A satellite view of Earth from space, showing the curvature of the planet and the blue of the oceans. The text is overlaid on a semi-transparent grey rectangle.

A Multi-Sensor Approach to the Remote Sensing of Volcanic Emissions

Vincent J. Realmuto

*Visualization and Scientific Animation Group
Modeling and Data Management Systems Section
Jet Propulsion Laboratory*

March 18, 2005

OBJECTIVES

Track Changes in SO₂ Emission Rate

Detect Passive Emissions Before an Eruption Occurs

Eruptions May be Preceded by Changes in Emission Rate

Few Volcanoes are Monitored with Necessary Frequency to Establish Baseline Emission Rates

Satellite Remote Sensing → Facilitate Monitoring

Study the Fate of SO₂ in Atmosphere

Conversion to Sulfate Aerosols

Local/Regional Hazard to Respiratory Health

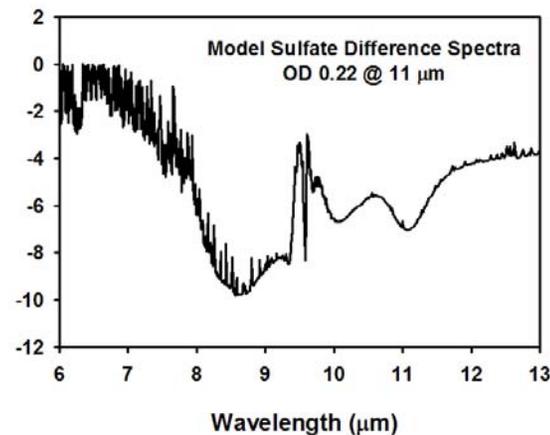
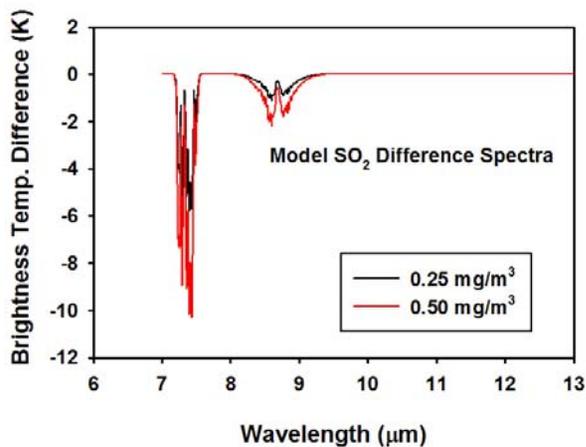
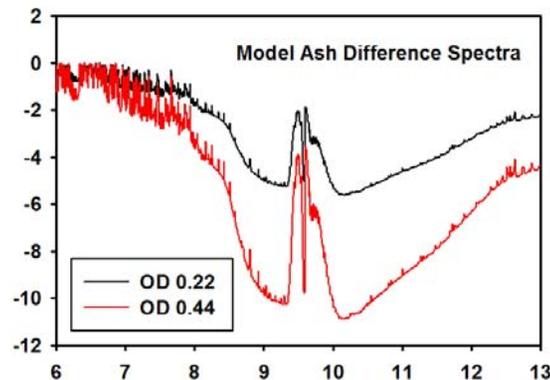
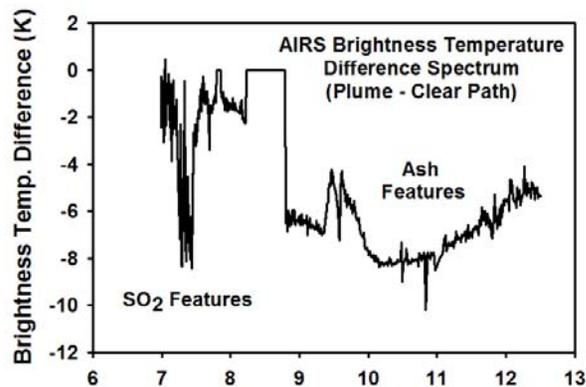
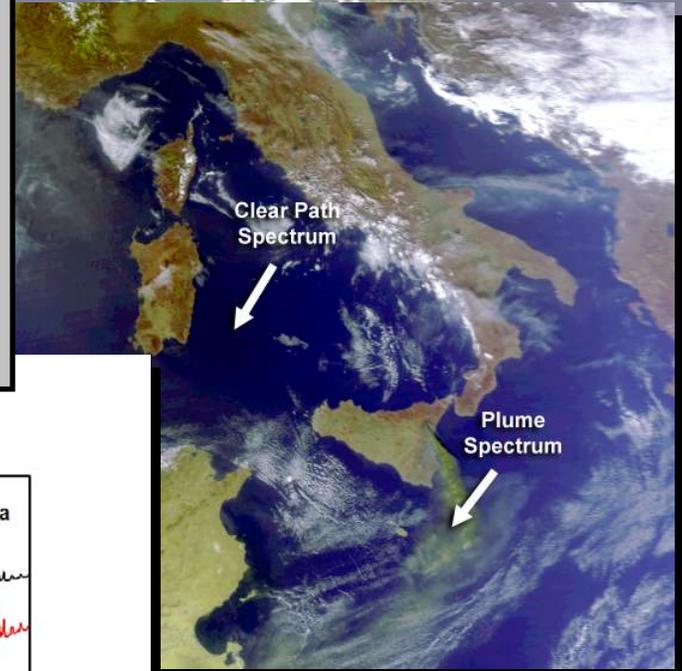
Regional/Global Climate Forcing

**Nucleation Sites for Polar Stratospheric Clouds →
Catalysts for Ozone Depletion**

AIRS Data Acquired over Mount Etna Eruption Plume: 28 October 2002

Constituents of Volcanic Plumes Amenable to Satellite
Remote Sensing: SO_2 , Silicate Ash, Sulfate Aerosol

Rare in "Normal" Atmosphere - Relatively Low
Concentrations Can Be Detected in the Thermal IR (TIR)



Forward Modeling Results

MODTRAN, CHARTS,
LBLTran run at 1 cm^{-1}
resolution

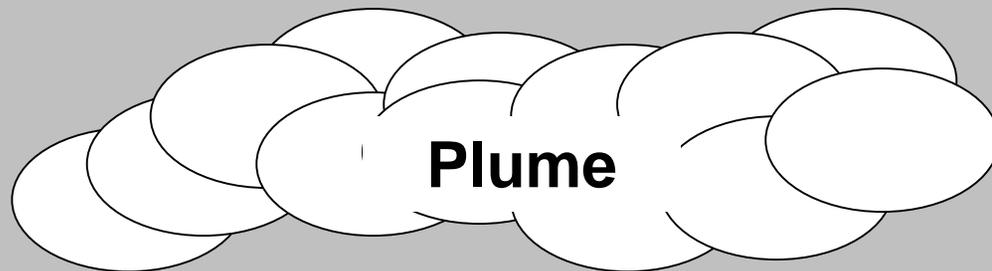
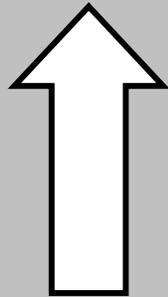
SO_2 concentrations
between 0.25 – 0.50
 mg/m^3

Silicate Ash Loading \gg
Sulfate Aerosol Loading

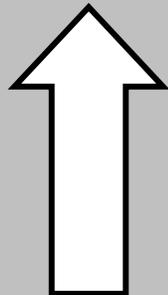
Ground Radiance
Modified By Plume
and Atmosphere:

Estimate Plume
Composition by
Modeling Changes in
Ground Radiance

Sensor



Plume



Ground

3-Slab Radiative Transfer Model

$$\alpha_3(\lambda, x_3) B(\lambda, T_3) + \tau_3(\lambda)[\text{Plume Radiance}]$$

$$\alpha_2(\lambda, x_2) B(\lambda, T_2) + \tau_2(\lambda)[\text{Slab 1 Radiance}]$$

$$\alpha_1(\lambda, x_1) B(\lambda, T_1) + \tau_1(\lambda)[\text{Ground Radiance}]$$

$$\varepsilon_o(\lambda) B(\lambda, T_o) + [1 - \varepsilon_o(\lambda)] \alpha_1(\lambda, x_1) B(\lambda, T_1)$$

Driver (V.10.5) [IRAD_20011030]

Action Menu

Current Selection

Starting Point		Ending Point	
Line	Sample	Line	Sample
425	306	426	308
Latitude	Longitude	Latitude	Longitude
19.2509	-155.041	19.2499	-155.039

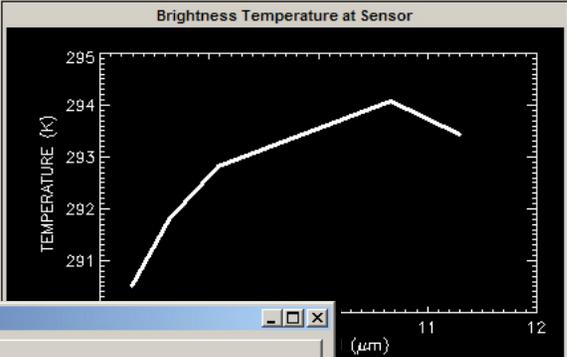
Plume Base Alt (km)	Plume Top Alt (km)	Max SO2 Conc (mg/m3)
1.00000	2.00000	5.00000
Sensor Alt (km)	Ground Elev (km)	Zenith Angle (deg)
705.000	0.000000	177.147

Panel Mode

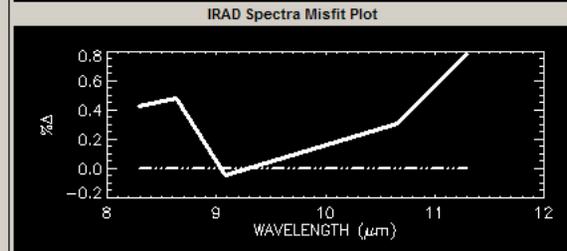
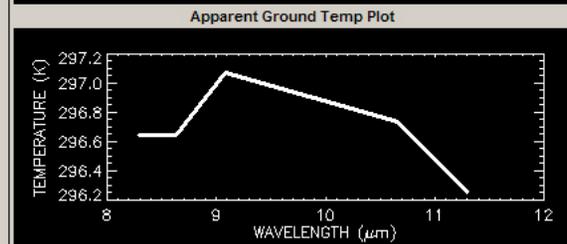
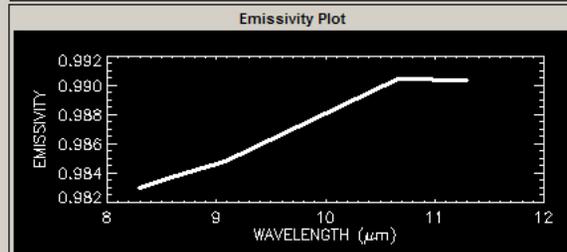
Plume Description Map Information

Messages

```
Index Image VNIR_RGB_20011030 Loaded
Temperature Map Read From v10.5_temperature_map
SO2 Map Read From v10.5_so2_map
H2O Map Read From v10.5_h2o_map
```



H2O Factor	SO2 Abund (g/m2)	Ground Temp (K)
0.900000	0.000000	297.071
O3 Factor	Least Sq. Misfit	Ground Elev (km)
1.00000	0.0891479	0.000000



VNIR_RGB_20011030

Quit

Display Menu Zoom

Current View SL: 0 SS: 0 EL: 511 Es: 649

MAP_SO2: Graphic Interface to MODTRAN

Radiance at the Sensor

$$L(\lambda, T_o) = \{\varepsilon(\lambda)B(\lambda, T_o) + [1 - \varepsilon(\lambda)]L_d(\lambda, T_a, x)\} \tau(\lambda, x) + L_u(\lambda, T_a, x)$$

Where:

T_o = Surface Temperature

$\varepsilon(\lambda)B(\lambda, T_o)$ = Radiance at the Surface

x = Atmospheric Composition

$\tau(\lambda, x)$ = Atmospheric Transmission

T_a = Atmospheric Temperature

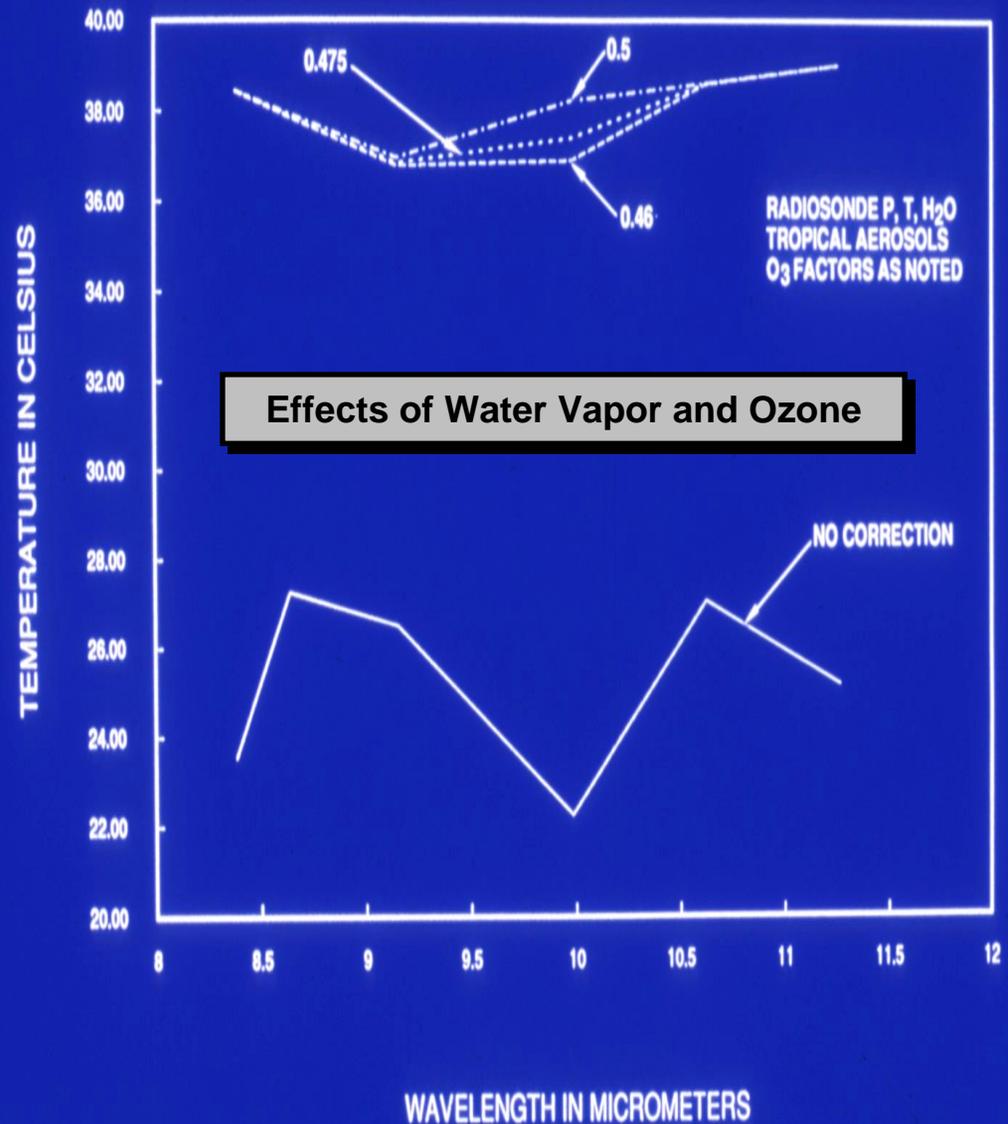
$L_d(\lambda, T_a, x)$ = Downwelling Atmospheric Radiance (Sky Radiance)

$L_u(\lambda, T_a, x)$ = Upwelling Atmospheric Radiance (Path Radiance)

Note:

The Atmosphere is Both a Source and Sink Of Radiation

ATMOSPHERE CORRECTIONS 20 Km ATMOSPHERIC PATH



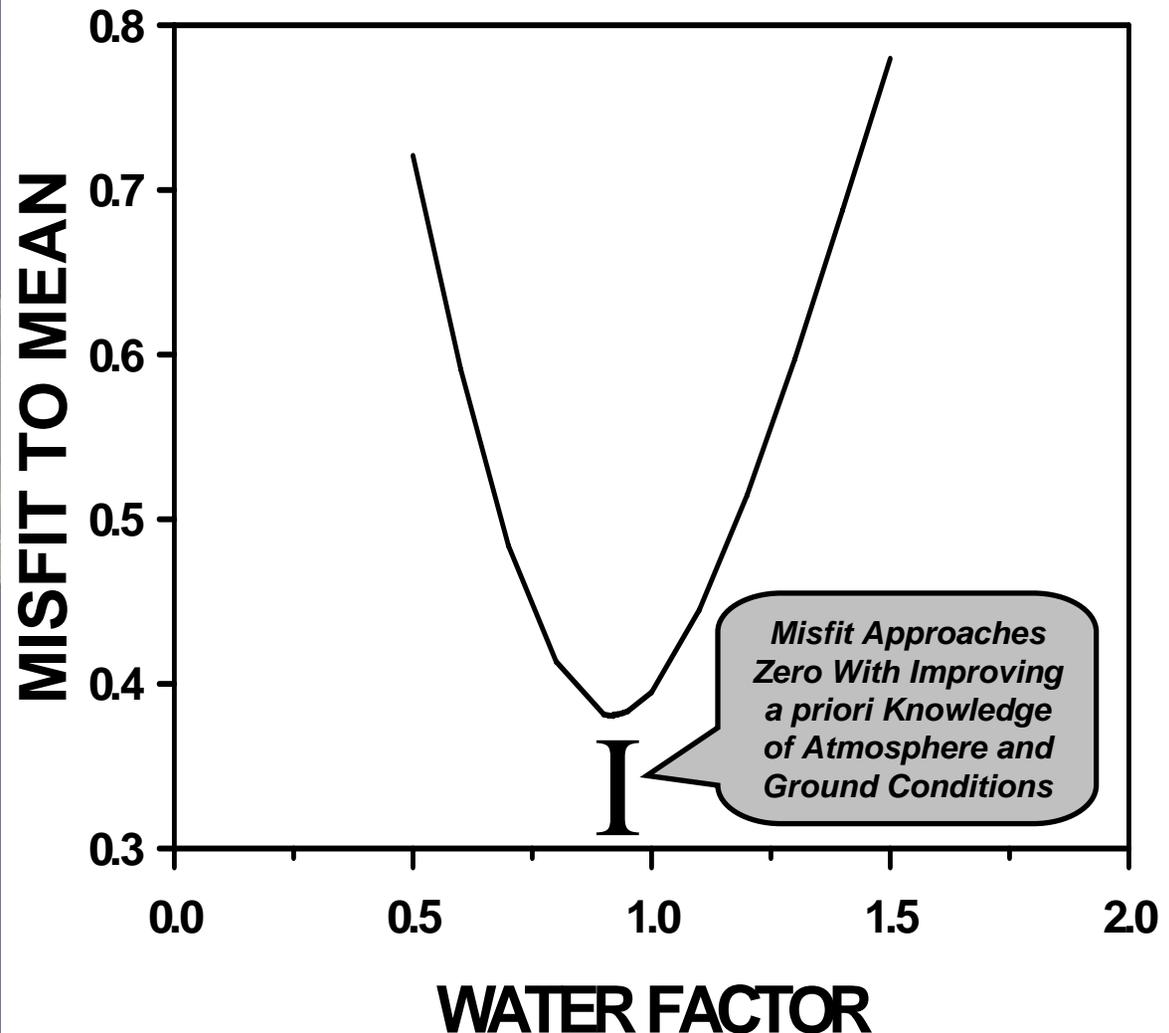
Spatially-Variable Optimal Water Vapor Correction

Ground Temperature is Independent of Wavelength – “Spectrum” Should be Flat Following Atmosphere and Emissivity Correction

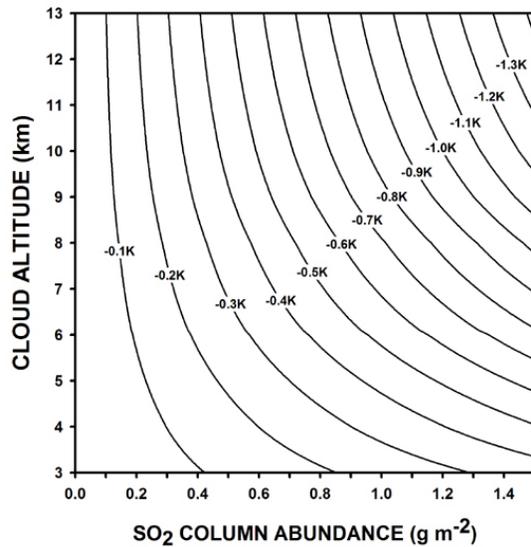
Iterate on Water Vapor Concentration Until “Flattest” Ground Temperature Spectrum is Achieved

Technique Provides Best Possible Correction Given Uncertainty Regarding Atmospheric and Ground Conditions

OPTIMAL WATER VAPOR CORRECTION

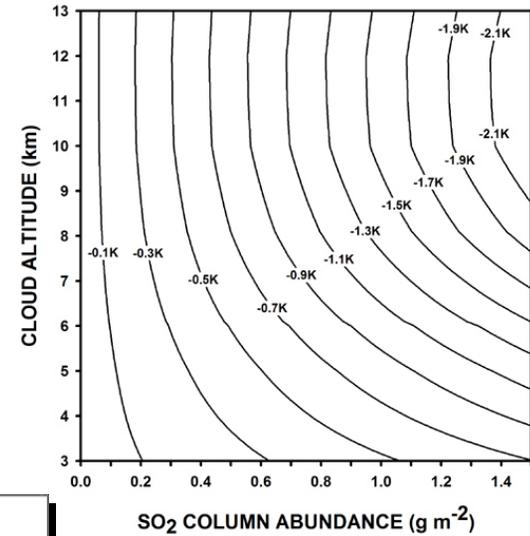


APPARENT CHANGE IN GROUND TEMPERATURE
Tropical Climatology, SZA = 0°

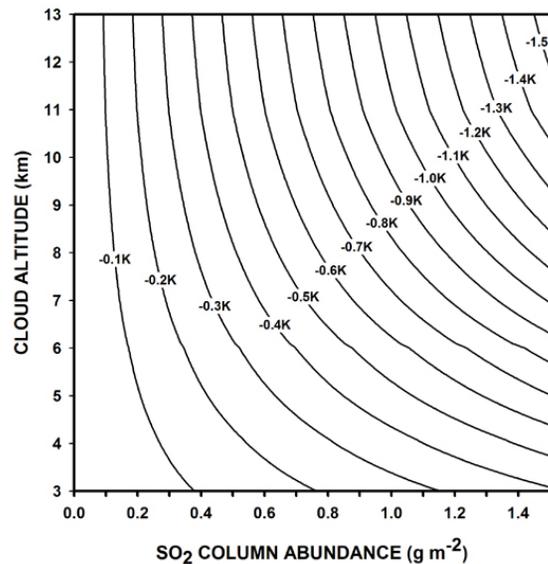


Sensitivity of Instrument Defined by Noise Equivalent Change in Temperature (NEΔT): 0.5 (C or K)

APPARENT CHANGE IN GROUND TEMPERATURE
Sub-Arctic Summer Climatology, SZA = 60°



APPARENT CHANGE IN GROUND TEMPERATURE
Mid-Latitude Summer Climatology, SZA = 30°



Detection Limits Under Various Atmospheric Conditions

General Trends:

Increasing Cloud Altitude (i.e. Increasing Temperature Contrast) Improves Detection

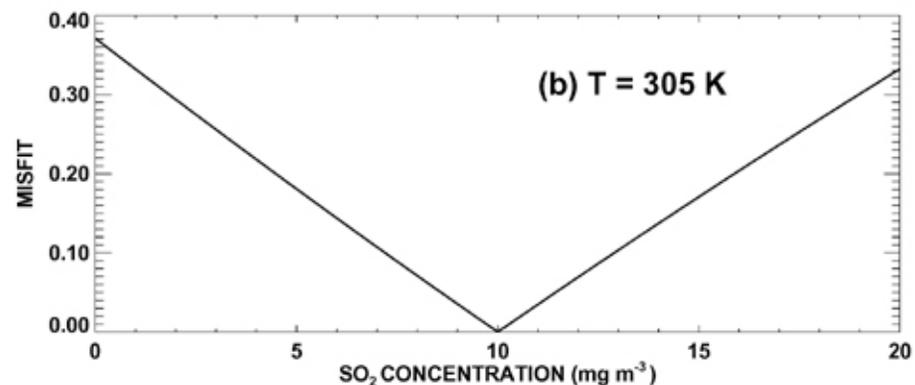
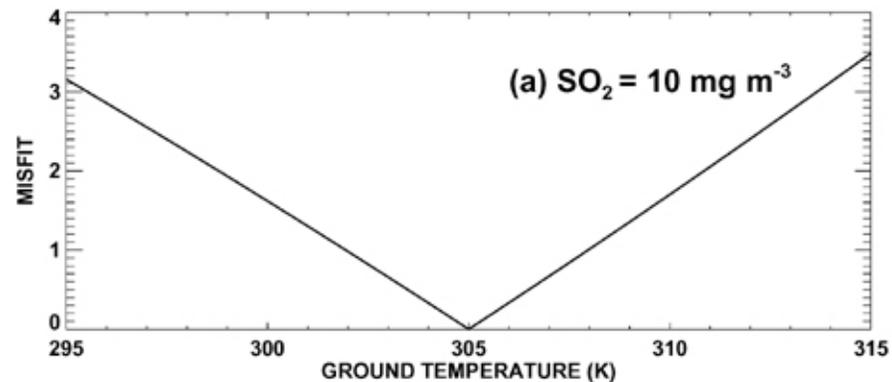
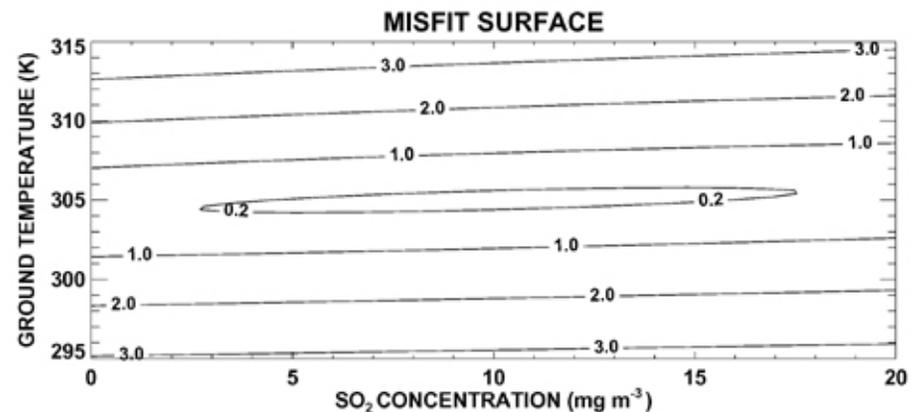
Increasing SZA Improves Detection

Sensitivity Analysis: Ground Temperature vs. SO₂ Concentration

Ground Temperature and
SO₂ Concentration are
Free Parameters

Ground Temperature has
Stronger Influence Than
SO₂ Concentration

Simultaneous Retrieval of
Temperature and SO₂ is
Difficult



Mapping Passive SO₂ Emissions from Space

Pu'u O'o Plume Map Derived from ASTER 90m TIR Data

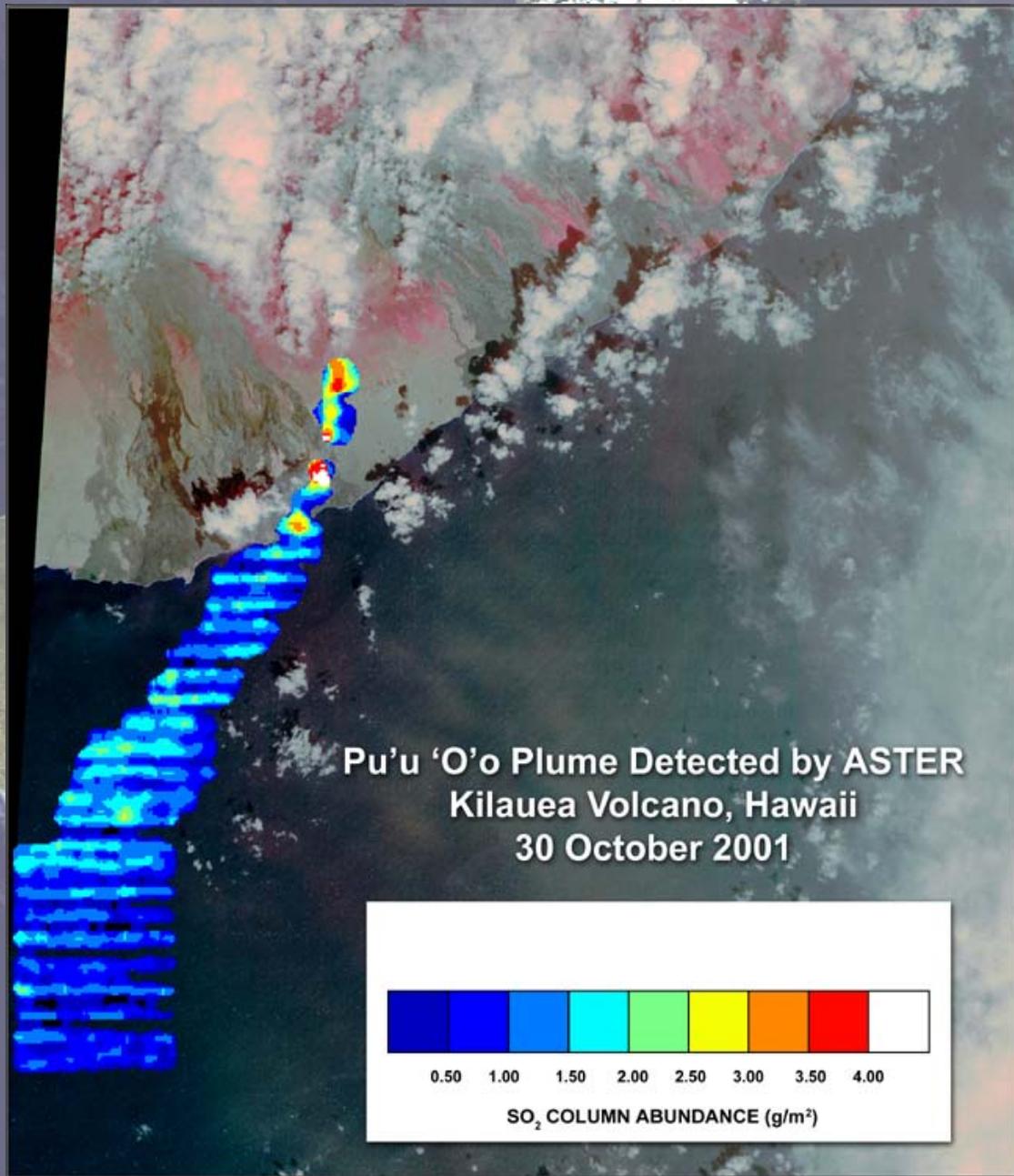
High Spatial Resolution => Greater Sensitivity to Low Levels of SO₂

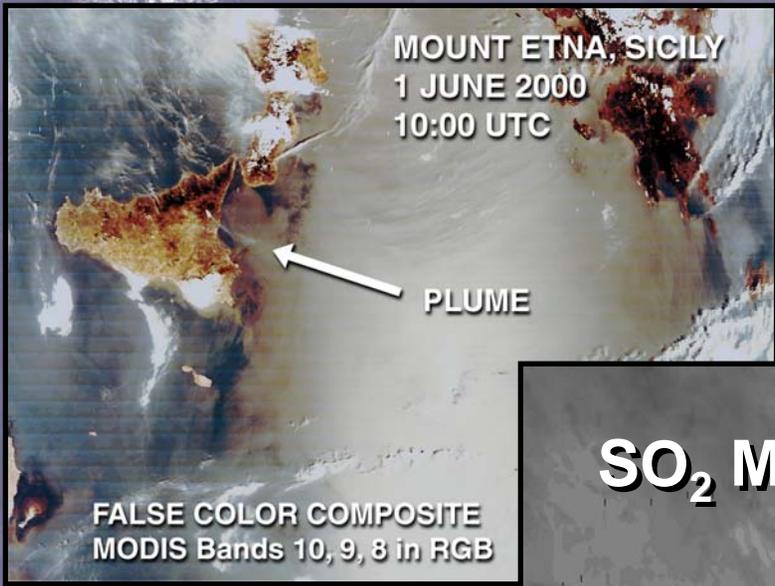
Mitigating Factors

Small Plume: typically 1 km in thickness and width

Low Altitude (typically 1.5 km asl): Low Temperature Contrast

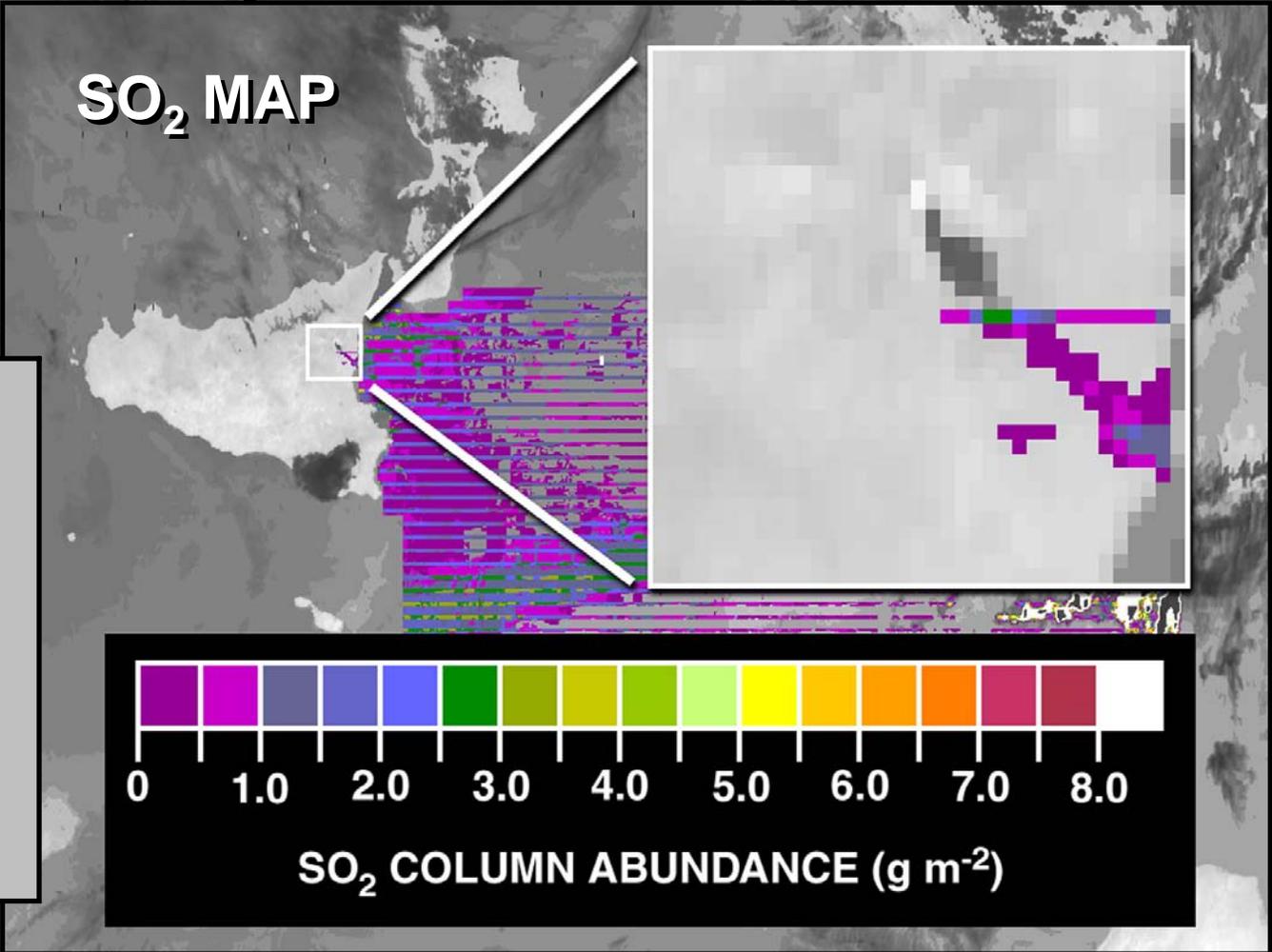
Warm, Humid Tropical Atmosphere: Decreased Temperature Contrast, Increased Atmospheric Absorption and Emission





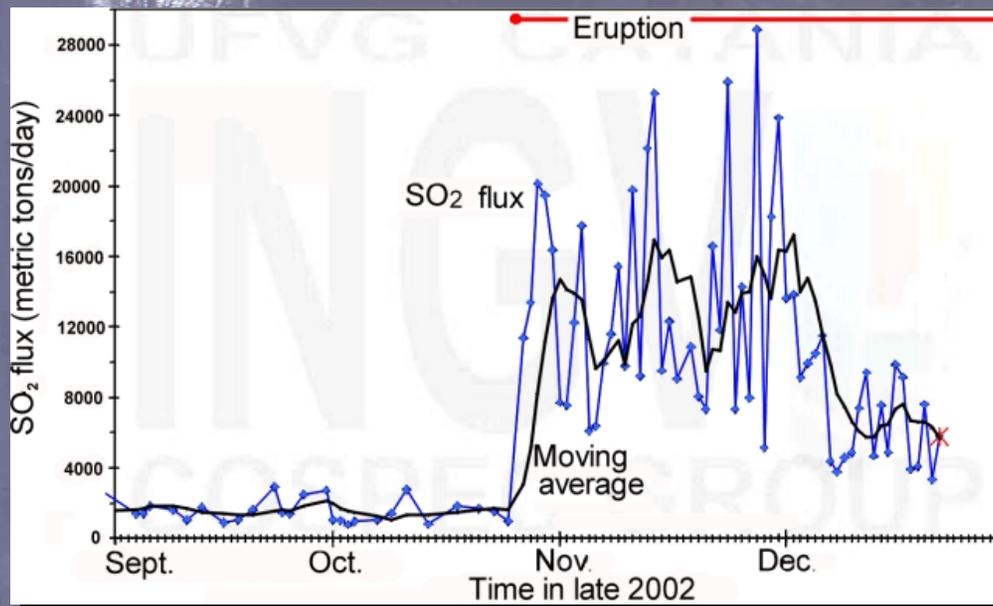
Mapping Passive SO₂ Emissions From Space:

Etna Plume Map Derived From 1 km MODIS TIR Data



Higher Temperature Contrast Over Land: Increased Sensitivity to SO₂

Lower Temperature Contrast Over Water: Retrievals Dominated by Scan-Line Noise



2002-2003 Eruption Of Mount Etna

27 Oct 2002 – 29 Jan 2003

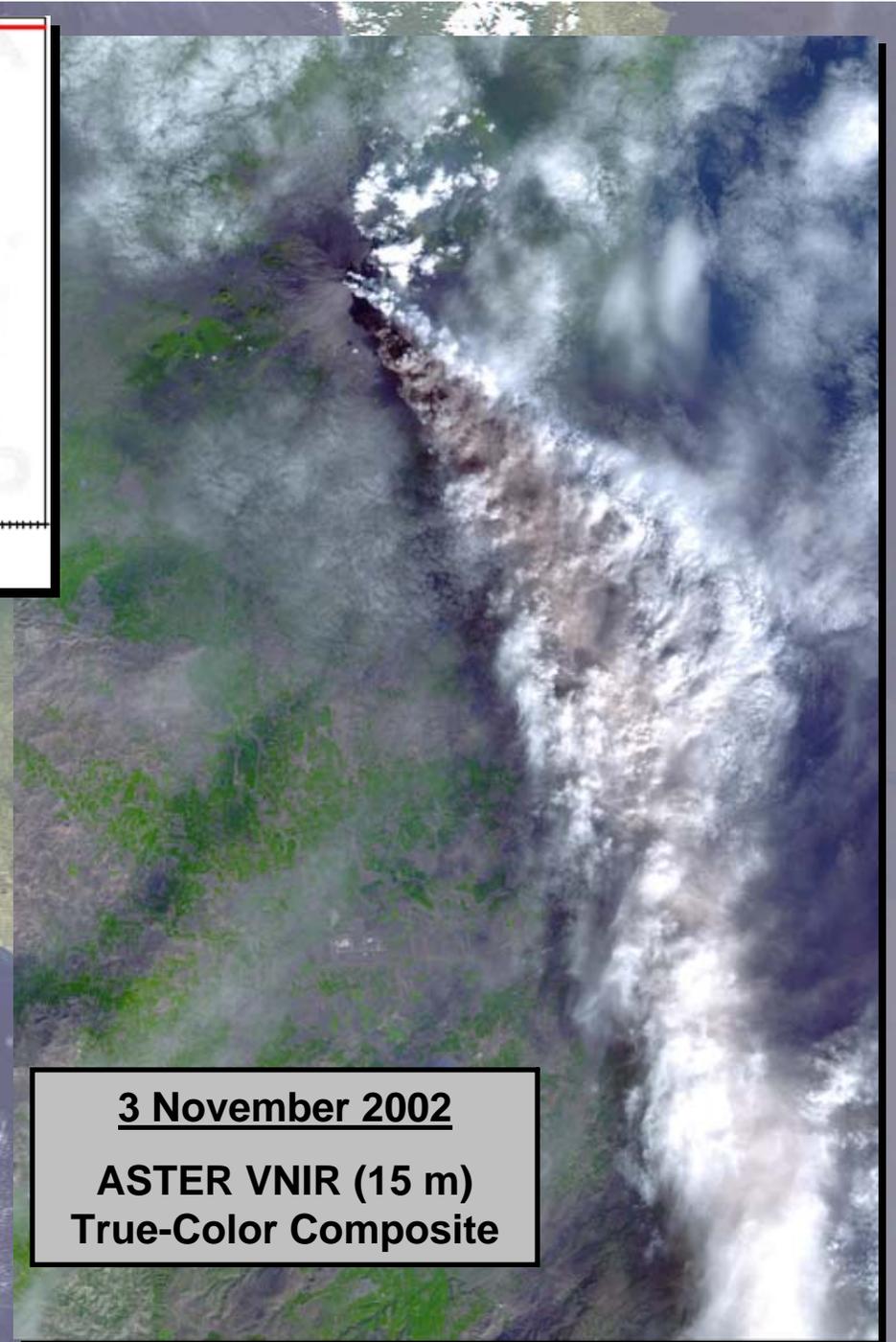
Terra/Aqua Record:

At least one daytime MODIS overpass per day

At least one daytime AIRS overpass every 2 days

Two MISR overpasses (one day apart) every 16 days

90 ASTER acquisitions between June and December 2002



3 November 2002

**ASTER VNIR (15 m)
True-Color Composite**

Synergy Between Measurements

ASTER (Terra)

SO₂, aerosols, ash at concentrations below detection limits of MODIS or AIRS

MISR (Terra)

Plume Altitude, Wind Velocity, fine ash and aerosols

Measurements are Coincident with MODIS-Terra

MODIS (Terra/Aqua)

SO₂, aerosols, ash at concentrations below detection limits of AIRS

Measurements are Coincident with MISR (Terra) and AIRS (Aqua)

AIRS (Aqua)

SO₂, aerosols, ash; unambiguous identification of constituents

Measurements are Coincident with MODIS-Aqua

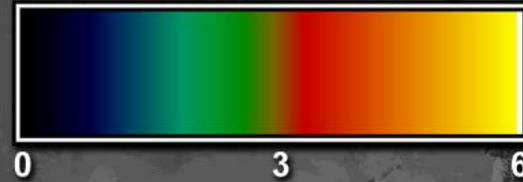
True-Color Composite



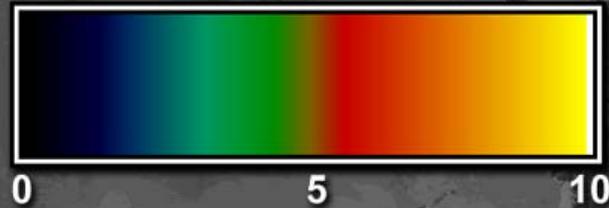
MODIS-Terra

27 October 2002
10:02 UTC

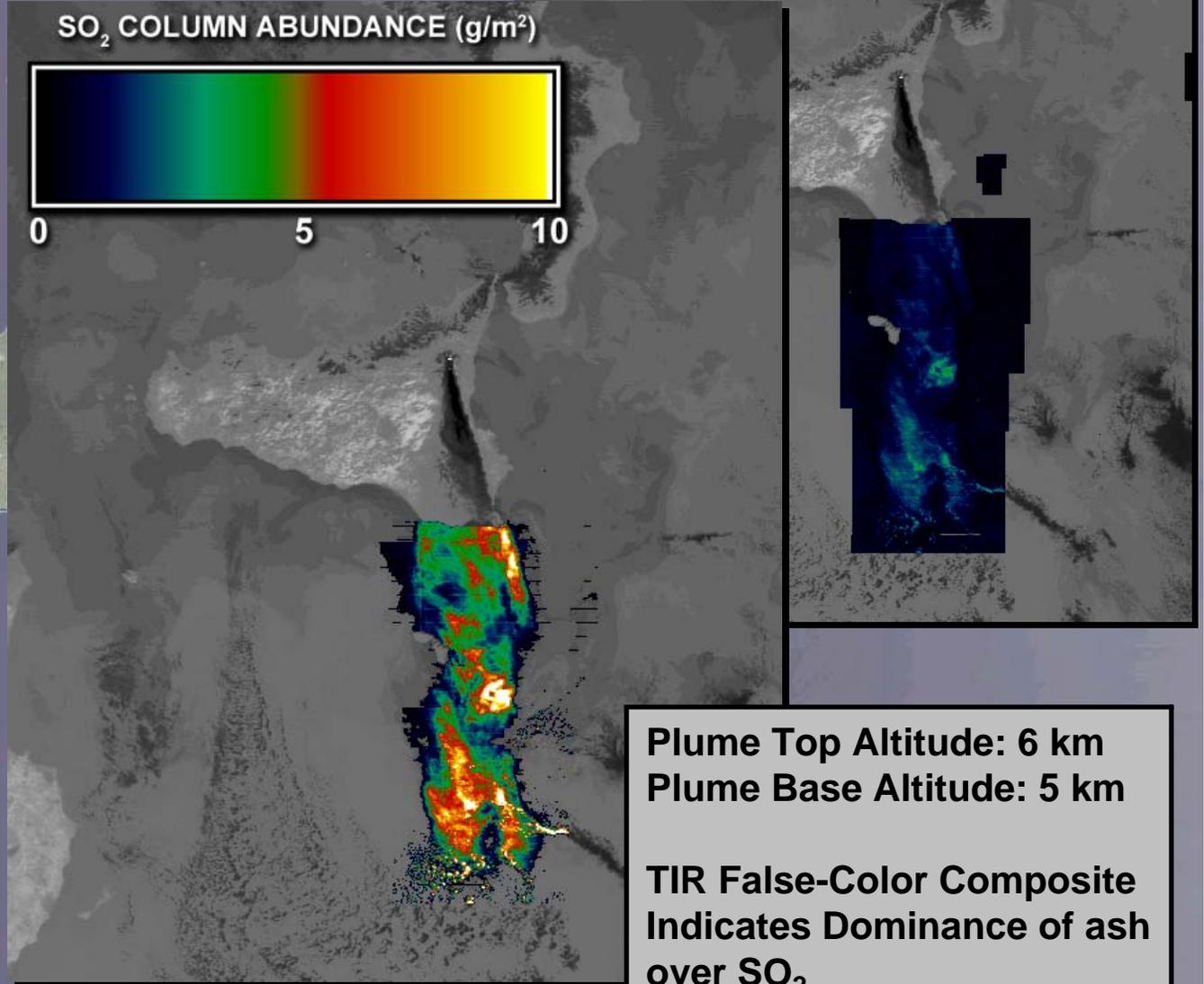
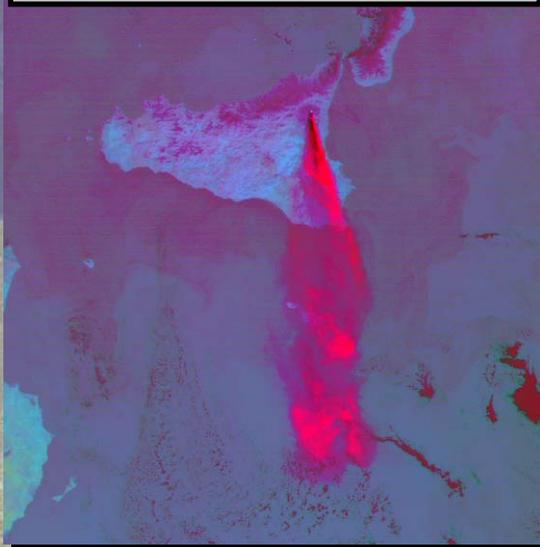
MISFIT TO OBSERVED RADIANCE



SO₂ COLUMN ABUNDANCE (g/m²)



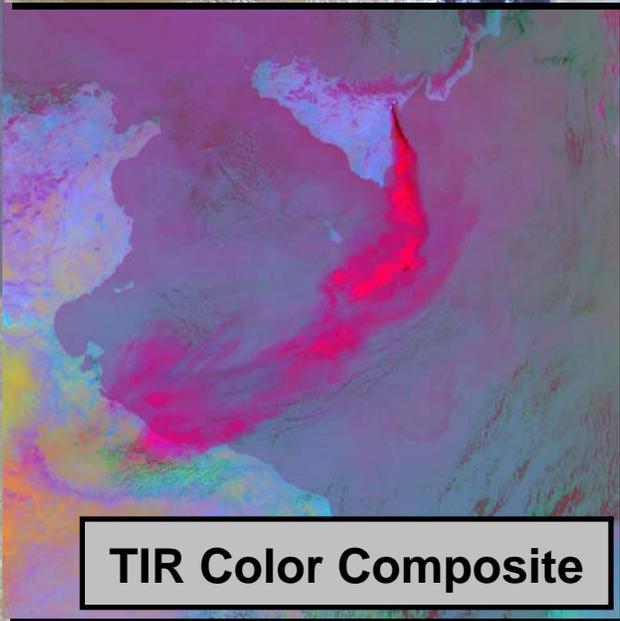
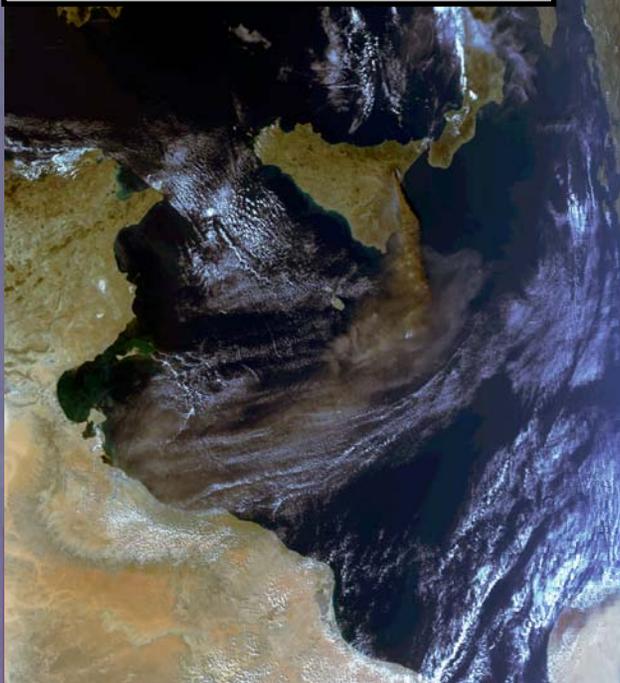
TIR False-Color Composite



Plume Top Altitude: 6 km
Plume Base Altitude: 5 km

TIR False-Color Composite
Indicates Dominance of ash
over SO₂

True Color Composite



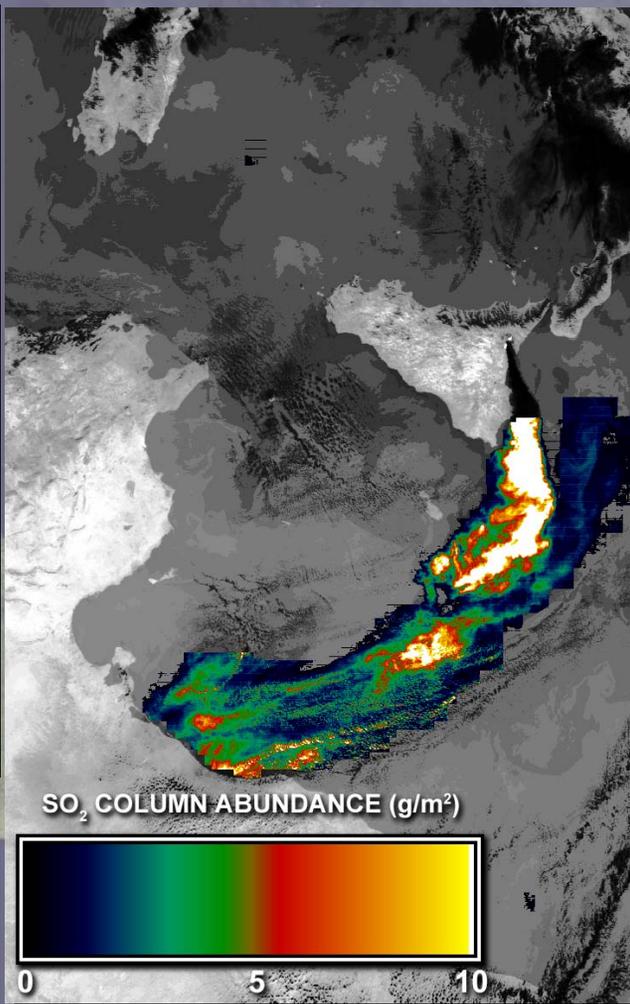
TIR Color Composite

MODIS-Aqua

28 October 2002, 12:15 UTC

Plume Top Altitude: 6 km
Plume Base Altitude: 5 km

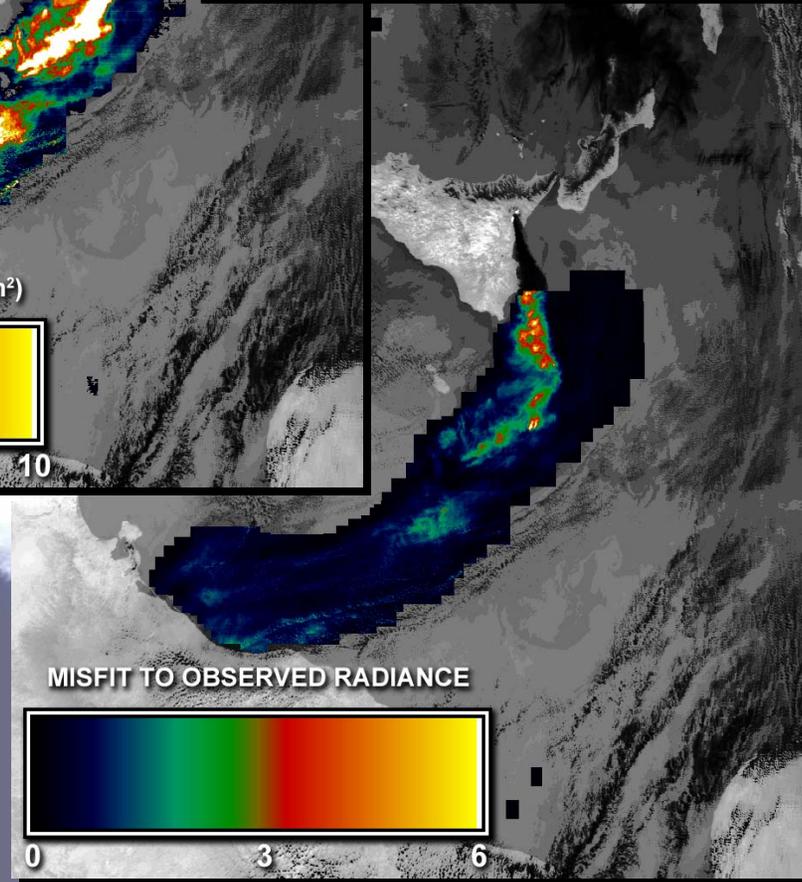
TIR False-Color Composite
Indicates Dominance of ash
over SO₂



SO₂ COLUMN ABUNDANCE (g/m²)



0 5 10



MISFIT TO OBSERVED RADIANCE

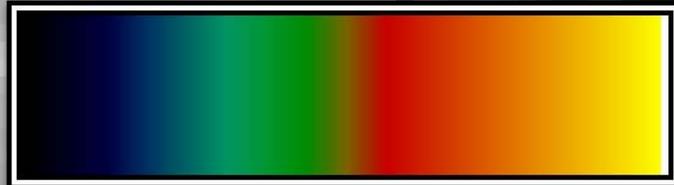


0 3 6

True Color Composite



SO₂ COLUMN ABUNDANCE (g/m²)



0

5

10

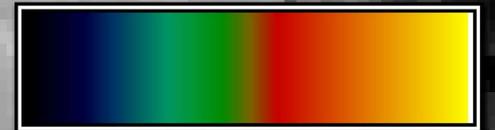
AIRS 28 October 2002

Plume Top Altitude: 6 km
Plume Base Altitude: 5 km

AIRS Misfit to Data is ~ 2X
That of MODIS

Need to Upgrade Version of
MODTRAN Used in MAP_SO2

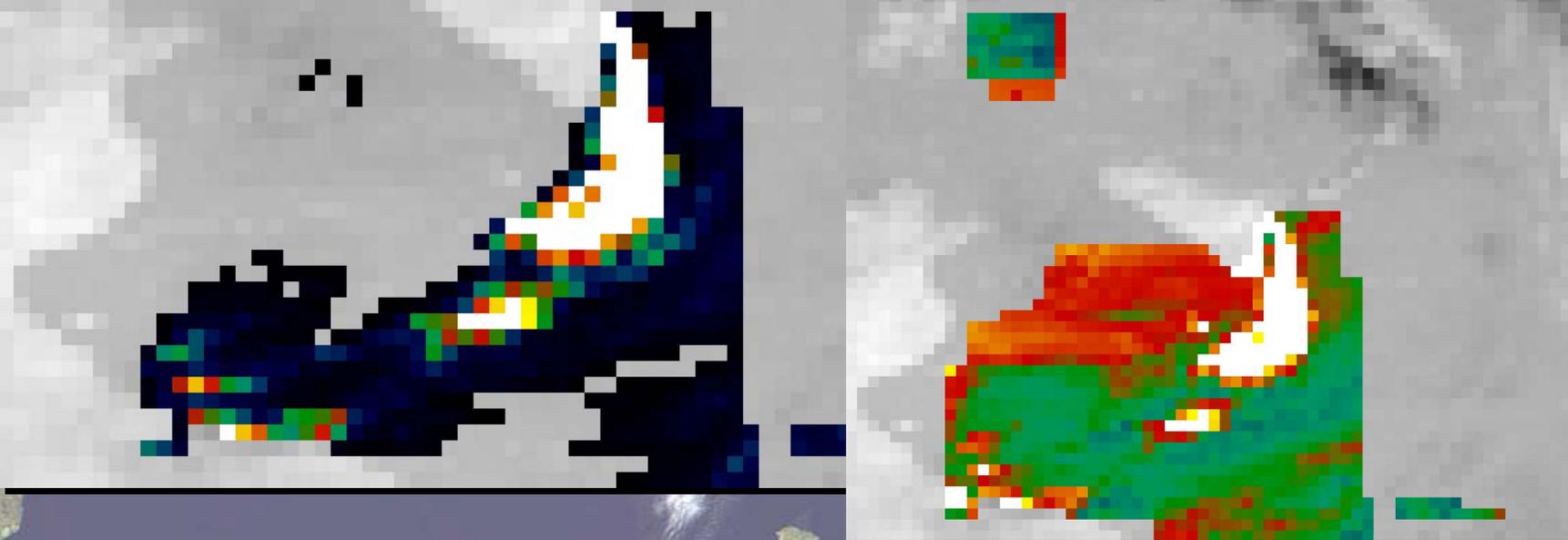
MISFIT TO OBSERVED RADIANCE



5

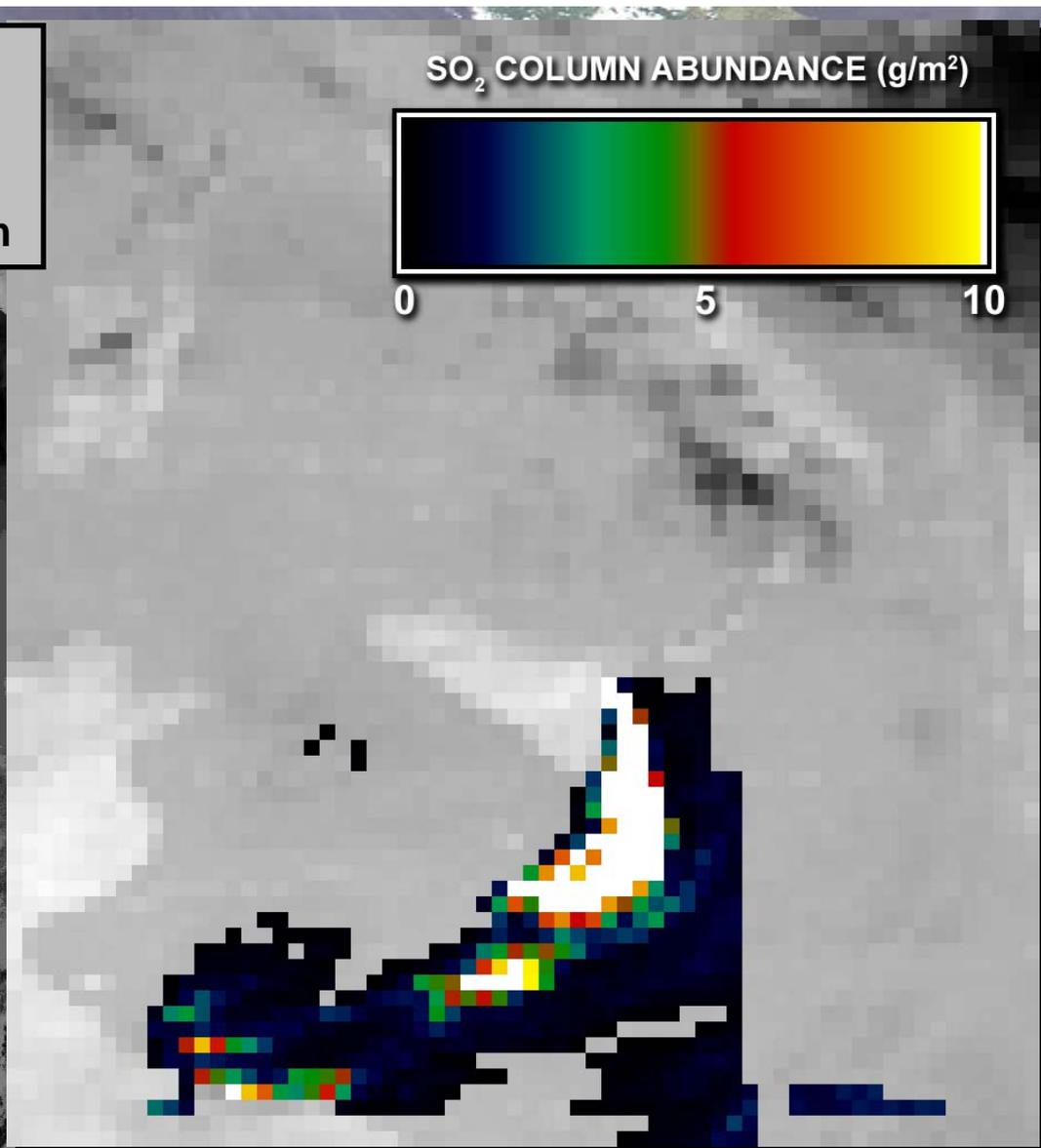
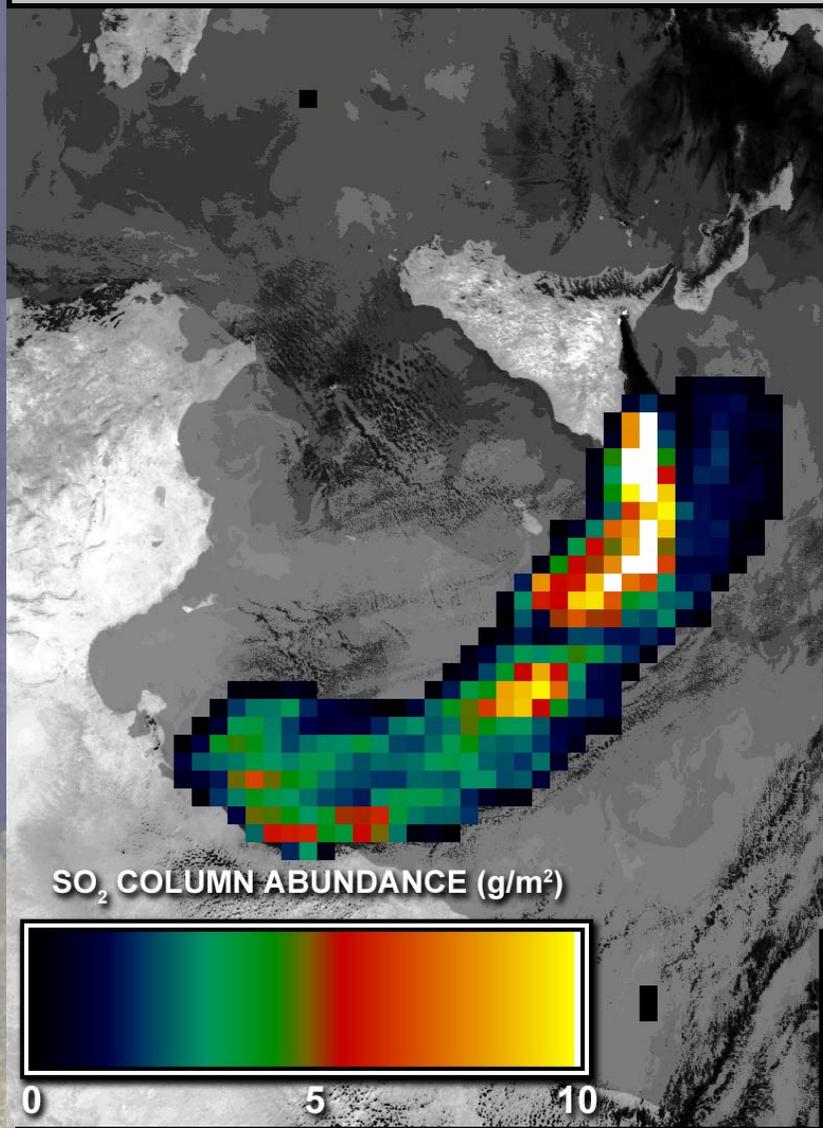
7.5

10



**MODIS-Aqua vs. AIRS
28 October 2002**

MODIS SO₂ Map Re-Sampled to ~ 17 km



Lower Spatial Resolution of AIRS Results in Less Sensitivity to Small (~ 3 g/m²) Changes in SO₂ Burden

MODTRAN Upgrade will Improve the Sensitivity of AIRS-Based SO₂ Retrievals

**MODIS Band 28:
Water Vapor
Channel**

Centered near 7.5 μm

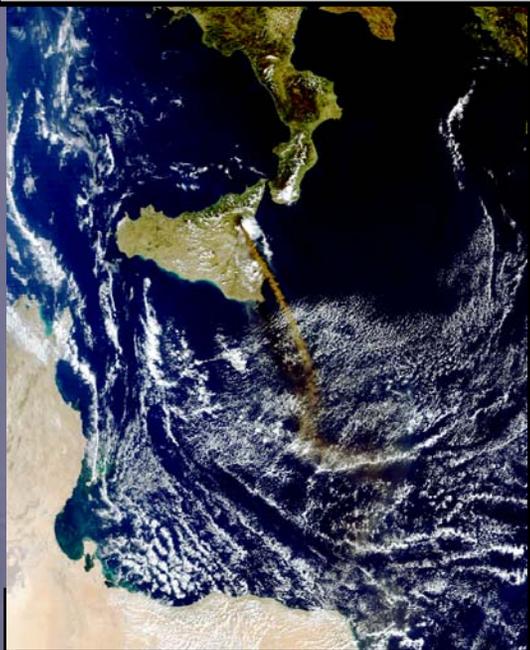
**Most of Atmospheric
Water Vapor is within
Five Kilometers of
Surface**

**Much of Etna Eruption
Plume is Above Water
Vapor**

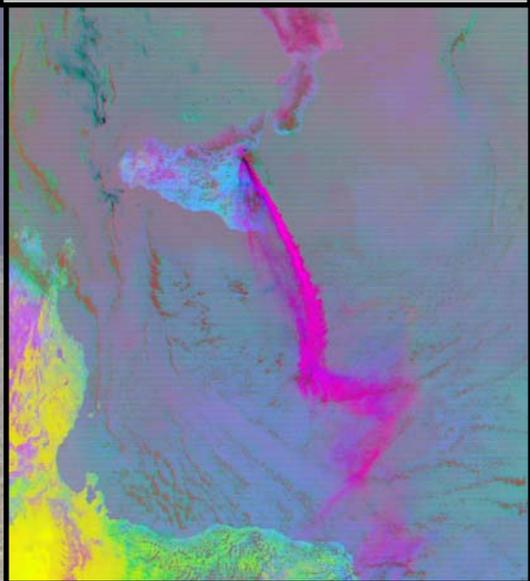
**Ground is Obscured,
Difficult to Model
Temperature Contrast
Between Plume and
Background**



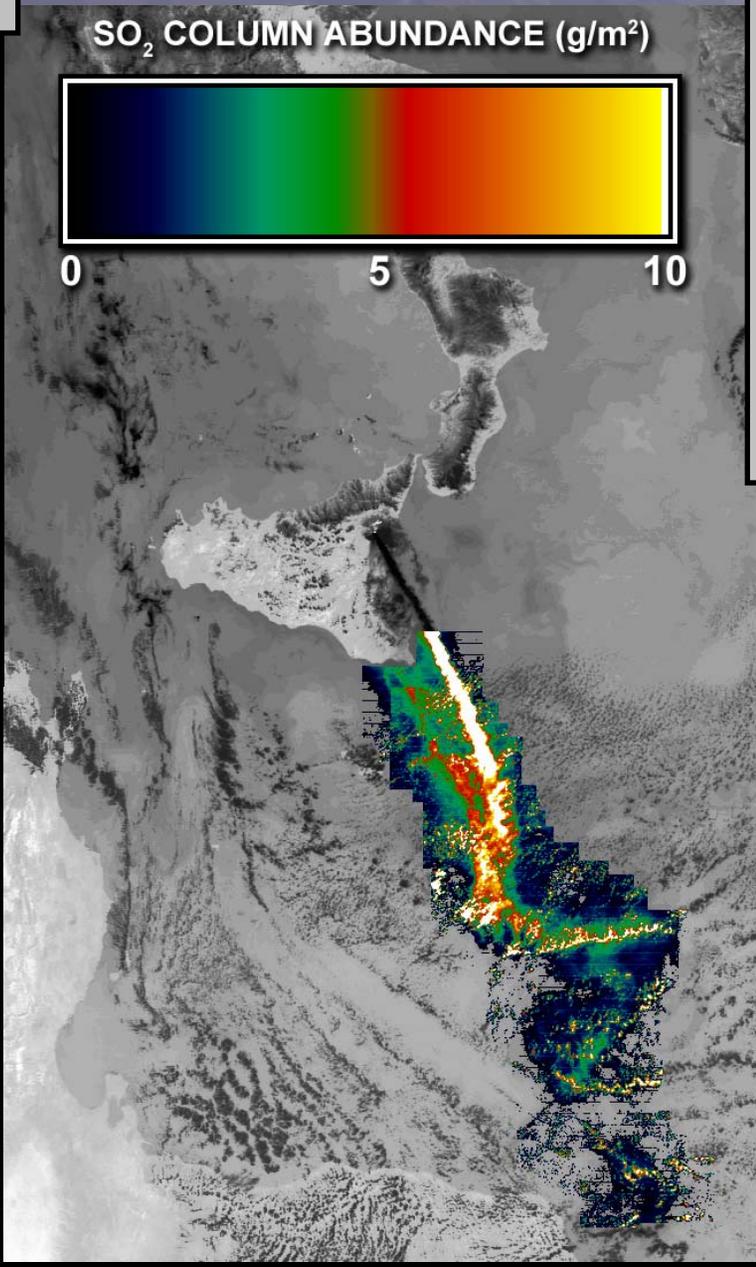
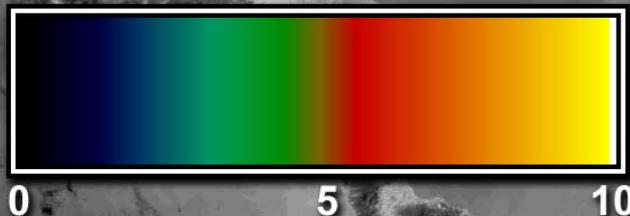
True Color Composite



TIR Color Composite



SO₂ COLUMN ABUNDANCE (g/m²)



MODIS-Terra

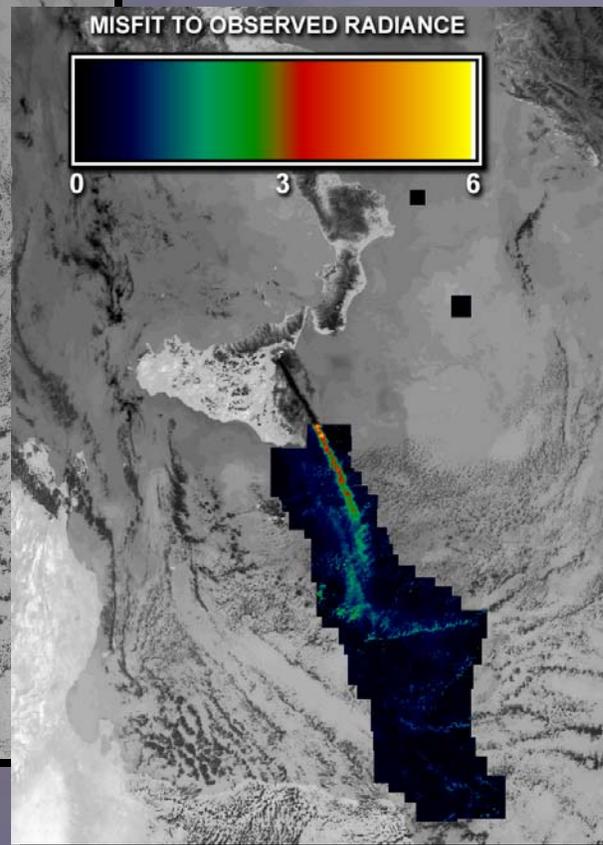
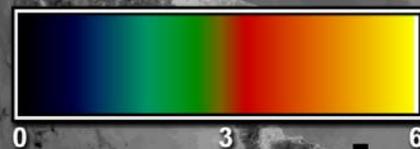
29 October 2002, 09:45 UTC

Plume Top Altitude: 6 km

Plume Base Altitude: 5 km

TIR False-Color Composite
Indicates Dominance of
Ash over SO₂

MISFIT TO OBSERVED RADIANCE

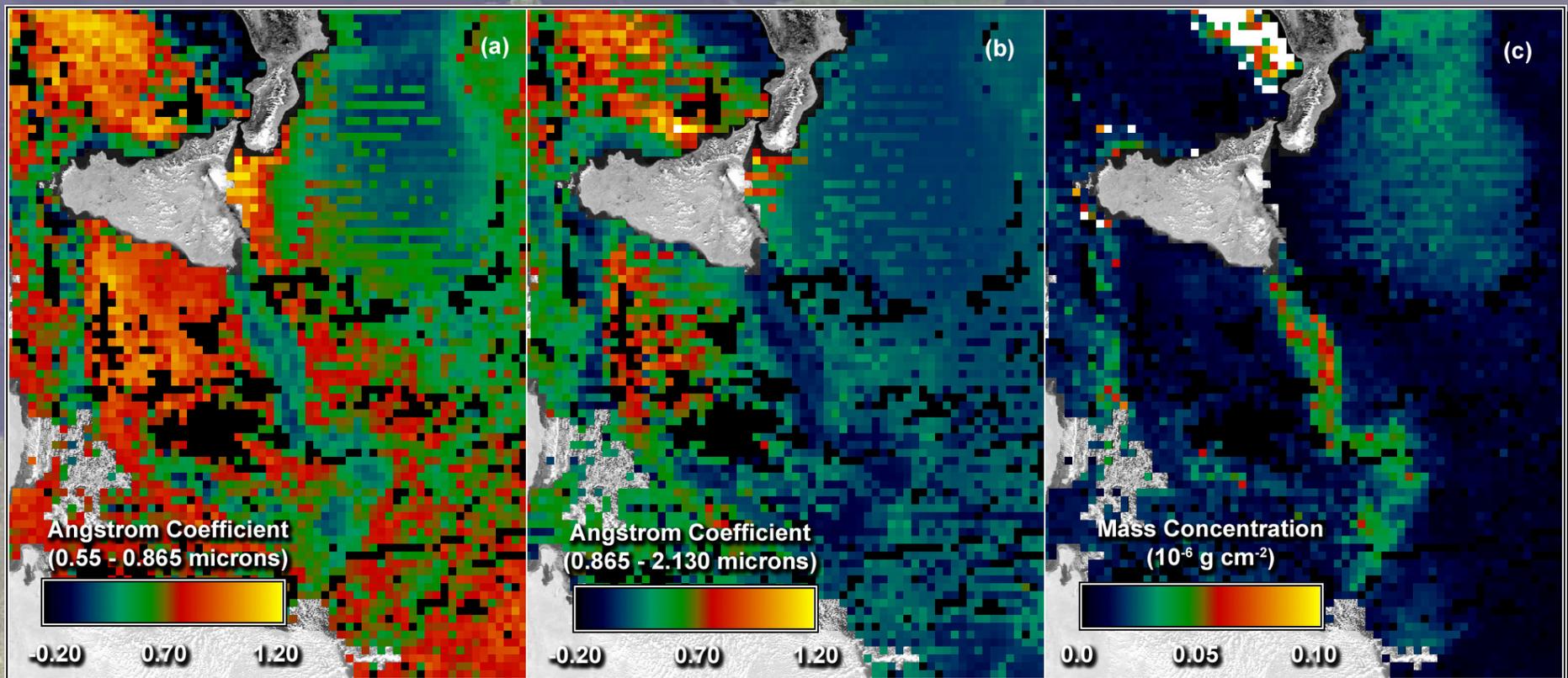


MODIS Aerosol Products

Mount Etna Eruption Plume, 29 October 2002

Standard Aerosol Products are Generated at Spatial Resolution of 10 km

Angstrom Coefficient: Smaller Values Indicate Coarser Aerosols





ASTER VNIR Color-Composite

30 December 2002, 10:00 UTC

Ash Plume From 2750 (m) Vent

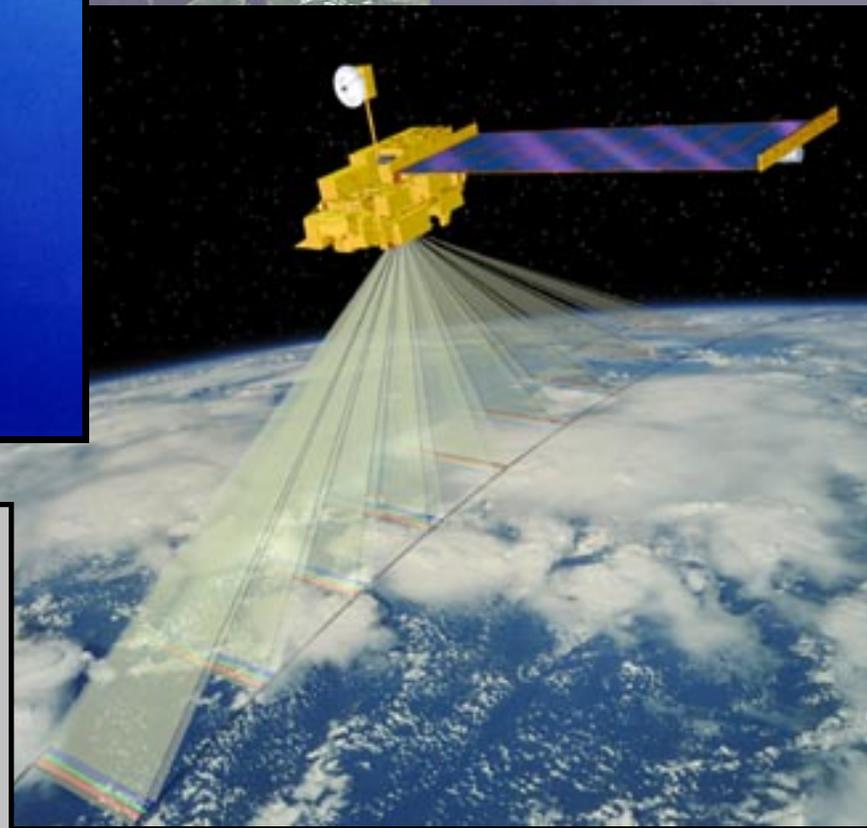
SO₂ Burden Generally < 1.0 g/m²

**Corresponding MODIS Data Yields
Virtually No SO₂**

**TIR False-Color Composites Do
Not Show Evidence of Ash or SO₂**



MISR
Multi-Angle Imaging Spectro-Radiometer



9 Cameras
Nadir (An), $\pm 26.1^\circ$ (Af, Aa) , $\pm 45.6^\circ$ (Bf, Ba),
 $\pm 60^\circ$ (Cf, Ca), $\pm 70.5^\circ$ (Df, Da)

4 Spectral Channels
Blue (446.4 nm), Green (557.5 nm),
Red, (671.7 nm), and NIR (866.4 nm)



Disparities (Displacements) Resulting from Height and Wind

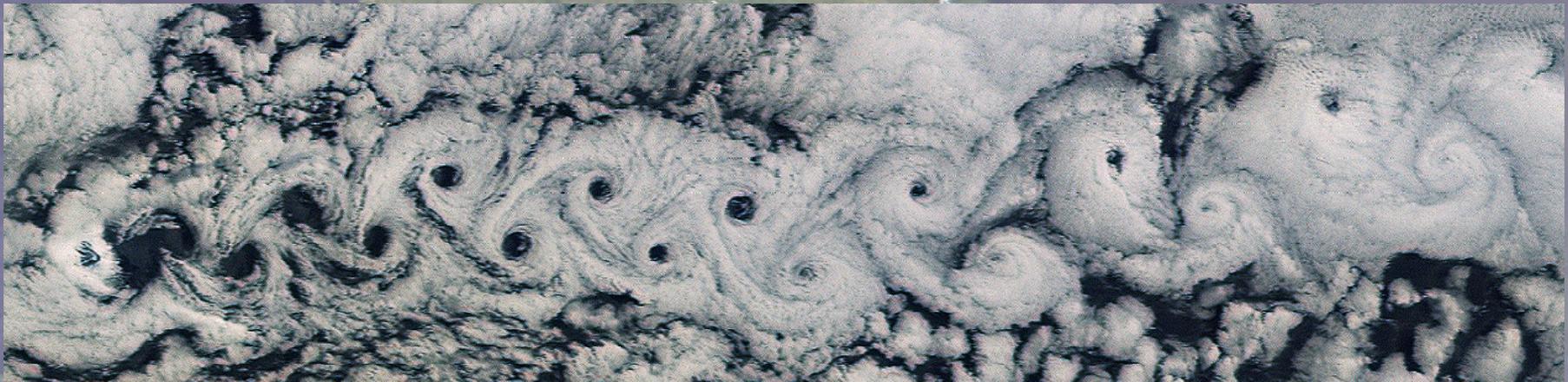
Along-Track Disparity for Any Features Above or Below Reference Elevation

$$\text{Ellipsoid-Projected Radiance: } \Delta y = \pm h \tan \Theta$$

7-Minute Delay Between Df and Da Images Results in Wind-Induced Disparities

$$\text{Cross Track Disparity: } \Delta x = \pm V_x \Delta t, \text{ Along-Track Disparity: } \Delta y = \pm V_y \Delta t$$

Both Types of Disparity Used to Estimate Cloud Height and Wind Speed

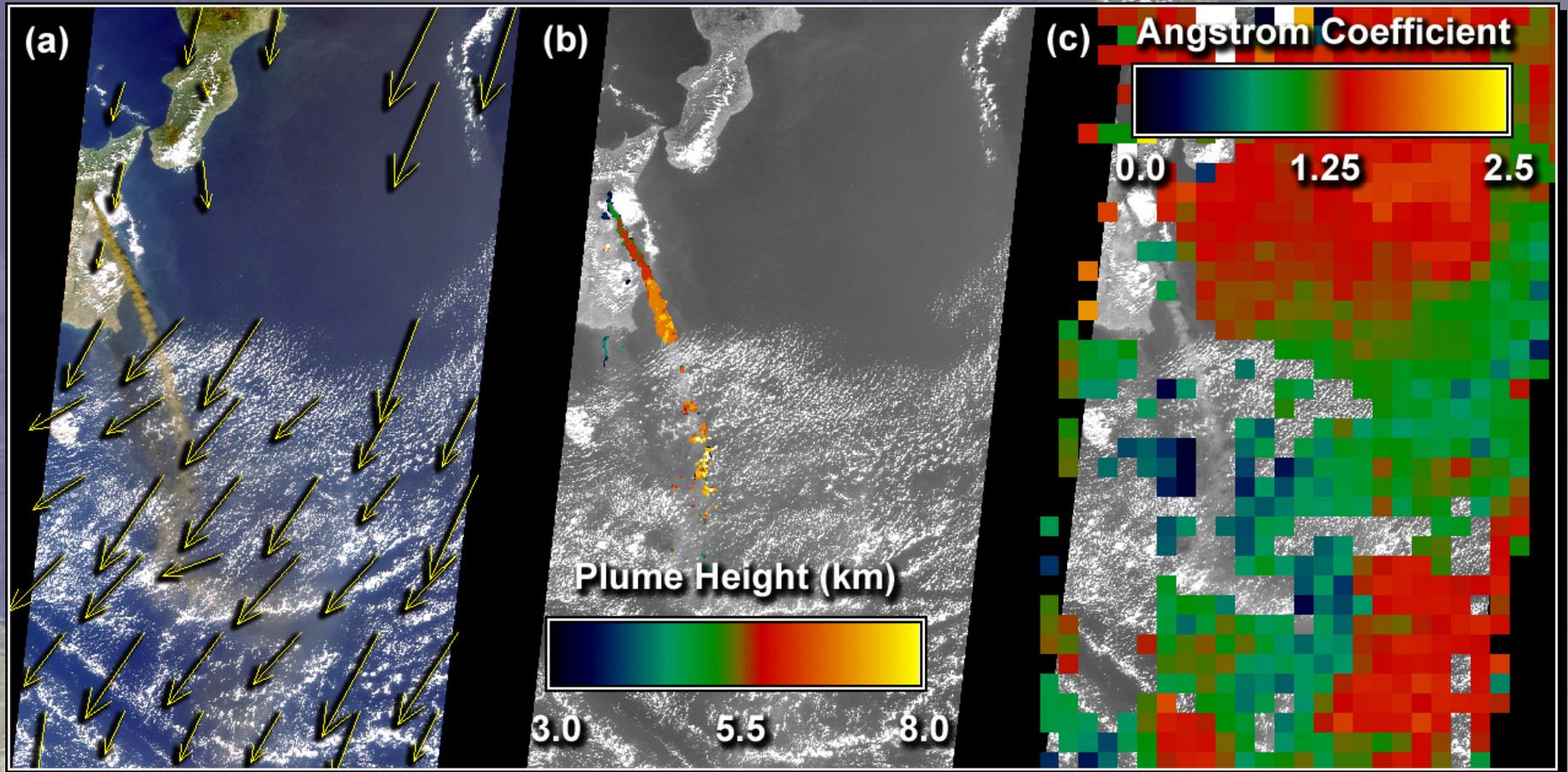


von Karman Vortices, Jan Mayen Island, Norway

MISR Data Products

Mount Etna Eruption Plume

29 October 2002



Wind Velocity Range: 2 – 20 m/s

MISR_SHIFT Tool (V.3.0) #1

Zoom Factor: 1

	Df	Cf
Line		
Sample		

Cameras in Loop

Df
 Cf
 Bf
 Af
 An
 Aa
 Ba
 Ca
 Da
 All

Current Camera: Df | # Loops: 5 | Delay (sec): 0.200000
 Play Loop
Quit

Cloud Height (km): 0.000000 | Cross-Track Wind (m/s): 0.000000 | Along-Track Wind (m/s): 0.000000
 Fine Tuner
Associate Pixels

	Zenith (theta)	Rel. Time (s)	Azimuth (phi)	X Offset (m)	Y Offset (m)
Df	-70.4000	-204.000	0.000000	0.000000	0.000000
Cf	-60.1000	-145.000	0.000000	0.000000	0.000000
Bf	-45.7000	-93.0000	0.000000	0.000000	0.000000
Af	-26.1000	-45.6000	0.000000	0.000000	0.000000
An	0.000000	0.000000	0.000000	0.000000	0.000000

MISR_Shift

**Mapping Plume
Geometry and Wind
Vectors @ 275 m**

MISR_SHIFT Tool (V.3.0) #1

Zoom Factor: 1

Cameras in Loop

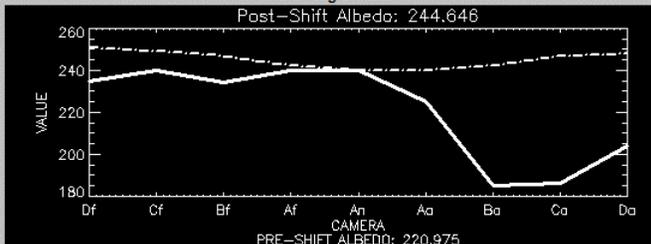
Df
 Cf
 Bf
 Af
 An
 Aa
 Ba
 Ca
 Da
 All

Current Camera: Df | # Loops: 5 | Delay (sec): 0.200000
 Play Loop
Quit

Cloud Height (km): 5.00000 | Cross-Track Wind (m/s): -6.00000 | Along-Track Wind (m/s): -12.5759
 Fine Tuner
Associate Pixels

	Zenith (theta)	Rel. Time (s)	Azimuth (phi)	X Offset (m)	Y Offset (m)
Df	-70.4000	-204.000	0.000000	1224.00	-11476.2
Cf	-60.1000	-145.000	0.000000	870.000	-6871.76
Bf	-45.7000	-93.0000	0.000000	558.000	-3954.13
Af	-26.1000	-45.6000	0.000000	273.600	-1876.01
An	0.000000	0.000000	0.000000	0.000000	0.000000
Aa	26.1000	45.6000	0.000000	-273.600	1876.01
Ba	45.7000	93.0000	0.000000	-558.000	3954.13
Ca	60.1000	145.000	0.000000	-870.000	6871.76
Da	70.4000	204.000	0.000000	-1224.00	11476.2

Multi-Angle Plots

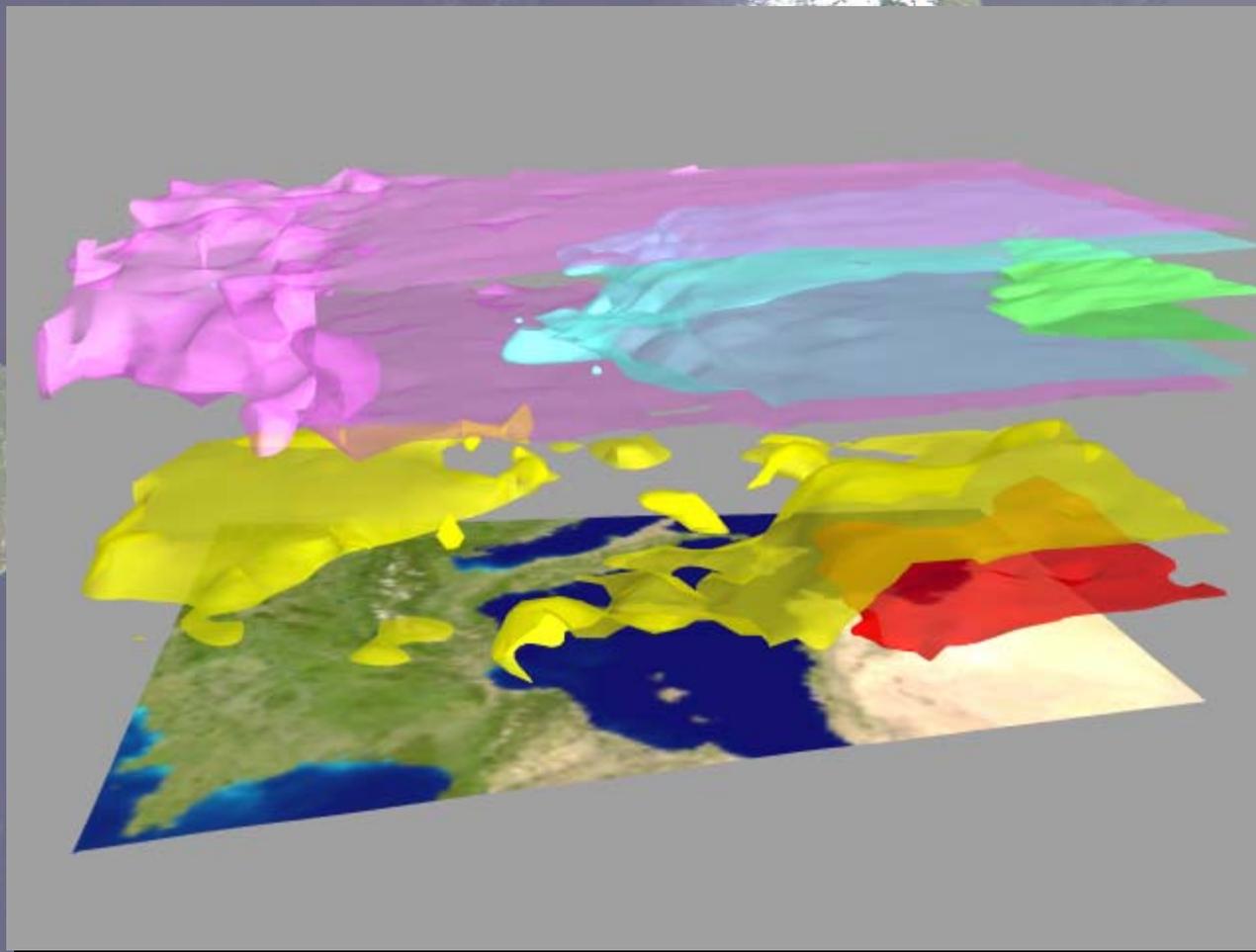
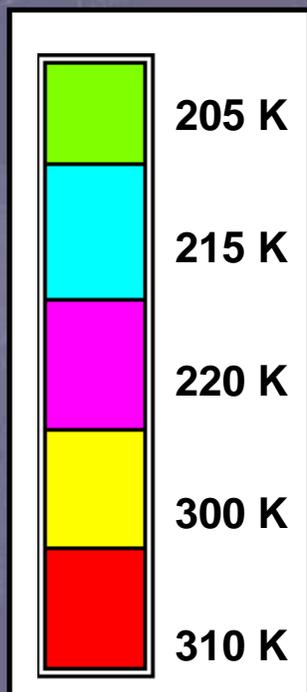


Cursor Position

	Df	Cf	Bf	Af	An	Aa	Ba	Ca	Da
Line	772	755	744	737	730	723	716	705	688
Sample	577	578	579	580	581	582	583	584	585

AIRS Level 2 Temperature Retrievals

8 September 2002



CONCLUDING REMARKS...

Retrievals Appear to be Consistent

Three Days of Activity; Three Instruments

MAP_SO2 Does Not Introduce Systematic Bias

**AIRS-Based Retrievals in General Agreement with
MODIS-Based Retrievals**

Future Efforts

**Focus on Days with Terra and Aqua Overpasses
(eg. 27 Oct 2002)**

Begin ASTER Processing (30 December 2002)

Incorporation of MISR-Based Plume Geometry

MODTRAN Upgrade

**Incorporation of AIRS-Based Atmospheric
Profiles**