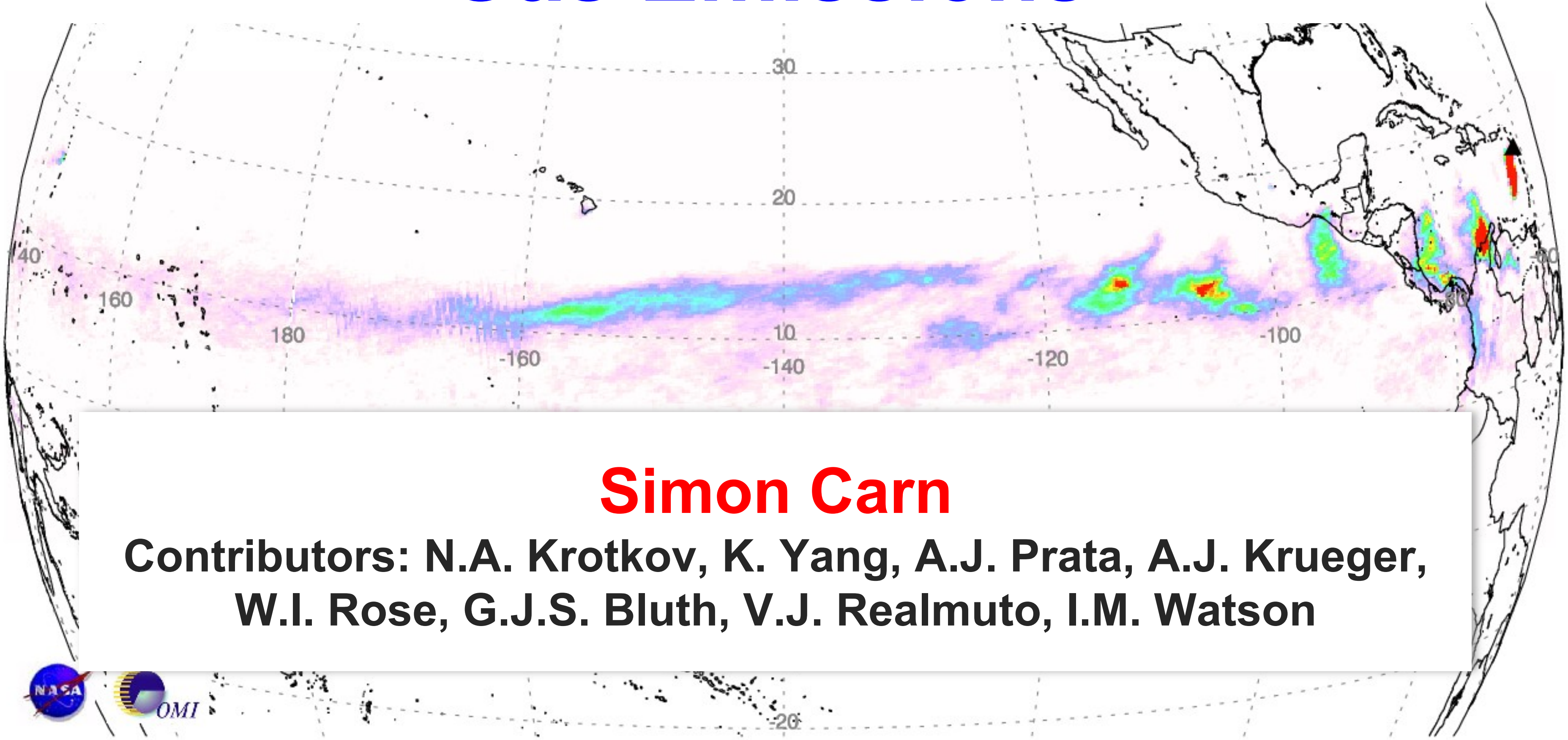
Remote Sensing of Volcanic Gas Emissions



Simon Carn

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IUGG Workshop VW02, Melbourne, Australia, June 2011

Overview

- Motivation for volcanic gas measurements
- Development of satellite remote sensing of SO_2
- Remote sensing theory (focus on SO_2 measurements)
- Survey of space-based SO_2 sensors
  - UV sensors: OMI, TOMS, GOME-2
  - IR sensors: MODIS, ASTER, TOVS, AIRS, IASI
- Application of Aura/OMI SO_2 data to volcano monitoring
  - SO_2 burden calculations
  - Burdens vs. emission rates
- Satellite sensor synergy: NASA's A-Train
- Ground-based FTIR multi-gas measurements

Volcanic gas compositions

mol%	Nyiragongo (DR Congo) RIFT	Kilauea* (Hawaii) HOTSPOT	Merapi* (Indonesia) SUBDUCTION	Etna* (Sicily) SUBDUCTION
H_2O	70	37	91	48
CO_2	24	49	5	20
SO_2	5	12	1	31
CO	1	2	0.1	0.4
HCl	0.3	0.08	0.6	-
HF	0.1	-	0.04	-

Trace constituents: CH_4, N_2, BrO, Zn, Cu, Hg, Au, As, Re, He, Ne, Ar…..

*Symonds *et al.* [1994]

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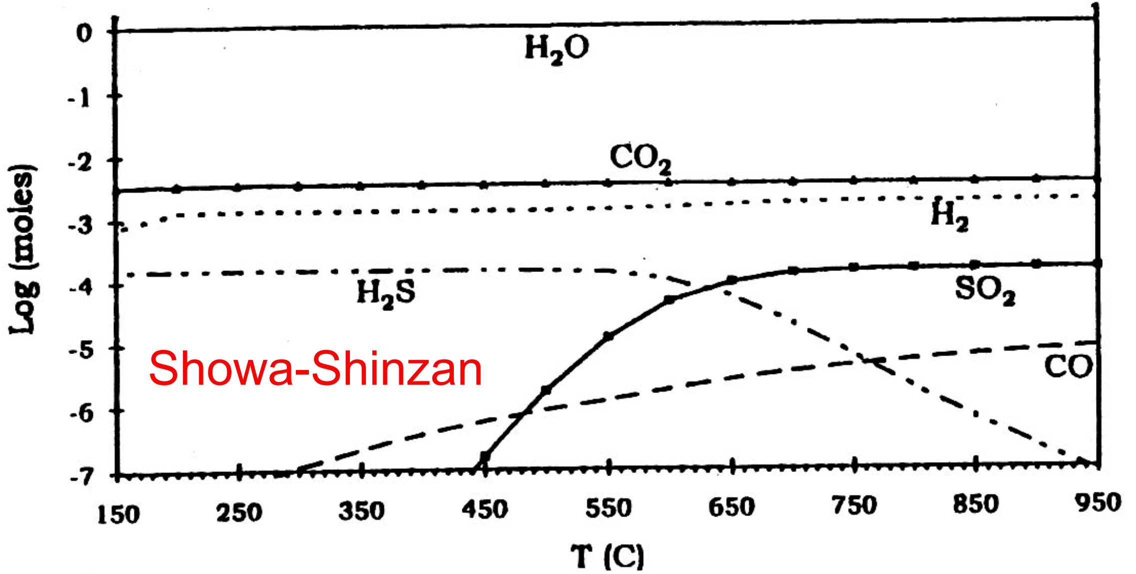
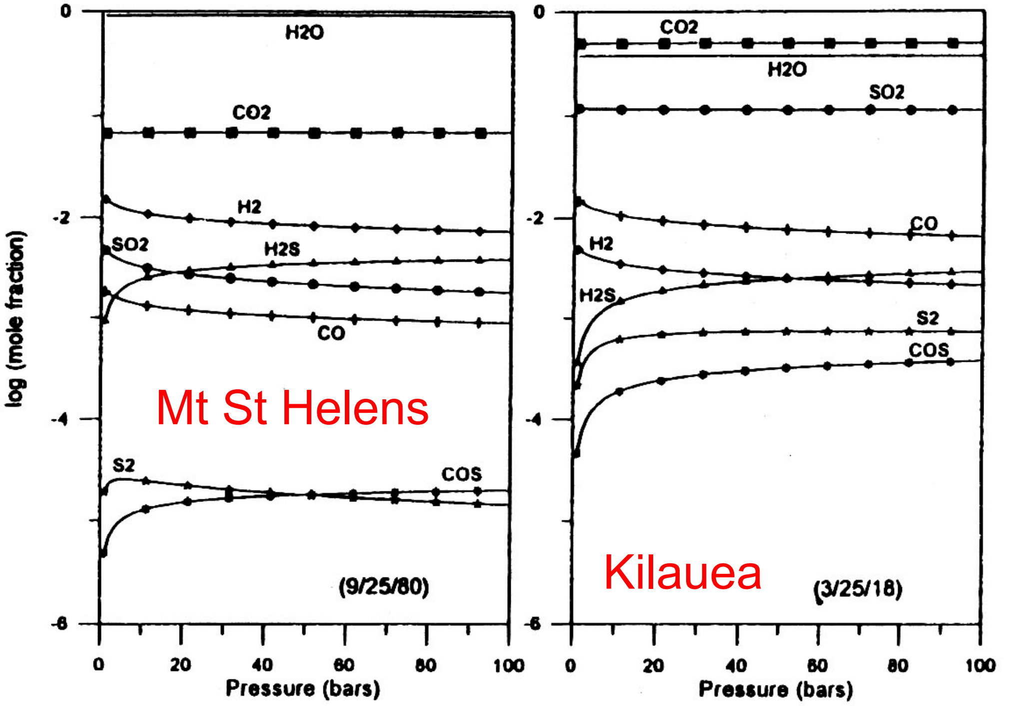
Motivation for volcanic SO_2 measurements

- SO_2 is the most abundant gas in volcanic emissions that can be easily measured by remote sensing techniques
  - Low background concentrations (cf. H_2O, CO_2)
  - No other major sources above the planetary boundary layer (PBL)
  - Well-characterized spectral absorption bands (UV, IR, microwave)
- Released from magma at high temperature and low pressure
  - Can indicate fresh magma rising within a volcanic system
  - Signature of magmatic eruptions with potential for high altitude eruption columns
  - H_2S (hydrogen sulfide) is the more stable sulfur species at high pressures and low temperatures (e.g., fumarole fields)
- Environmental, health and climate impacts (sulfate aerosol)

Temperature and pressure effects on volcanic gas species



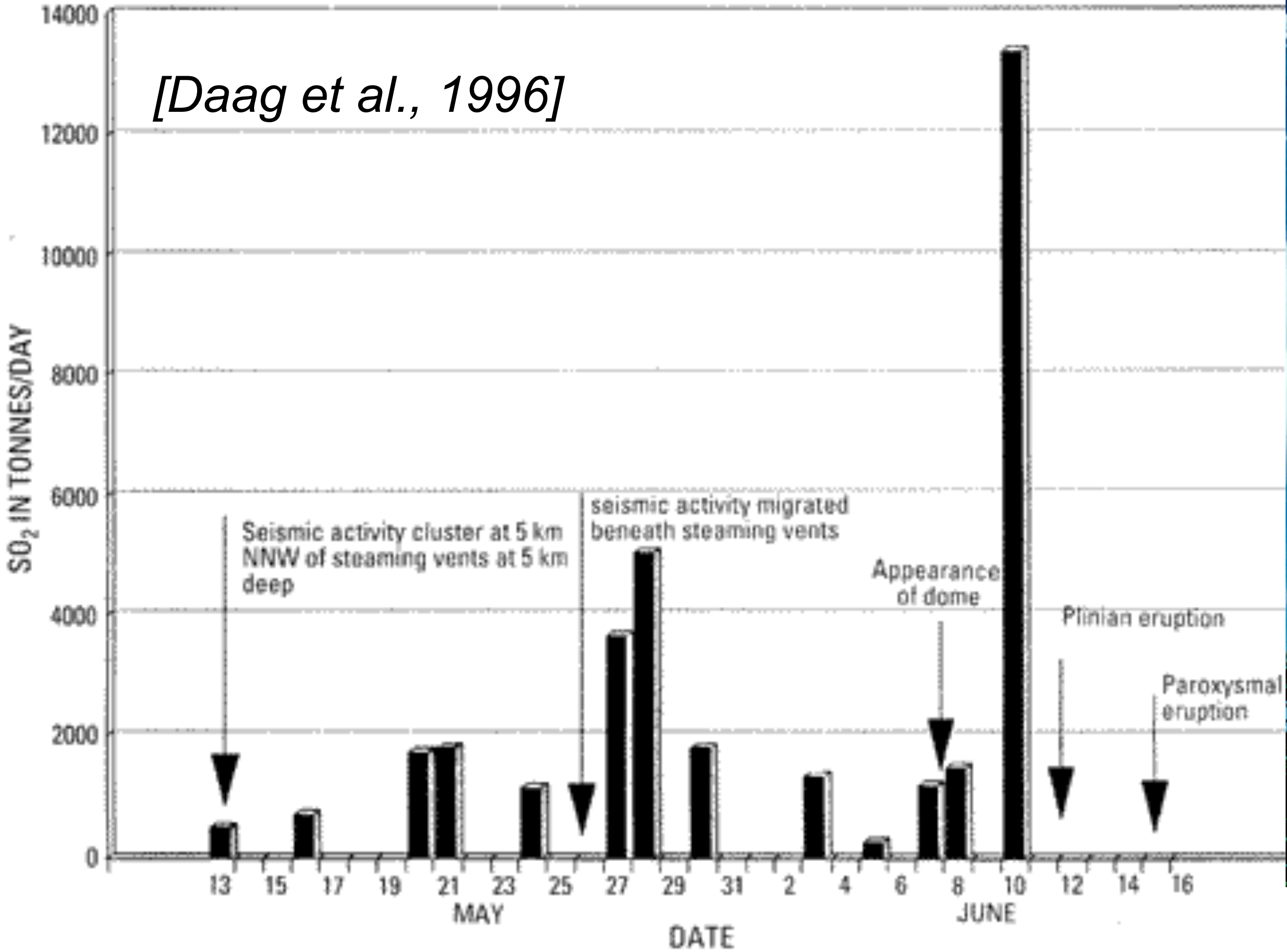
$$SO_2 + 3H_2 = H_2S + 2H_2O$$



$$\log (SO_2/H_2S) =$$
$$\log K_T - 3 \log (H_2/H_2O) -$$
$$\log P \,.\, X_{H2O}$$

[Symonds et al., Rev. Mineral., 1994; Aiuppa et al., 2004]

Pre-eruptive volcanic degassing


[Daag et al., 1996]


Pinatubo 1991

- Increase in SO_2 emissions prior to a major eruption

SO_2 flux and LP seismicity at Galeras (Colombia)

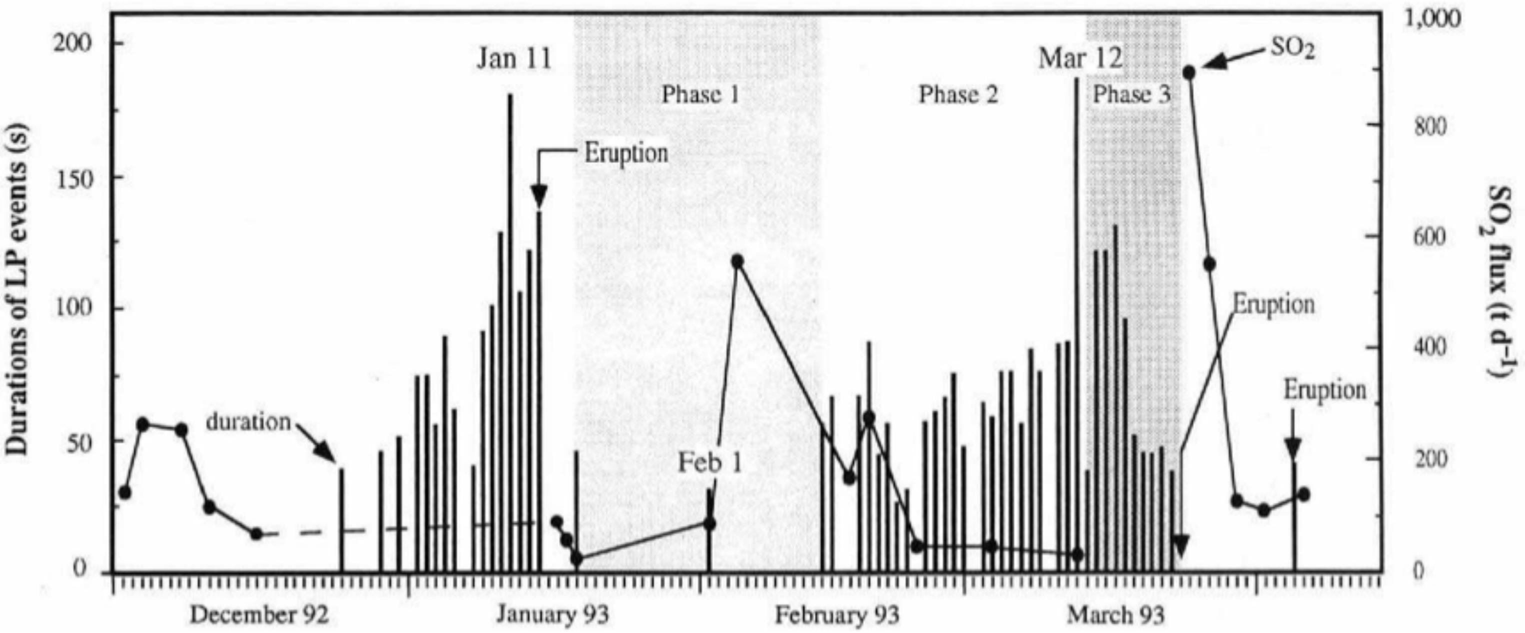


FIG. 2 SO_2 flux in metric tons per day (●) and durations of recorded long-period (⩾22 s) events (vertical bars) plotted against time, also showing the eruptions during the same time period. The SO_2 flux is measured using correlation spectrometer (COSPEC) methodology[15]. Uncertainty depends mostly on recorded wind speeds. The error at Galeras is assumed to be ±20%, in general, and ±40%, in the worst case. True SO_2 flux is likely to be higher than the calculated value. The three phases reflect changes in fluid dynamics along pathways through which gases flow, as interpreted from seismic and gas flux data.

[Fischer et al., Nature, 1994]

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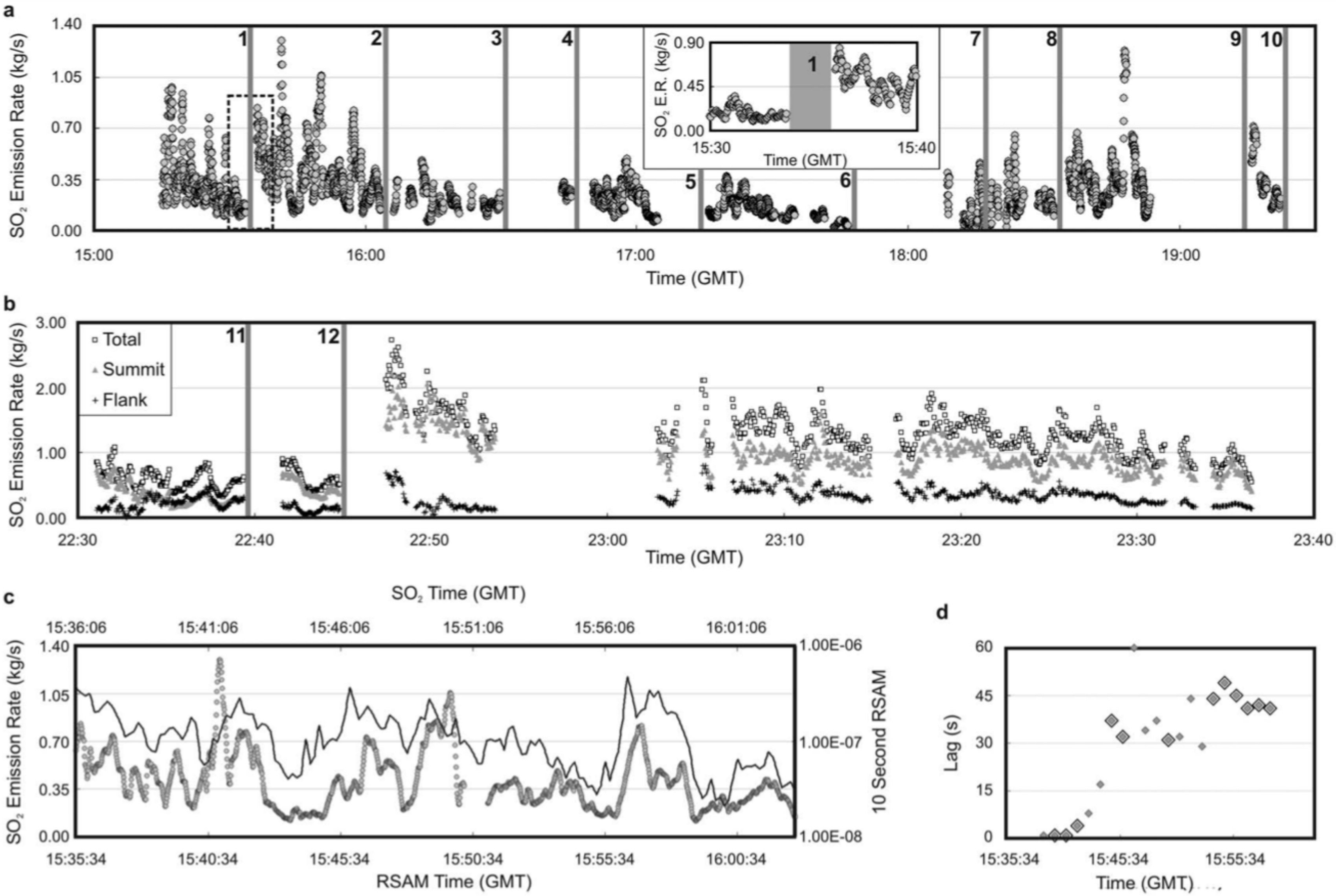
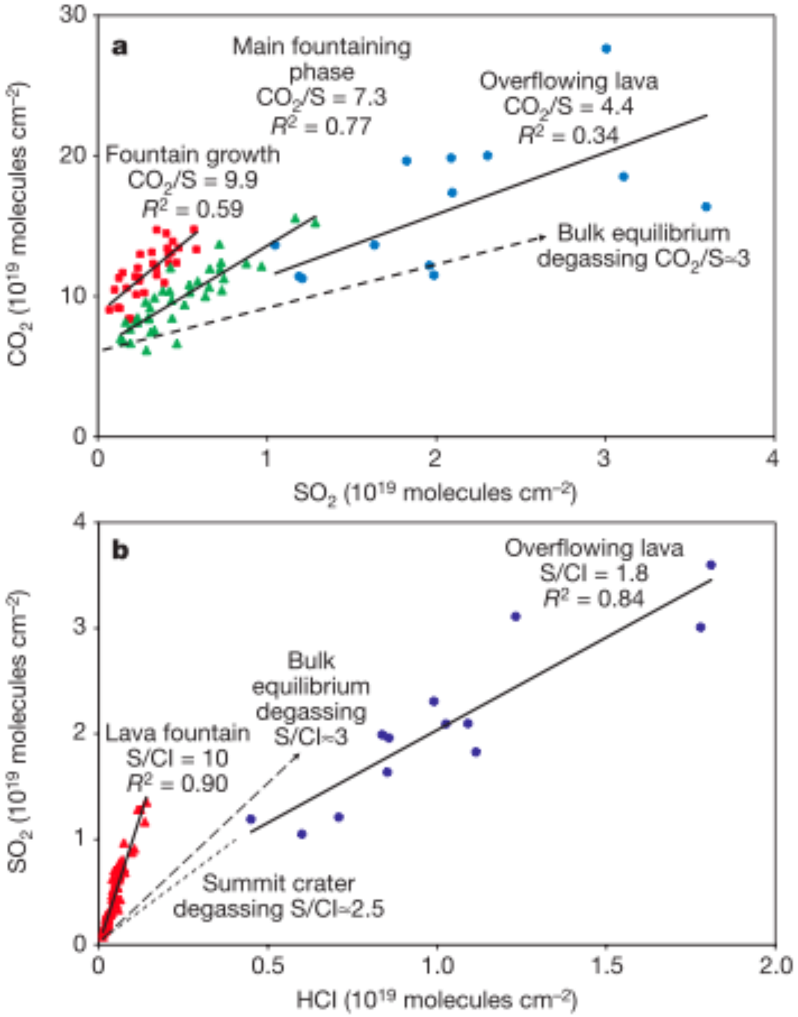
SO$_2$ emissions and RSAM at Fuego (Guatemala)



[Nadeau et al., GRL, 2011]

FTIR gas ratios at Etna



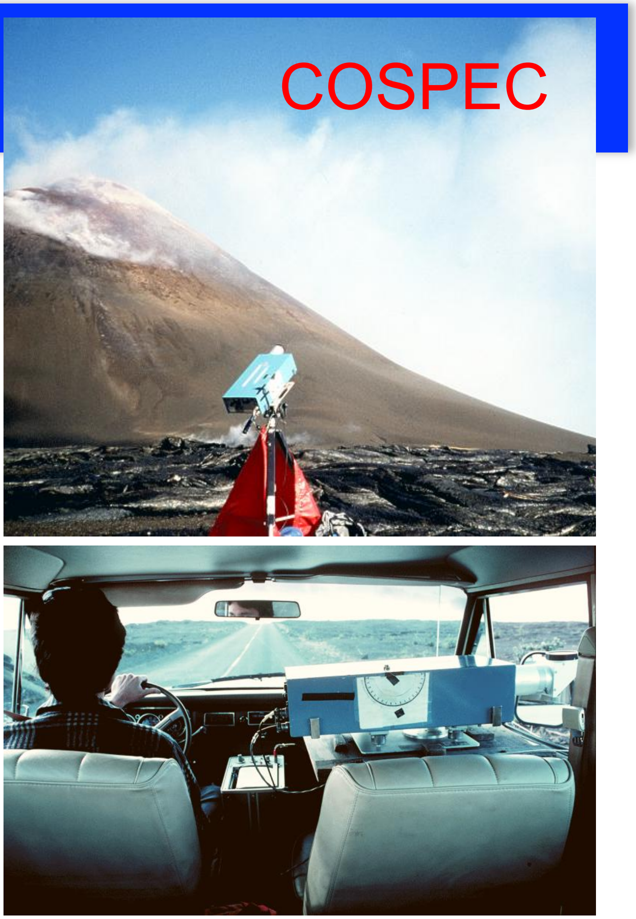
- Volatile solubility: F/Cl ≥ $H_2O > SO_2 > CO_2$
- Petrological data needed to interpret gas data

[Allard et al., 2005]

Volcanic gas monitoring techniques

Chemical sensors

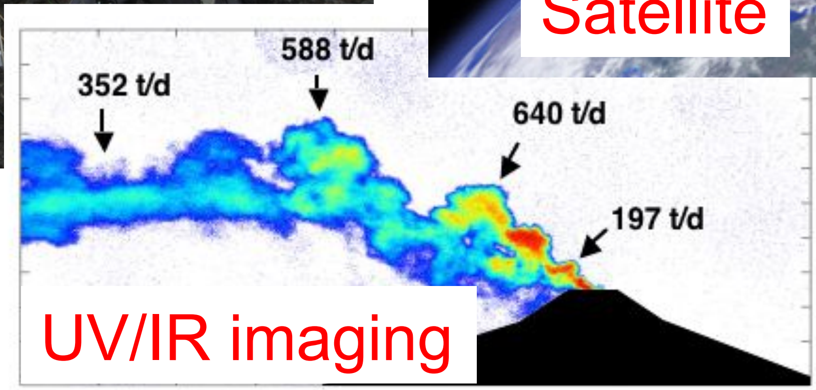
Mini UV spec



COSPEC

FTIR

Satellite



UV/IR imaging

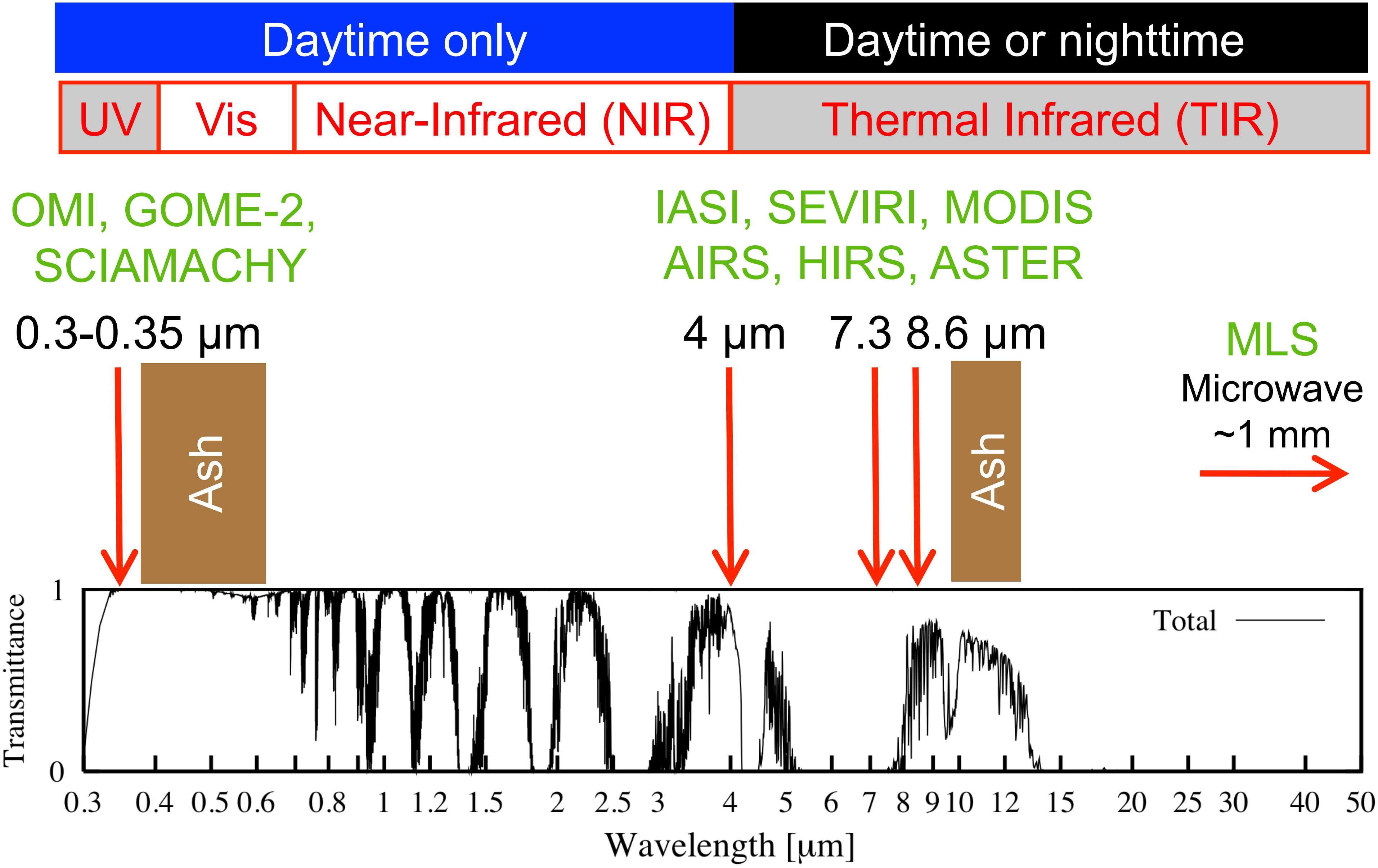
Direct sampling

Volcanic gas monitoring techniques

Technique	Gases	Hazard	Cost	Frequency
Direct sampling	Total gas composition	High	Low	Low
In-situ sensors	SO_2, H_2S, CO_2	High	Low	High
COSPEC	SO_2	Moderate	$10k	≥ Minutes
Mini-DOAS	SO_2, BrO, NO_2, ClO	Moderate	$10k	1 Hz
FTIR	SO_2, CO_2, H_2O, HCl, HF	Moderate	$40k	1 Hz
UV camera	SO_2	Low-Mod	$20k	>1 Hz
IR camera	SO_2	Low-Mod	$20k	Seconds
Satellites	SO_2, HCl (strat.), CO_2?	None	Free	≥15 minutes

- In addition, variation in spatial coverage and atmospheric interference

Electromagnetic spectrum – SO_2 absorption



Daytime only

Daytime or nighttime

UV

Vis

Near-Infrared (NIR)

Thermal Infrared (TIR)

OMI, GOME-2,
SCIAMACHY

IASI, SEVIRI, MODIS
AIRS, HIRS, ASTER

0.3-0.35 μm

4 μm

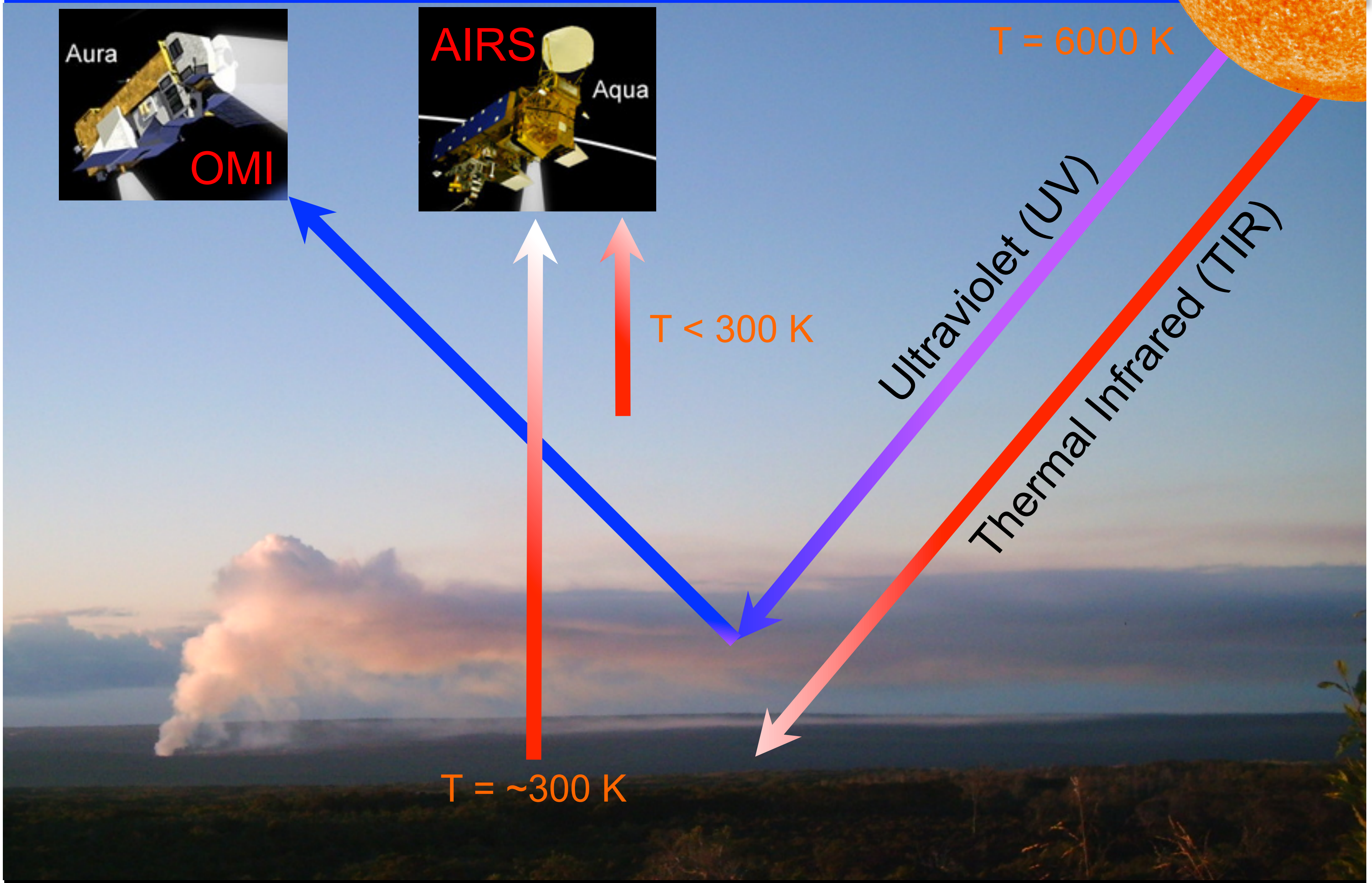
7.3 8.6 μm

MLS
Microwave
~1 mm

Ash

Ash

UV and IR remote sensing



Aura

OMI

AIRS

Aqua

T = 6000 K

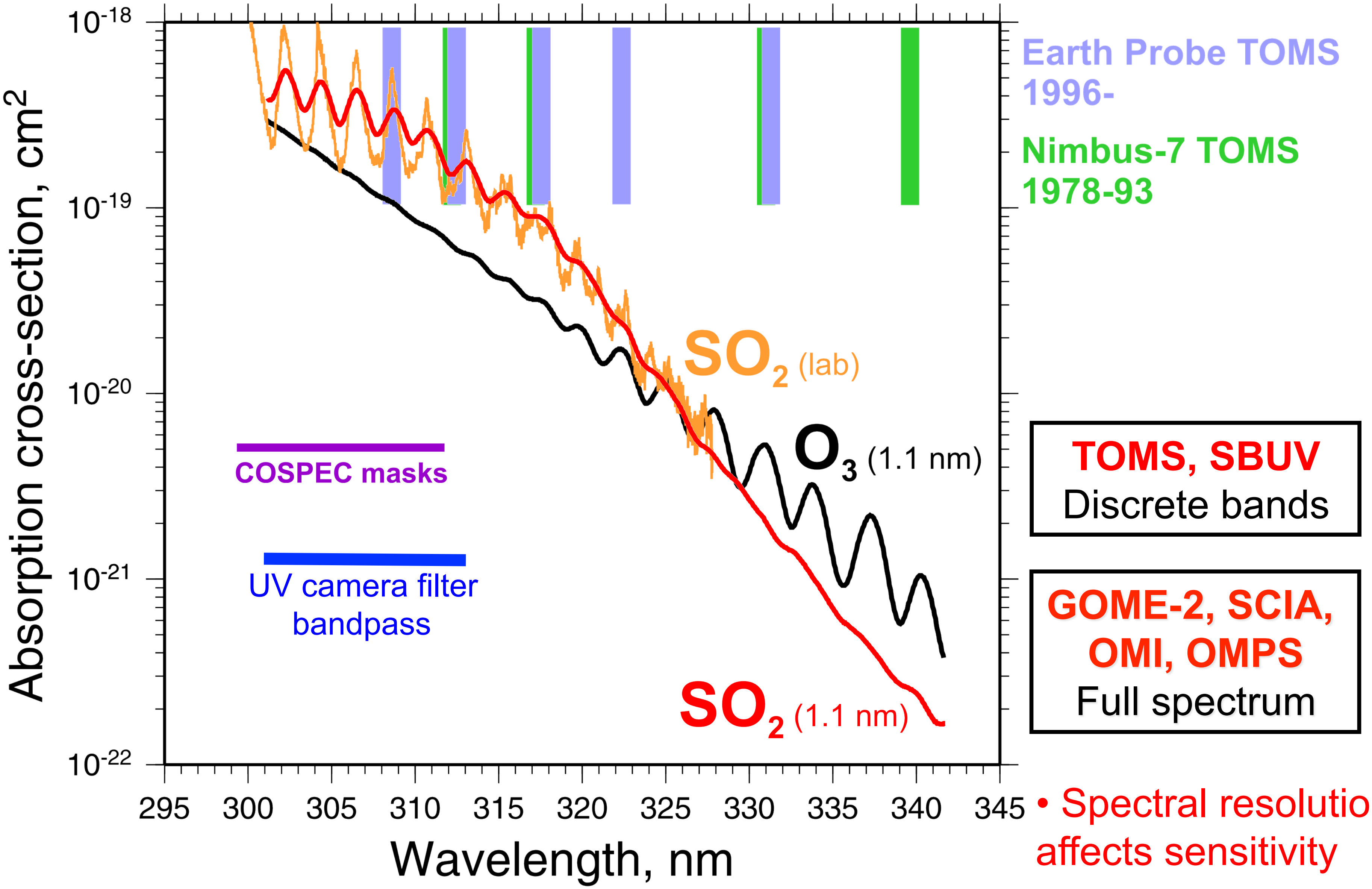
Ultraviolet (UV)

Thermal Infrared (TIR)

T < 300 K

T = ~300 K

UV SO_2 and O_3 absorption spectra and instrument bands

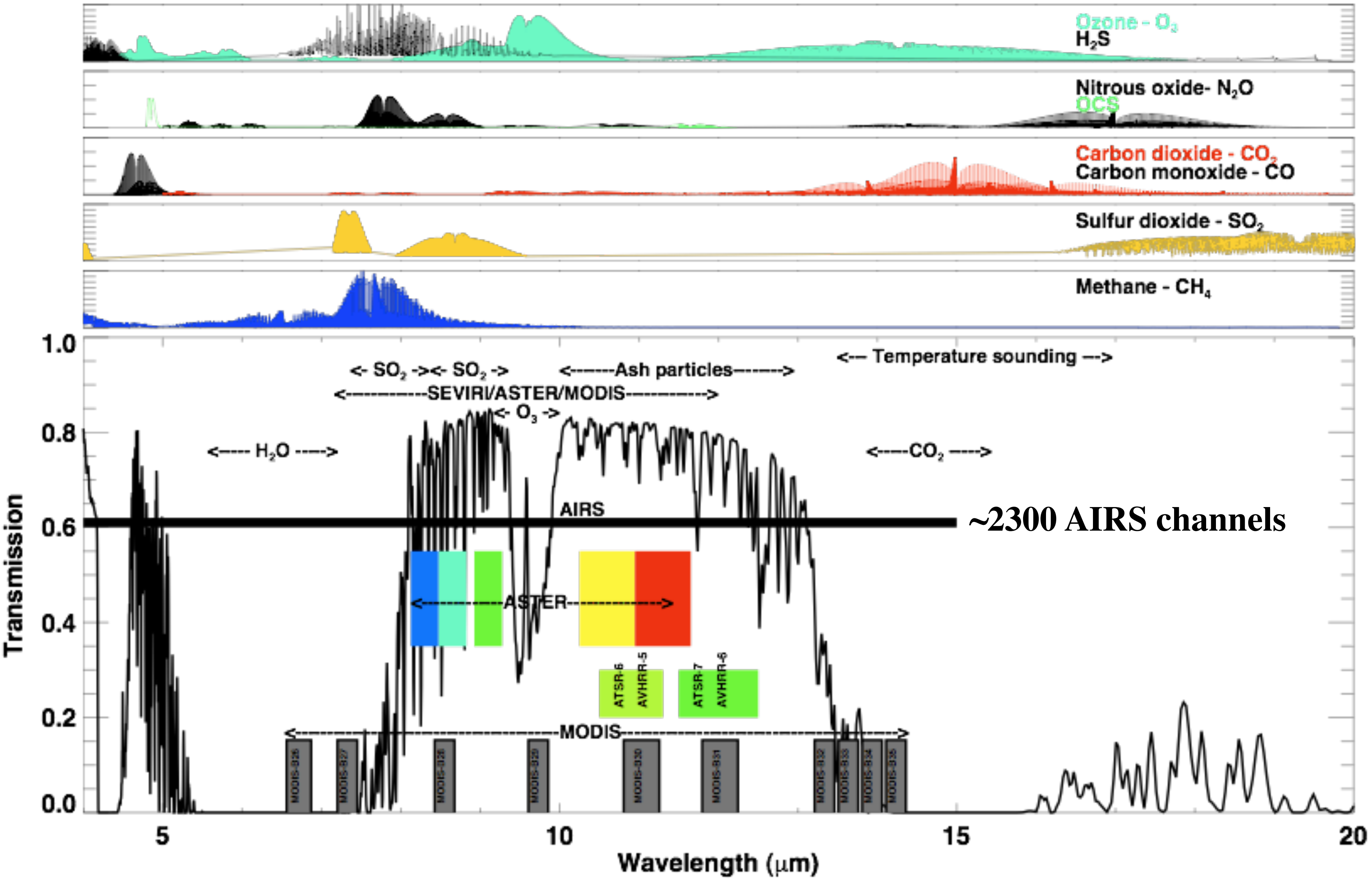


TOMS, SBUV
Discrete bands

GOME-2, SCIA, OMI, OMPS
Full spectrum

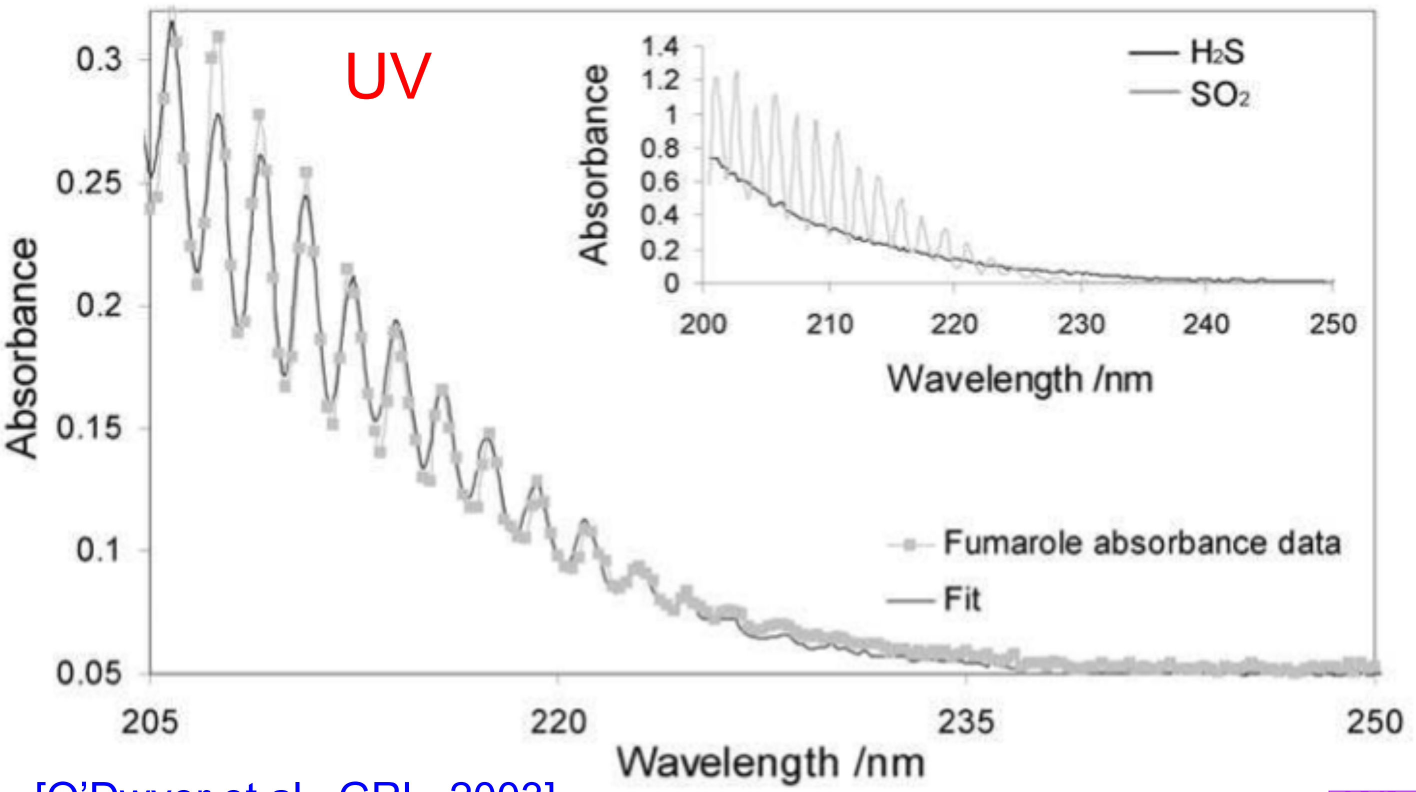
- Spectral resolution affects sensitivity

IR-active trace gases and instrument channels



~2300 AIRS channels

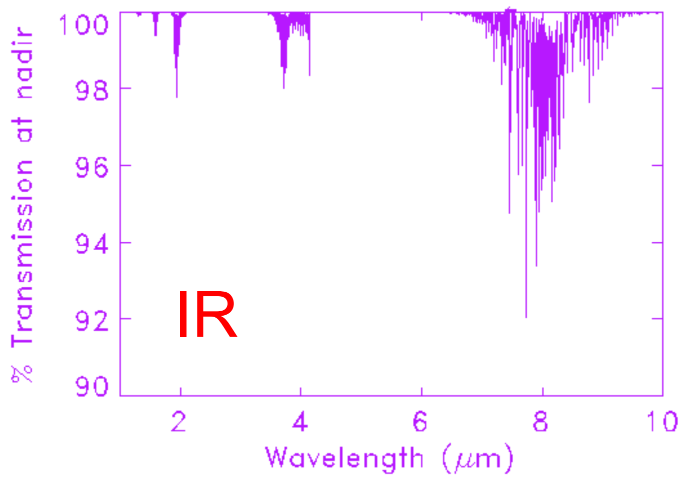
What about H_2S?



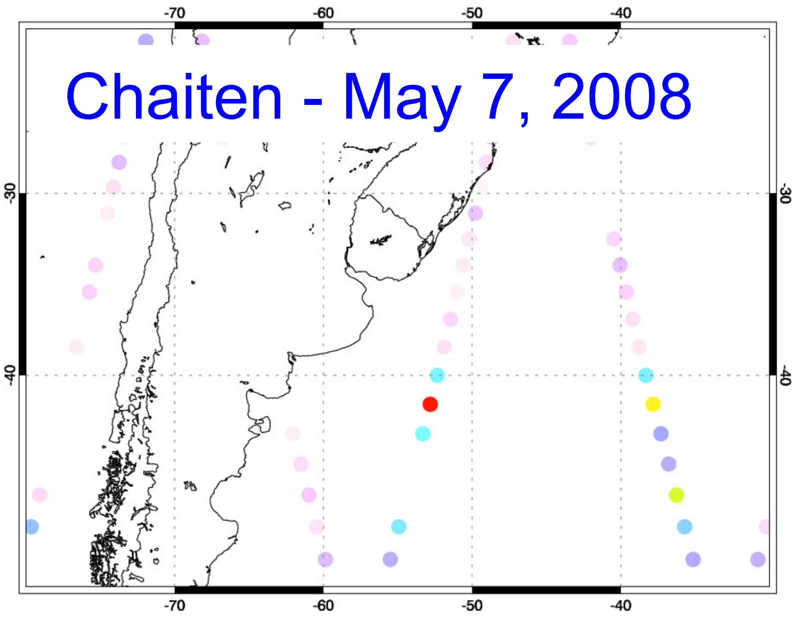
$SO_2 + 3H_2 =$
$H_2S + 2H_2O$

[O'Dwyer et al., GRL, 2003]

- May be a significant component of total S budget at some volcanoes
- Mid-UV absorption bands require active source
- IR absorption bands are very weak

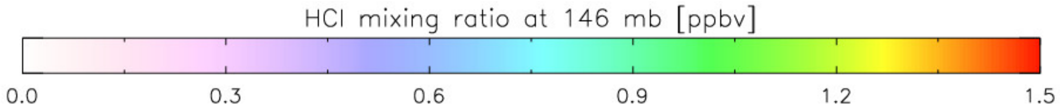


Detection of HCl in volcanic clouds from space



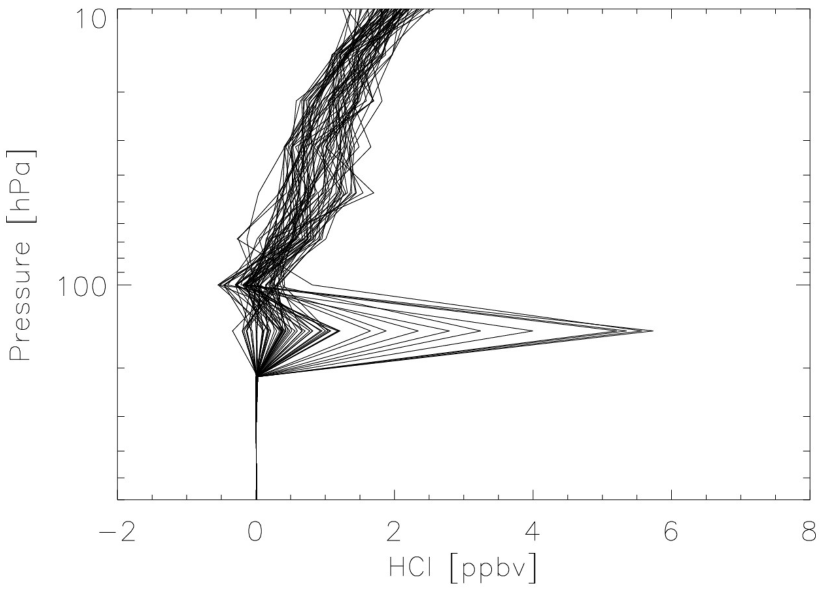
Microwave Limb Sounder (MLS)

- HCl only detected in May 6 eruption cloud
- Maximum HCl vmr of ~2 ppbv at 146 hPa
- SO_2/HCl (mass) = ~30
- HCl mass loading = ~100 tons



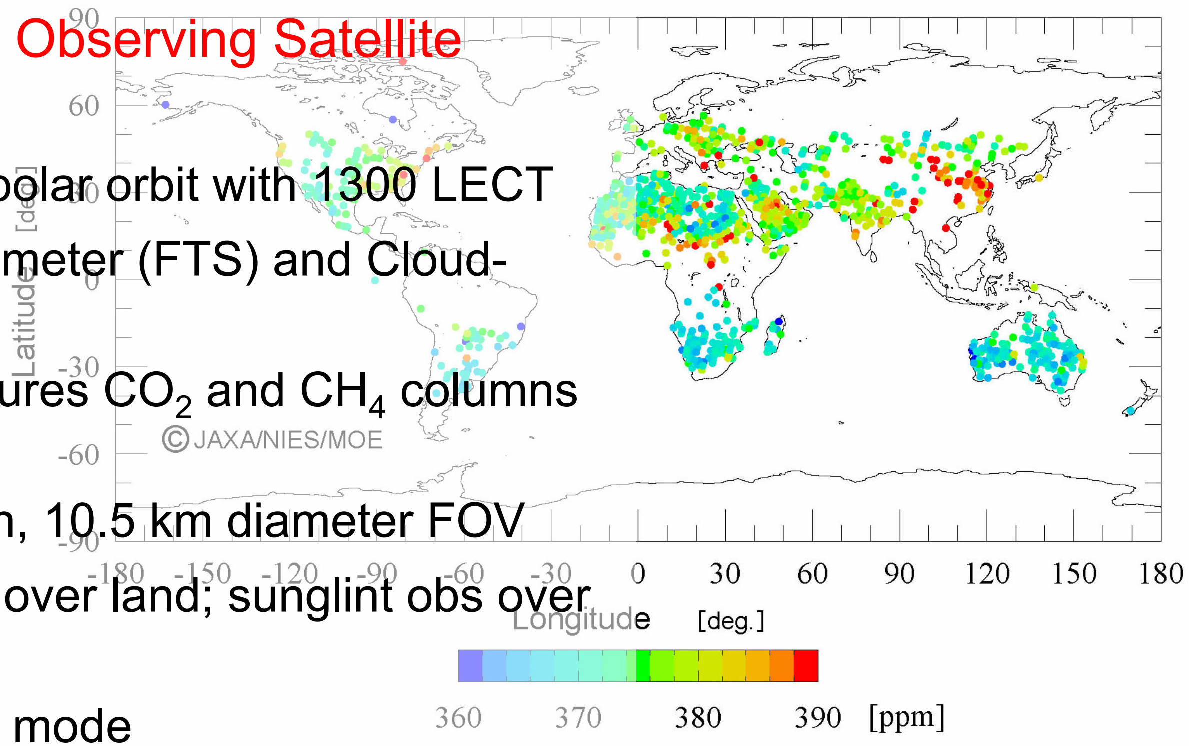
MLS volcanic HCl (ppbv)

Manam 2005:	4-6
Anatahan 2005:	8
Okmok 2008:	5
Kasatochi 2008:	5
Redoubt 2009:	4-5
Sarychev 2009:	7
Merapi 2010:	6



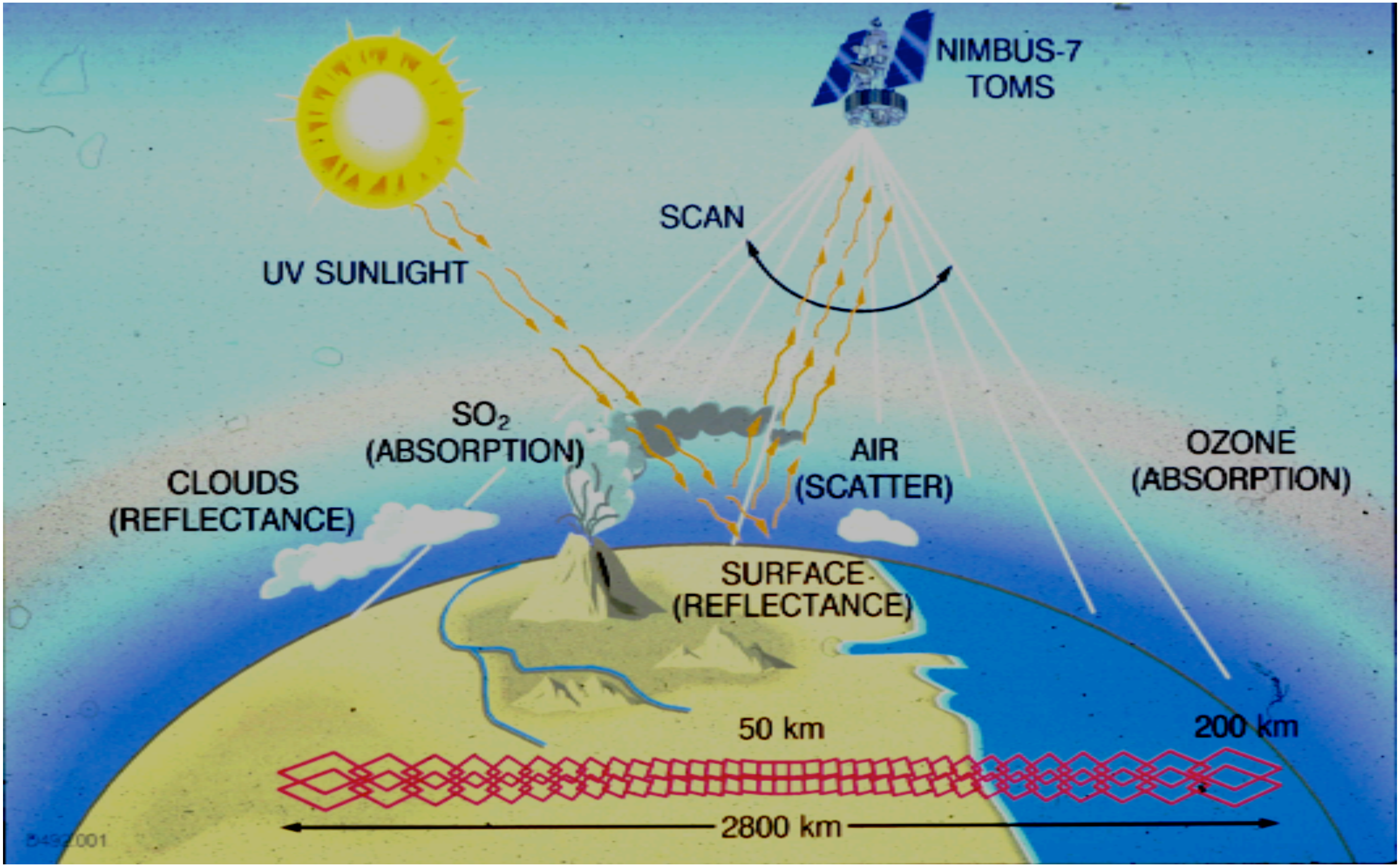
GOSAT: Measuring CO_2 from space

- NASA Orbiting Carbon Observatory (OCO) – failed at launch
- Japanese Greenhouse Gas Observing Satellite (GOSAT)
    - Launched January 2009; polar orbit with 1300 LECT
    - Fourier Transform Spectrometer (FTS) and Cloud-Aerosol Imager (CAI)
    - TANSO-FTS sensor measures CO_2 and CH_4 columns and profiles in SWIR/TIR
    - 0.2 cm^{-1} spectral resolution, 10.5 km diameter FOV
    - 56,000 observation points over land; sunglint obs over oceans
    - Special observation 'stare' mode
    - ppm-level sensitivity to changes in CO_2 column
    - Evaluation of GOSAT data for volcanic CO_2 detection underway



XCO_2 (Column averaged dry air mole fraction)
(uncalibrated data)

UV Backscatter instrument - basic operation



Forward-model SO_2 retrieval (e.g., TOMS, OMI)

- Simulate at-satellite UV radiances as a function of viewing geometry, latitude, column O_3 and SO_2 amounts, surface pressure and reflecting surface conditions, using a radiative transfer model

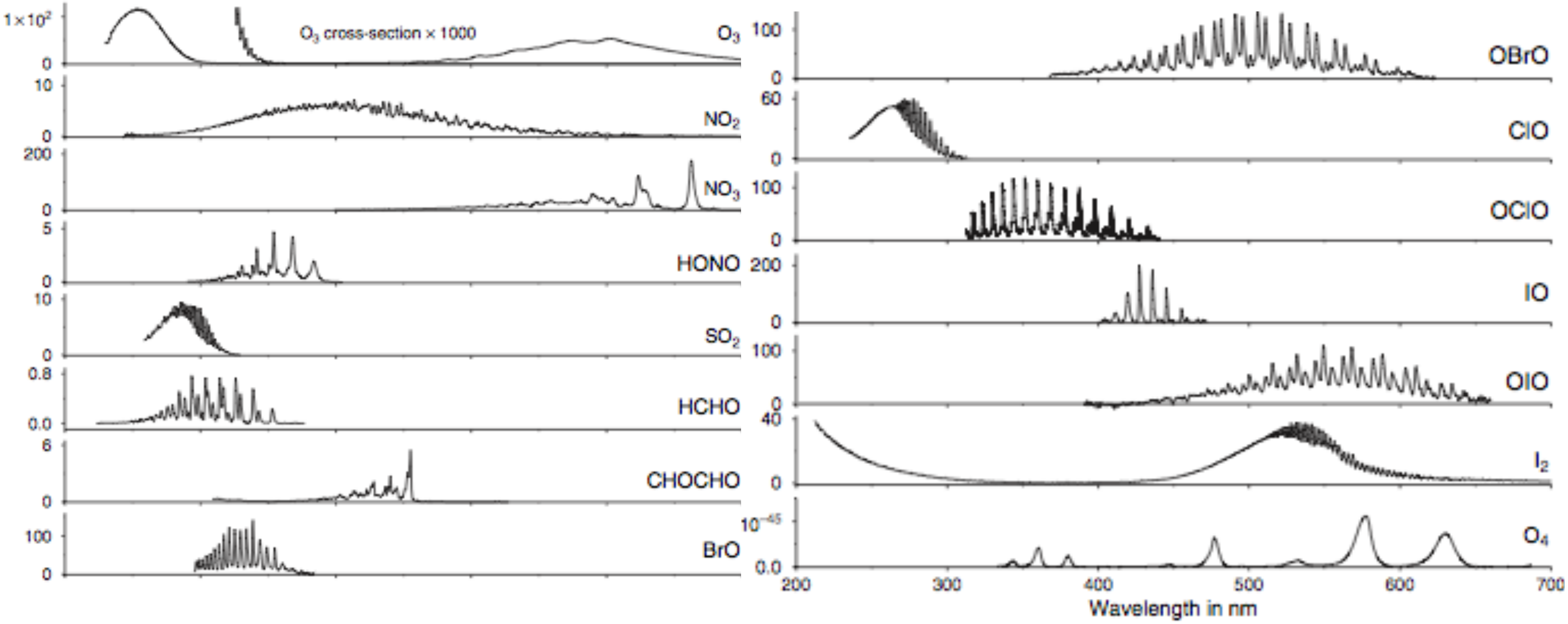
- Compare measured normalized radiances with theoretical radiances calculated for the conditions of the measurement

- Derive column O_3 and SO_2 amounts in the scene by finding the values that give a computed radiance equal to the measured radiance

- Errors: highest in the presence of significant ash or sulfate aerosol, and at scan edges

Differential Optical Absorption Spectroscopy (DOAS)

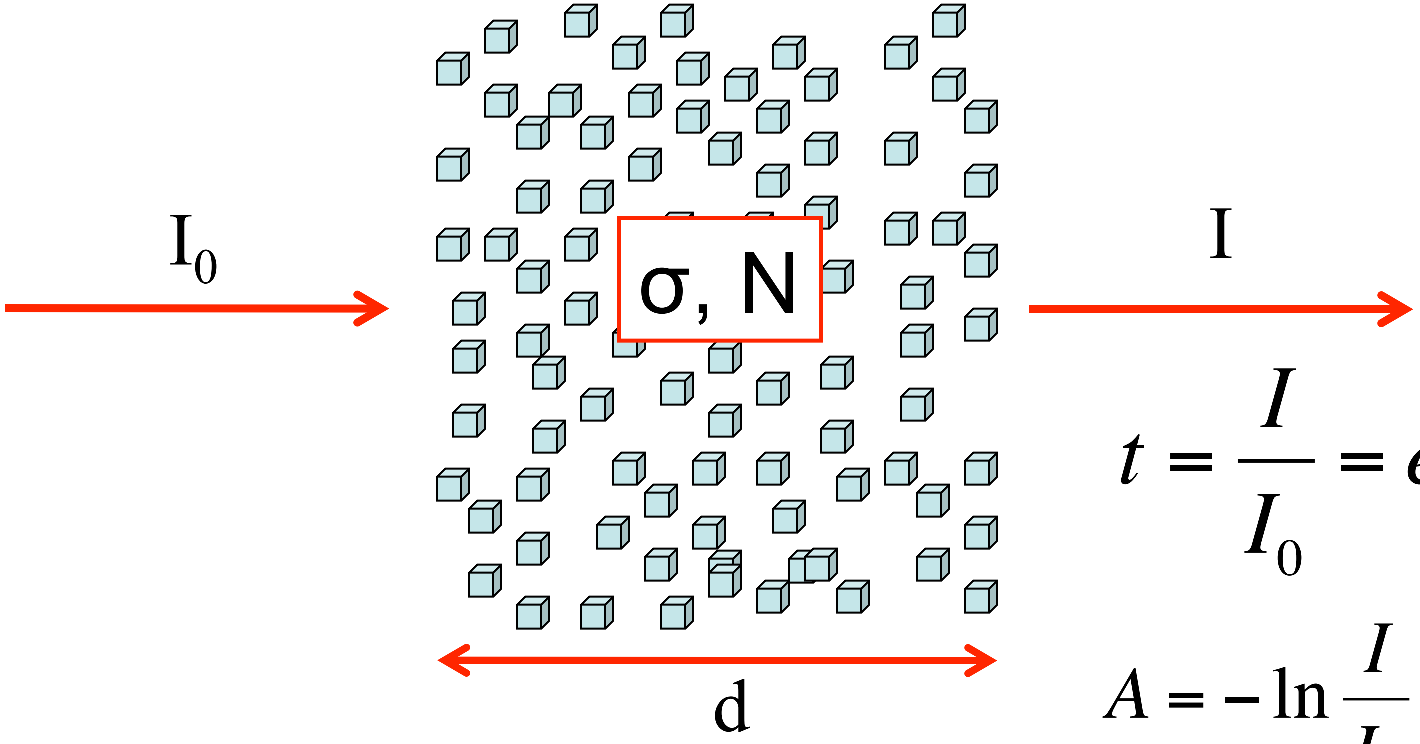
Measured UV-visible spectra contain overlapping structures due to the solar spectrum (Fraunhofer lines), elastic scattering, trace gas absorption, aerosol absorption and the Ring effect (inelastic Raman scattering)



Absorption cross-sections of trace gases in the 200-700 nm wavelength range

Beer-Bouguer-Lambert (Beer's) Law

For a gaseous absorber, the absorption coefficient (β) is written as the product of an absorption cross-section (σ, cm^2) and the number density of absorbers (N, molecules cm^{-3}):

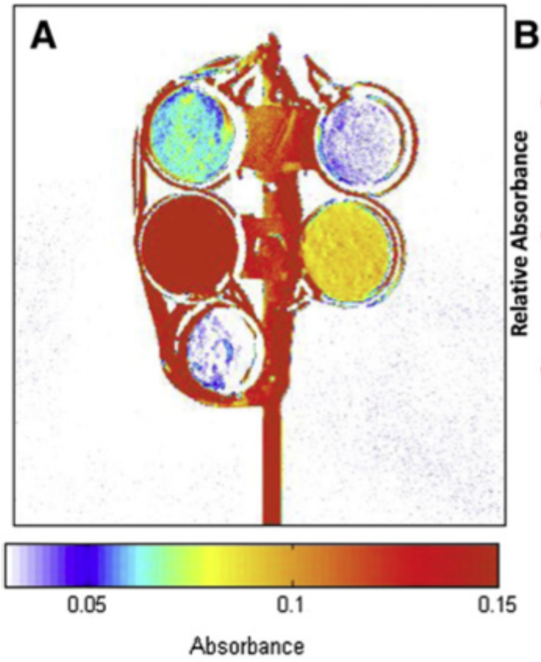


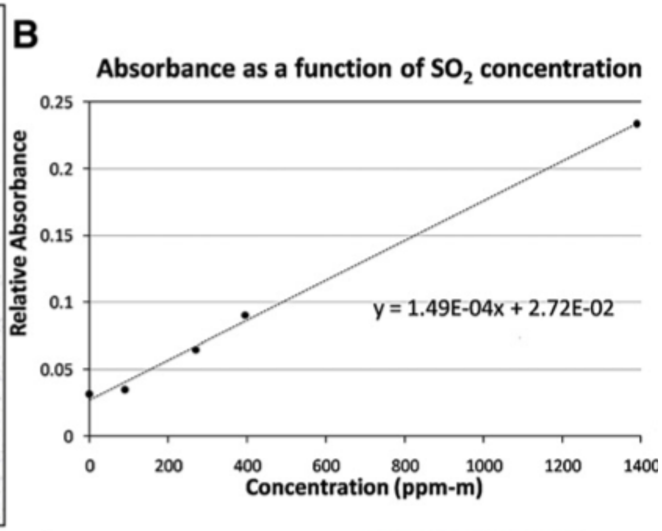
$$t = \frac{I}{I_0} = e^{-\sigma N d}$$

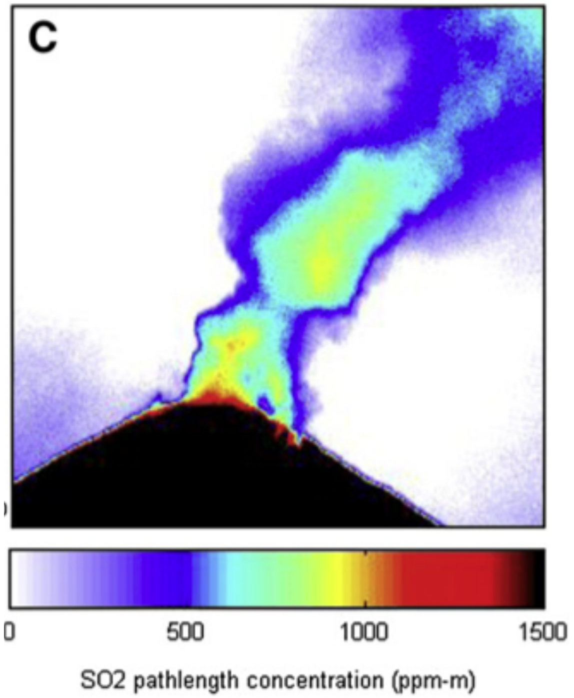
$$A = -\ln\frac{I}{I_0} = \sigma N d$$

- Beer's Law applies to direct beam only
- Deviations from Beer's Law occur at high concentrations

Use of SO_2 calibration cells







UV Camera
(Dalton et al., 2009)

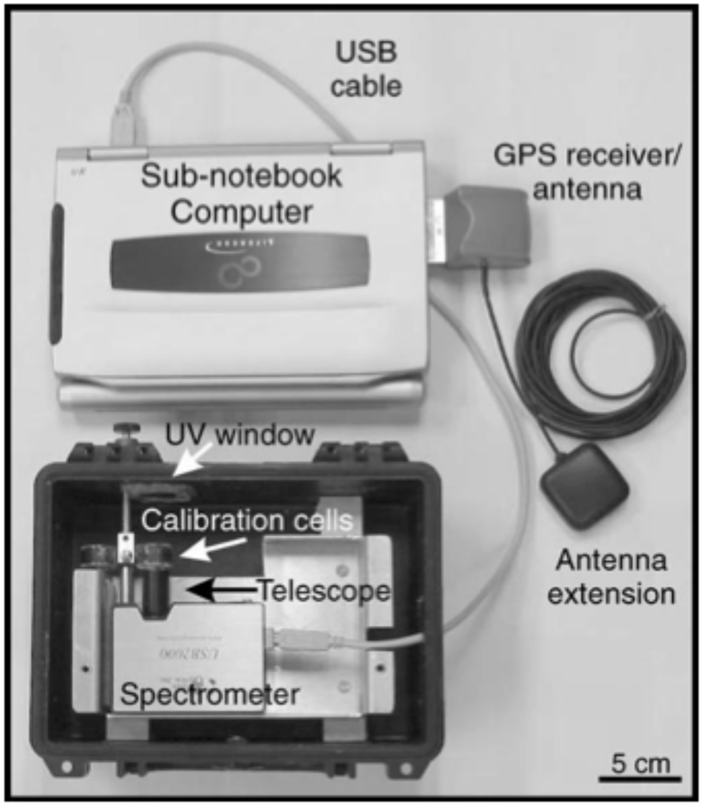


Fig. 1 FLYSPEC components consisting of a miniature spectrometer, sub-notebook computer, and GPS. High and low calibration SO_2 gas cells are shown mounted above the spectrometer and telescope. The "telescope" is a fiber-optic collimating lens mounted directly to the spectrometer input aperture. The lens, in combination with the UV band-pass filter window mounted on the case, provides a field of view of approximately 2.5°. Power for the spectrometer and GPS is supplied by the computer

FLYSPEC *(Horton et al., 2005)*

Detection of April 1982 El Chichon SO_2 cloud with the Total Ozone Mapping Spectrometer (TOMS)

24 JUNE 1983 · VOL. 220 · NO. 4604

$2.50

SCIENCE

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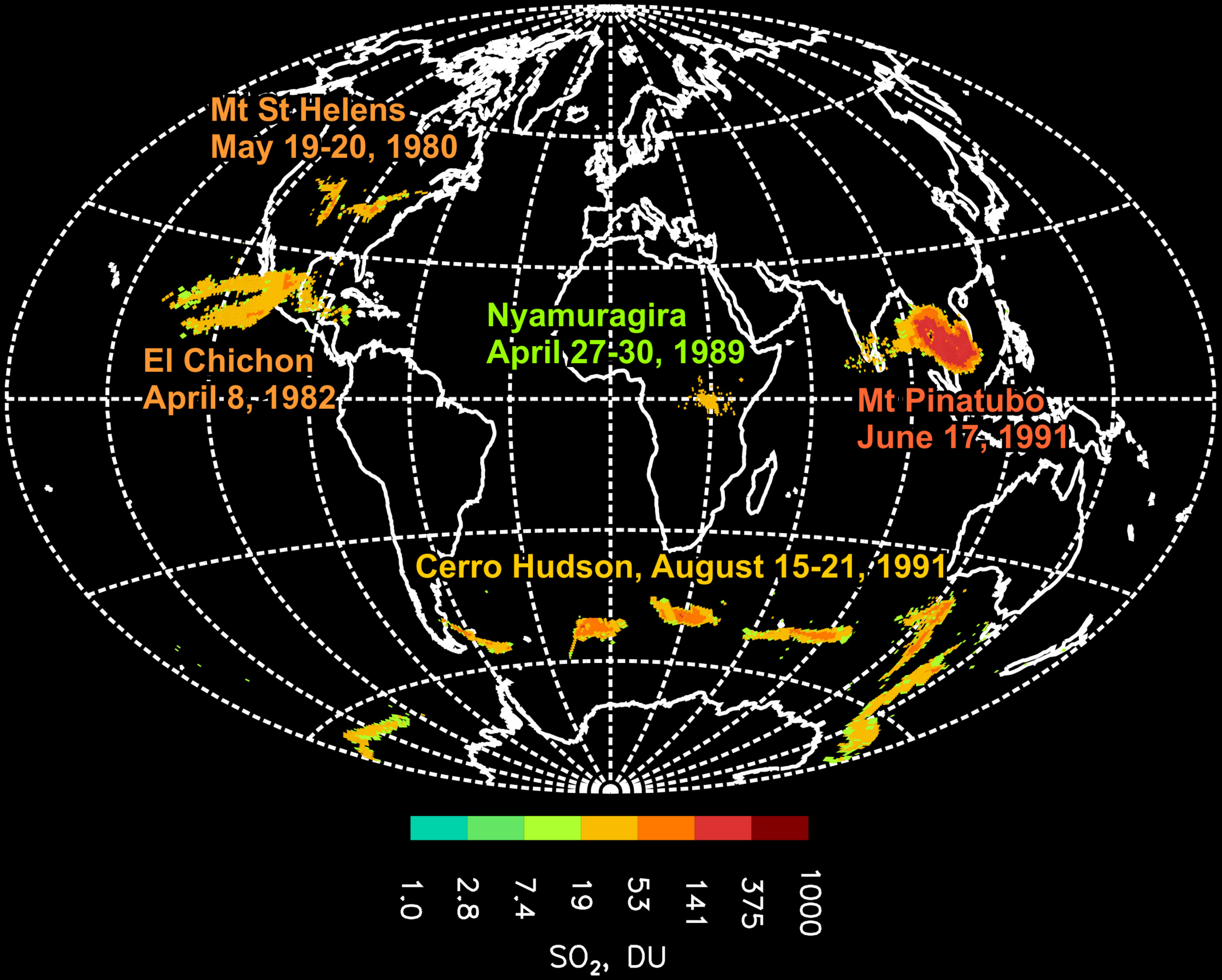
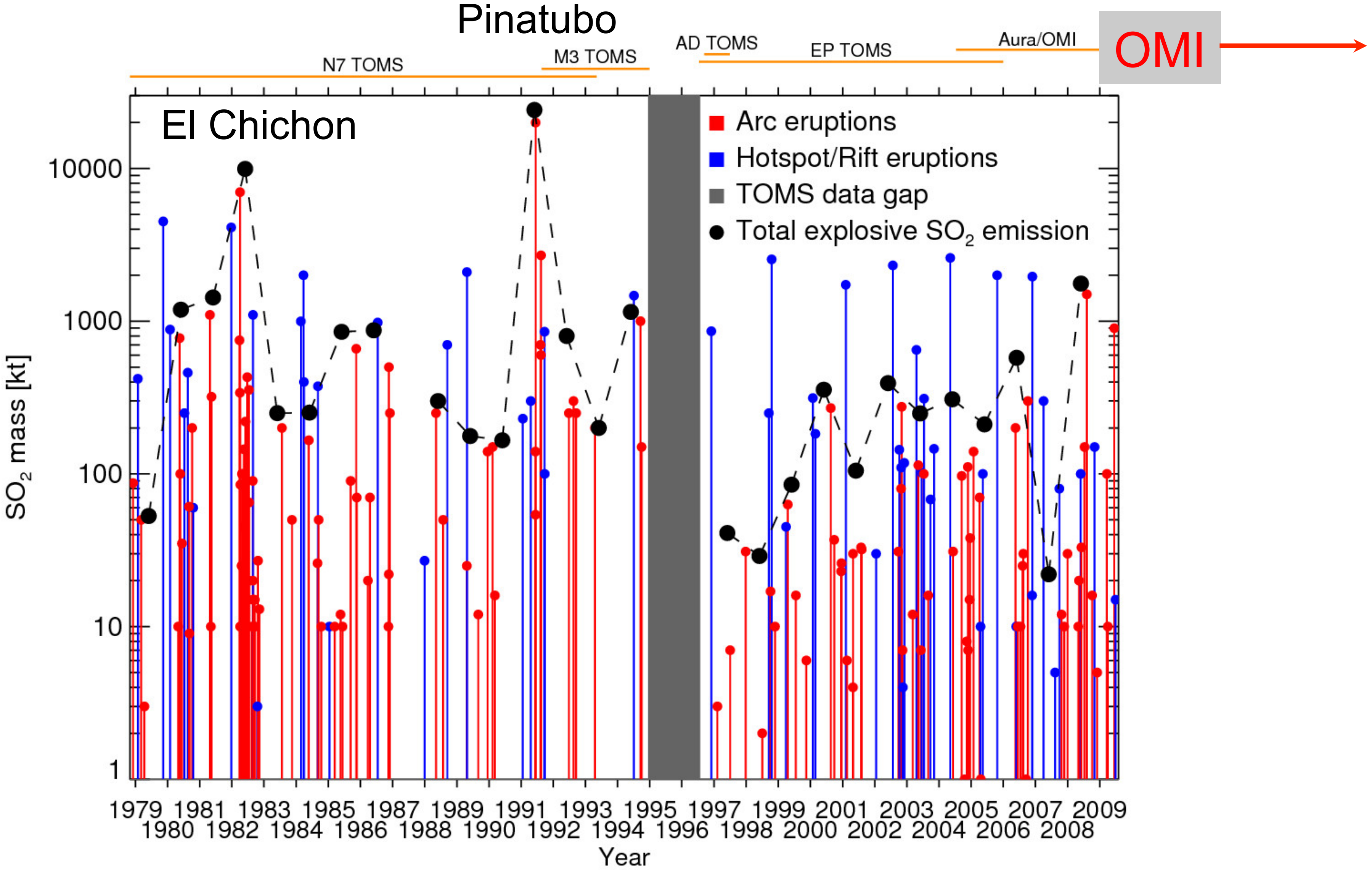
[*Krueger, Science, 1983*]

Volcanic SO_2 clouds measured by TOMS



Volcanic SO_2 Emissions Inventory



[Bluth et al., 1993; Carn et al., 2003]

IUGG Workshop VW02, Melbourne, Australia, June 2011

Exploiting A-Train synergy for volcanic cloud studies

Aura

OMI - SO_2, O_3, NO_2, BrO

TES - SO_2

MLS - strat. SO_2, HCl, O_3

Aqua

MODIS - SO_2, ash, sulfate

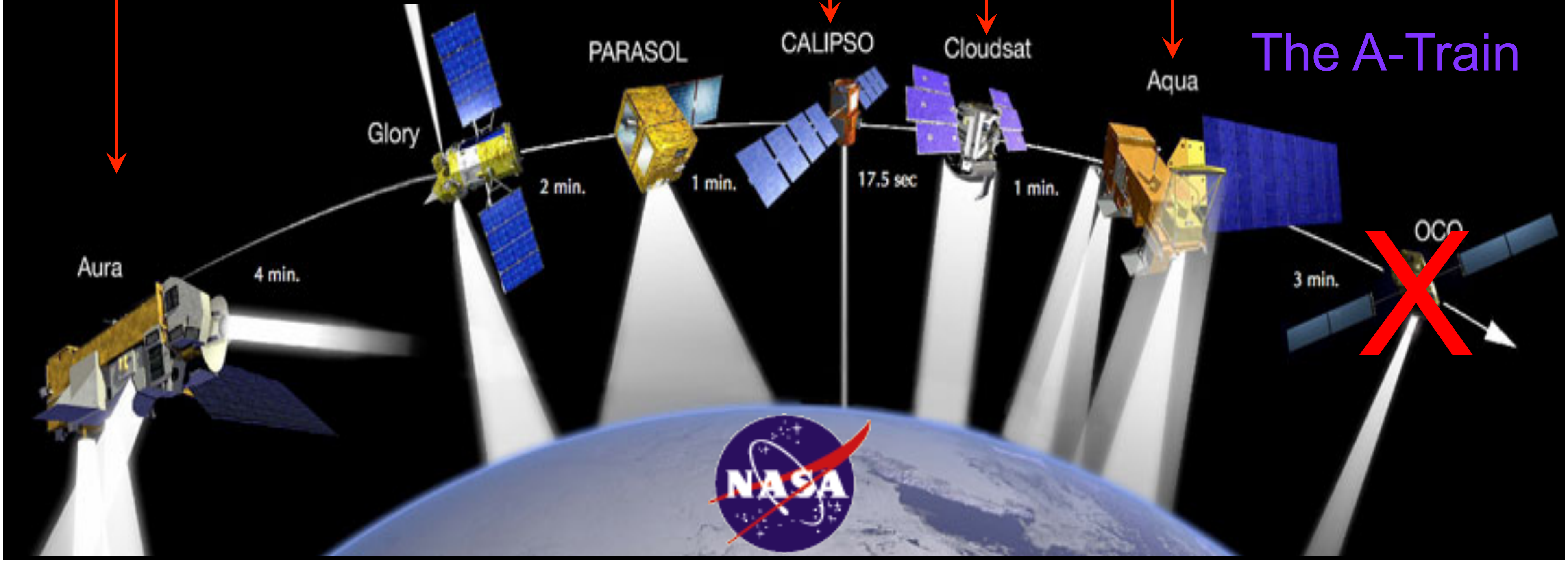
AIRS - UTLS SO_2, aerosols, SO_2 profile?

CloudSat

CPR – precipitation, hydrometeors

CALIPSO

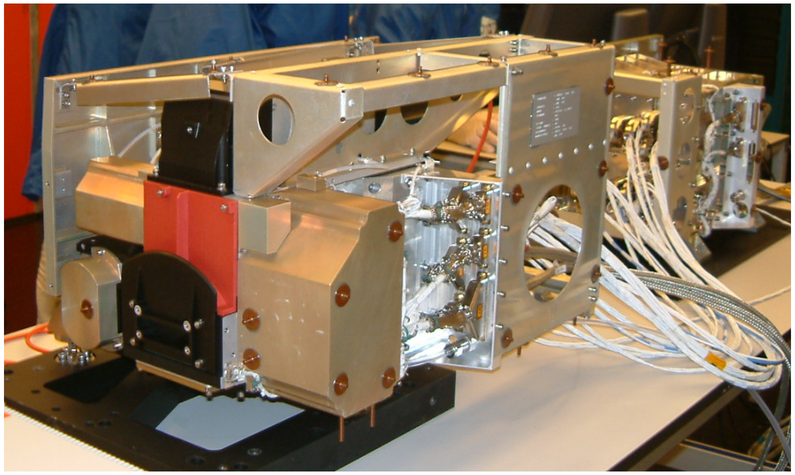
CALIOP - cloud altitude, aerosol phase/type

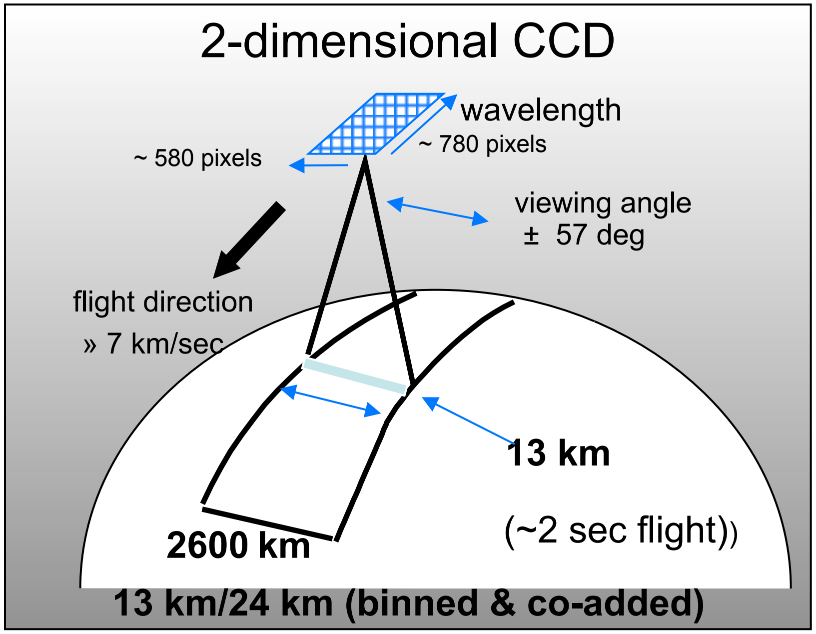


The A-Train

Aura - Ozone Monitoring Instrument (OMI)

- UV/VIS sensor that succeeded TOMS
- Dutch/Finnish contribution to NASA’s EOS/Aura mission (launched July 2004)
- Daily contiguous global coverage
- 13 x 24 km nadir footprint - best ever for UV measurements from space
- Overpass at 1:30-2:00 pm local time
- Data publically available and *free*
- *Row anomaly since August 2008 – some data gaps*
- The first space-borne sensor to provide daily, global SO_2 measurements with sensitivity to the lower troposphere (i.e., passive degassing)





2-dimensional CCD

wavelength

~ 780 pixels

~ 580 pixels

viewing angle
± 57 deg

flight direction
» 7 km/sec

13 km

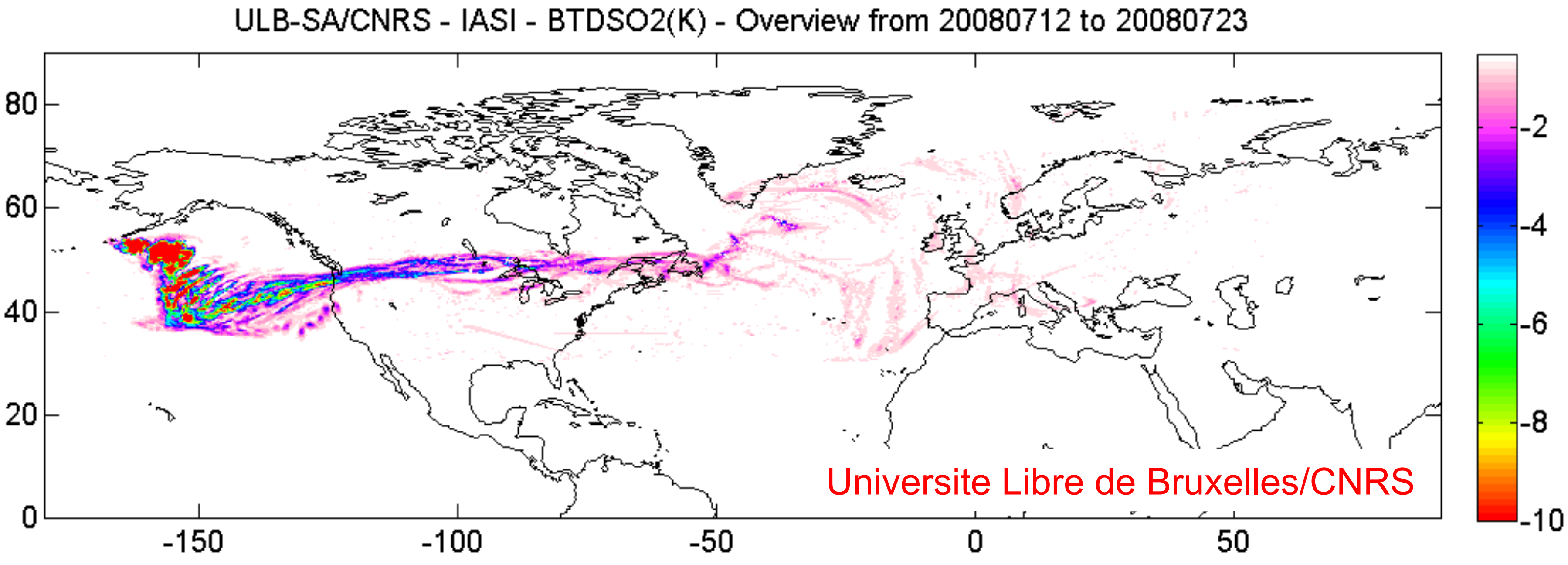
(~2 sec flight))

2600 km

13 km/24 km (binned & co-added)

Infrared Atmospheric Sounding Interferometer (IASI)

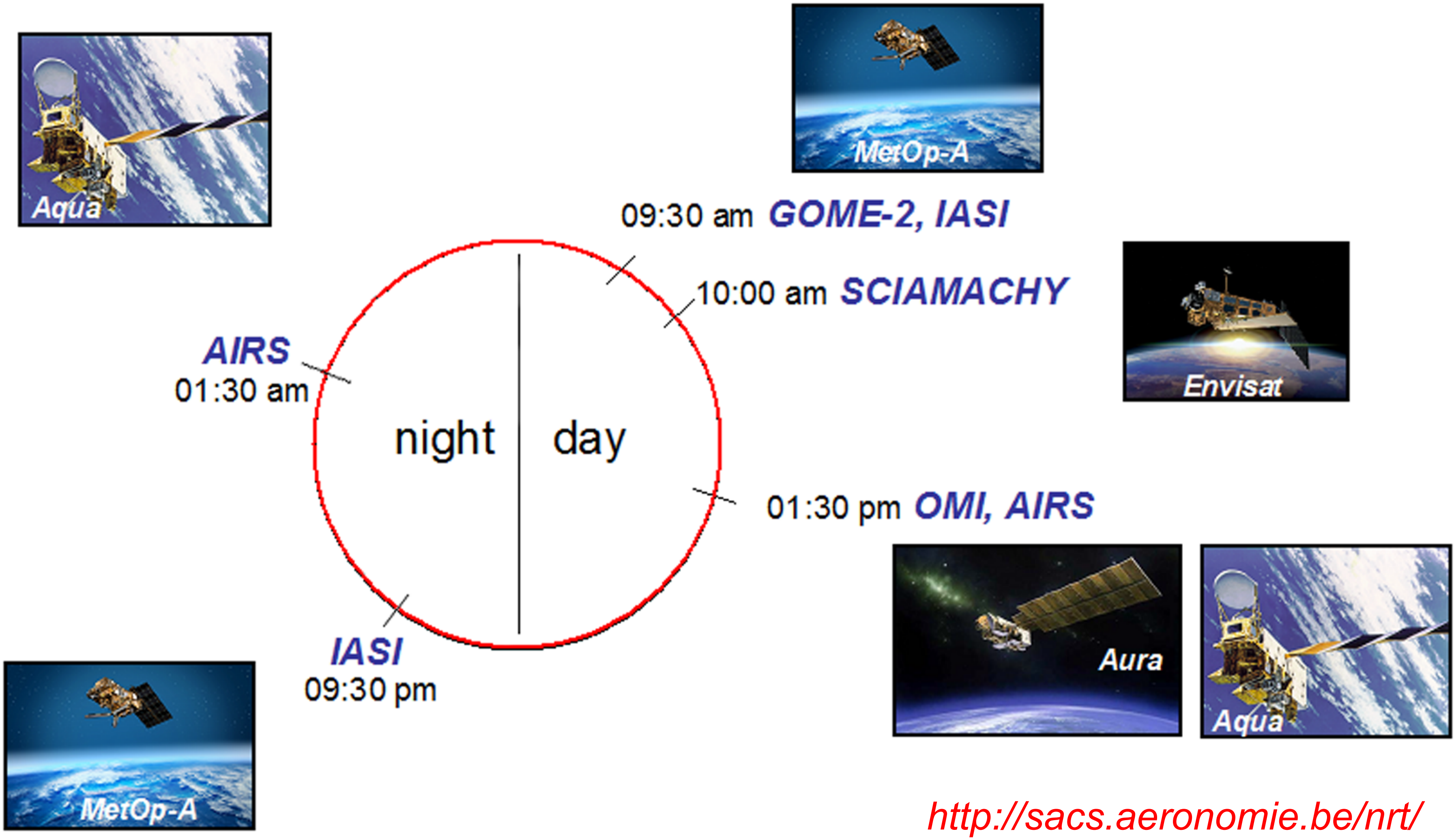
- 3.4 – 15 µm (infrared) wavelengths
- High spectral resolution, Fourier transform interferometer
- Mapping and vertical profiling of SO_2 possible
- 25 km horizontal resolution, 1 km vertical resolution
- Covers 3 SO_2 absorption bands in the IR
- Measurements at 9:30 am and 9:30 pm local time (IR)
- High sensitivity to eruptions; degassing may be detectable



Universite Libre de Bruxelles/CNRS

Up to 7 daily SO_2 measurements from UV/IR sensors

Satellites equatorial overpass solar local time



http://sacs.aeronomie.be/nrt/

Satellite instruments - UV

Instrument	Satellite(s)	Data coverage dates	Daily global coverage?
Total Ozone Mapping Spectrometer (**TOMS**)	Nimbus-7, Meteor-3, ADEOS, Earth Probe	Nov 78 – Dec 94 Jul 96 – Dec 2005	Yes
Global Ozone Monitoring Experiment (**GOME**)	European Remote Sensing Satellite (ERS-2)	July 95 – present	No
Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (**SCIAMACHY**)	European Environmental Satellite (Envisat-1)	Sept 03 – present	No
Ozone Monitoring Instrument (**OMI**)	NASA EOS Aura	Sept 2004 – present	Yes (until late 2008)
Global Ozone Monitoring Experiment-2 (**GOME-2**)	MetOp A, B, C	Oct 2006 - present	No
Ozone Mapping and Profiler Suite (**OMPS**)	National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP)	2011?	Yes

Operational SO_2 data products

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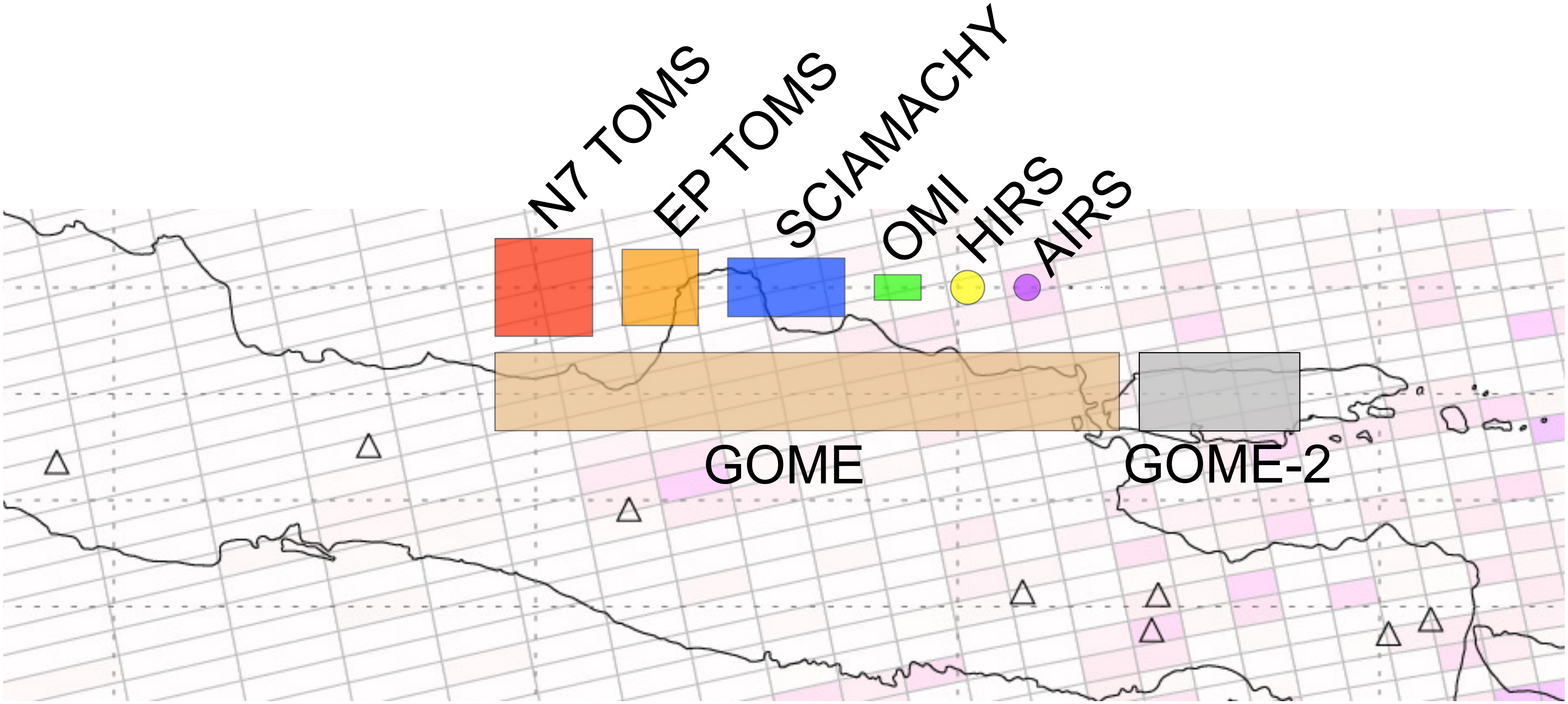
Satellite instruments – Microwave & IR

Instrument	**Satellite(s)**	**Data coverage dates**	**Daily global coverage?**
Microwave Limb Sounder (**MLS**)	Upper Atmosphere Research Satellite (UARS), EOS Aura	1991 – 1994 (UARS) 2004 – (EOS Aura)	No
High Resolution Infrared Radiation Sounder (**HIRS, HIRS/2**)	TIROS-N, NOAA-6-14	Oct 78 – present	Yes (day/night)
Moderate Resolution Imaging Spectroradiometer (**MODIS**)	EOS Terra, Aqua	Feb 2000 –	Yes (day/night)
Advanced Spaceborne Thermal Emission & Reflection Radiometer (**ASTER**)	EOS Terra	Feb 2000 – (request only)	No
Atmospheric Infrared Sounder (**AIRS**)	EOS Aqua	Sept 2002 –	No
Spinning Enhanced Visible and Infrared Imager (**SEVIRI**)	Meteosat Second Generation (MSG)	2004 –	No
Infrared Atmospheric Sounding Interferometer (**IASI**)	MetOp A, B, C	Oct 2006 -	No

Satellite instrument footprints (nadir)



UV instrument SO_2 sensitivity

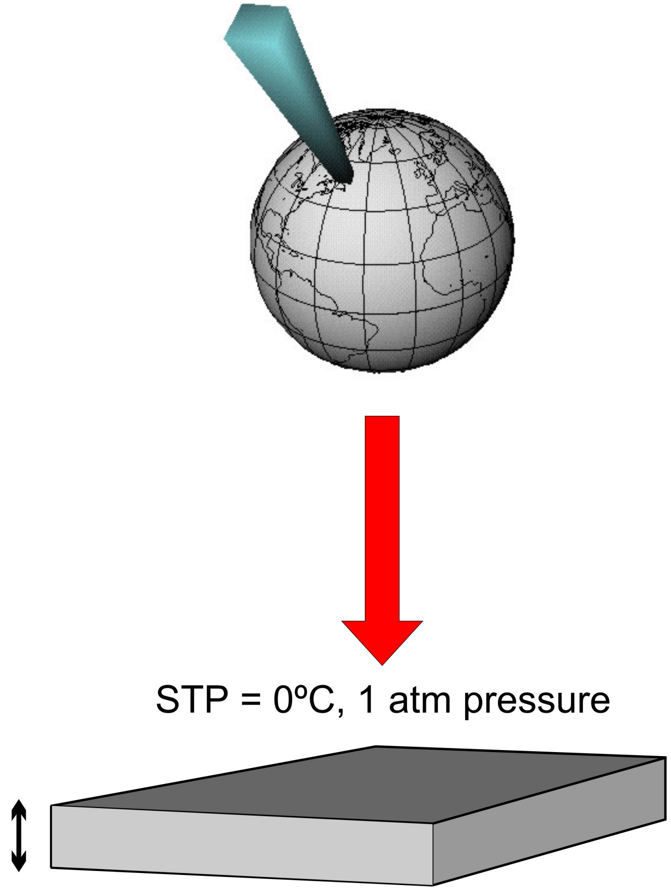
Instrument	**Footprint area (km^2)**	**Sensitivity (DU)** 1σ		**Smallest cloud detection limit (tons)** 5 pixels at 5σ	
		Stratosphere 20 km	Troposphere <5 km	Stratosphere 20 km	Troposphere <5 km
EP TOMS	1521 (39×39)	3.5	7	3900	7800
GOME	12800 (40×320)	0.2	0.4	3600	7100
SCIAMACHY	1800 (30×60)	0.2	0.4	125	251
GOME-2	3200 (40x80)	0.2	0.4	460	914
OMI	312 (13×24)	0.2	0.4	43	87
OMPS	2500 (50×50)	0.2	0.4	350	700

IR instrument SO_2 sensitivity

Instrument	**Footprint area (km^2)**	**Sensitivity (DU)*** **1σ**		**Smallest cloud detection limit (tons)** **5 pixels at 5σ**	
		Stratosphere 20 km	Troposphere <5 km	Stratosphere 20 km	Troposphere <5 km
MODIS	1 (1×1)	9	250	6	174
ASTER	0.008 (0.09×0.09)	9	250	0.05	1.4
AIRS	143 (d = 13.5 km)	1	30	100	2986
SEVIRI	23 (4.8×4.8)	9	250	144	4009

*Based on *Realmuto* [1999], AGU Geophysical Monograph 116, p101-115 (except AIRS)

Units for SO_2 column amount measurements



STP = 0ºC, 1 atm pressure

1 Dobson Unit (DU) = 1 Milli Atm cm
1 DU = 0.01 mm thickness at STP
e.g. 800 DU = 8 mm thick layer
1 DU = 10 ppmm at STP

- Satellites provide measurements of ‘column amount’ or ‘total column’ SO_2
  - US units: Dobson Unit (DU)
  - 1 DU = 2.69×10^{16} molecules cm^{-2} = 0.0285 g m^{-2} SO_2
  - European units: molecules cm^{-2}
  - *Milli atm cm* also used (same as DU)
- Typical values in volcanic clouds
  - Fresh eruption cloud: 100s – 1000+ DU
  - Non-eruptive degassing: <20 DU
  - Measured column amount depends on spatial resolution of sensor
  - Can be converted to mass or concentration (if cloud thickness is known)
- Emission rate not directly measured

UV radiation penetrates clouds

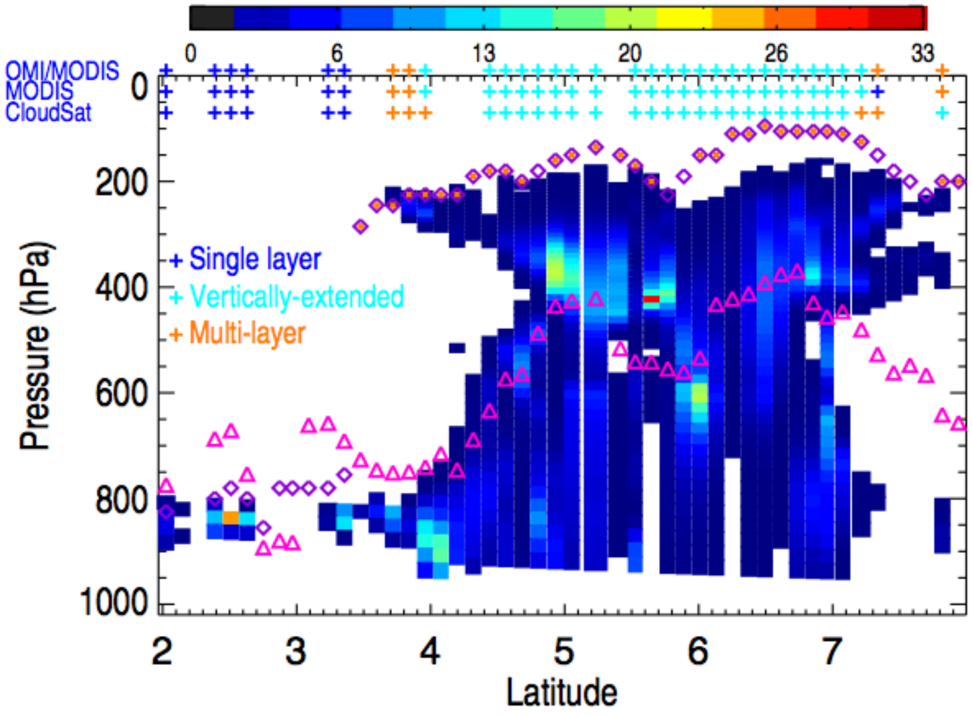


Fig. 7. CloudSat 2B-Tau cross section of cloud extinction (km^{-1}) along OMI orbit 12 402 (western track in tropical Pacific highlighted in Fig. 6); Averaged along-track over OMI pixel (∼13 km); Pink triangles: OMI optical centroid cloud pressure; Purple diamonds: MODIS minimum cloud-top pressure within closest passive sensor footprint, orange-filled where MODIS maximum multi-layer flag >2.

(Joiner et al., ATMD, 2009)

- IR cloud top ≠ UV cloud pressure

CLOUD SLICING MEASUREMENTS OF OZONE INSIDE THICK CLOUDS

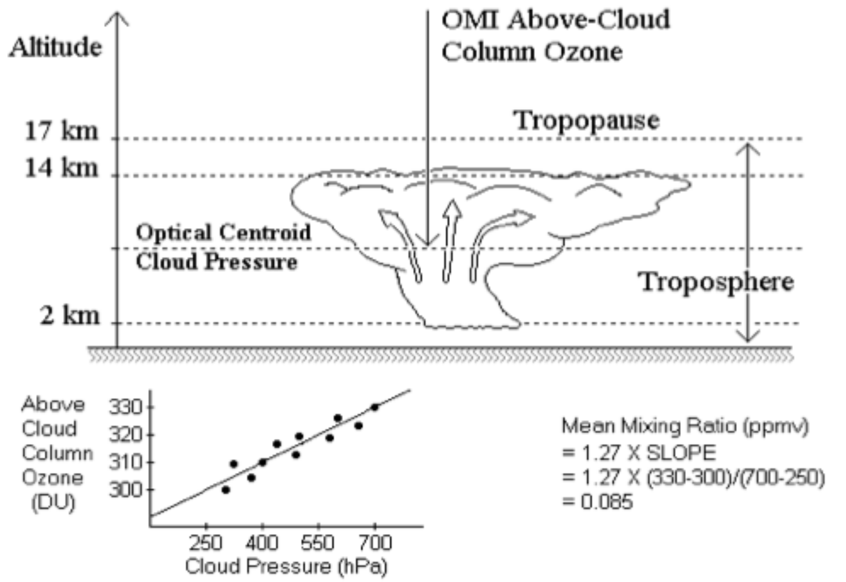
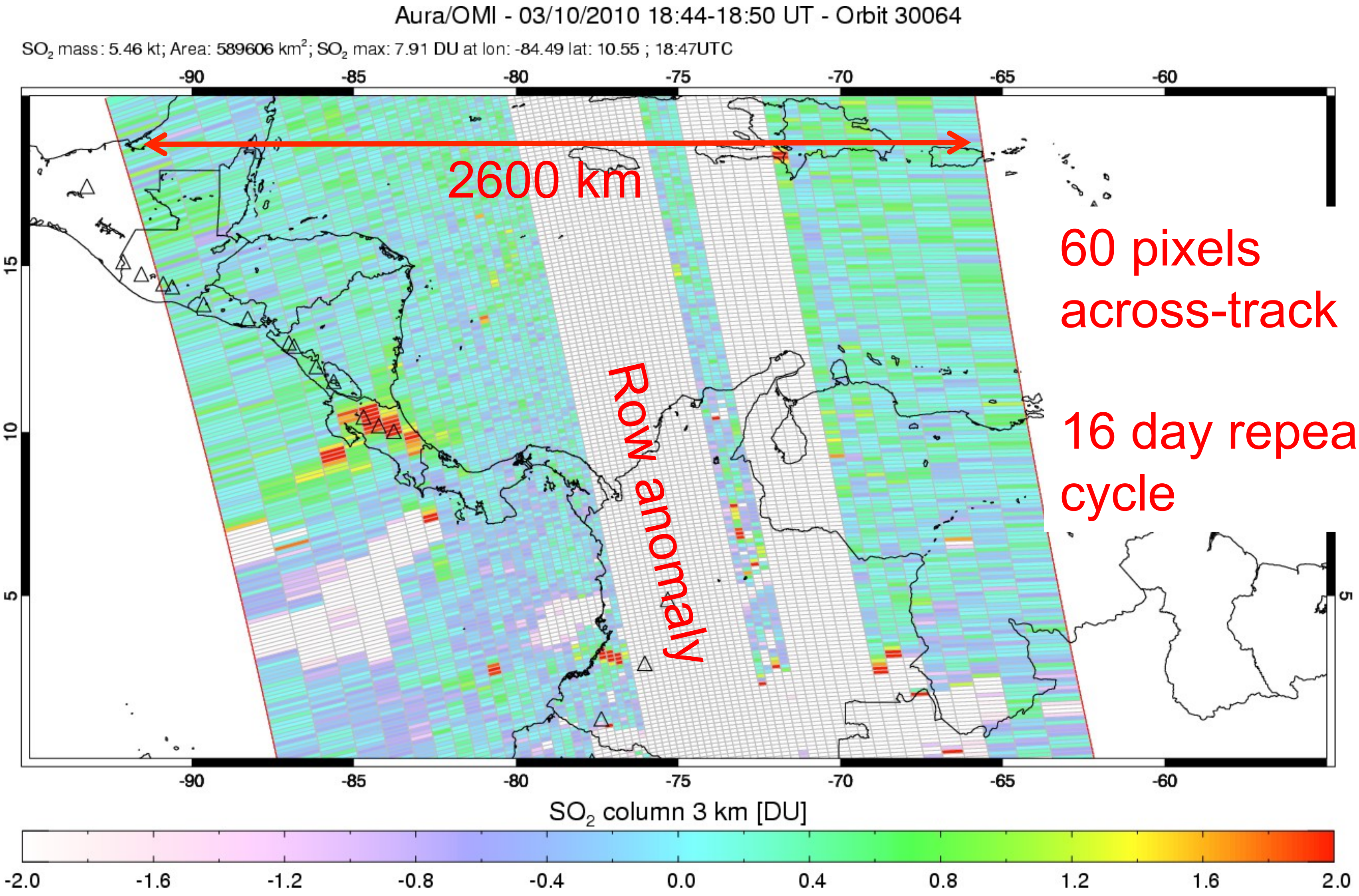


Fig. 4. Schematic diagram illustrating the ensemble cloud-slicing method. The figure shows that a satellite UV instrument is sensitive to the O_3 column from the top of the atmosphere down to the OCCP altitude which may lie several hundred hPa below geometrical cloud top. The lower half of the figure illustrates that using an ensemble of such measurements over a fixed region, mean volume mixing ratio can be determined from the slope of column O_3 plotted versus OCCP.

(Ziemke et al., ACP, 2009)

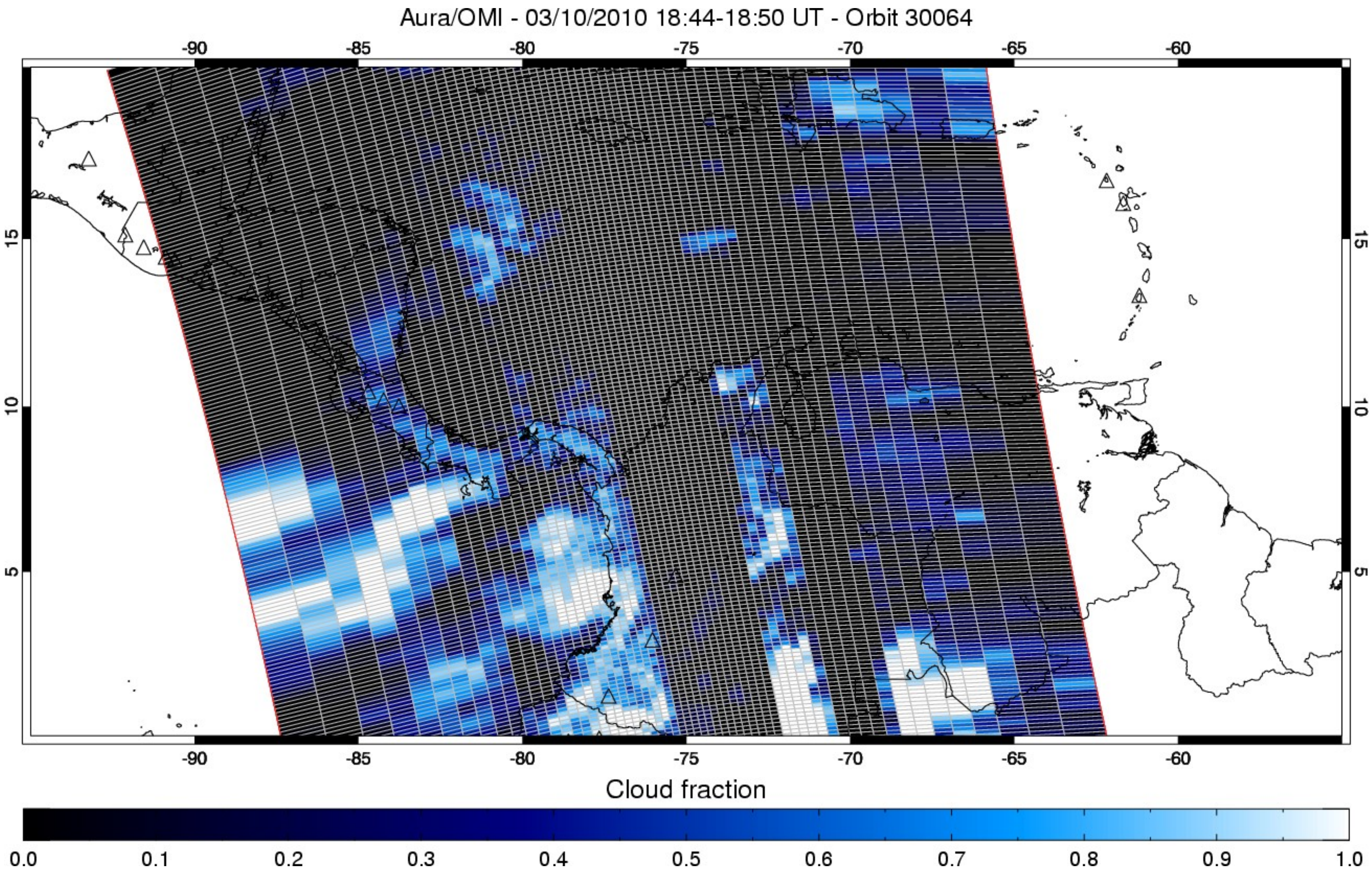
OMI data products – SO_2



60 pixels across-track

16 day repeat cycle

OMI data products – Cloud fraction



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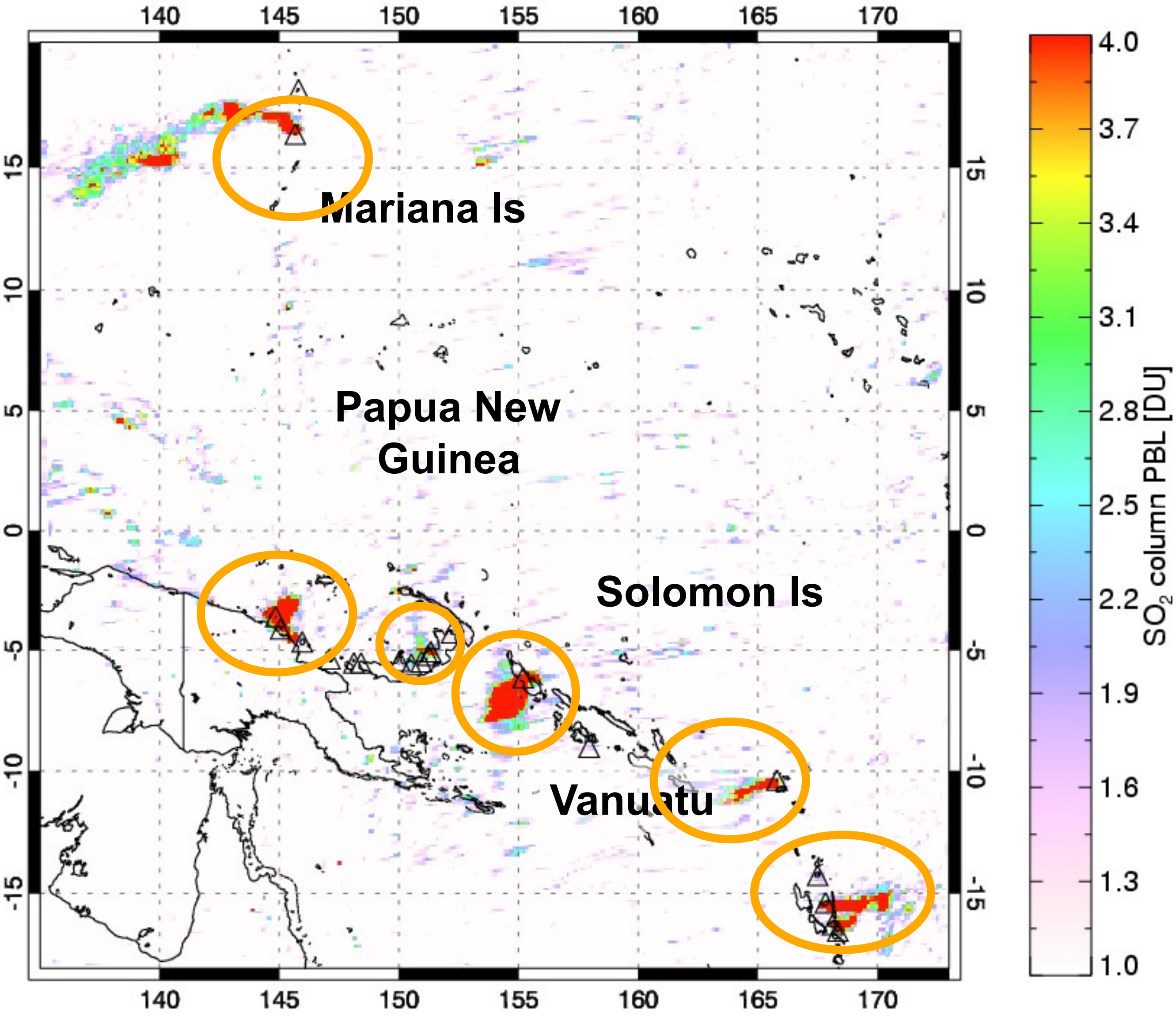
Detection of passive SO_2 degassing with OMI



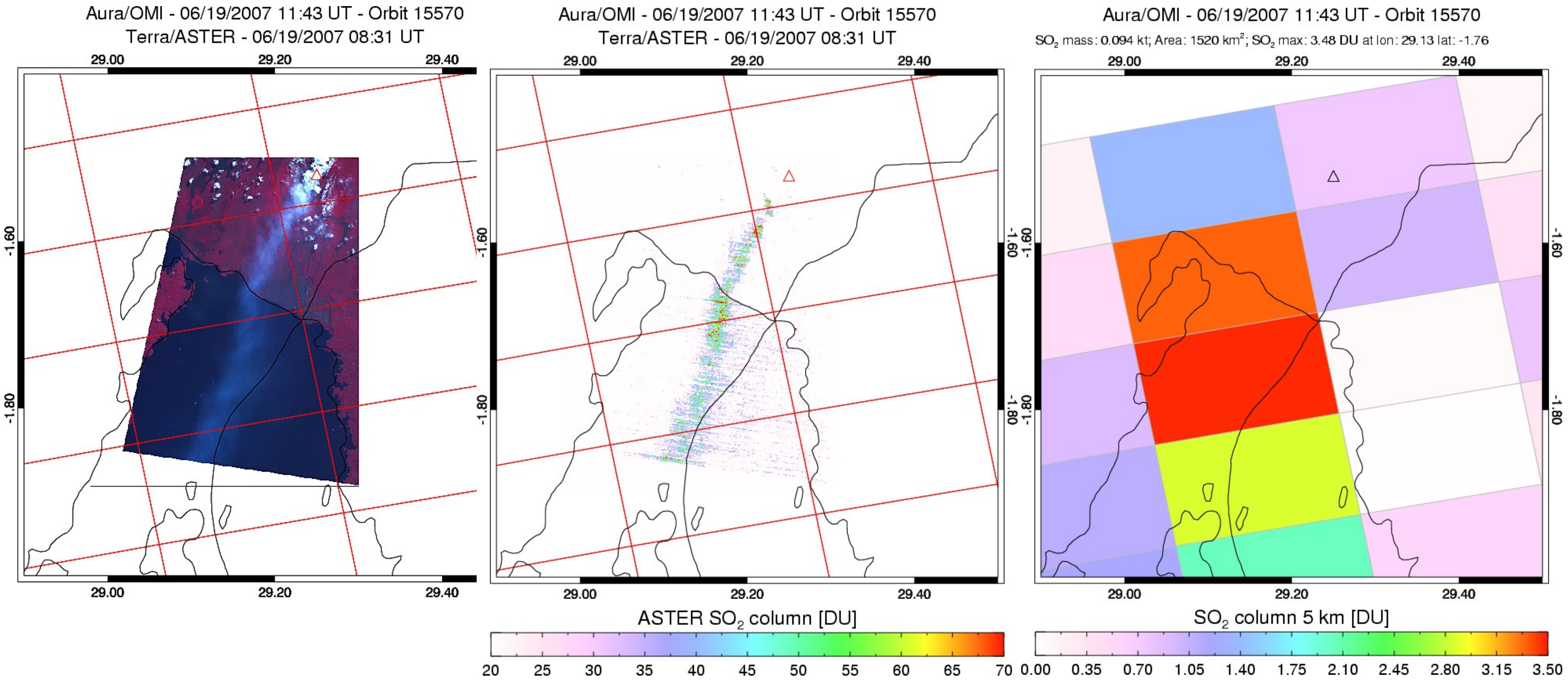
Aura/OMI - 04/23/2006 02:20-05:39 UT

SO_2 mass: 19.481 kt; Area: 104445 km^2; SO_2 max: 17.41 DU at lon: 154.72 lat: -7.10

OMI and ASTER: Nyiragongo (DR Congo), Jun 19, 2007

Terra ASTER (10:30 am)

Aura OMI (1:45 pm)

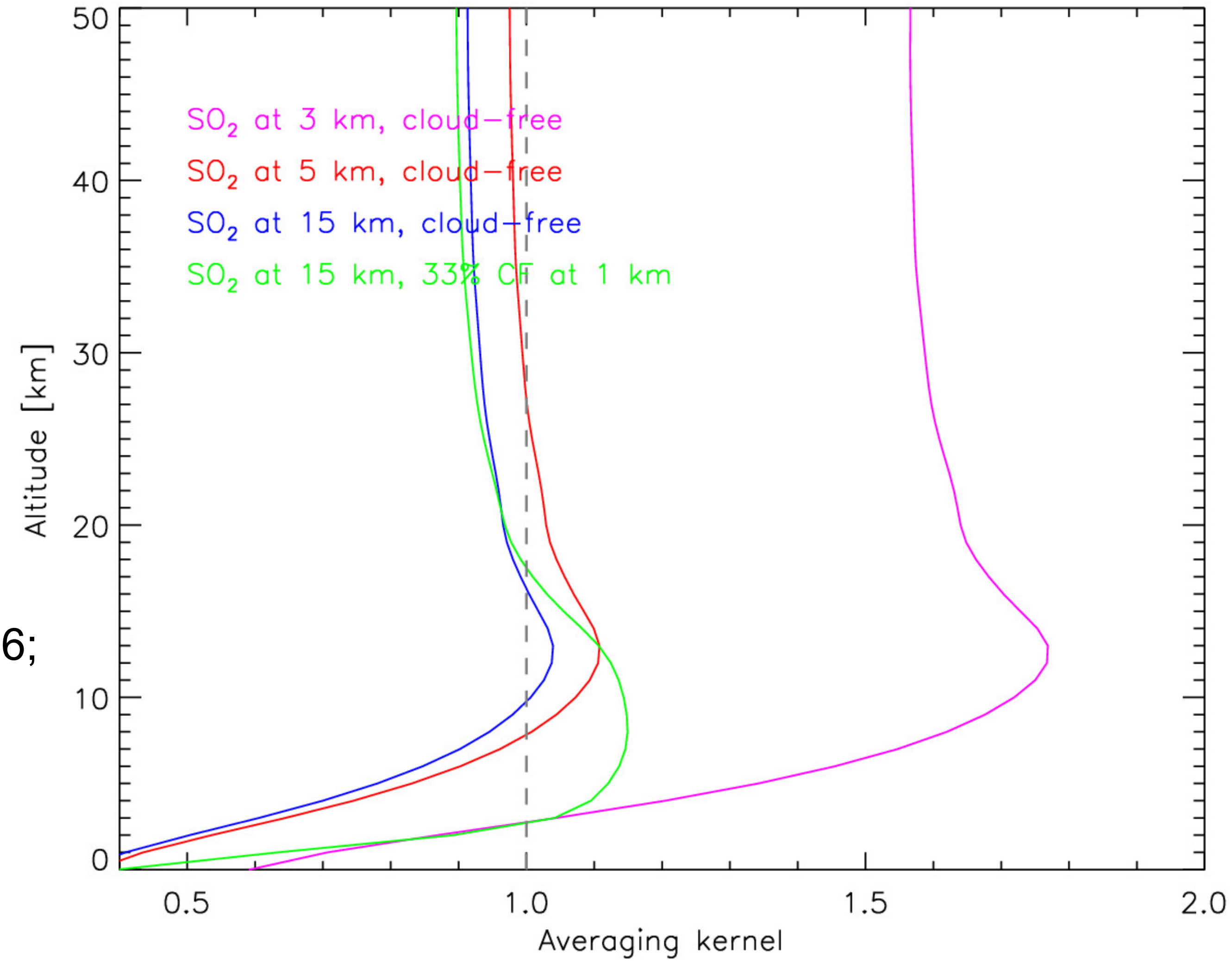


(ASTER 8.6 µm SO_2 retrieval; F. Prata, NILU)

- Plume extent relative to size of satellite FOV constrains detection of degassing plumes from space

Effect of volcanic plume altitude on SO_2 retrievals

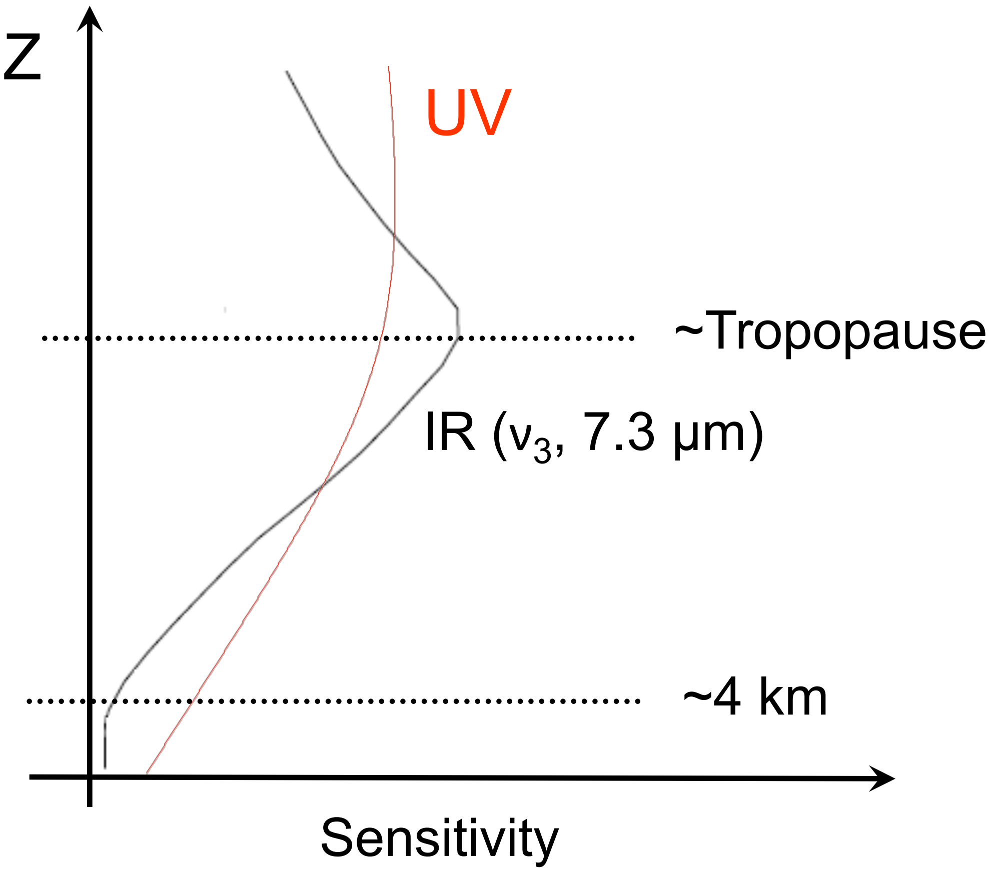
- OMI SO_2 product
- 4 *prescribed* SO_2 profiles:
  - PBL (<3 km)
  - TRL (0-5 km)
  - TRM (5-10 km)
  - STL (15-20 km)
  - 2 SO_2 algorithms [Krotkov *et al.*, 2006; Yang *et al.*, 2007]



- Knowledge of SO_2 cloud altitude is critical for accurate SO_2 retrieval
- Satellite sensitivity increases with altitude in the troposphere

[Krotkov *et al.*, IEEE TGRS, 2006; Yang *et al.*, JGR, 2007]

Relative sensitivity of UV and IR measurements



Courtesy of L. Clarisse, ULB

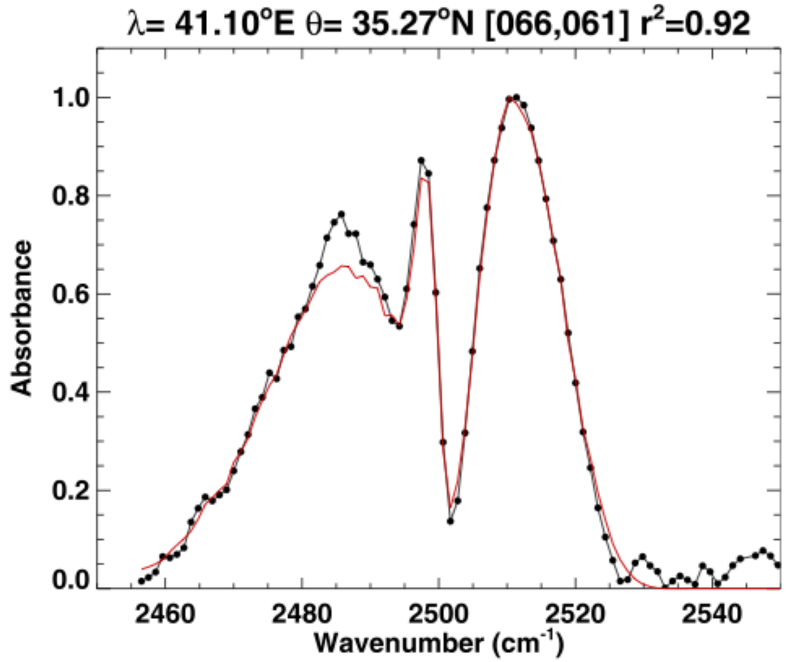
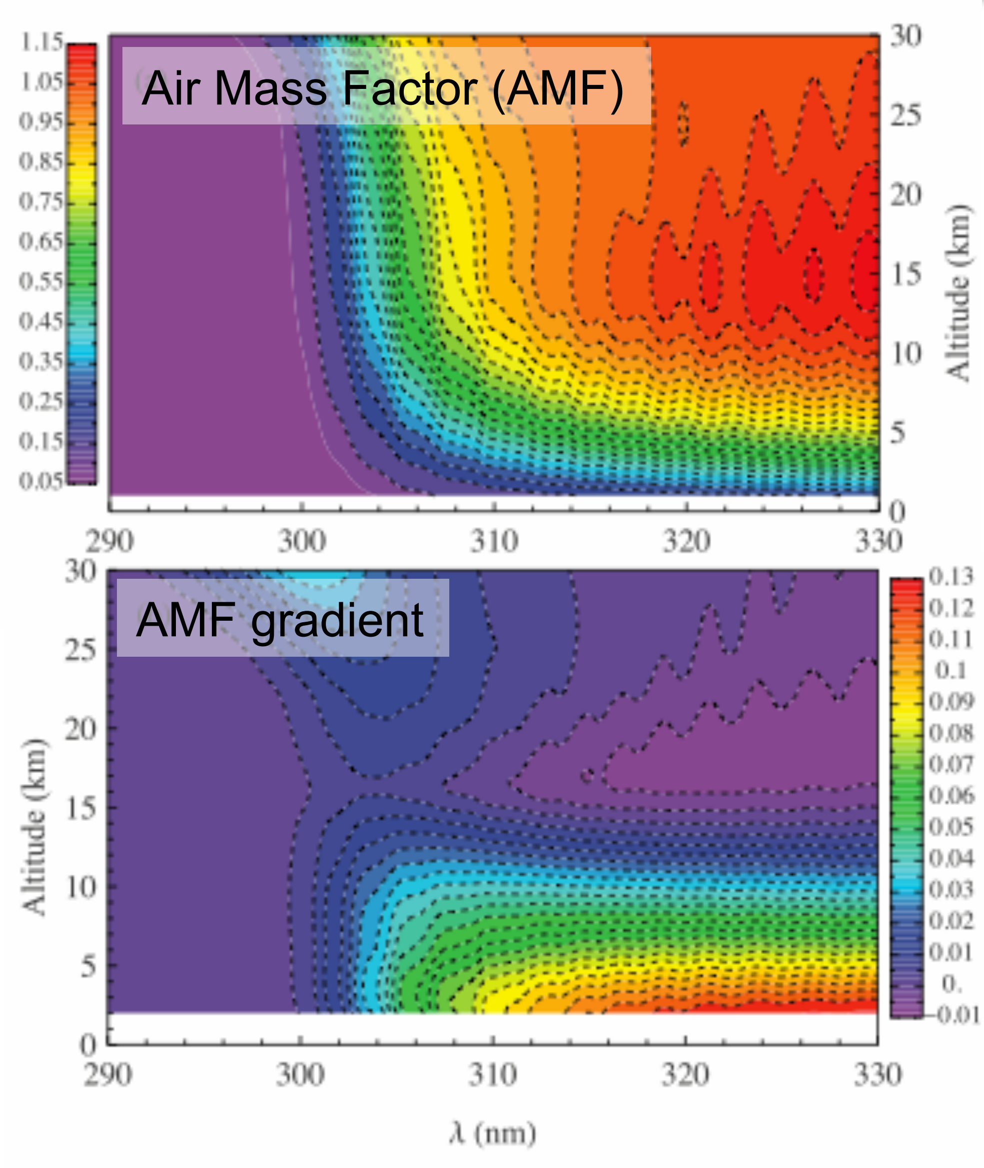


Figure 15. Spectral matching plot for the 4 μm band of SO_2. The red line shows a synthetic absorbance spectrum and the black line shows AIRS measurements. The data are for an AIRS image of the Al-Mishraq (Iraq) SO_2 plume on 25 June 2003.

Prata and Bernardo, 2007

- IR channels at ~4 μm and ~8.6 μm can detect lower tropospheric SO_2

Direct retrieval of SO_2 altitude from UV radiances



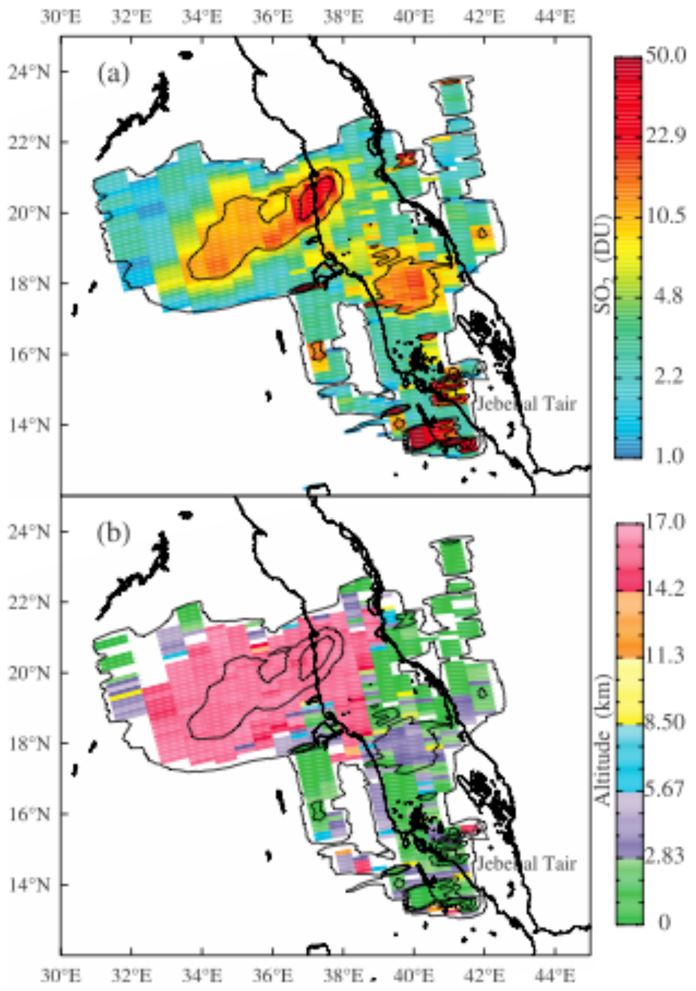


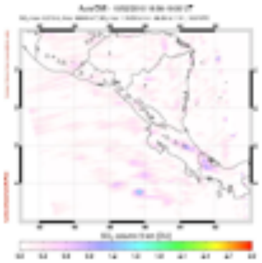
Figure 3. (a) SO_2 vertical column and (b) effective altitude maps derived from OMI UV (both UV-1 and UV-2) radiances for the Jebel al Tair volcanic plume at 10:59 UT on October 1, 2007, using the extended ISF algorithm.

- Midlatitude O_3 profile, 325 DU, nadir, clear sky, SZA=45º

[Yang *et al.*, GRL, 2009]

Daily OMI SO_2 measurements

http://so2.gsfc.nasa.gov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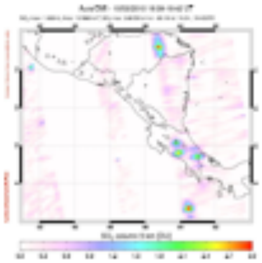
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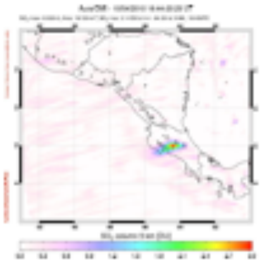
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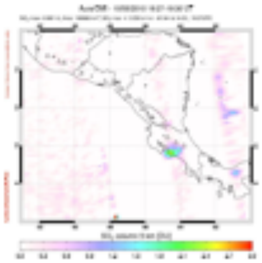
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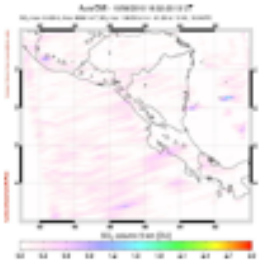
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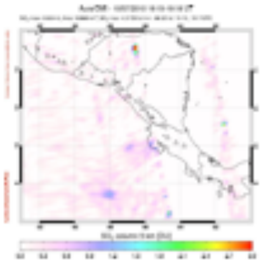
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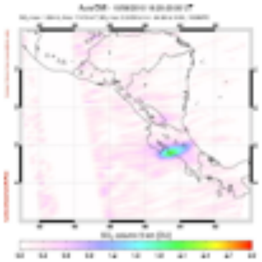
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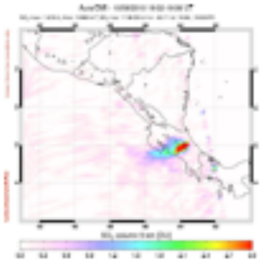
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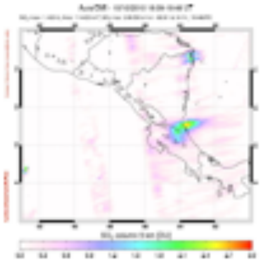
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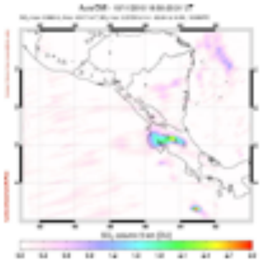
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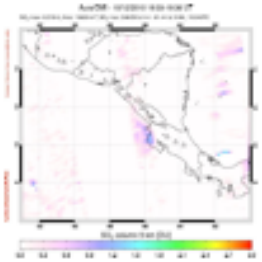
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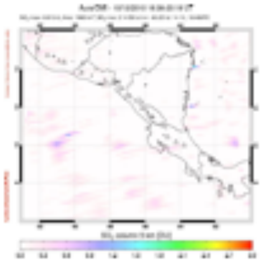
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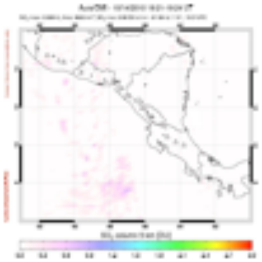
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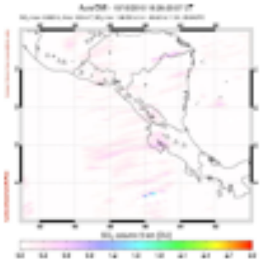
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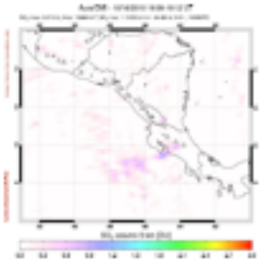
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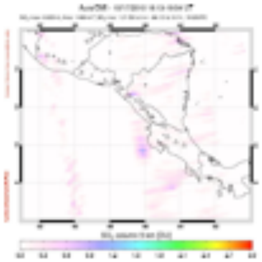
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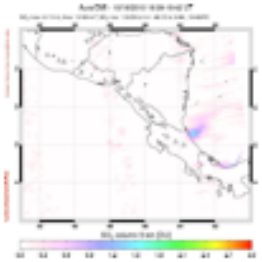
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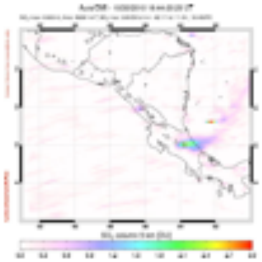
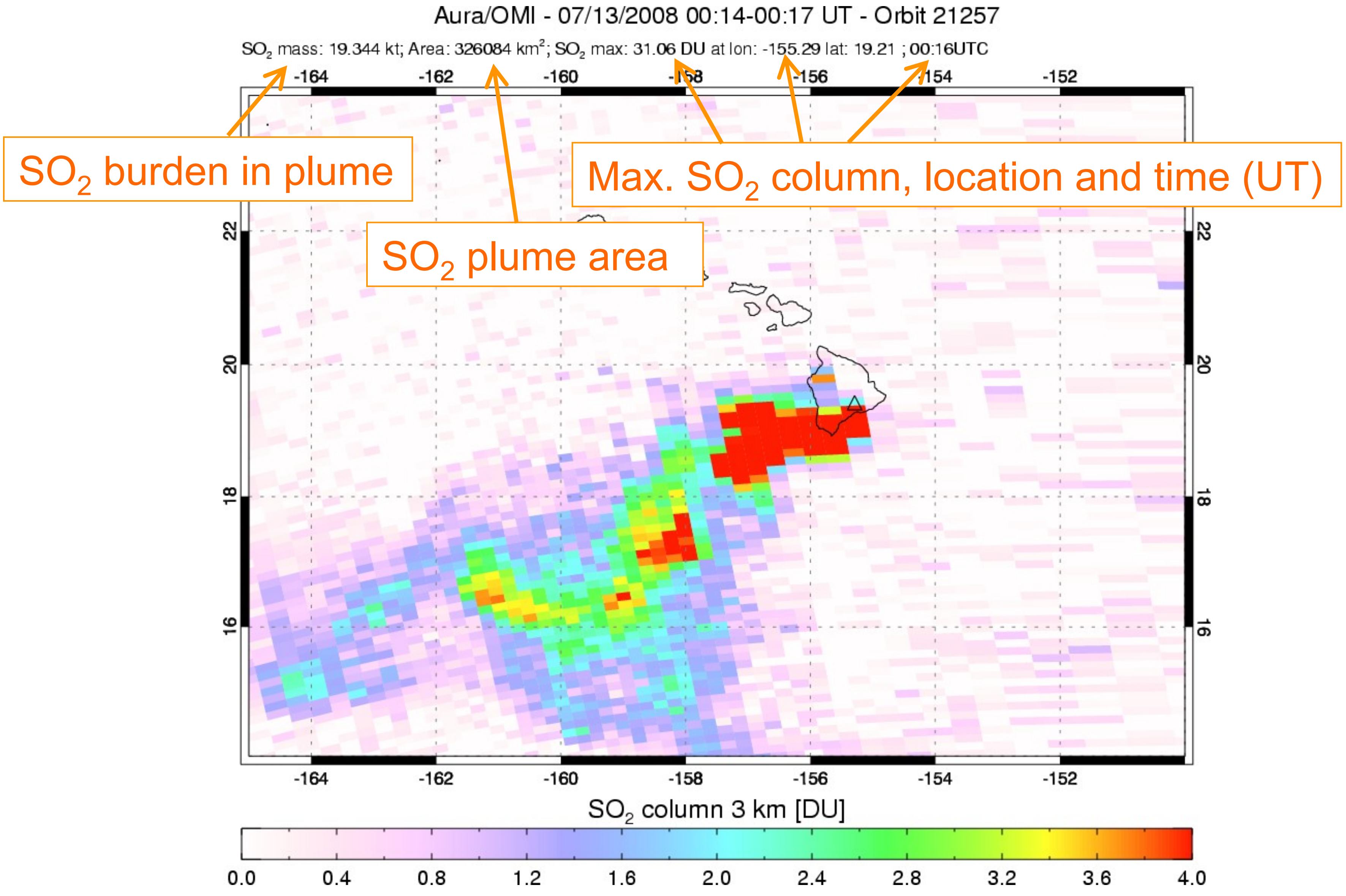

Oct 20, 2010

- Satellites measure column amounts of gases, NOT emission rates

Daily OMI SO_2 measurements for Kilauea

http://so2.gsfc.nasa.gov



Aura/OMI - 07/13/2008 00:14-00:17 UT - Orbit 21257

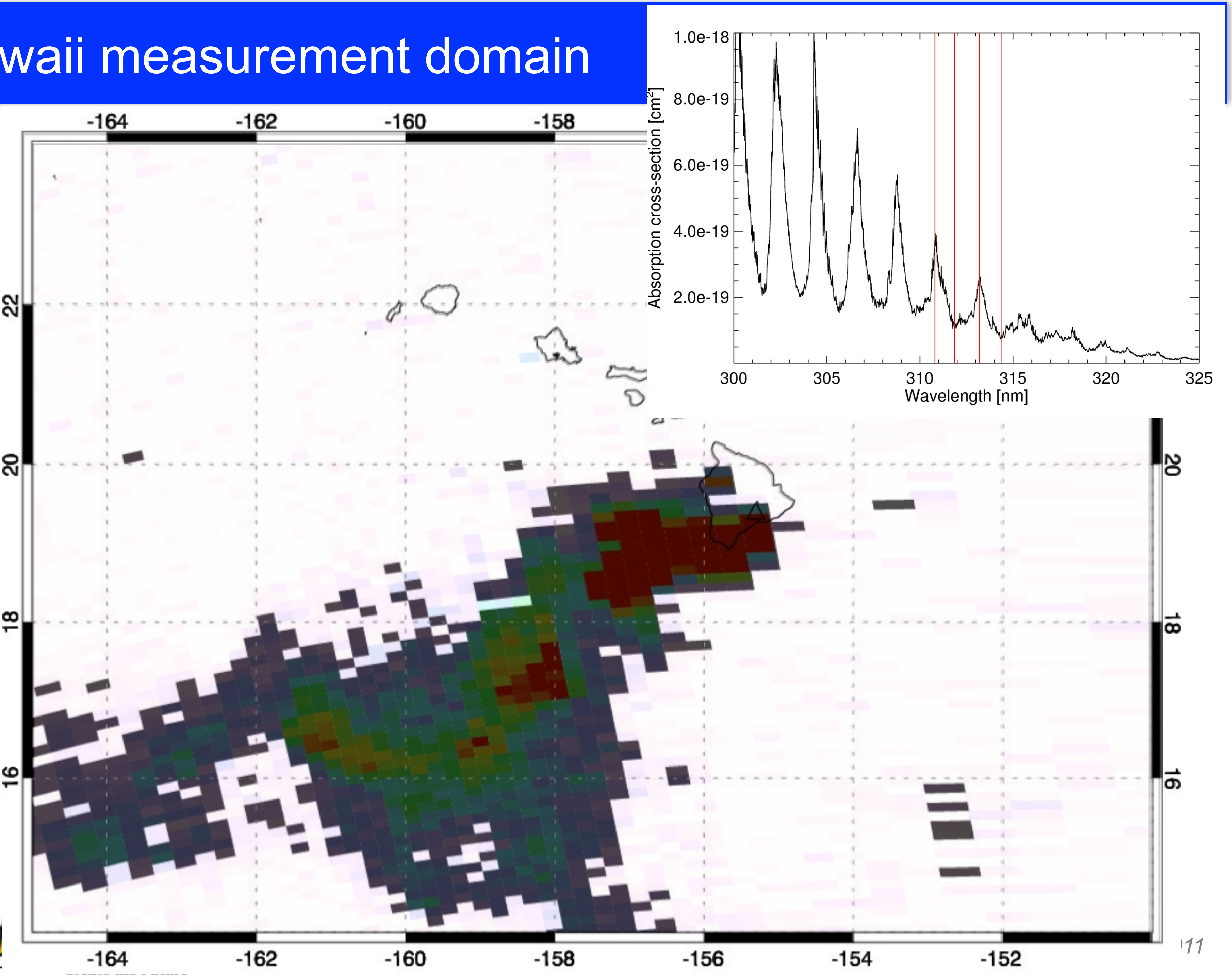
SO_2 mass: 19.344 kt; Area: 326084 km^2; SO_2 max: 31.06 DU at lon: -155.29 lat: 19.21 ; 00:16UTC

SO_2 burden in plume

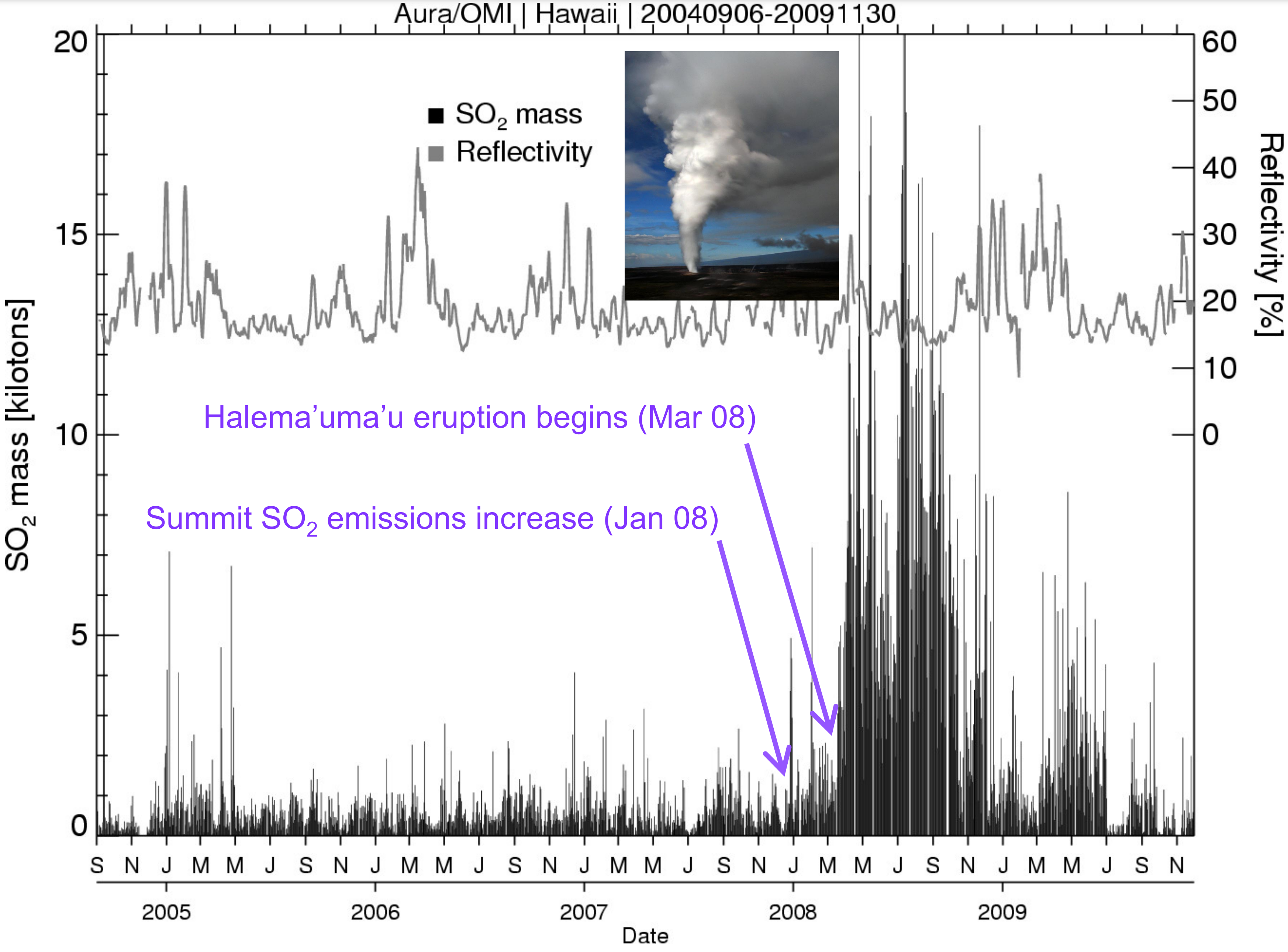
SO_2 plume area

Max. SO_2 column, location and time (UT)

Hawaii measurement domain



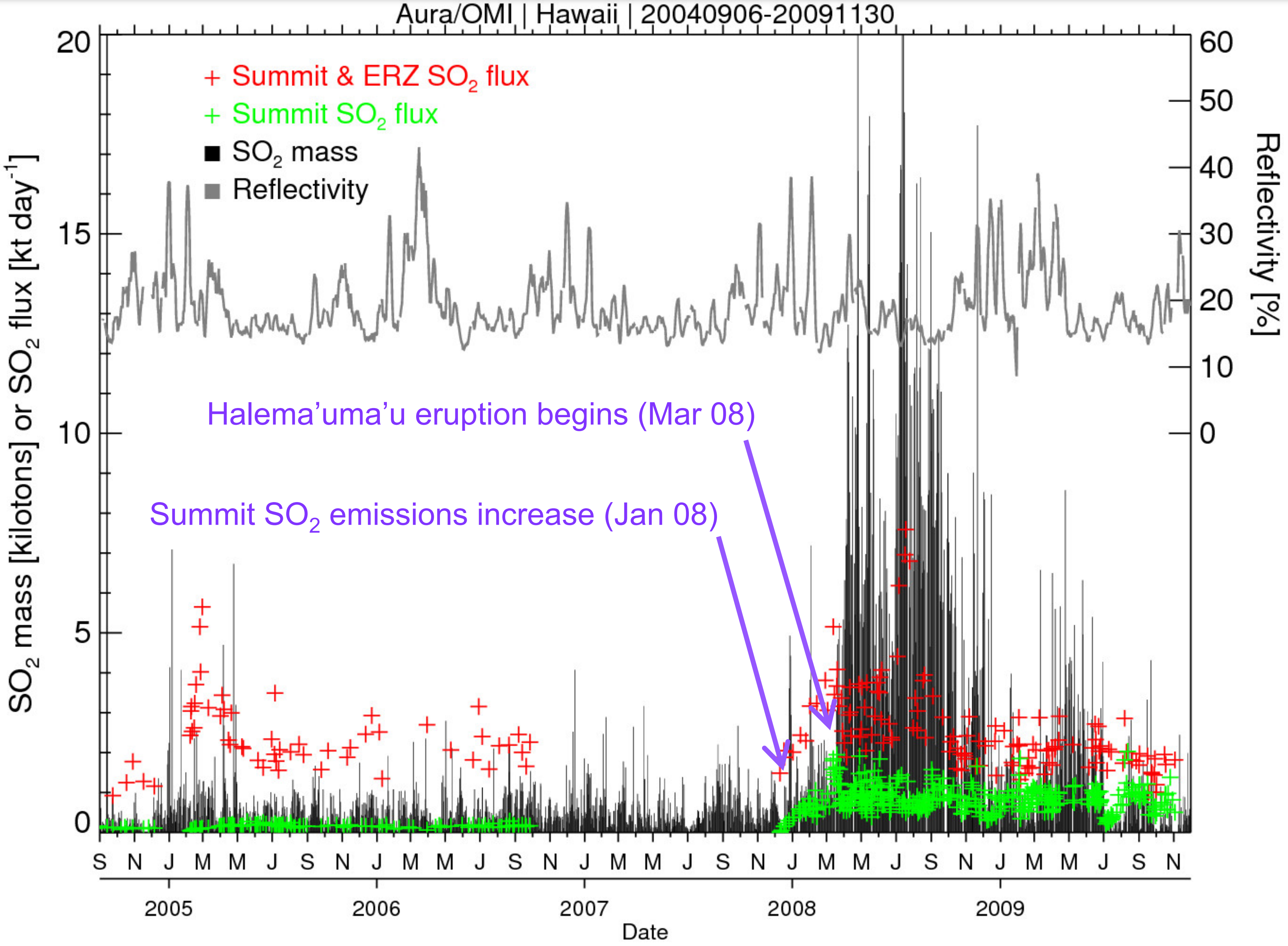
Kilauea plume SO_2 burdens: 2004-2009



Halema’uma’u eruption begins (Mar 08)

Summit SO_2 emissions increase (Jan 08)

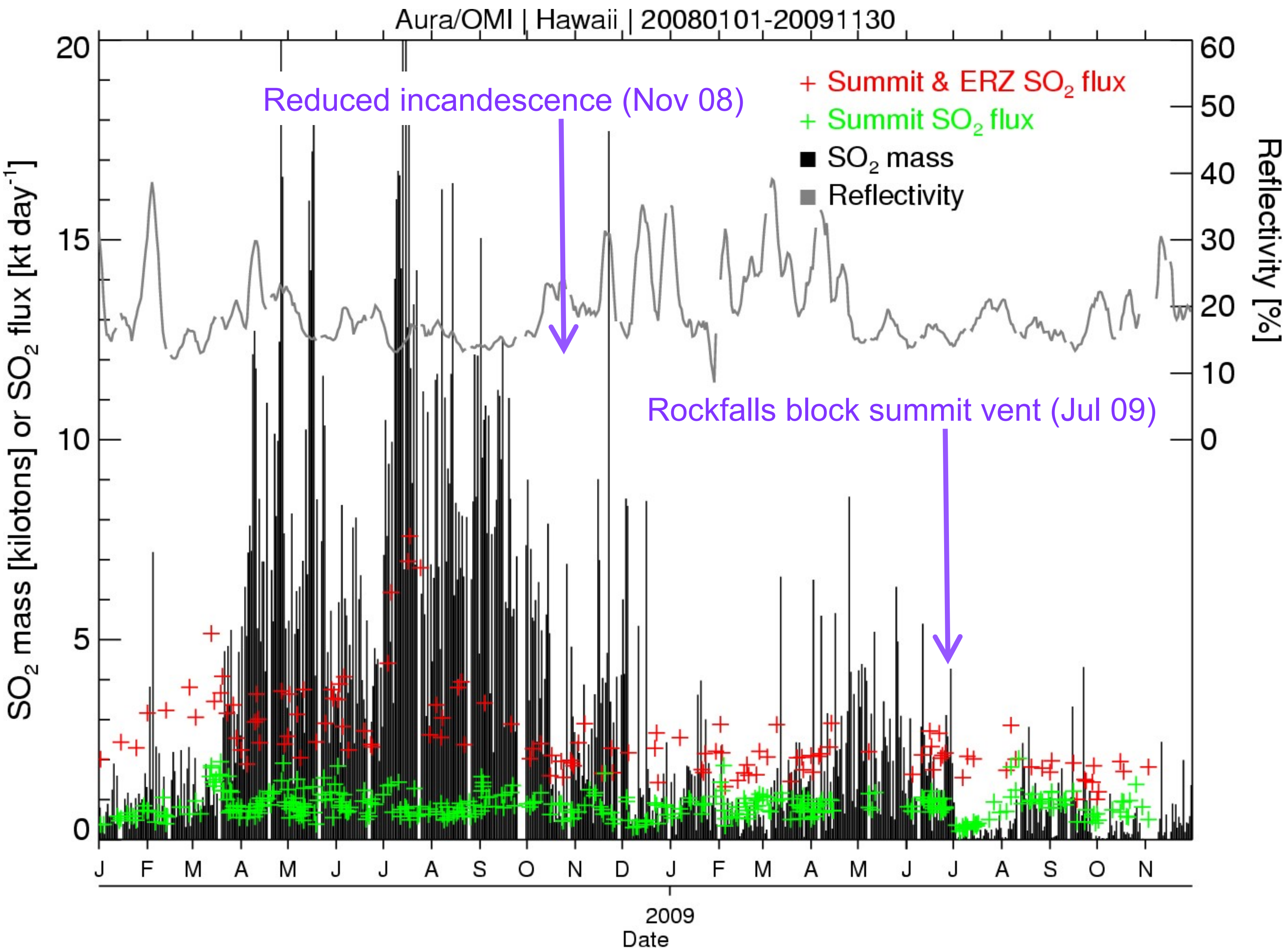
Kilauea plume SO_2 burdens: 2004-2009



Halema'uma'u eruption begins (Mar 08)

Summit SO_2 emissions increase (Jan 08)

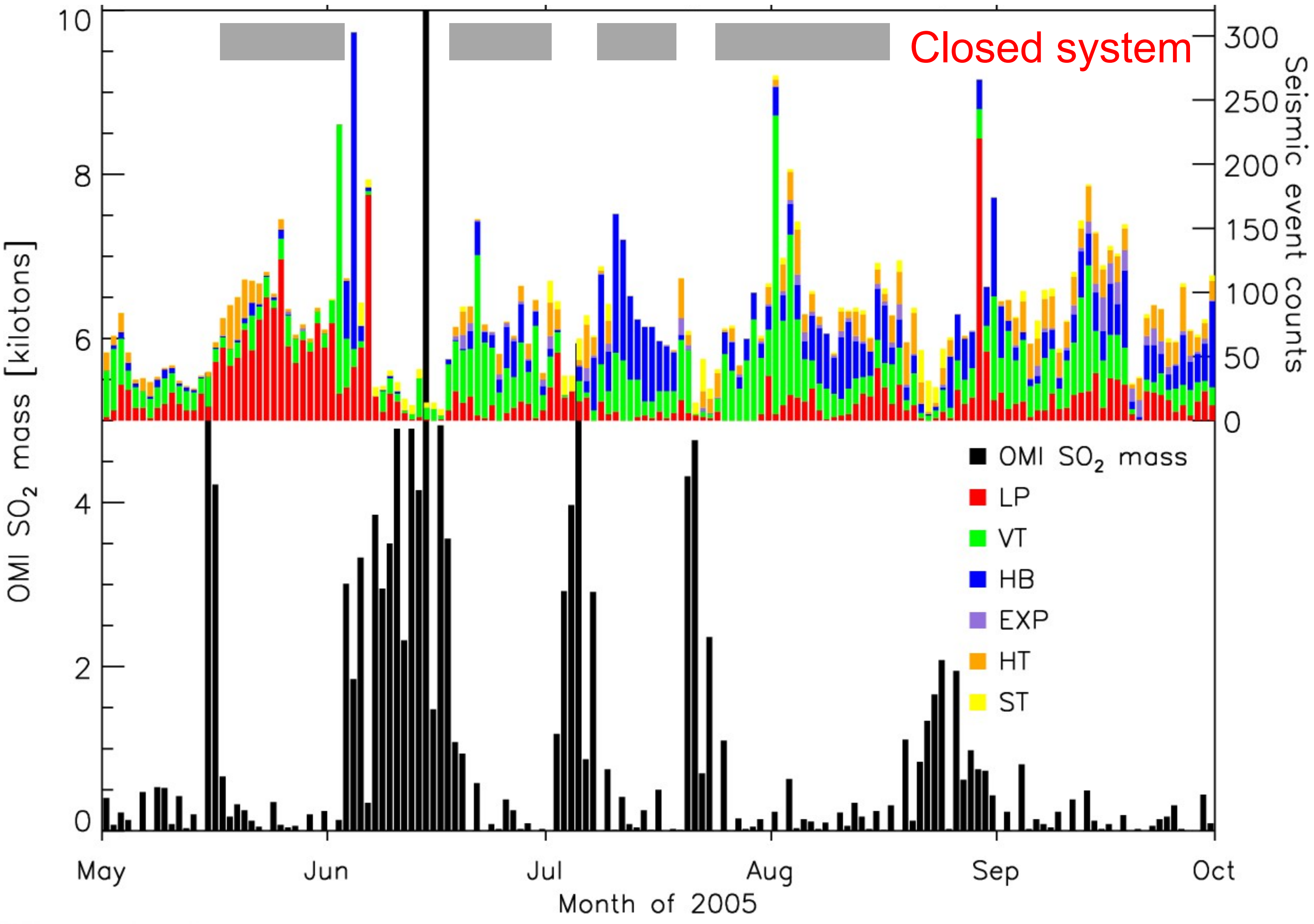
Kilauea plume SO_2 burdens: 2008-2009



Reduced incandescence (Nov 08)

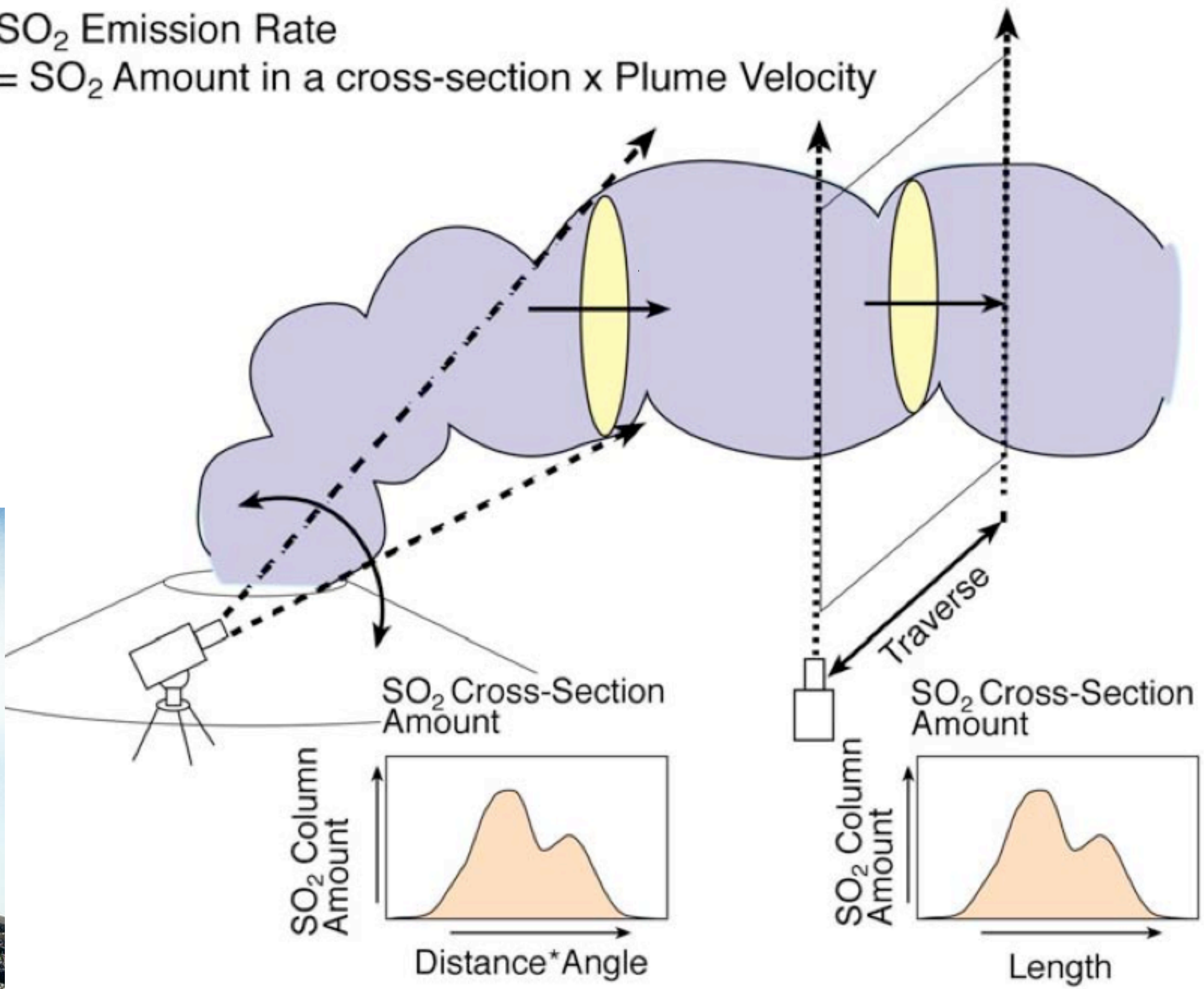
Rockfalls block summit vent (Jul 09)

Reventador (Ecuador) seismicity and OMI SO_2 data



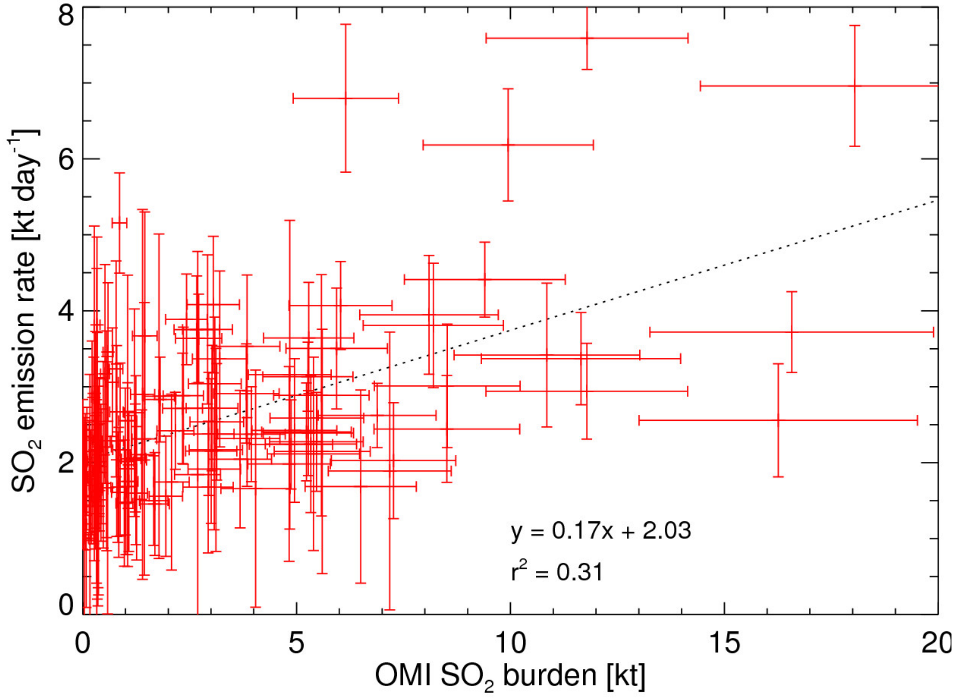
[Carn et al., JVGR, 2008]

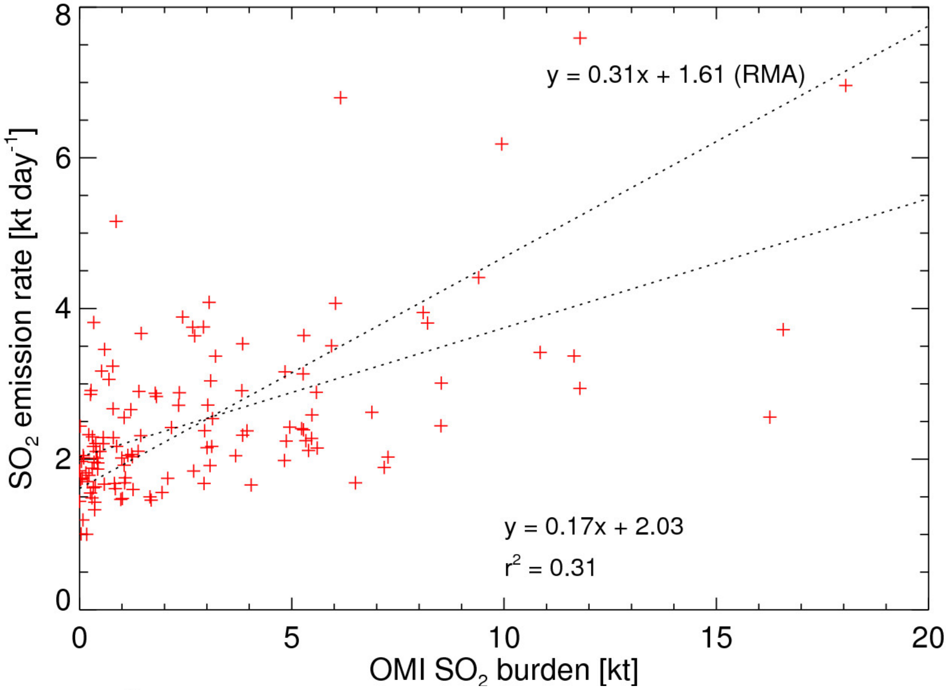
Volcanic SO_2 flux measurements



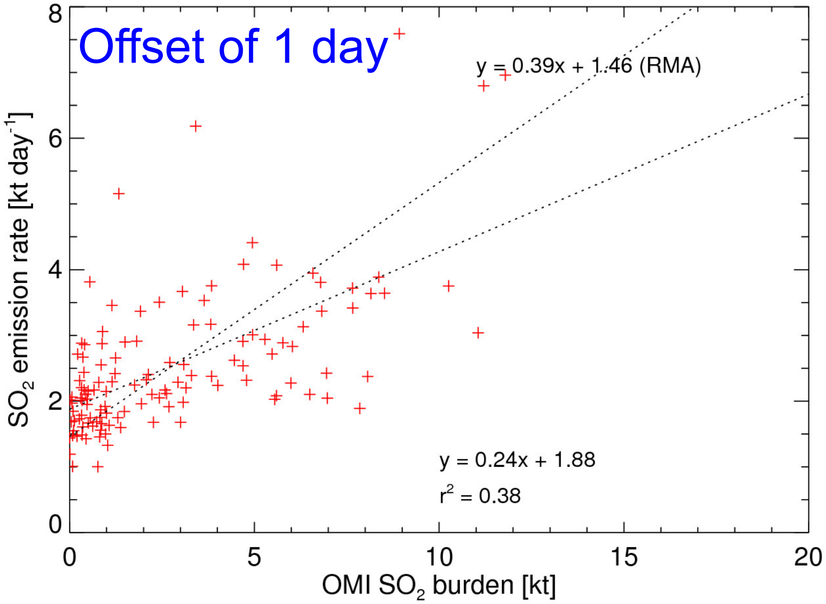
SO_2 Emission Rate
= SO_2 Amount in a cross-section x Plume Velocity

Comparing OMI SO_2 burdens with SO_2 emission rates (Kilauea)





- Direct comparison of SO_2 emission rates (summit + ERZ) and OMI SO_2 burdens complicated by variability, meteorology and errors
- Broad positive correlation


Offset of 1 day

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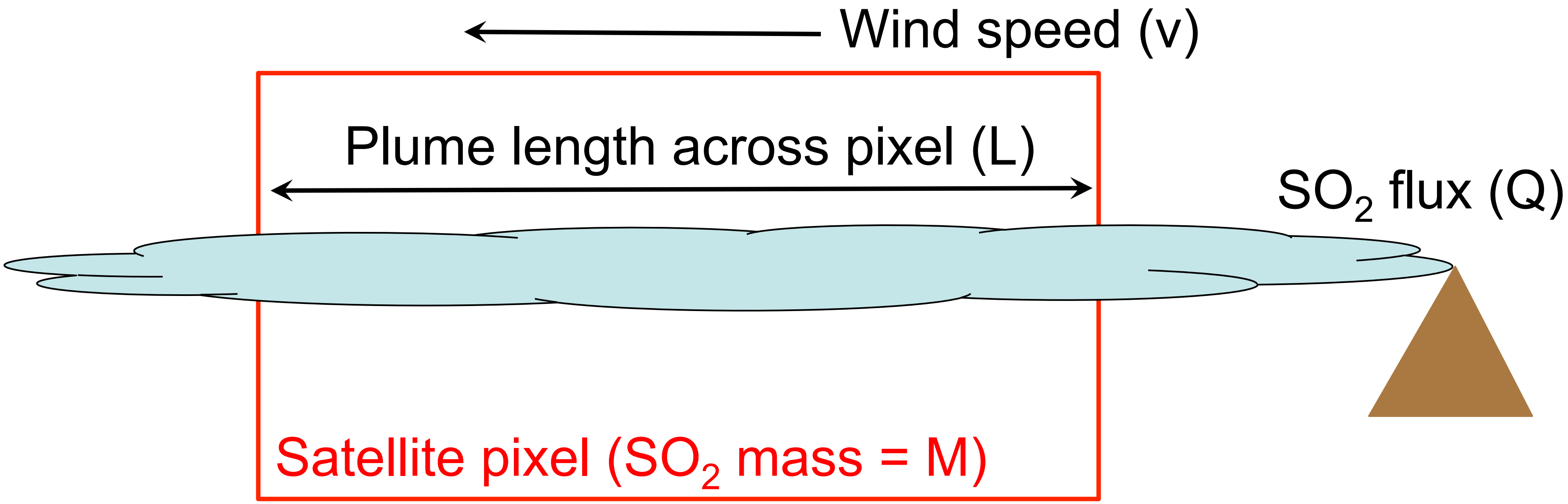
SO_2 flux estimation from satellite data

- Satellite ‘snapshots’ measure SO_2 burden, not flux
- To first order, SO_2 emission rates can be inferred using the SO_2 burden and an estimate of the SO_2 lifetime
    - SO_2 lifetime short (hours) at low altitudes and in humid environments
    - May be a few hours in tropical boundary layers

$$Q = \frac{M}{\tau}$$

- Q = SO_2 emission rate (tons/day), M = SO_2 burden (tons), τ = SO_2 lifetime (days)

SO_2 flux estimation from satellite data



Wind speed (v)

Plume length across pixel (L)

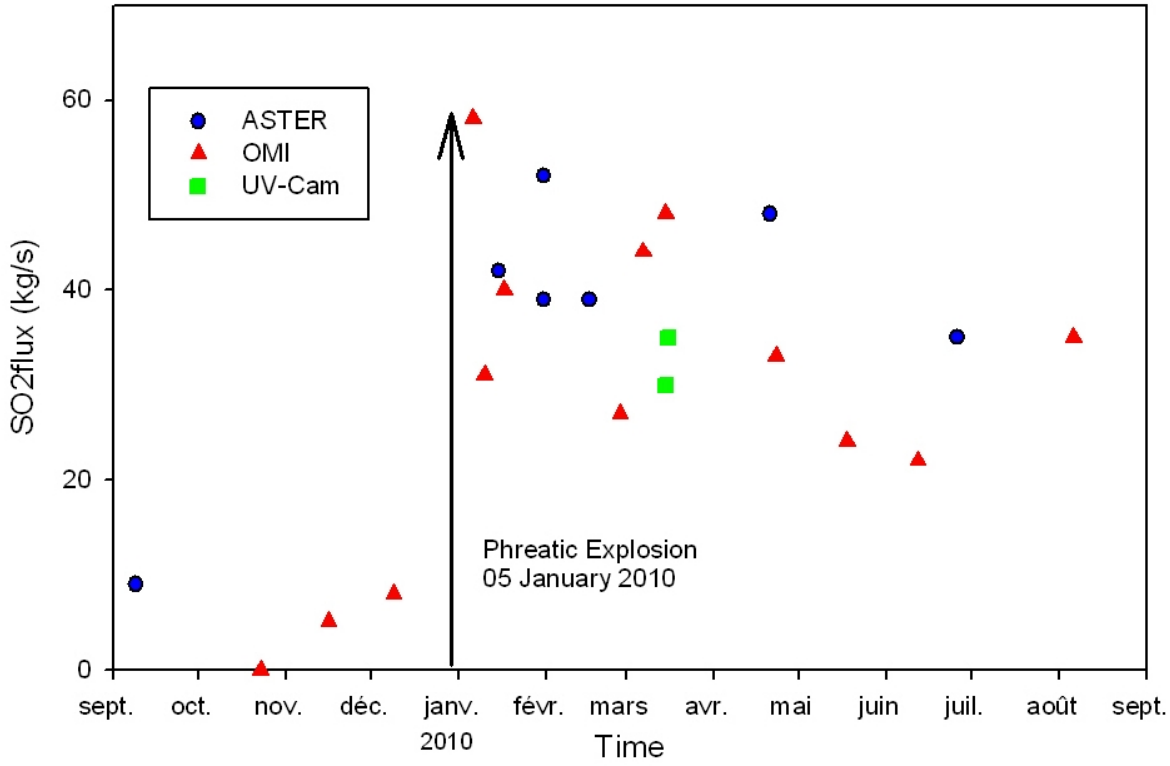
SO_2 flux (Q)

Satellite pixel (SO_2 mass = M)

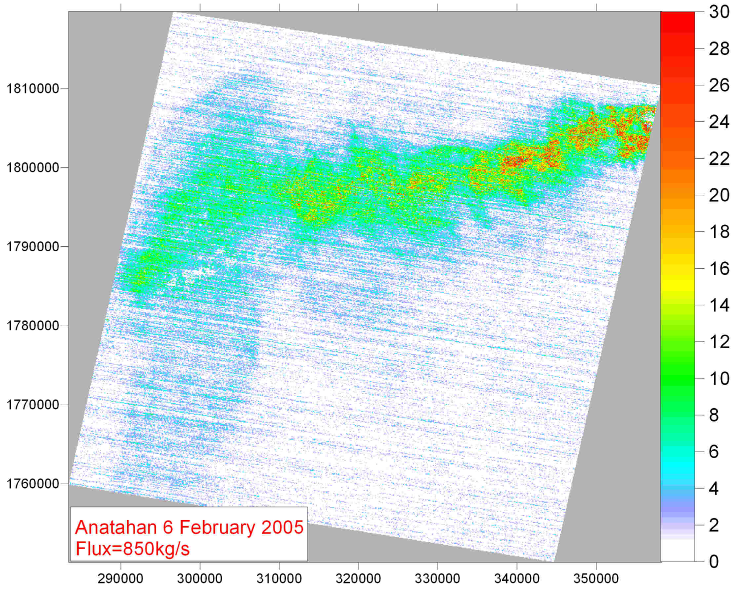
$$Q = \left[\frac{vM}{L}\right]$$

- Similar approach used to estimate smoke emissions from fires [*Ichoku and Kaufman*, 2005]
- Note that asymmetry of OMI pixel affects plume detection

SO_2 flux estimation from satellite data (Turrialba)



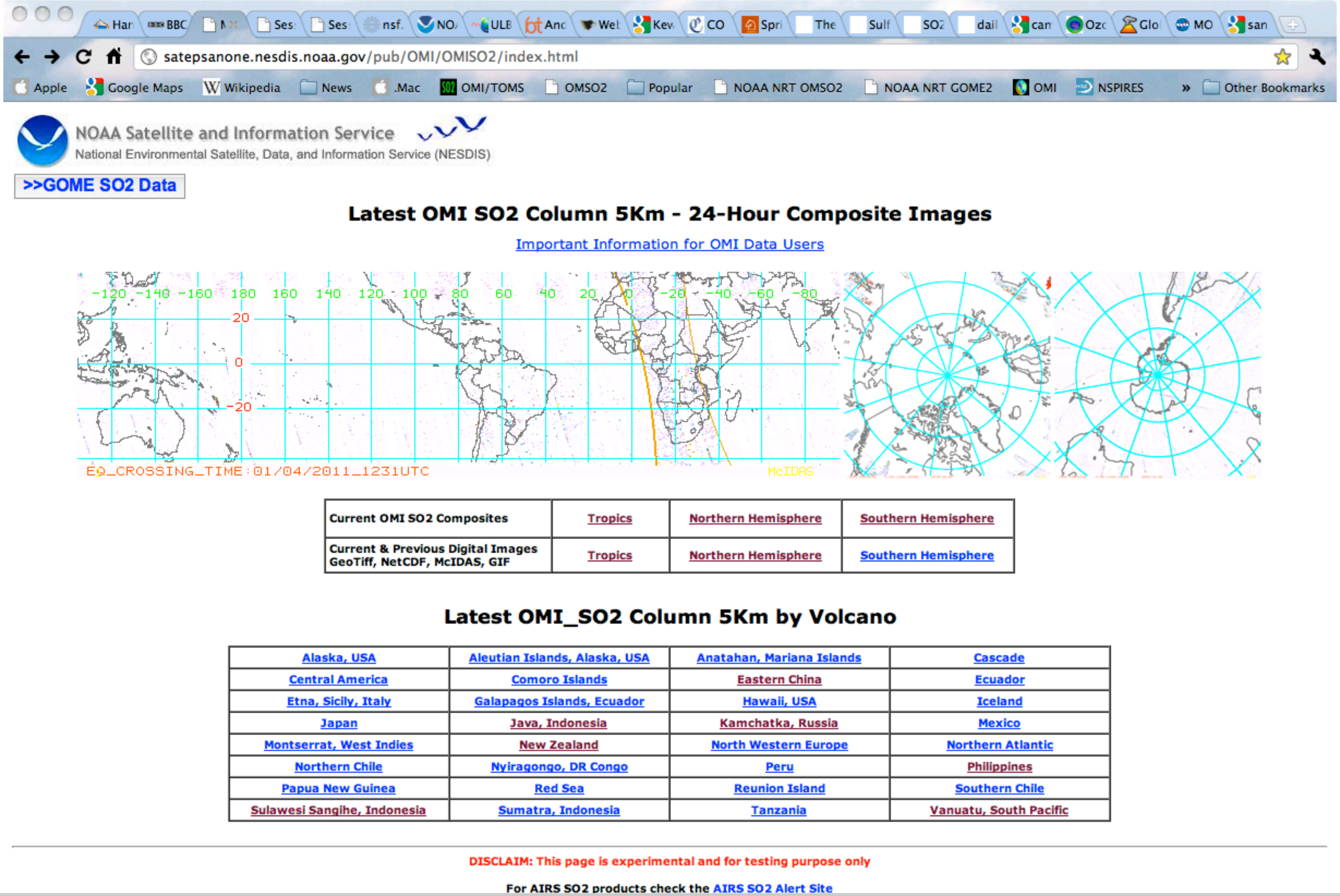
Phreatic Explosion
05 January 2010



Anatahan 6 February 2005
Flux=850kg/s

- Comparison between Turrialba SO_2 emission rates derived from ASTER, OMI and UV camera [*Campion et al.*, in prep.]

OMI SO_2 websites - NRT



NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)

>>GOME SO2 Data

Latest OMI SO2 Column 5Km - 24-Hour Composite Images

Important Information for OMI Data Users

Current OMI SO2 Composites	Tropics	Northern Hemisphere	Southern Hemisphere
Current & Previous Digital Images GeoTiff, NetCDF, McIDAS, GIF	Tropics	Northern Hemisphere	Southern Hemisphere

Latest OMI_SO2 Column 5Km by Volcano

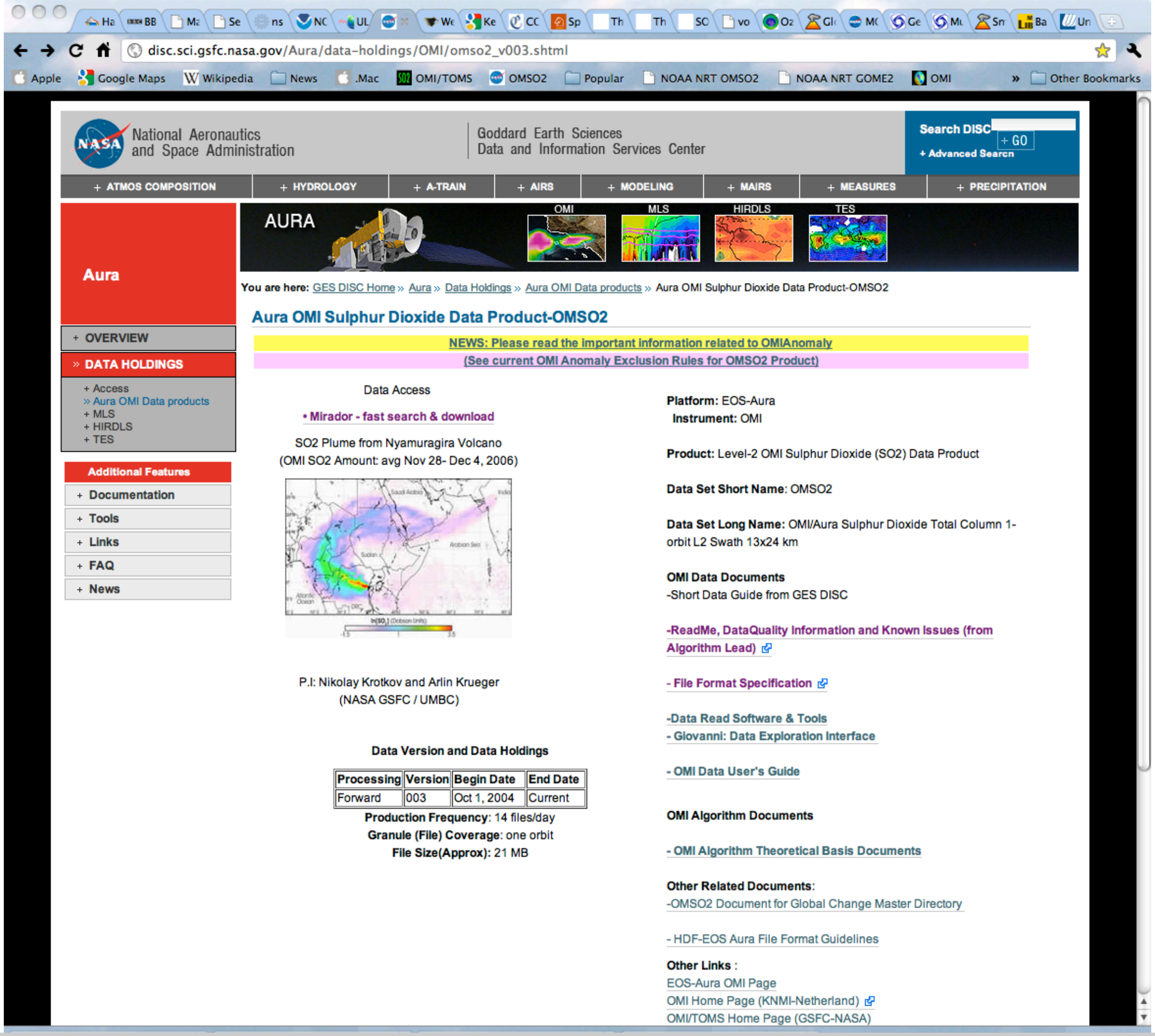
Alaska, USA	Aleutian Islands, Alaska, USA	Anatahan, Mariana Islands	Cascade
Central America	Comoro Islands	Eastern China	Ecuador
Etna, Sicily, Italy	Galapagos Islands, Ecuador	Hawaii, USA	Iceland
Japan	Java, Indonesia	Kamchatka, Russia	Mexico
Montserrat, West Indies	New Zealand	North Western Europe	Northern Atlantic
Northern Chile	Nyiragongo, DR Congo	Peru	Philippines
Papua New Guinea	Red Sea	Reunion Island	Southern Chile
Sulawesi Sangihe, Indonesia	Sumatra, Indonesia	Tanzania	Vanuatu, South Pacific

DISCLAIM: This page is experimental and for testing purpose only

For AIRS SO2 products check the AIRS SO2 Alert Site

Near real-time: http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html

Operational OMI SO_2 data from NASA Mirador



You are here: GES DISC Home » Aura » Data Holdings » Aura OMI Data products » Aura OMI Sulphur Dioxide Data Product-OMSO2

Aura OMI Sulphur Dioxide Data Product-OMSO2

NEWS: Please read the important information related to OMIAnomaly

(See current OMI Anomaly Exclusion Rules for OMSO2 Product)

Data Access

• Mirador - fast search & download

SO2 Plume from Nyamuragira Volcano
(OMI SO2 Amount: avg Nov 28- Dec 4, 2006)

P.I: Nikolay Krotkov and Arlin Krueger
(NASA GSFC / UMBC)

Data Version and Data Holdings

Processing	Version	Begin Date	End Date
Forward	003	Oct 1, 2004	Current

Production Frequency: 14 files/day
Granule (File) Coverage: one orbit
File Size(Approx): 21 MB

Platform: EOS-Aura
Instrument: OMI

Product: Level-2 OMI Sulphur Dioxide (SO2) Data Product

Data Set Short Name: OMSO2

Data Set Long Name: OMI/Aura Sulphur Dioxide Total Column 1-orbit L2 Swath 13x24 km

OMI Data Documents
-Short Data Guide from GES DISC

-ReadMe, DataQuality Information and Known Issues (from Algorithm Lead)

- File Format Specification

-Data Read Software & Tools
- Giovanni: Data Exploration Interface

- OMI Data User's Guide

OMI Algorithm Documents

- OMI Algorithm Theoretical Basis Documents

Other Related Documents:
-OMSO2 Document for Global Change Master Directory

- HDF-EOS Aura File Format Guidelines

Other Links :
EOS-Aura OMI Page
OMI Home Page (KNMI-Netherland)
OMI/TOMS Home Page (GSFC-NASA)

http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml

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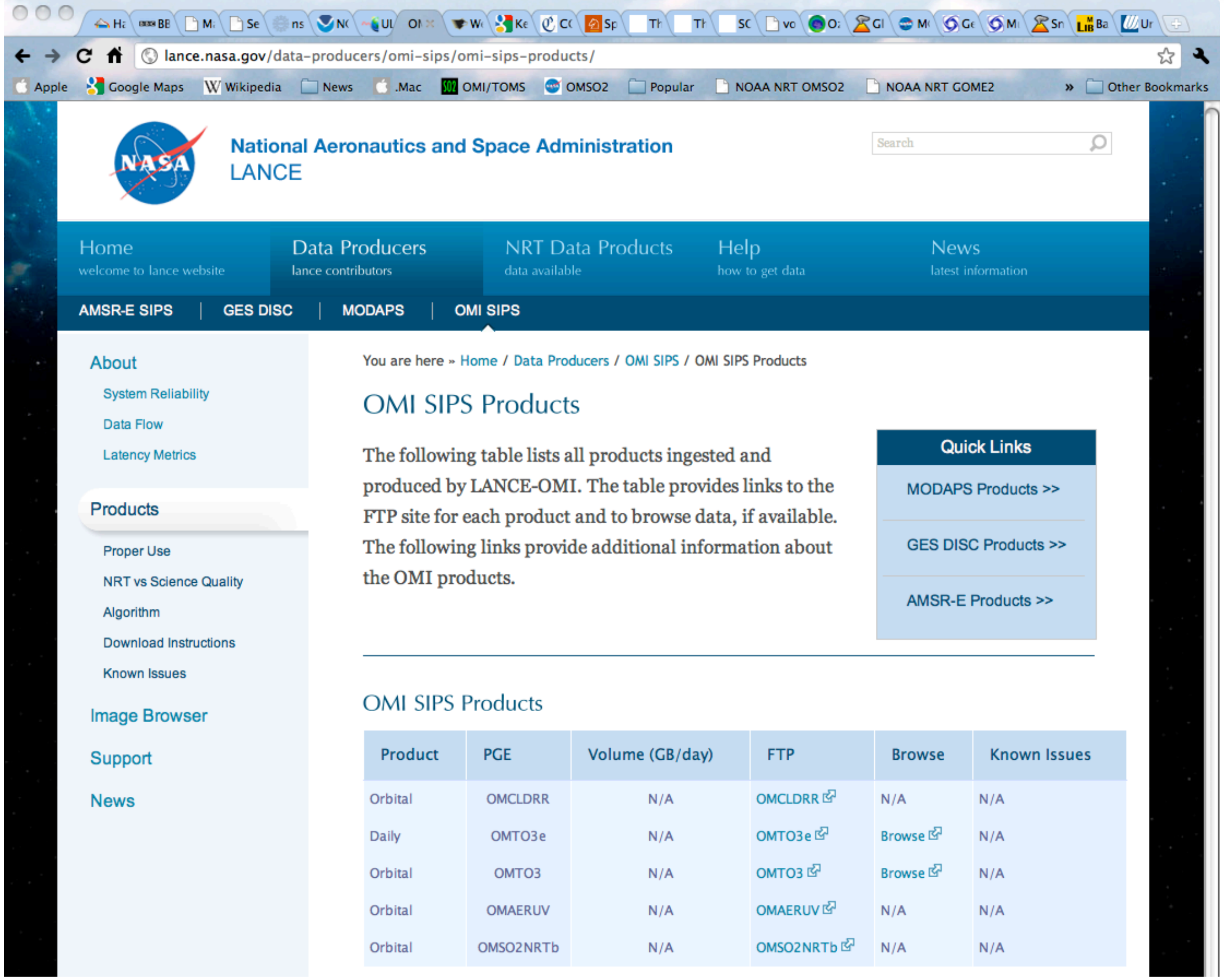
Near real-time OMI SO_2 data from NASA LANCE



National Aeronautics and Space Administration
LANCE

You are here » Home / Data Producers / OMI SIPS / OMI SIPS Products

OMI SIPS Products

The following table lists all products ingested and produced by LANCE-OMI. The table provides links to the FTP site for each product and to browse data, if available. The following links provide additional information about the OMI products.

Quick Links
- MODAPS Products >>
- GES DISC Products >>
- AMSR-E Products >>

OMI SIPS Products

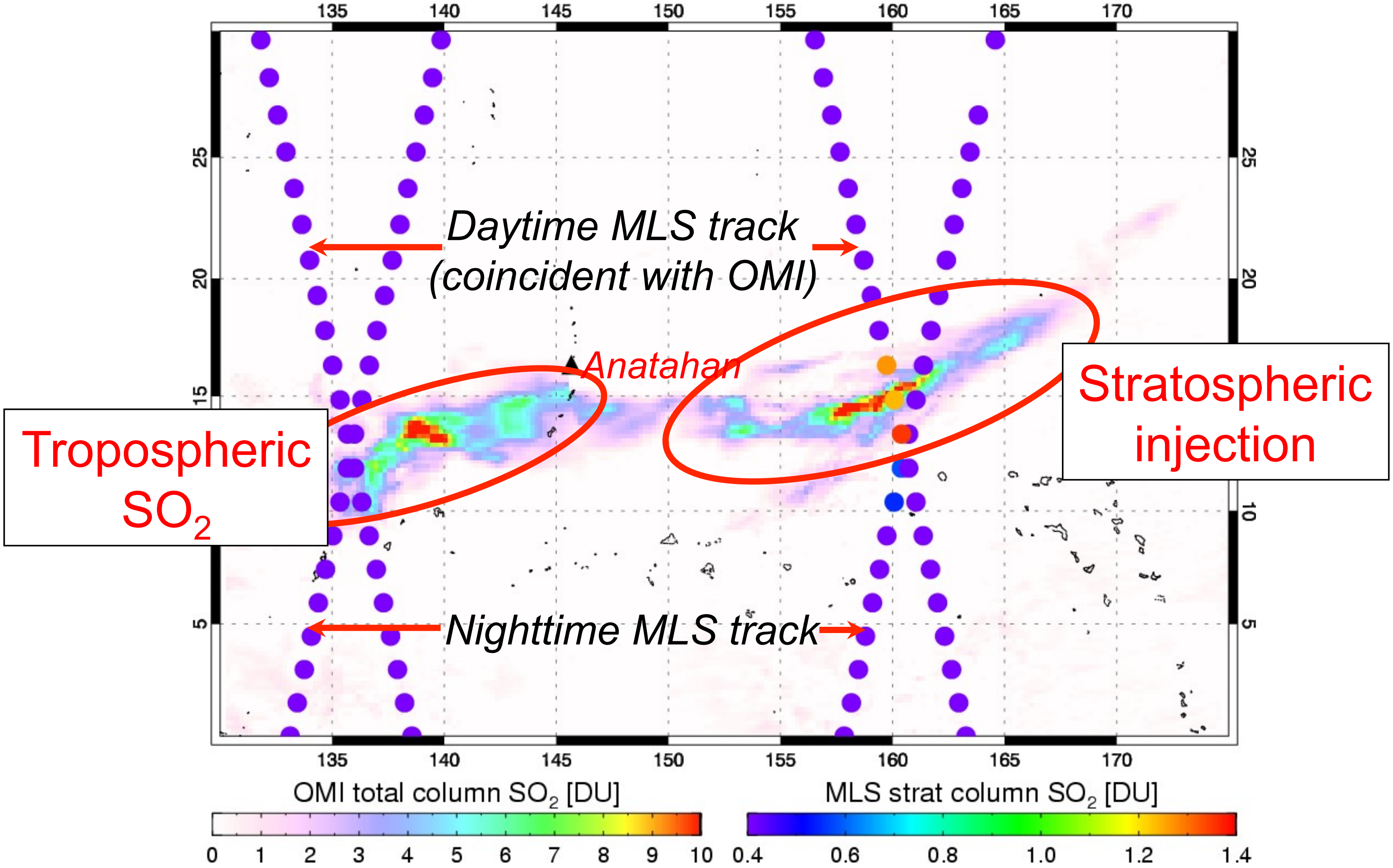
Product	PGE	Volume (GB/day)	FTP	Browse	Known Issues
Orbital	OMCLDRR	N/A	OMCLDRR	N/A	N/A
Daily	OMTO3e	N/A	OMTO3e	Browse	N/A
Orbital	OMTO3	N/A	OMTO3	Browse	N/A
Orbital	OMAERUV	N/A	OMAERUV	N/A	N/A
Orbital	OMSO2NRTb	N/A	OMSO2NRTb	N/A	N/A

http://lance.nasa.gov/data-producers/omi-sips/omi-sips-products/

(Registration required)

Michigan Tech
Create the Future

Aura/OMI - Aura/MLS: Anatahan (CNMI), April 7, 2005



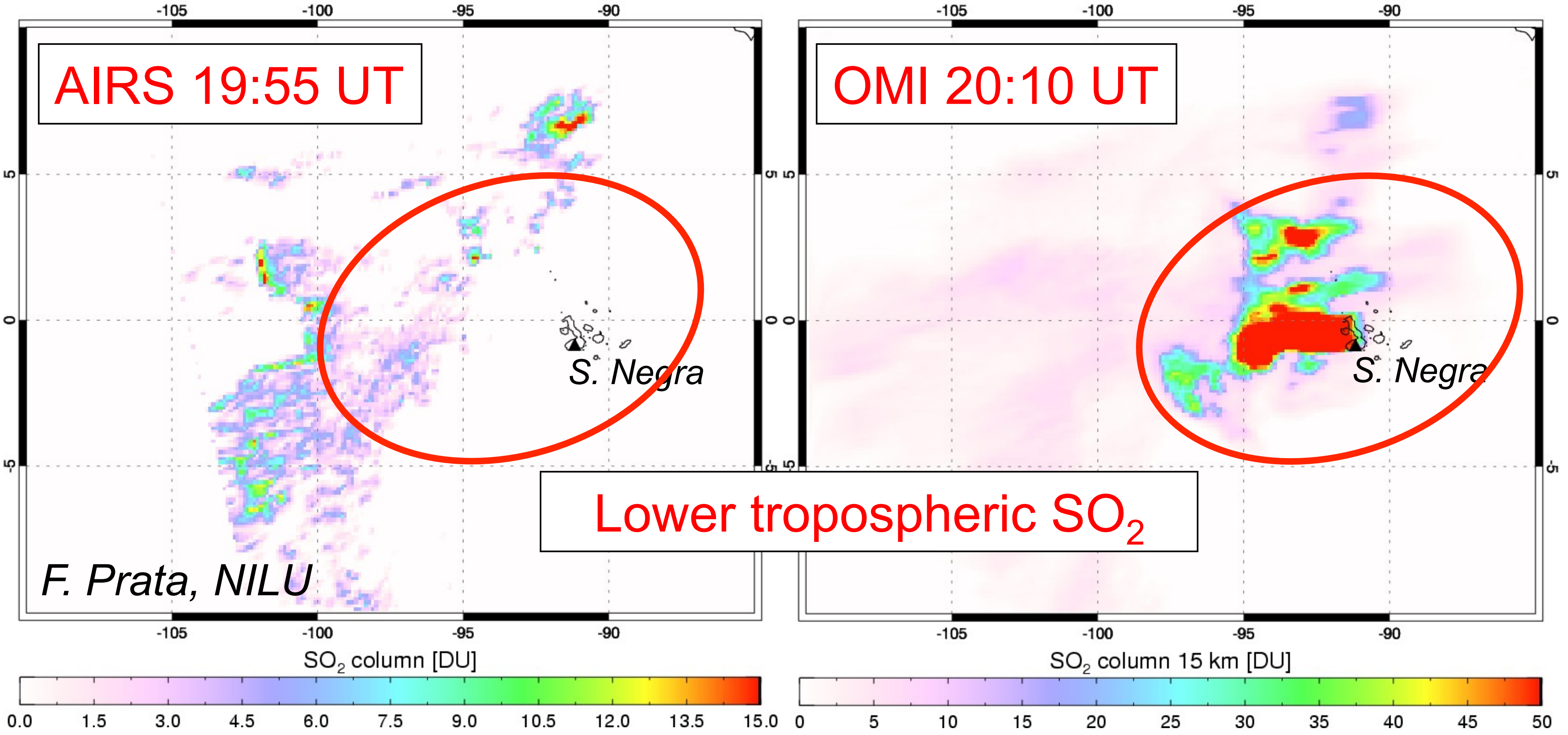
Daytime MLS track (coincident with OMI)

Nighttime MLS track

Tropospheric SO_2

Stratospheric injection

Aura/OMI - Aqua/AIRS: Sierra Negra (Galapagos) 2005

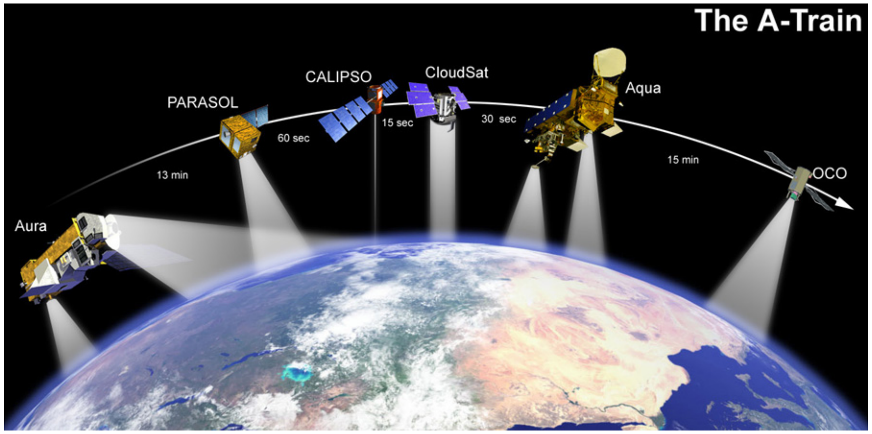


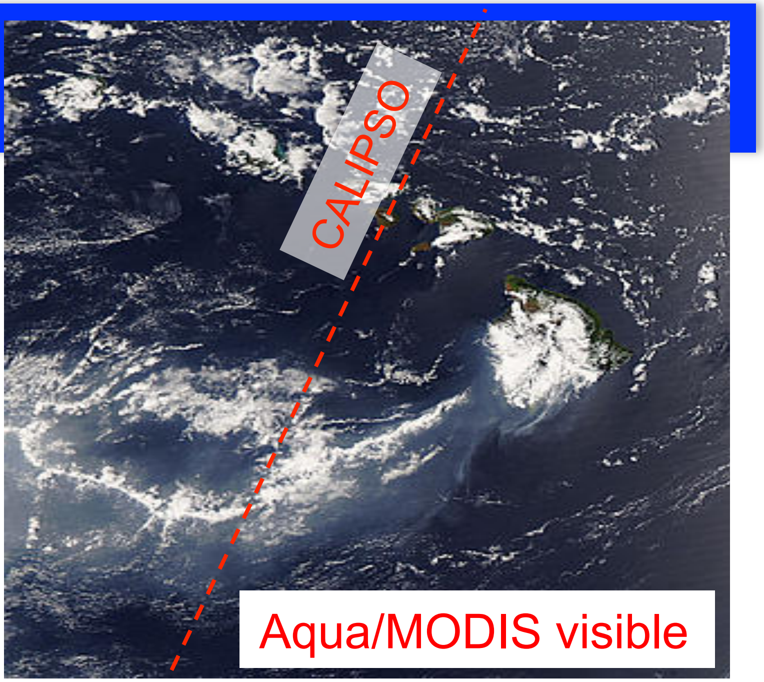
Lower tropospheric SO$_2$

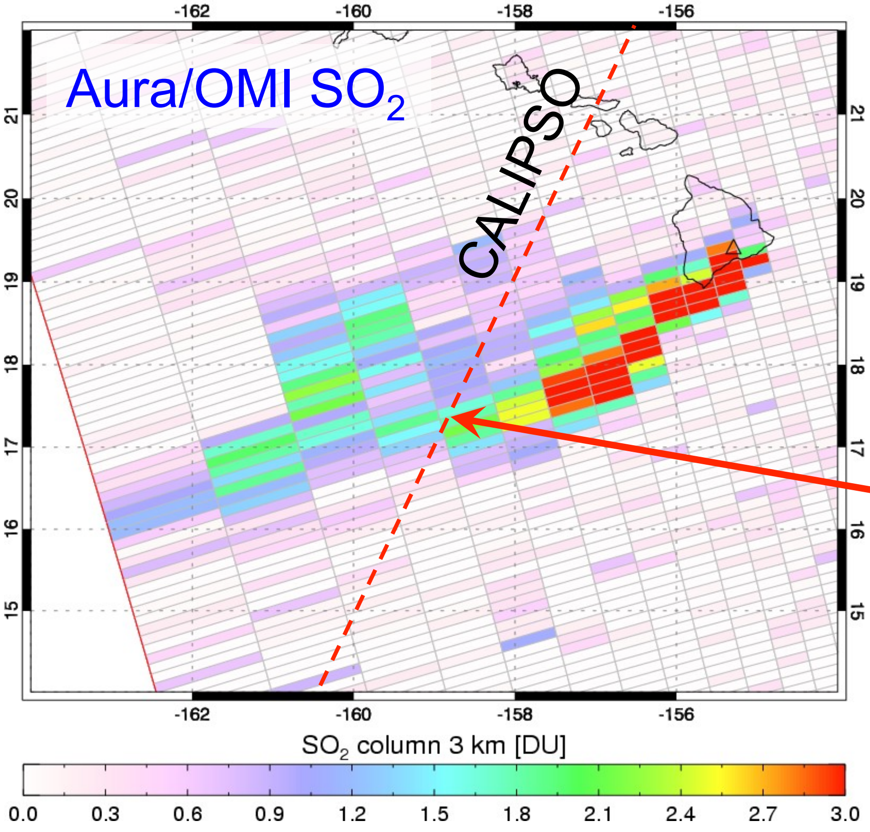
F. Prata, NILU

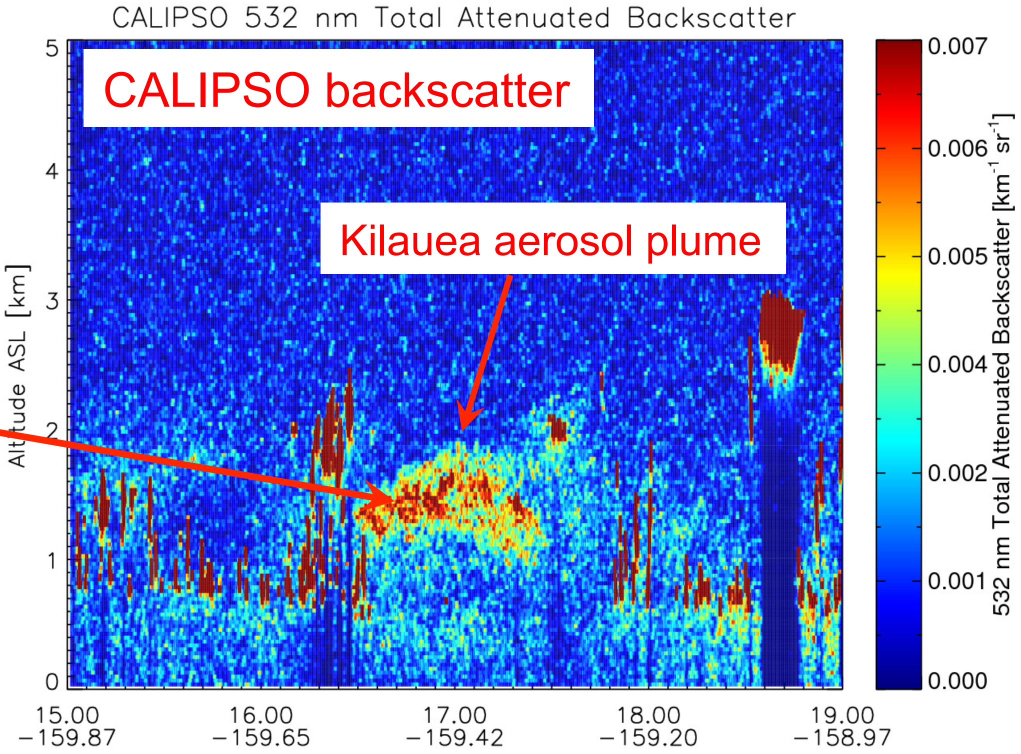
- Sierra Negra (Galapagos) eruption, October 24, 2005
- OMI-AIRS synergy indicates SO$_2$ concentrated in the lower troposphere

Kilauea degassing – April 7, 2008









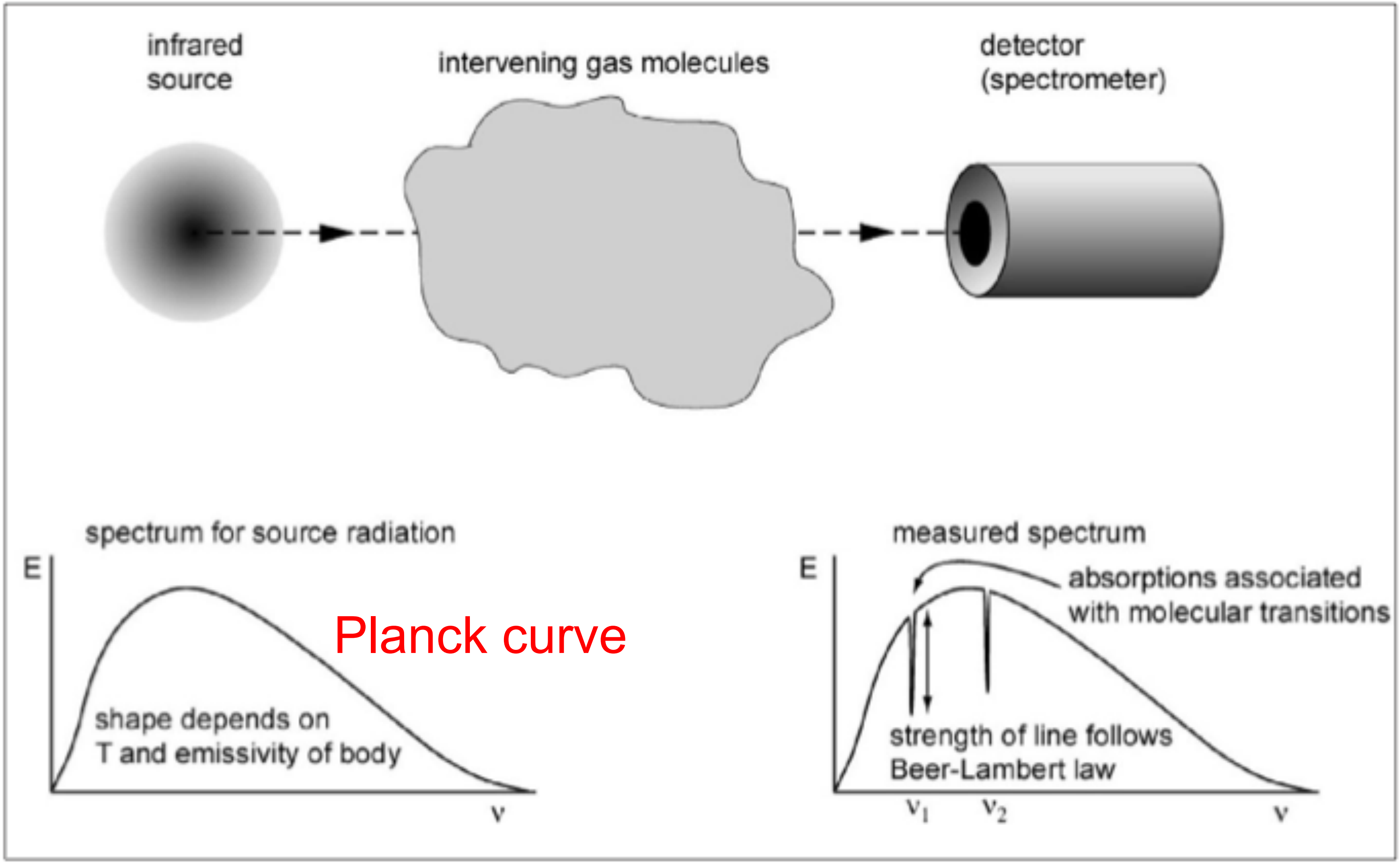
Summary

- Numerous satellite sensors now provide SO_2 measurements
- Some have standard SO_2 products, others require application of retrieval algorithms to yield quantitative SO_2 data
- Aura/OMI is an economical and effective tool for monitoring volcanic SO_2 degassing on a regional or local (single volcano) scale
- OMI's high SO_2 sensitivity and global coverage allows detection of nearly all significant volcanic eruption clouds, assisting aviation hazard mitigation and improving our understanding of the atmospheric impacts of volcanism
- Detection of tropospheric SO_2 plumes by OMI depends on several factors, hence the lower detection limit in terms of SO_2 flux is variable (with latitude, vent altitude etc.)
- Altitude sensitivity must be considered when evaluation satellite SO_2 data
- New satellite constellations (A-Train) provide opportunities for sensor synergy and '3D' analysis of volcanic clouds
- Many datasets are now available online in near-real time

Fourier Transform Infrared (FTIR) Spectroscopy

- Basis of many IR satellite remote sensing instruments
- Ground-based FTIR spectrometers also used for various applications

Absorption spectroscopy



Planck curve

FTIR deployment modes (absorption)

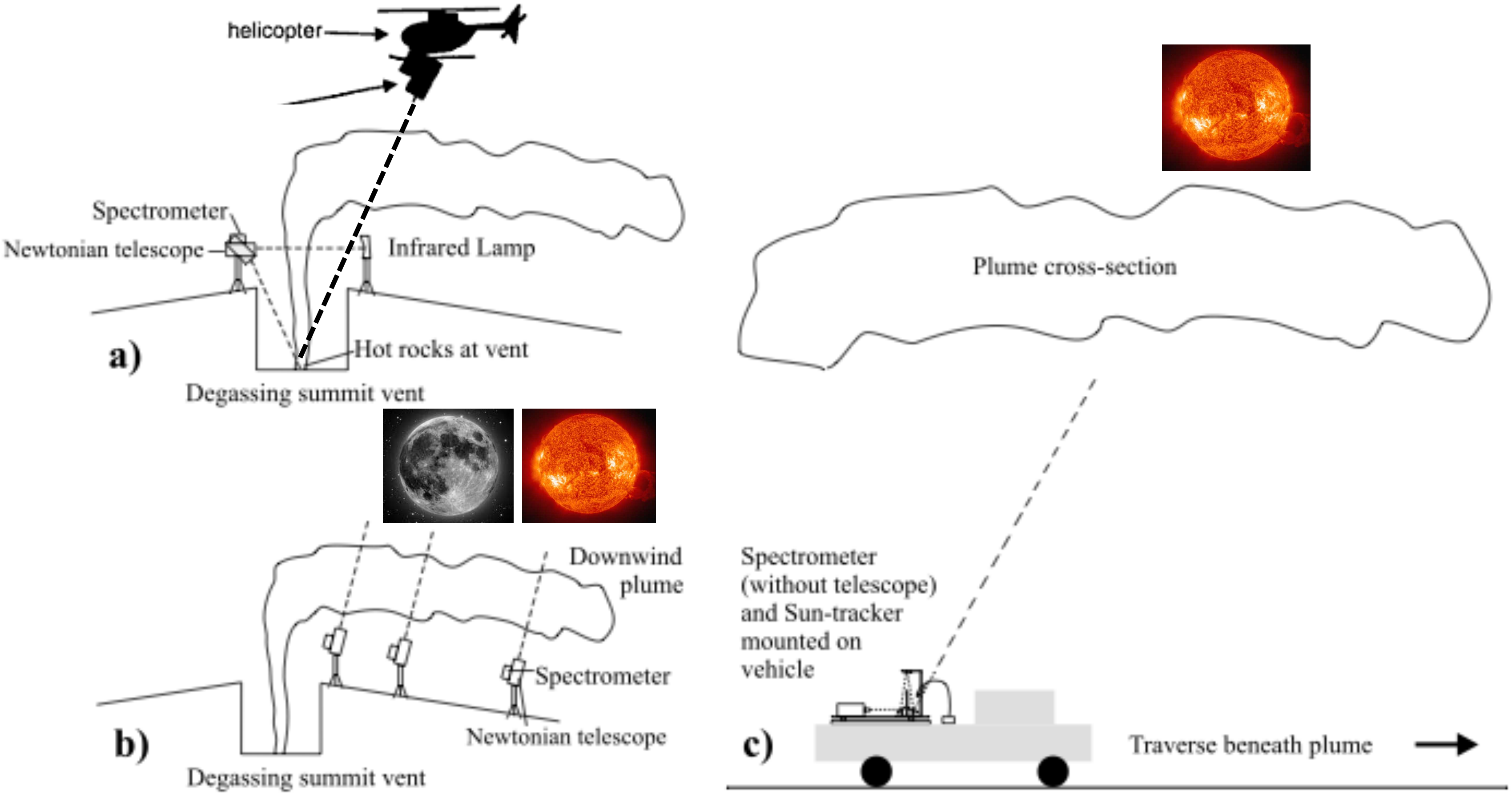


Fig. 2. Diagrams showing modes of FTS deployment. (a) and (b) are from Oppenheimer et al. (1998). (a) Infrared lamp or hot rocks used as source over a specified pathlength. (b) Sun used as infrared source. Both the lamp and Sun can be used as IR sources at the summit or at different distances downwind from the volcano. A Newtonian telescope is used to collimate the light into the spectrometer. (c) Sun used as infrared source and a Sun-tracker allows cross-sectional traverses beneath the plume. This can also be used in a fixed position instead of using the Newtonian telescope.

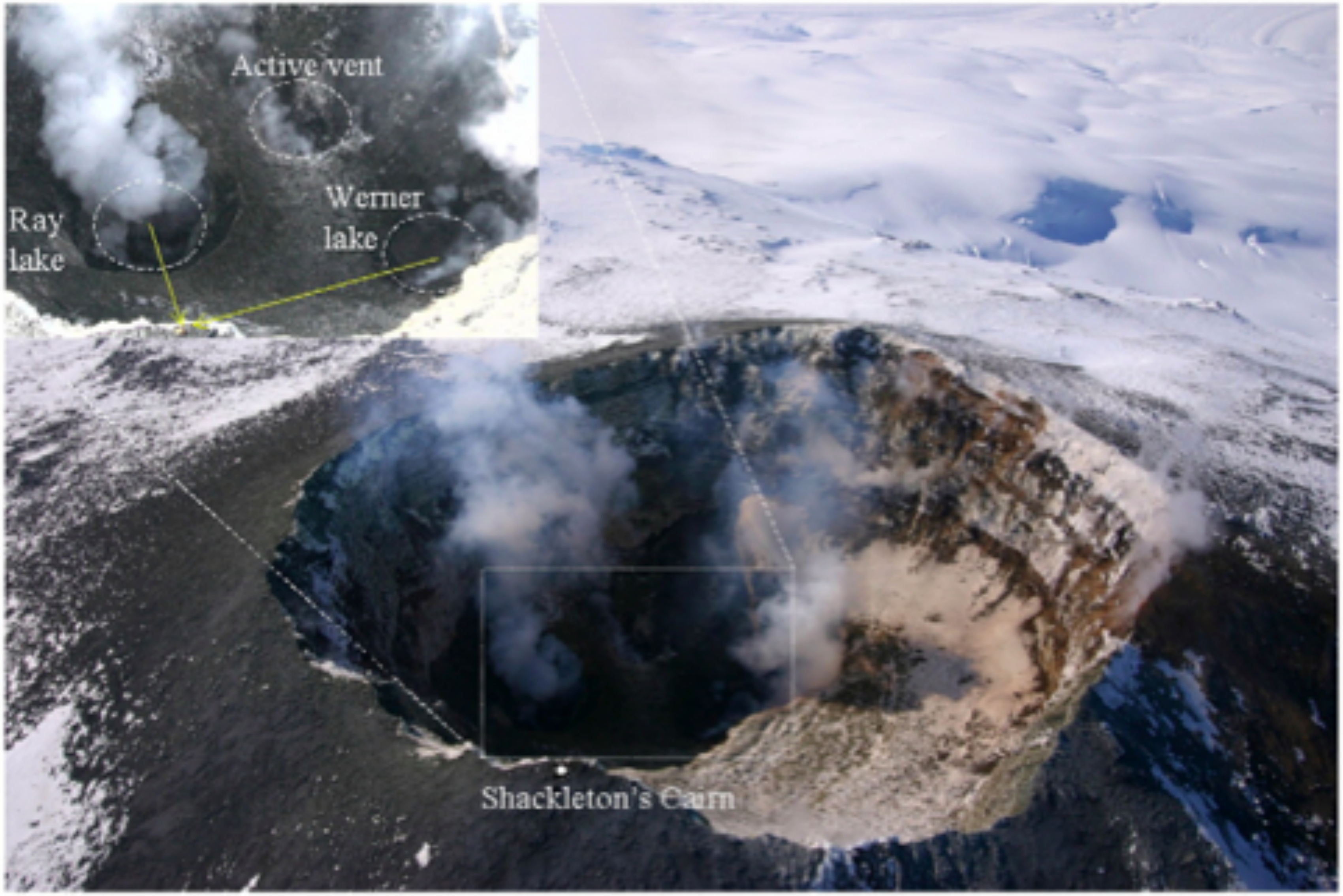

Nyiragongo, DR Congo
FTIR

FTIR at Erta 'Ale (Ethiopia)

Fig. 2. Photograph of Erta 'Ale lava lake from the observation site on the north eastern rim of the central pit. The black circle approximates the 1.5 m 'footprint' of the FTIR spectrometer.

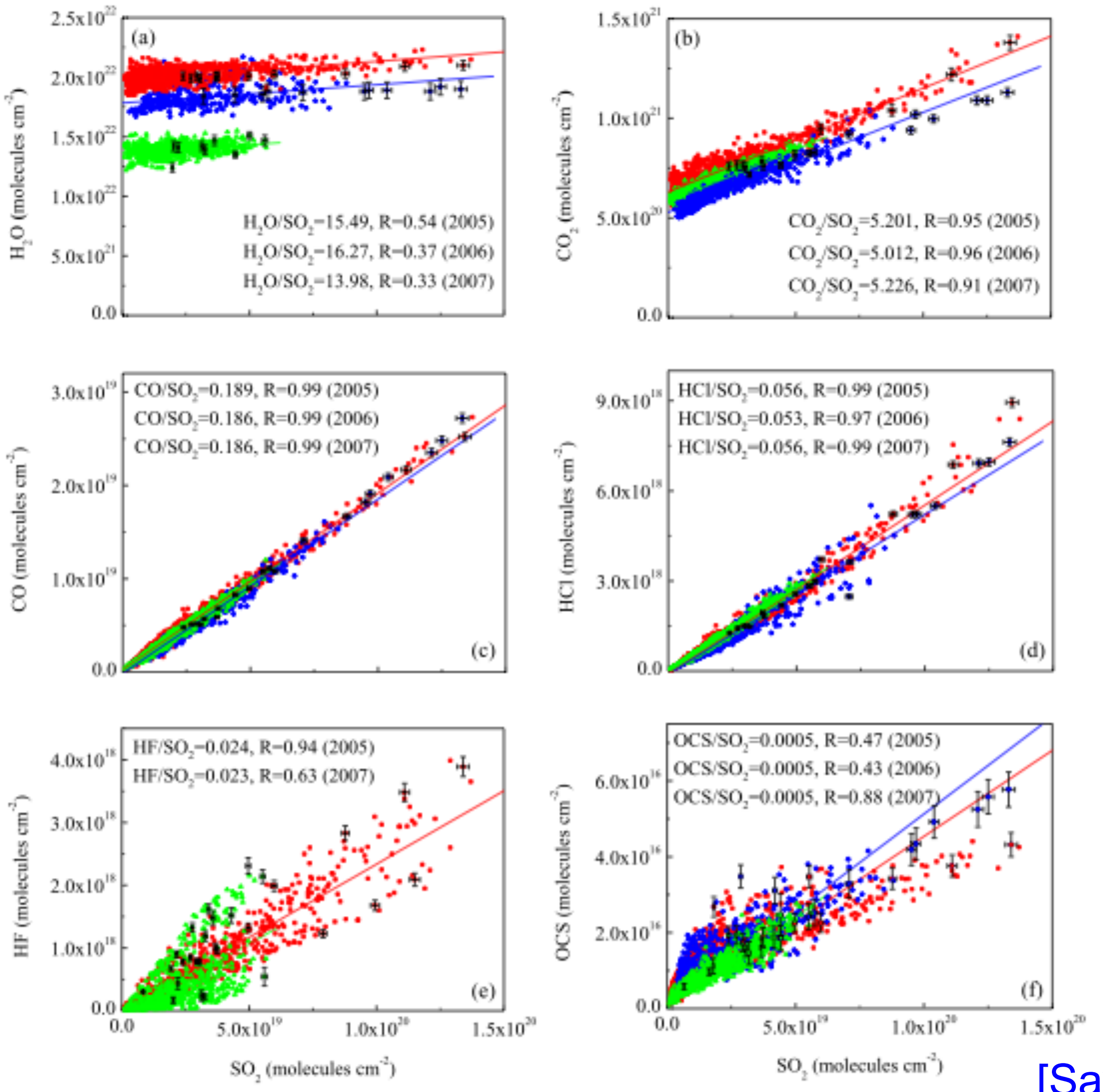
[Sawyer et al., 2008]

FTIR at Erebus (Antarctica)



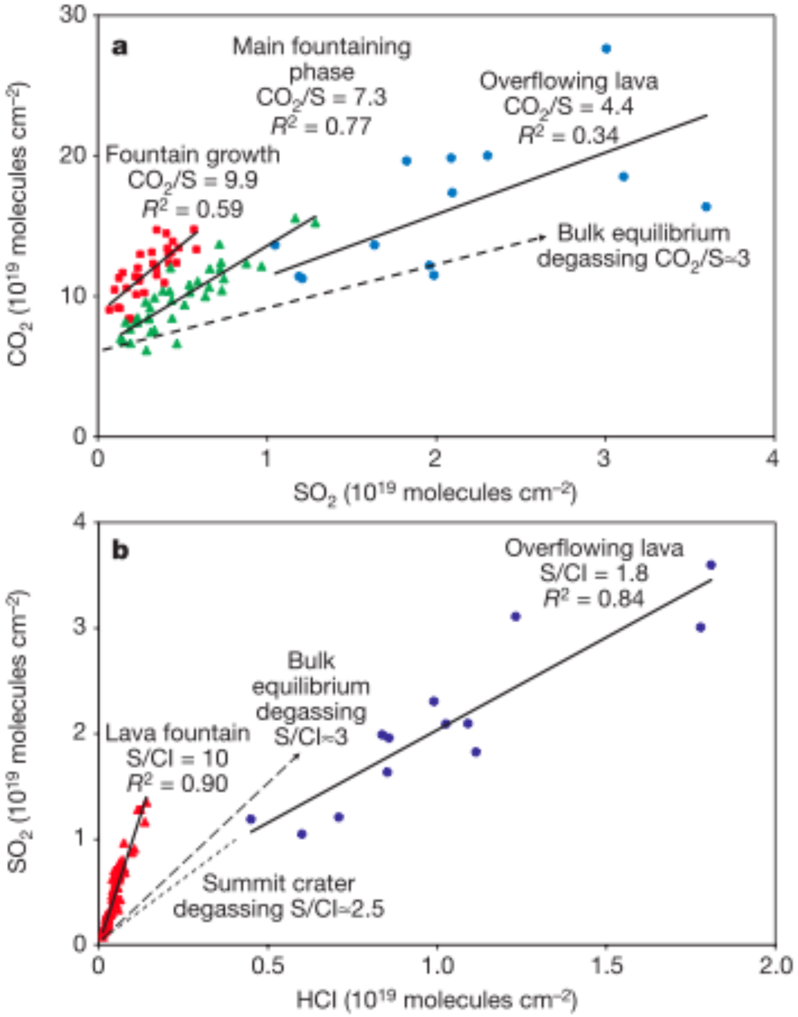
[Oppenheimer et al., 2008]

Gas ratios at Nyiragongo, 2005-2007



[Sawyer et al., 2008]

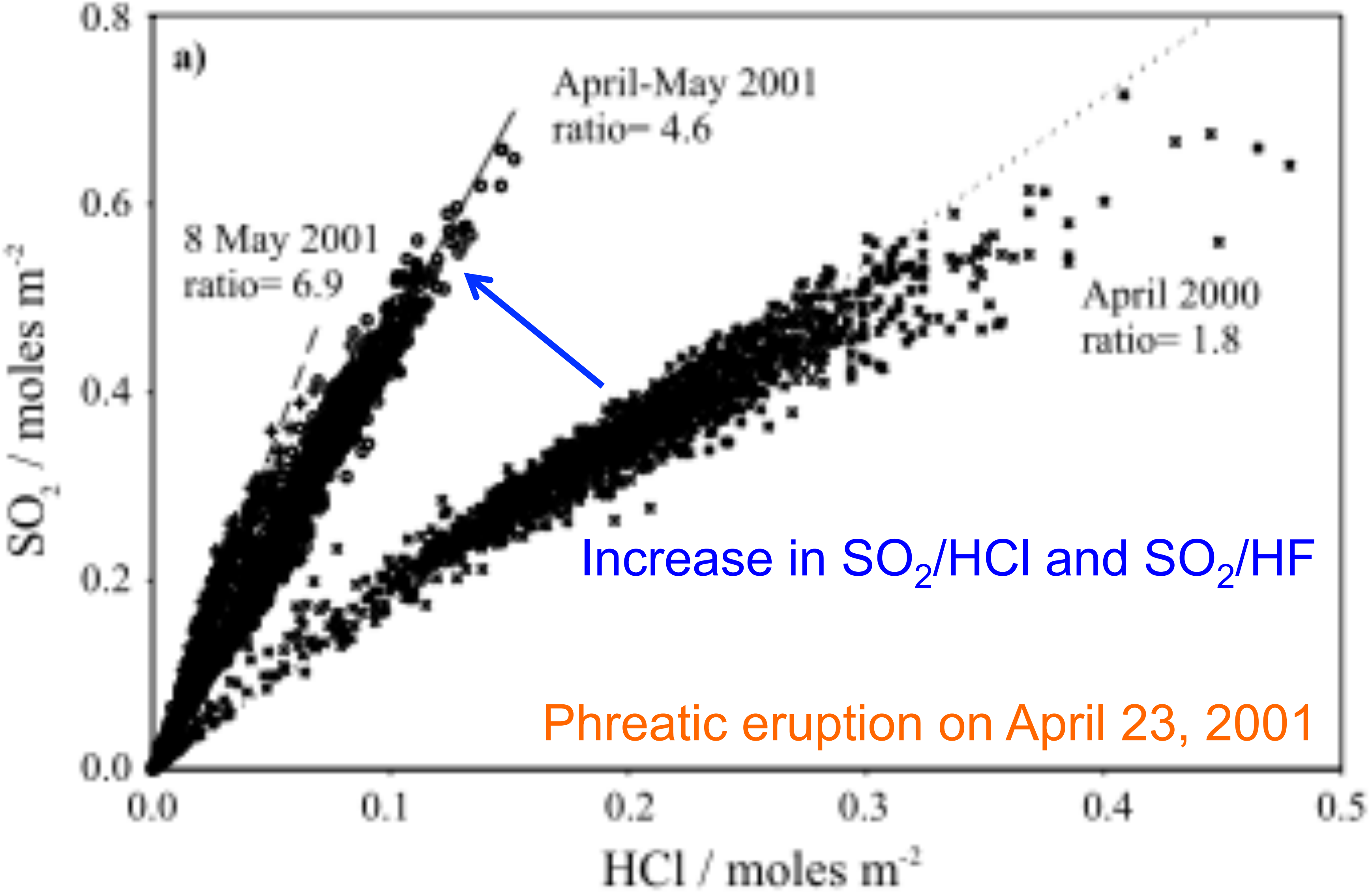
FTIR gas ratios at Etna



- Volatile solubility: F/Cl > H_2O > SO_2 > CO_2
- Petrological data needed to interpret gas data

[Allard et al., 2005]

Change in gas ratios prior to eruption at Masaya

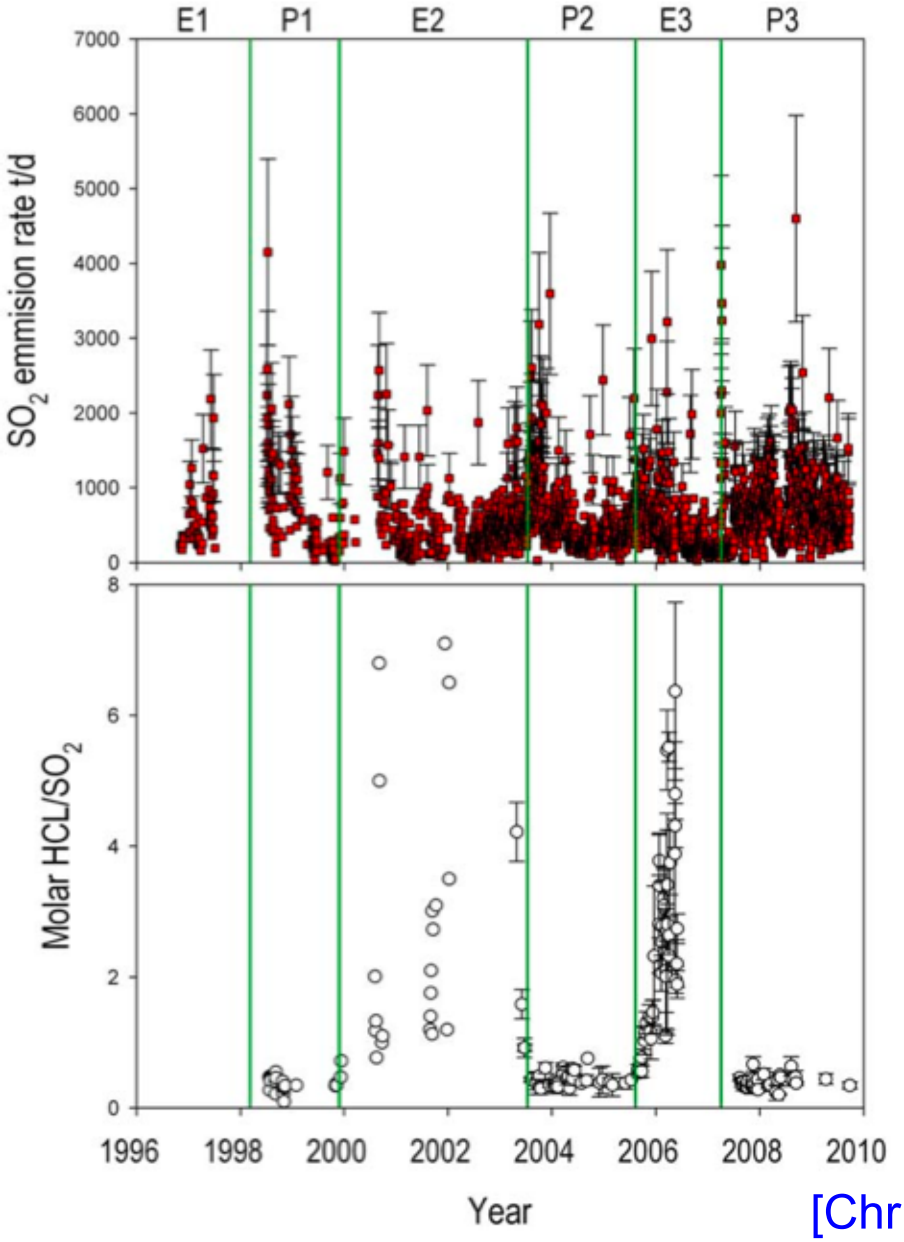


Increase in SO_2/HCl and SO_2/HF

Phreatic eruption on April 23, 2001

[Duffell et al., 2003]

Dome growth and HCl/SO$_2$ at Soufriére Hills volcano



E = lava effusion
P = pause

[Christopher et al., GRL, 2010]

Nocturnal volcanic plume studies

SO_2/HCl (night) = 2.2±0.28 (±1σ).
SO_2/HCl (day) = 1.6±0.02 (±1σ).

[Burton et al., 2001]