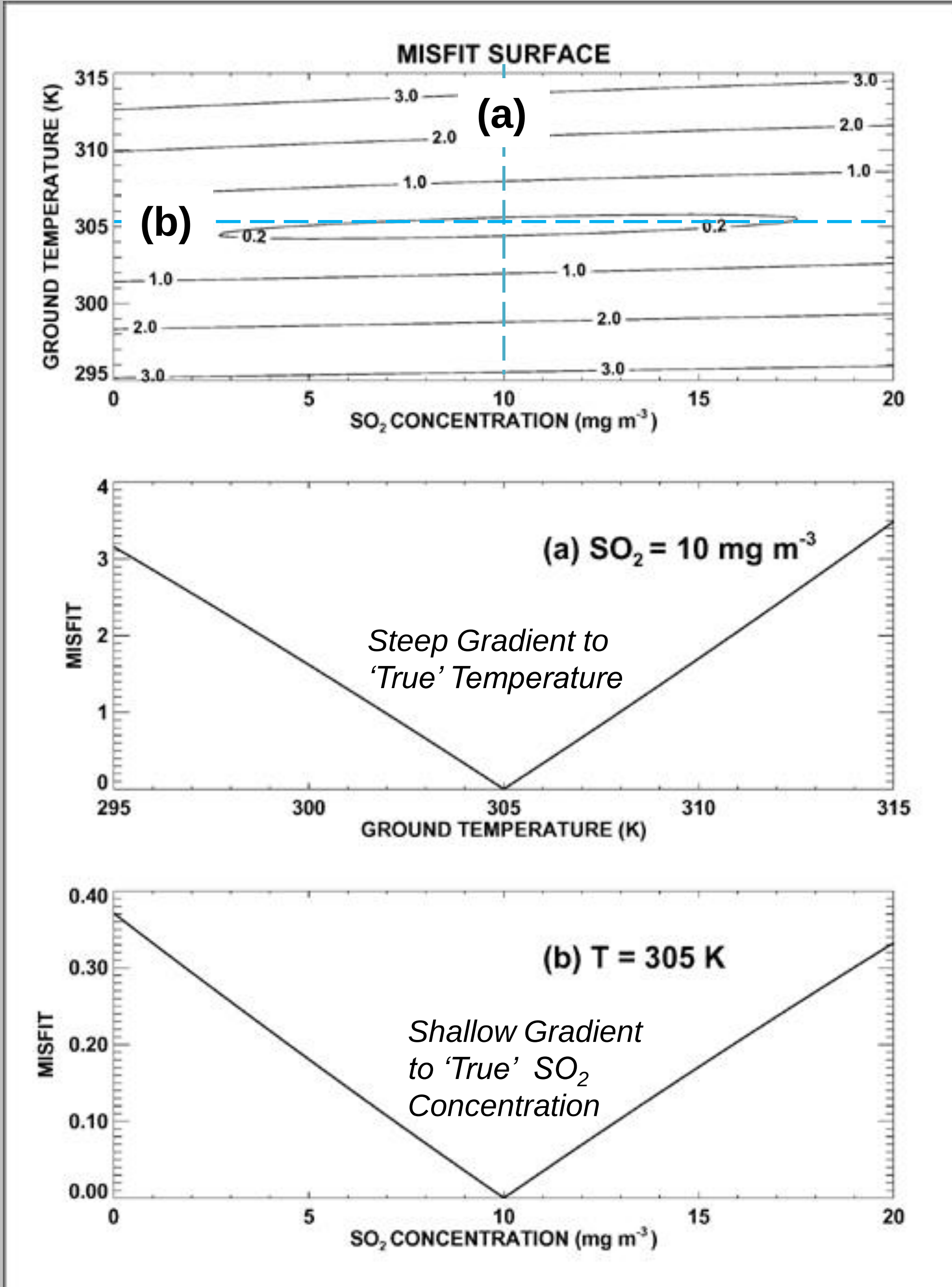
# Sensitivity to Gas is a Function of Contrast Between Plume and Surface Temperatures

- Detection Threshold: Apparent Change in Temperature Must Exceed NE$\Delta$T of Instrument
- 0.25 – 0.5 K: Realistic NE$\Delta$T for ASTER or MODIS
- Land vs. Sea Surface: 20 K Decrease in Temperature = 2X Increase in Detection Threshold






# Retrieval of Surface Temperature and Gas Concentration

**Temperature is Well-Constrained by Radiance Measurements, Relative to the Constraint on Gas Concentration**

**Simultaneous Retrieval of Temperature and Gas Concentration is Difficult:**

- **Misfit Surface Resembles "Taco Shell"**
- **Rapid Convergence on Temperature Estimate**
- **Little to No Convergence on Concentration Estimate**

**Cascading (Serial) Retrieval is a Better Approach**

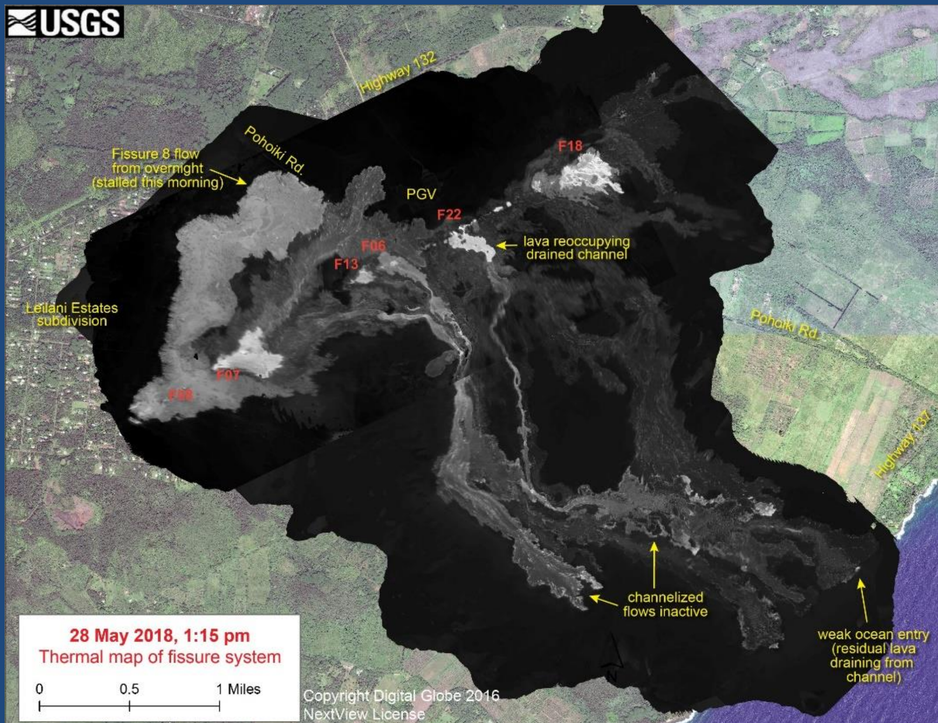
- **Estimate Surface Temperature**
- **Estimate Gas Concentration**

# Validation Efforts

Kilauea May/2018 plumes

# Summit - Lower East Rift Zone (LERZ) Eruption

- Fissures open in Leilani Estates on May 3
- $SO_2$ emission rates in excess of 15,000 t/d
- Ash eruptions at Summit began May 15
- Ash plumes heights up to 10 km

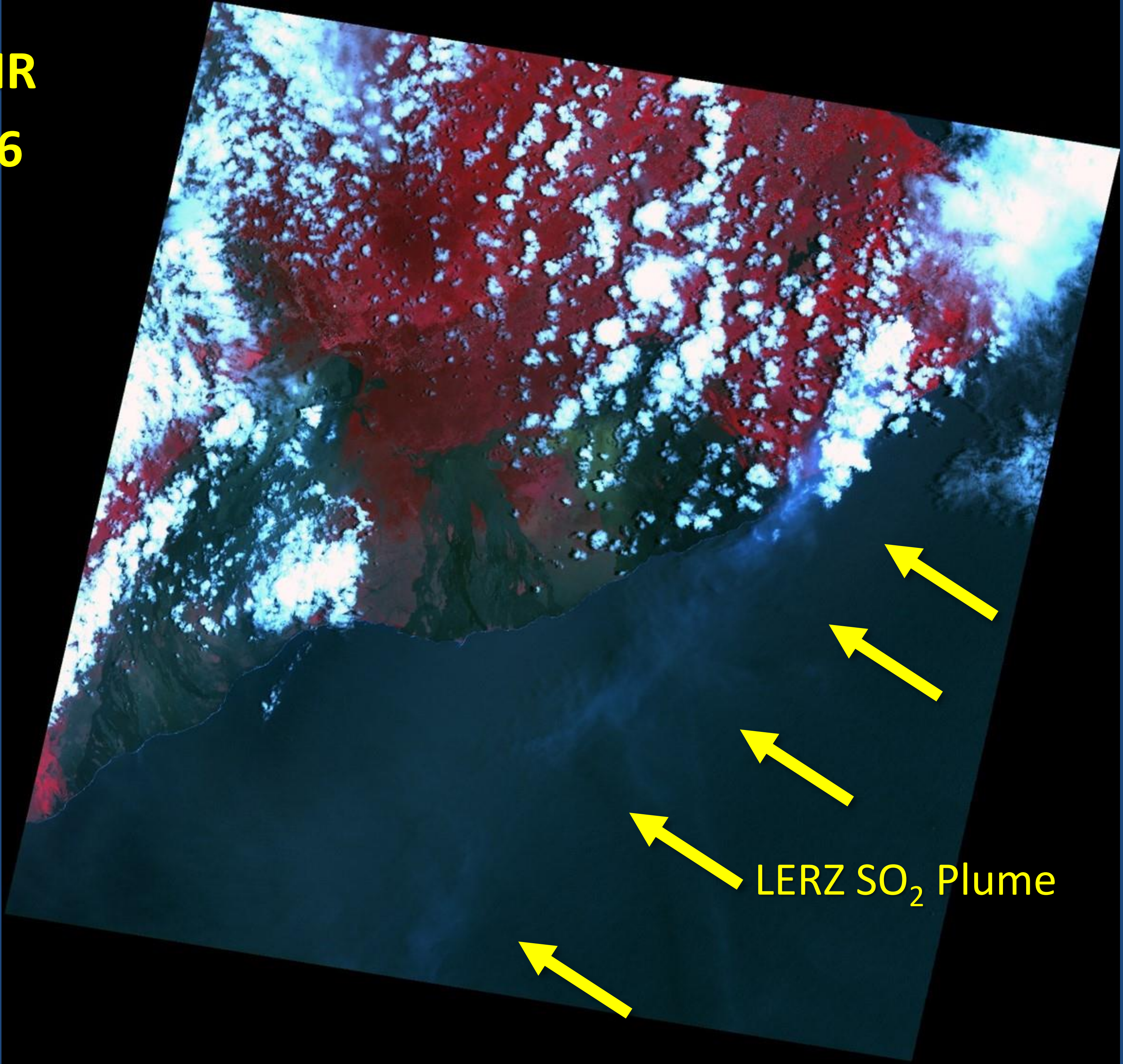



*Published 17 May 2018, Getty Images*

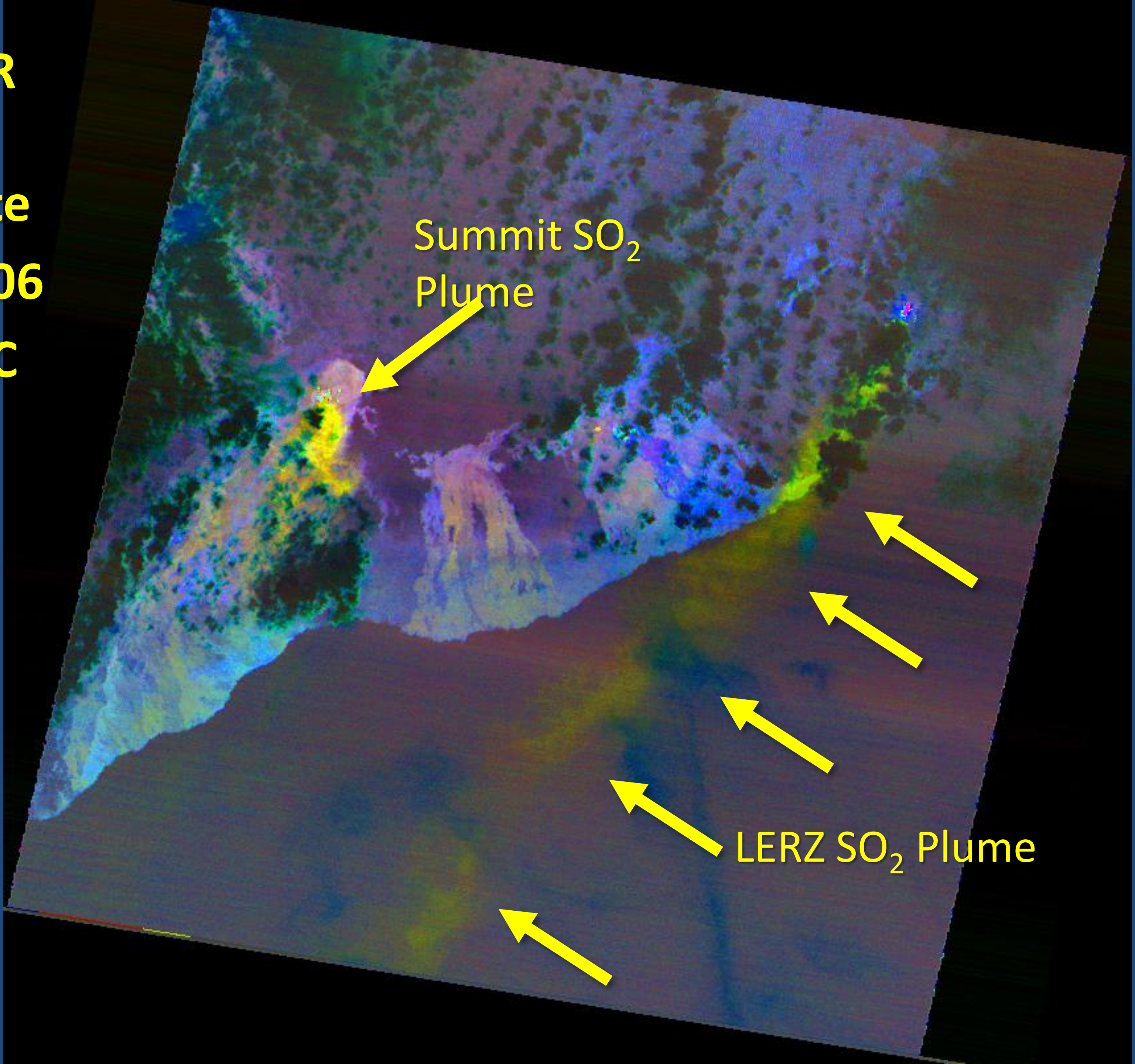
*Published 16 May 2018, Vice News*

*Published 17 May 2018, Getty Images*

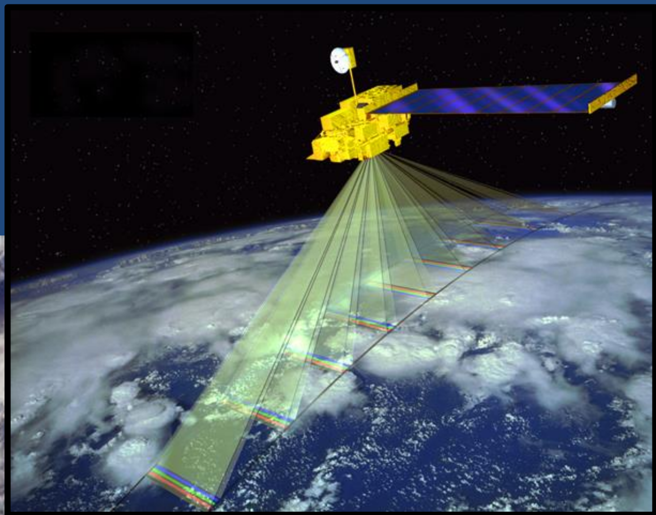
ASTER VNIR
2018-05-06
21:01 UTC



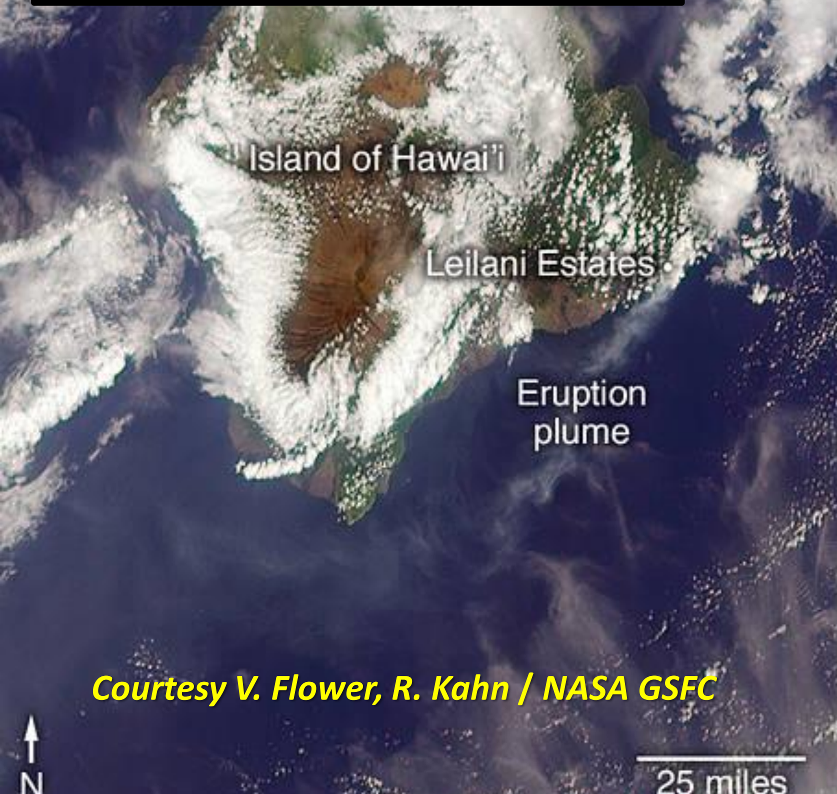
# ASTER TIR Color-Composite 2018-05-06 21:01 UTC



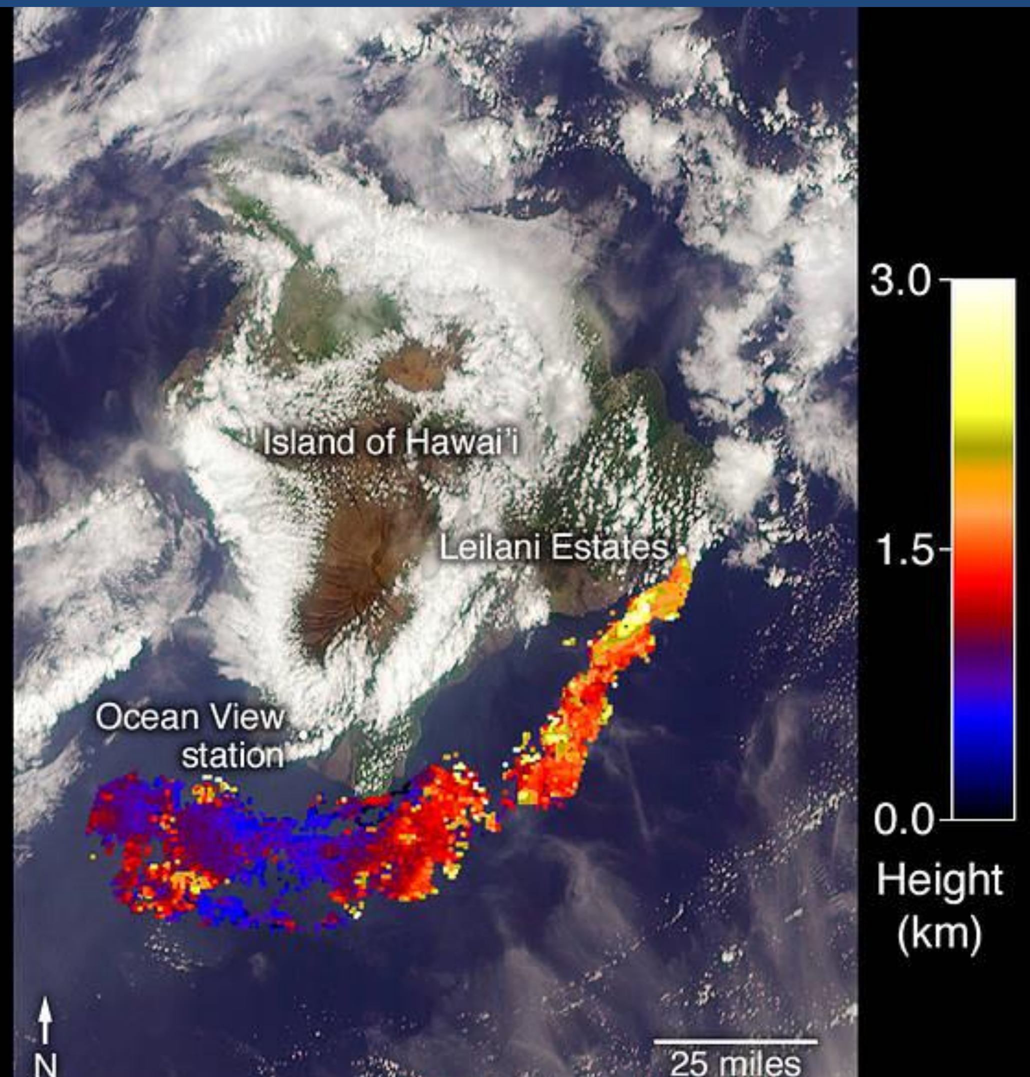
# MISR Analysis of Plume Height



- Multi-angle Imaging SpectroRadiometer – 9 cameras provide stereoscopic coverage of plume
- MISR observations coincident with ASTER – constrain plume height for $SO_2$ retrievals in the TIR

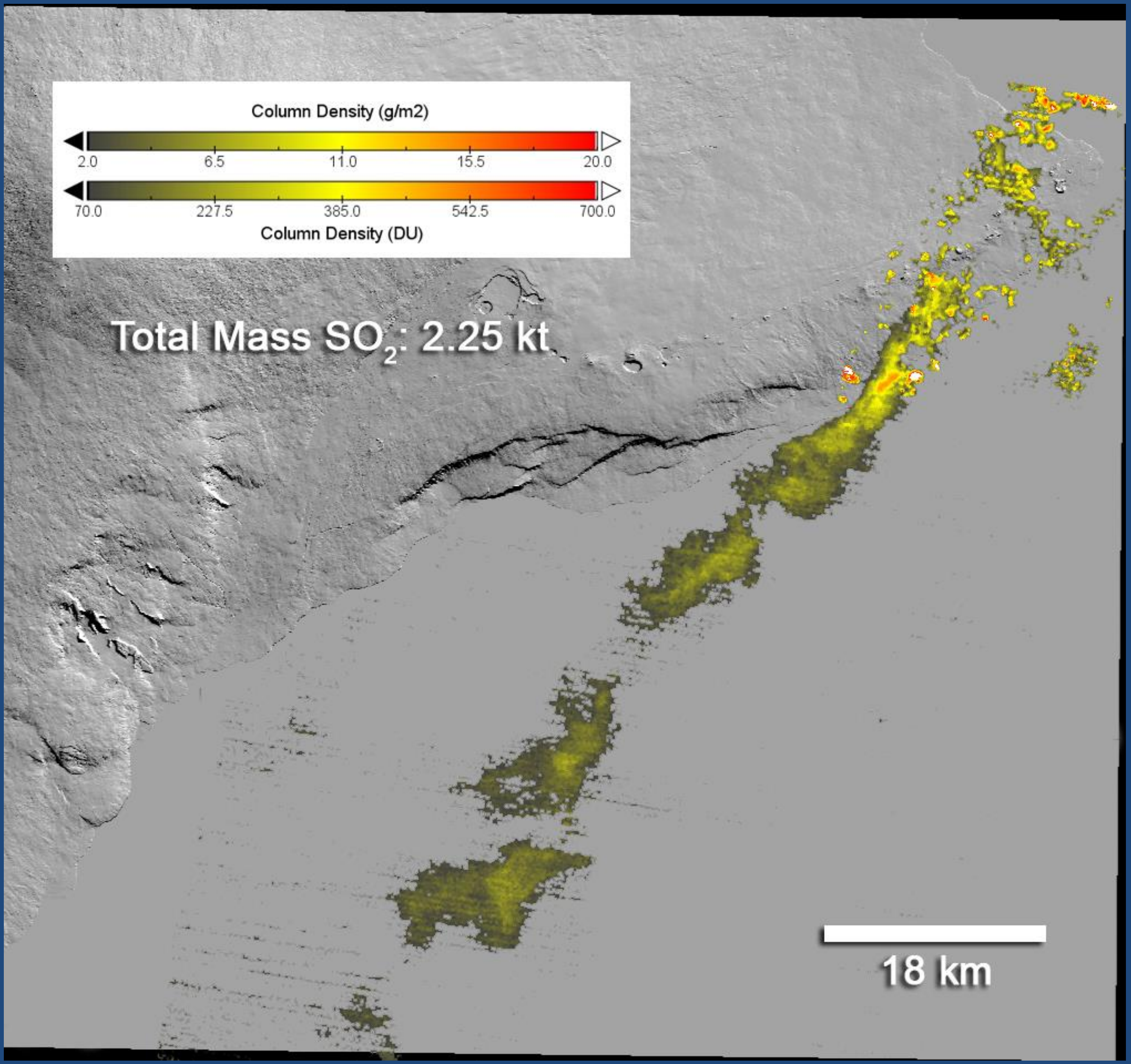


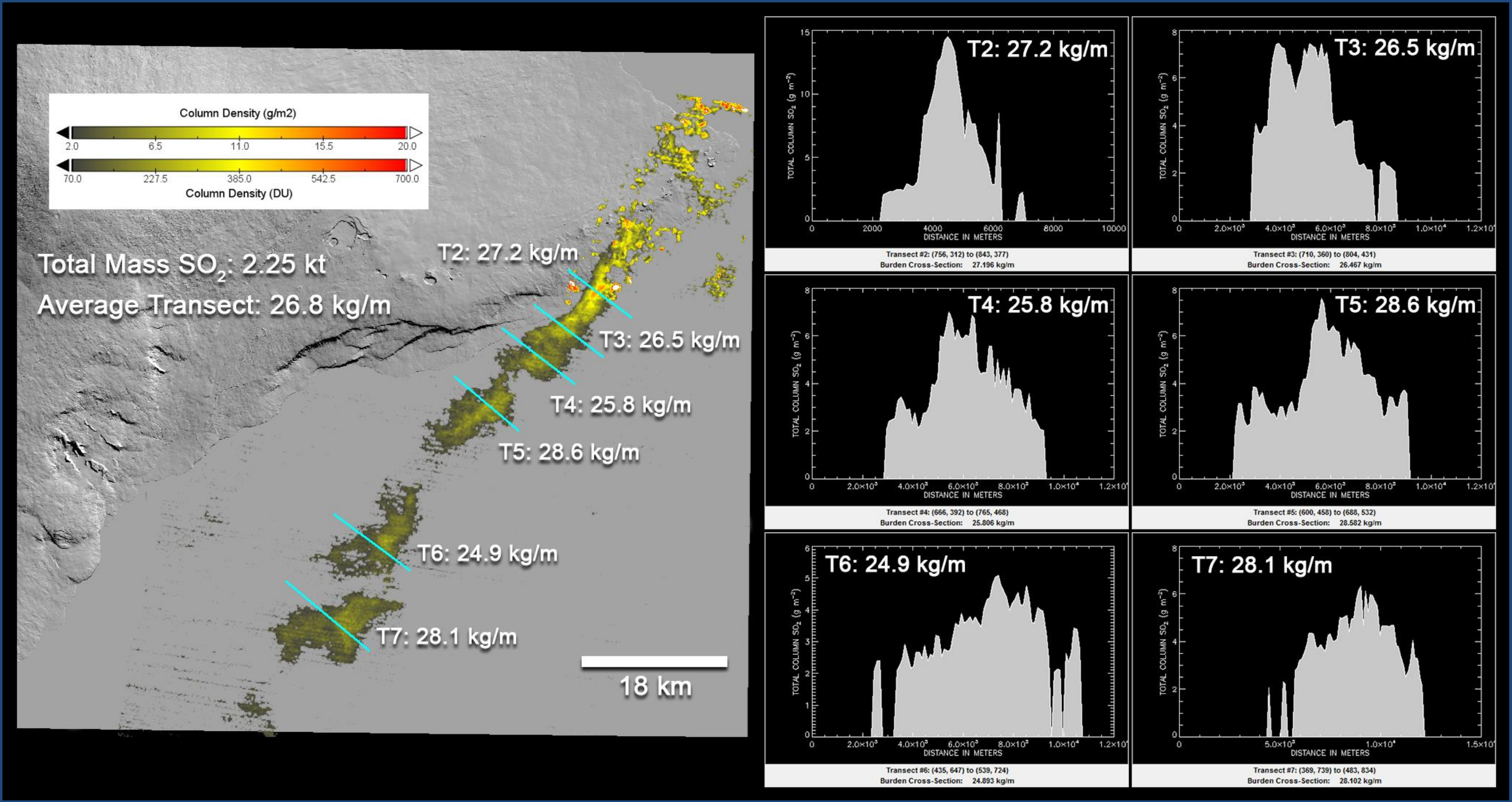

*Courtesy V. Flower, R. Kahn / NASA GSFC*



**ASTER-Based Estimates of $SO_2$ Column Density**

- Column Density can scale inversely with size of IFOV (pixel)
- Total Mass is sum of Column Density over all pixels
- Total Mass useful for comparing $SO_2$ retrievals based on different airborne or satellite instruments
- How do we compare satellite-based estimates with field measurements?






ASTER-Based Transect of $SO_2$ Plume - Analogous to Vehicle Traverse Beneath Plume

- Integrate Column Density across transect lines
- Average ASTER transect: 26.8 ± 1.4 kg/m (11:01 AM local time)
- HVO Vehicle Traverse: 32.8 kg/m (4:28 PM)

# Integrating the MODTRAN6 engine into Plume Tracker

Previous Plume Tracker based on MODTRAN 3.5, with a custom API developed at JPL.

Instead of writing/reading files, Plume Tracker calls functions to communicate with MODTRAN.

MODTRAN6 API: SSI developed an IDL API, on top of the C API.

## API example (MODTRAN 6)

```
modtran = obj_new('modlib')
inp = ModUtil.createInputDefault()
inp.NAME = 'SO2plmLOCAL'
inp.DESCRIPTION = 'Simulates a localized SO2 plume'
inp.options.IEMSCT = 'RT_THERMAL_ONLY'
inp.options.IMULT = 'RT_DISORT'
inp.aerosols.IHAZE = 'AER_RURAL'
inp.geometry.H1ALT = 100.0D
inp.atmos.M1 = 'ATM_MIDLAT_SUMMER'
inp.atmos.CO2MX = 380.0
inp.atmos.S_UMIX = [1.0, 1.0, 1.050, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0 ]

print, 'Case create: ',modtran.caseCreate() ;create one case
print, 'Input set: ',modtran.caseInputSet(inp) ; configure the case

if modtran->execute() eq 1 then begin
  outamb = modtran->outputScanned(0)
  outplm = modtran->outputScanned(0,LOS=1) ;local plume
endif
```

# Improvements with MODTRAN6

- More accurate band models and scattering
- Discrete chemical plume, no need to make a plume layer
- Multiple spectral resolutions
- VSWIR and TIR modelling of heterogeneous plumes
- More portable and practical object-based IDL API

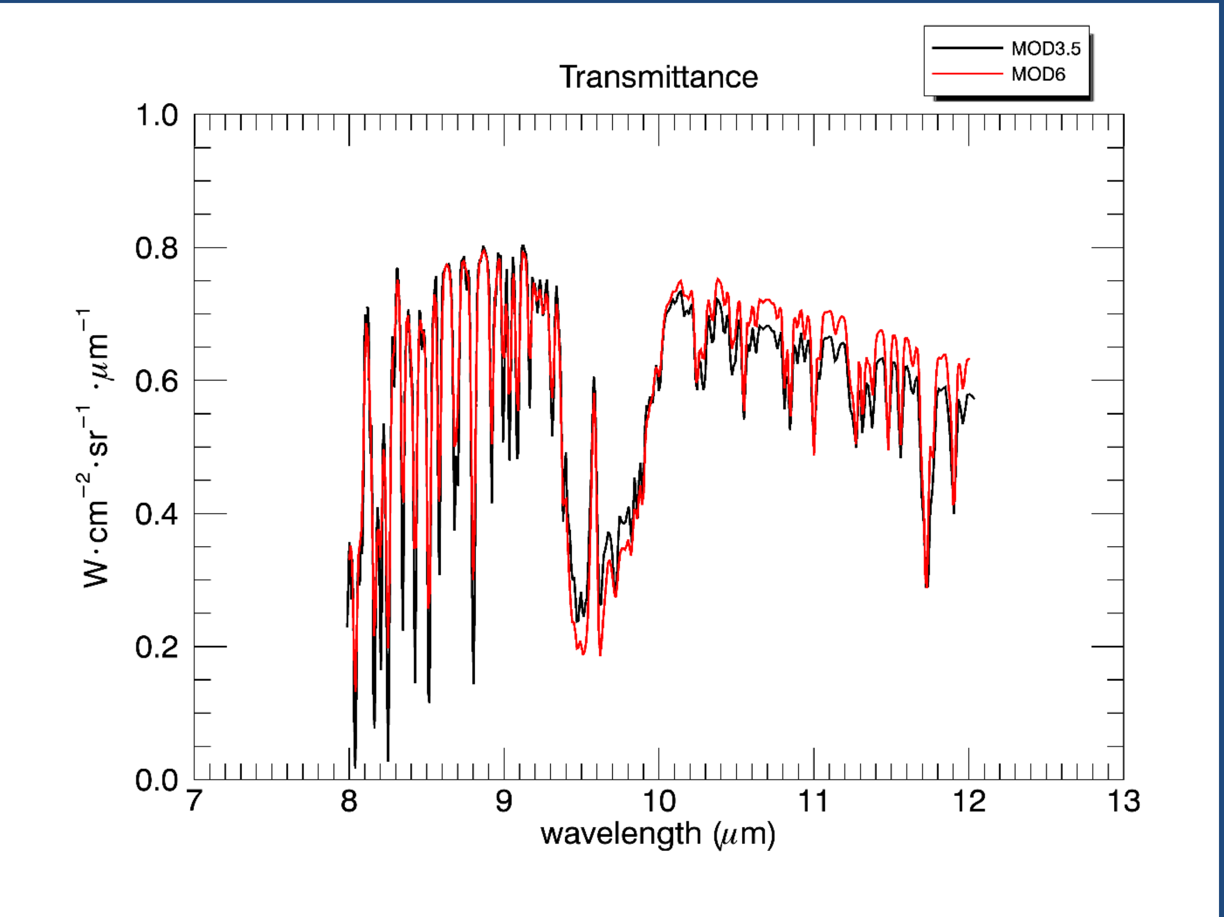
# Current status

Forward modelling already implemented

Inversion in progress, depends some API additions changes to obtain RT outputs and set some inputs.

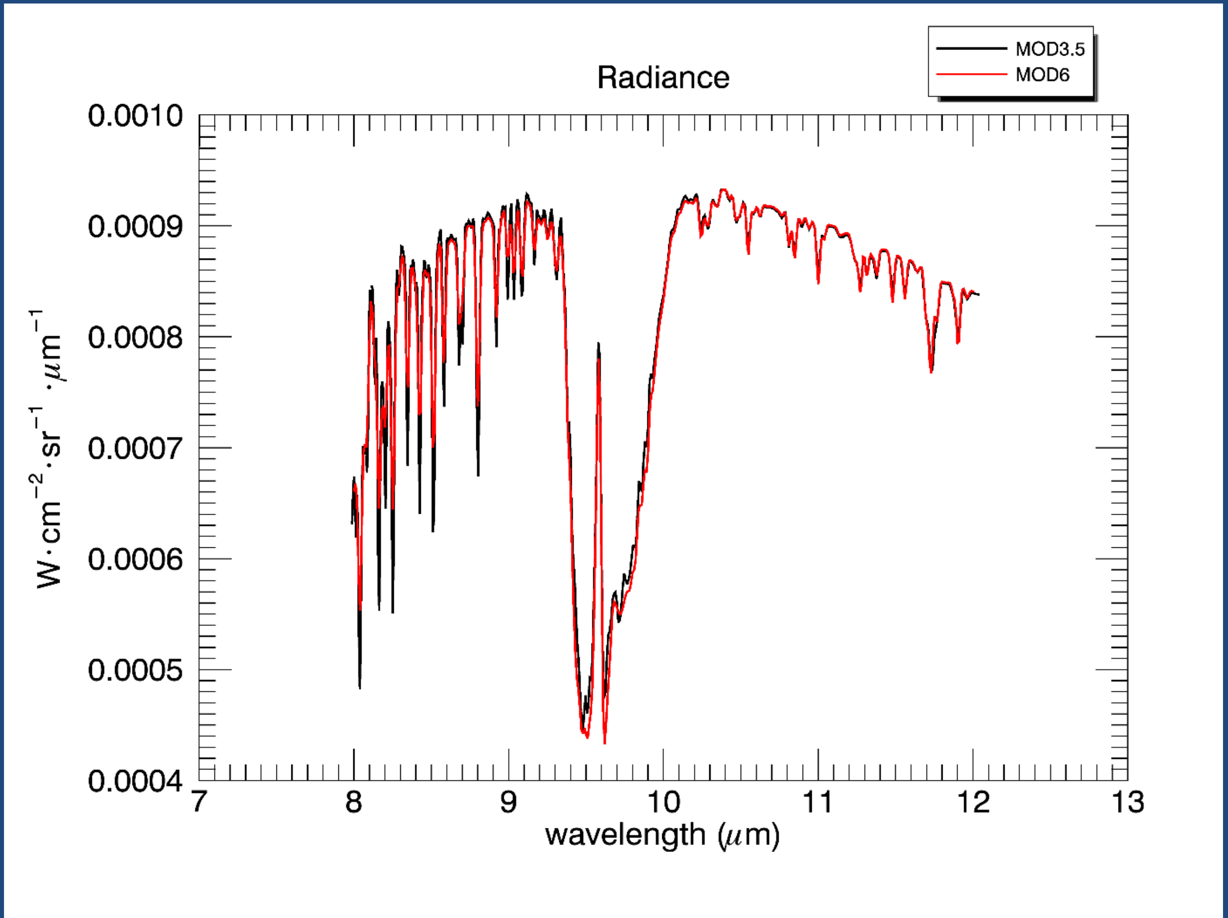
# Forward modelling comparison

## SO2+ash plume model



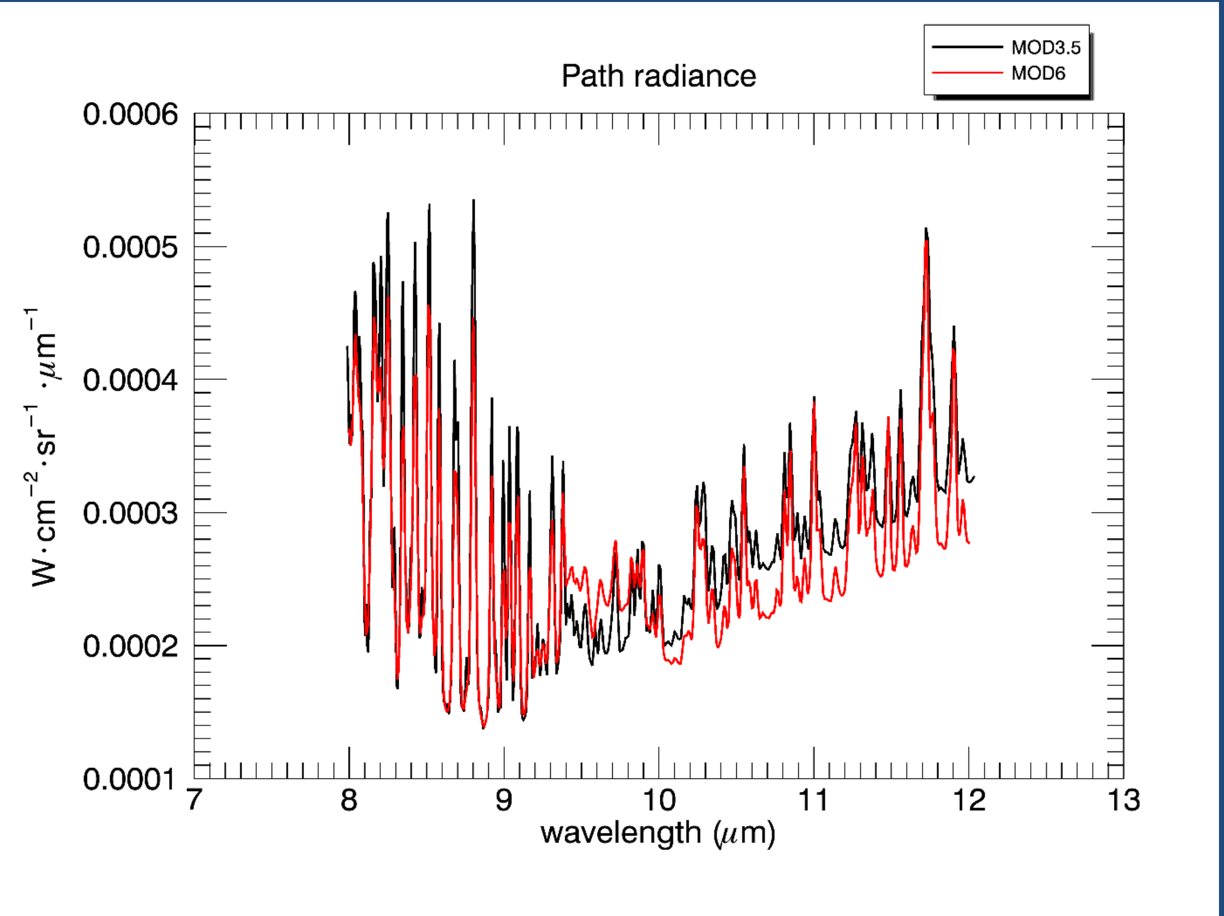
# Forward modelling comparison

SO2+ash plume model



# Forward modelling comparison

SO2+ash plume model



# Forward modelling comparison

SO2+ash plume model