Observing and measuring SO$_2$ clouds from space

William I Rose
I.M. Watson, V.J. Realmuto, G.J.S. Bluth, A.J. Prata, S.A. Carn

San José, Costa Rica, June 14-15, 2007
Overview:

• Remote sensing of volcanic emissions
  • Why study volcanic emissions?
  • A satellite view of volcanic clouds
  • Survey of current satellite SO$_2$ methods and results
    • UV methods: TOMS and OMI
    • IR methods: MODIS/ASTER, TOVS, AIRS
  • Conclusions
Why quantify gas emissions?

• Indicators of volcanic activity

• Hazardous to population, wildlife, environment and infrastructure

• Long-lived pollutants and climatologically active

• Aircraft hazard mitigation
### Global SO$_2$ budgets in Tg yr$^{-1}$

<table>
<thead>
<tr>
<th>Source</th>
<th>SO$_2$</th>
<th>SO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil-fuel combustion +industry</td>
<td>70</td>
<td>2.2</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>2.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Oceans</td>
<td>–</td>
<td>40–320</td>
</tr>
<tr>
<td>Plants+soils</td>
<td>–</td>
<td>2–4</td>
</tr>
<tr>
<td>Volcanoes</td>
<td>7–8</td>
<td>2–4</td>
</tr>
</tbody>
</table>
Strong Plume--
Volcanic clouds
rise quickly,
disperse at neutral
bouyancy level,
overshoot, create
shadows

Sheveluch
29 March 2007
0200 UTC
MODIS

R. Clucas, April 21, 1990.
Weak Plume bends over

Cloud patterns reflect different altitudes

Chikurachi, 5 April 2007 MODIS
Volcanic Cloud color and ash

Klyuchevskaya, 24 May 2007
0100 UTC MODIS
Tungurahua
MODIS

Bifurcating ash plume

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Dispersal often reflects an altitude that differs from other clouds---how do you interpret this?

Tungurahua
MODIS
Anatahan
30 May 2006
MODIS
Gas plumes lead to sulfates and a white droplet cloud.
Most volcanic clouds disperse at one main altitude.
Ash-poor gas plume develops into a sulfate aerosol cloud which seeds liquid droplets.
Vertical explosions of gas and fine ash occur about 1-2 times each hour as the conduit moves at Santiaguito.
A series of explosions leads to pattern of volcanic cloud

Santiaguito
15 Jan 2007
MODIS
Ash-rich and ash-poor volcanic clouds---Separation

Manam
27 Jan 2005
0355 UTC
MODIS
1-4-3 True
Web sites for volcanic cloud info

Washington VAAC: http://www.ssd.noaa.gov/VAAC/messages.html
Volcanic Clouds site: http://www.geo.mtu.edu/volcanoes/vc_web/index.html
NOAA Volcano events: http://www.osei.noaa.gov/Events/Volcano/
Toulouse VAAC: http://www.meteo.fr/aeroweb/info/vaac/homepage/esat.html

Smithsonian/USGS Weekly Activity:
http://www.volcano.si.edu/reports/usgs/

NASA Earth Observatory archive:
http://earthobservatory.nasa.gov/NaturalHazards/Archive/natural_hazards_archive.php3?
topic=volcano

JPL Earth’s Volcanoes:
http://www.jpl.nasa.gov/earth/natural_hazards/volcanoes_index.cfm

AVO Satellite Archive:
http://www.avolcanoes.avo.alaska.edu/images/image_search_results.php?volcano=&year%5B%5D=
&type=13&caption=&lastname=&firstname=&recent=&limit=25

NGDC Volcano Information:
MODIS Data--new

- http://www.nrlmry.navy.mil/nexsat-bin/nexsat.cgi

Guatemala
4/10/2007
MODIS
Any image contains information that is useful.

There are many aspects of interpretation.
What you need for HYSPLIT

- URL: http://www.arl.noaa.gov/ready/hysplit4.html
- Time of eruption, start and finish
- Time of satellite data
- Estimate of height of cloud
- Latitude, longitude for volcano
  - S and W are negative
Universal Time UTC or Z

http://www.timeanddate.com/worldclock/converter.html

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Space Shuttle Photo
Etna Volcano 2002
Satellite Data: Used for Daily Monitoring

<table>
<thead>
<tr>
<th>SATELLITE</th>
<th>TEMPORAL RES.</th>
<th>SPATIAL RES.</th>
<th>SPECTRAL RES.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOES</td>
<td>15 - 30 minutes</td>
<td>2-8 km at 60°N</td>
<td>5 channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visible; 0.6 - 0.7 microns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Infrared 3.0 – 12.0 microns</td>
</tr>
<tr>
<td>AVHRR*</td>
<td>Every couple hrs. Avg.</td>
<td>1 km</td>
<td>5 channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visible; 0.60 - 0.7 microns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Infrared 3.0 – 12.0 microns</td>
</tr>
<tr>
<td>MODIS*</td>
<td>1 every 3 hrs. Avg.</td>
<td>250 m – 1 km</td>
<td>36 channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vis.-NIR; 0.4 – 2.0 microns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TIR 3 – 14.0 microns</td>
</tr>
</tbody>
</table>

* Satellite receiving stations at UAF.

Low spatial resolution but multiple images per day
## Satellite Data: Used for Retrospective Analysis

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<th>SPECTRAL RES.</th>
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<tbody>
<tr>
<td>Landsat</td>
<td>16 – 30 days.</td>
<td>15 m – 60 m</td>
<td>7 channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vis.-NIR; 0.4 – 2.0 microns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TIR 3 – 14.0 microns</td>
</tr>
<tr>
<td>ASTER</td>
<td>variable.</td>
<td>15 -90 m</td>
<td>14 channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vis - TIR 0.6 – 12 microns</td>
</tr>
<tr>
<td>ERS</td>
<td>16 – 30 days.</td>
<td>25 m</td>
<td>1 channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Radar C band 5.7 cm</td>
</tr>
<tr>
<td>RadarSat</td>
<td>16 – days.</td>
<td>1 km - 250 m</td>
<td>1 channel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Radar L band 5.7 cm</td>
</tr>
</tbody>
</table>

High spatial resolution but images recorded monthly
### SO$_2$ Applications of satellite sensors

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<tr>
<th>Retrieval</th>
<th>Application</th>
<th>Disadvantages</th>
<th>Spatial resolution</th>
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<td>Large scale to passive degassing</td>
<td>?</td>
<td>13 x 24 km</td>
<td>2 years</td>
</tr>
<tr>
<td>0.27-0.50 µm</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Large scale eruptions</td>
<td>Spatial resolution</td>
<td>16 km</td>
<td>&lt; 4 years</td>
</tr>
<tr>
<td>Hyperspectral</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODIS TOVS</td>
<td>Mid scale eruptions</td>
<td>Higher altitude required</td>
<td>1 km 18 km</td>
<td>6 years 30 years!</td>
</tr>
<tr>
<td>7.34µm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODIS/ASTER 8.6µm</td>
<td>Mid-scale – passive degassing</td>
<td>Ash and sulfate interferences</td>
<td>1 km 0.09 km</td>
<td>6 years</td>
</tr>
</tbody>
</table>

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Theory of SO$_2$ sensing--overview

$T_{\text{source}} = 5800$ K

TOMS - OMI
0.29 - 0.32 μm (near UV)
SO$_2$, [aerosols]

AVHRR, GOES,
GMS, MODIS, ASTER -
8-12 μm (thermal infrared)
ash, sulfate, ice, SO$_2$

$T_{\text{ground}} = 300$ K
14 MODIS Bands
~2300 AIRS channels
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Ozone - $O_3$
Nitrous oxide - N$_2$O
Carbon dioxide - CO$_2$
Carbon monoxide - CO
Sulphur dioxide - SO$_2$
Methane - CH$_4$

~2300 AIRS channels
TOMS and OMI are driven by the crisis presented by ozone changes in the stratosphere, and volcanic SO2 applications are an unexpected gift...
TOMS sensor SO$_2$ results

http://toms.umbc.edu/

Spatial resolution varies from 25-60 km

Cannot “see” low level emissions
Details of TOMS UV SO$_2$ retrieval

- SO$_2$ is a very similar molecule to O$_3$ (both group VI)
- SO$_2$ has a similar absorption spectrum to O$_3$
  - Both molecules absorb in the near UV (0.30 - 0.34 µm)
  - SO$_2$ absorption is higher at the shorter wavelengths (0.30 - 0.32 µm)
- Theoretical look-up-tables (LUTs) have been calculated for different SO$_2$ burdens in the atmosphere, at different geometries,
- These LUTs account for Rayleigh scattering, SO$_2$ absorption and surface reflection
- pairs of radiances (where SO$_2$ does and does not absorb) are used to remove most noise effects
The OMI instrument will distinguish between aerosol types, such as smoke, dust, and sulfates, and can measure cloud pressure and coverage, which provide data to derive tropospheric ozone.

OMI will continue the TOMS record for total ozone and other atmospheric parameters related to ozone chemistry and climate. OMI measurements will be highly synergistic with the other instruments on the EOS Aura platform.

The OMI instrument employs hyperspectral imaging in a push-broom mode to observe solar backscatter radiation in the visible and ultraviolet. The hyperspectral capabilities will improve the accuracy and precision of the total ozone amounts and will also allow for accurate radiometric and wavelength self calibration over the long term.

The instrument is a contribution of the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the EOS Aura mission.
OMI Key Facts

+ Heritage: TOMS, SBUV, GOME, SCIAMACHY, GOMOS+

+ Nadir-viewing wide-field-imaging spectrometer

+ Measure key air quality components such as NO$_2$, SO$_2$, BrO, OClO, and aerosol characteristics.

+ Daily global coverage

+ Capable of mapping pollution products on urban-to-super-regional scales.

+ Contributing Contractors: TNO-TPD (Netherlands), Patria Finavitec (Finland), VTT (Finland)
OMI Parameters

The instrument observes Earth's backscattered radiation with a wide-field telescope feeding two imaging grating spectrometers. Each spectrometer employs a CCD detector. Onboard calibration includes a white light source, LEDs, and a multi-surface solar-calibration diffuser. A depolarizer removes the polarization from the backscattered radiation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wavelength range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible:</td>
<td>350 - 500 nm</td>
</tr>
<tr>
<td>UV:</td>
<td>UV-1, 270 to 314 nm, UV-2 306 to 380 nm</td>
</tr>
<tr>
<td>Spectral resolution:</td>
<td>1.0 - 0.45 nm FWHM</td>
</tr>
<tr>
<td>Spectral sampling:</td>
<td>2-3 for FWHM</td>
</tr>
<tr>
<td>Telescope FOV: 114¡ (2600 km on ground)</td>
<td></td>
</tr>
<tr>
<td>IFOV:</td>
<td>3 km, binned to 13 x 24 km</td>
</tr>
<tr>
<td>Detector:</td>
<td>CCD: 780 x 576 (spectral x spatial) pixels</td>
</tr>
<tr>
<td>Mass:</td>
<td>65 kg</td>
</tr>
<tr>
<td>Duty cycle:</td>
<td>60 minutes on daylight side</td>
</tr>
<tr>
<td>Power:</td>
<td>66 watts</td>
</tr>
<tr>
<td>Data rate:</td>
<td>0.8 Mbps (average)</td>
</tr>
</tbody>
</table>
OMI application to volcanic clouds

OMI was launched on the EOS-Aura satellite in July 2004 and superseded Earth Probe (EP) TOMS in 2006. OMI SO2 data have not yet been officially released to the public, though we are currently evaluating preliminary, unvalidated OMI SO2 data and welcome enquiries.

OMI is a hyperspectral UV-Visible spectrometer with 8-fold better ground resolution (13x24 km at nadir) and an order of magnitude higher sensitivity to SO2 than TOMS. Hence, OMI can detect passive volcanic degassing in addition to the eruptive emissions measured in the past by TOMS. OMI can also measure anthropogenic SO2 emissions. Some examples of early data from OMI can be seen on the NASA Earth Observatory website (see links above under Top Stories). The OMI instrument is a Dutch-Finnish Instrument, provided to the EOS/Aura mission by The Netherlands and Finland. NIVR (the Dutch space agency) is the overall program manager, in coordination with FMI (the Finnish Meteorological Institute). The Royal Netherlands Meteorological Institute (KNMI) is the Principal Investigator institute.
Soufrière Hills Eruption 20 May - June 11, 2006
Popo 24 March 2007

Key reference:

Krotkov et al., 2006
IEEE Trans 44 (5) 1259
Vanuatu, May 2007

Low level SO2 emission from Ambrym
Since late May, the autoprocessed OMI SO2 maps show cloudy regions in white. These areas are where OMI is not completely effective.

Krotkov et al., 2006, IEEE Trans 44 no 5.
### SO\textsubscript{2} Applications of satellite sensors

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<td>MODIS TOVS 7.34(\mu m)</td>
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<td>1 km 0.09 km</td>
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</tbody>
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OMI sees lower level SO$_2$ burdens such as those obtained from burning fossil fuels. This image shows an air pollution event in China, Dec 24, 2004.
The Physics of infrared SO$_2$ sensing
Figure 1.

Species Interference

- 3 μm andesite
- 5 μm ice
- 0.5 μm 75% H$_2$SO$_4$

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<table>
<thead>
<tr>
<th>Species</th>
<th>Original Sensor [and channels]</th>
<th>Reference</th>
<th>Year</th>
<th>MODIS channels</th>
<th>ASTER channels</th>
<th>AIRS channels</th>
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<tbody>
<tr>
<td>Ash</td>
<td>AVHRR [4,5]</td>
<td>Prata</td>
<td>1989 a,b</td>
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<td>SO₄²⁻</td>
<td>HIRS/2 [5-10]</td>
<td>Yu and Rose</td>
<td>2000</td>
<td>30 - 34</td>
<td>N/A</td>
<td>10-15</td>
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<tr>
<td>SO₂</td>
<td>TOVS¹ [8,11,12]</td>
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<td>2003</td>
<td>27, 28, 31</td>
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SO$_2$ retrieval theory, Realmuto et al., (1994)

\[ L_s(\lambda, T_0) = \{\varepsilon(\lambda) B(\lambda, T_0) + [1-\varepsilon(\lambda)]L_d(\lambda)\} \tau(\lambda) + L_u(\lambda) \]

Where \( L_s \) = at-sensor radiance, \( L_d \) = ambient (sky) radiance at the sensor, \( L_u \) = ambient (sky) radiance at the ground, \( \lambda \) = wavelength of channel, \( B \) = Planck function, \( T_0 \) = temperature of the ground, \( \varepsilon(\lambda) \) = emissivity of the ground, \( 1 - \varepsilon(\lambda) \) = transmissivity of the cloud, \( \tau \) = spectral transmittance of the atmosphere

- \( L_u \) and \( \tau \) calculated by MODTRAN

- Model ground temperature retrieved for ideal MODIS channels

- SO$_2$ calculated that produces best fit between modelled and observed radiances
TIR SO\textsubscript{2} mapping procedure

- Uses 8.6 μm absorption by SO\textsubscript{2} to discriminate and quantify SO\textsubscript{2} burdens

- Requires the user to input atmospheric profiles, and to specify a background region of interest

- The model calculates the background emissivity (\(\varepsilon_b\)) and true ground temperature (\(T_b\))

- The model then applies \(\varepsilon_b\) to the pixels containing the plume (again, user specified) to obtain the perceived ground temperature

- The difference between ‘true’ and perceived ground temperature is iteratively reduced by adding SO\textsubscript{2} (absorption) to the model until agreement is met

- The SO\textsubscript{2} burden is mapped for each pixel producing an SO\textsubscript{2} cloud image
Plumes can be identified in satellite data using “spectral” discrimination - e.g. MODIS data.

MODIS Data: 2000-272-1245 UT  Rejection criterion: ΔT< 2.0K Channel: 31  Reference channel: 32
8.6 µm - 12 µm temperature difference
Scale comparisons
ASTER SO$_2$ image of Etna Volcano 29 July 2001

area 24 x 30 km

SO$_2$ plume shown in purple false color
Ash-laden case – Cleveland, Aleutians

Figure 4.

Cleveland 23:10 02/19/2001
MODIS B31-B32

BTD
-9.0 -6.5

Figure 5.

Cleveland 23:10 02/19/2001
MODIS SO$_2$ retrieval

SO$_2$ burden g m$^{-2}$
0.5 18
TOMS- MODIS comparison
Passive degassing emission rates
Pacaya, Guatemala
Zoom window (showing Pacaya plume and interrogation statistics)
ASTER image of Soufriere Hills Volcano, Montserrat, 29 Oct 2002
## Previous work

<table>
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<th>Species</th>
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TIROS Operational Vertical Sounder

HIRS instrument with 20 channels
~18x18 km² pixels at nadir
NOAA satellites
Continuous since 1979
Same platform as AVHRR
Day/night operation
Satellite (or airborne) detector

\[ l(z) = \begin{cases} 
    l_a(z) & \text{if } b \leq z \\
    l_a(z) + \alpha_s(b - z) & \text{if } a \leq z \leq b, \\
    l_a(z) + \alpha_s(b - a) & \text{if } z \leq a 
\end{cases} \]

\[ t(z) = \begin{cases} 
    t_a(z) & \text{if } b \leq z \\
    t_a(z) \exp(-\alpha_s(b - z)) & \text{if } a \leq z \leq b, \\
    t_a(z) \exp(-\alpha_s(b - a)) & \text{if } z \leq a 
\end{cases} \]
\[ \tau_s = \alpha_s (b - a) \quad \text{and} \quad t_s = \exp(-\tau_s). \]

Emission to space from SO\textsubscript{2}-free atmosphere

\[ I_a = B_0 t_a (0) + \int_0^\infty dz \alpha_a (z) B(z) t_a (z), \]

Emission above SO\textsubscript{2} layer

\[ I_a^+ = \int_b^\infty dz \alpha_a (z) B(z) t_a (z), \]

\[ I = t_s I_a + (1 - t_s) I_a^+ + I_{as} + I_{sa}. \]

Emission from layer modified by SO\textsubscript{2} absorption

\[ I_{as} = \int_a^b dz \alpha_a B(z) t_a (z) t_s \left[ e^{\tau_s(z-a)/(b-a)} - 1 \right]. \]

Emission from SO\textsubscript{2} modified by atmosphere

\[ I_{sa} = \int_a^b dz \alpha_s B(z) t_a (z) e^{-\tau_s (b-z)/(b-a)}. \]
Weighting functions for some TOVS channels

The weighting function is:

\( \frac{\partial t}{\partial z} \).
Simplifying assumptions

1. We assume that the SO$_2$ layer lies above the peak of the weighting function for H$_2$O in the 7.3 µm channels, so that the absorption coefficient $\alpha_a(z)$ is zero for $z > a$. This is a significant assumption because H$_2$O absorbs strongly at 7.3 µm and the weighting function peaks relatively high in the atmosphere.

2. The SO$_2$ layer is assumed to be isothermal and therefore can be characterized by a single temperature $T_s$. Clearly this assumption is questionable when the SO$_2$ layer is very deep.
SO$_2$ from TOVS

Global, Long-Term Sulphur Dioxide Measurements From TOVS data: A New Tool for Studying Explosive Volcanism and Climate

A. J. Prata$^1$, W. I. Rose$^2$, S. Self$^3$, and D. M. O’Brien$^1$

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$^2$Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan, USA.
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AGU Geophys Mono 139:75-92, 2003
TOVS

TOMS

14-15 June 2007
San Jose, Costa Rica
Volcano Remote Sensing Workshop
Re-evaluation of $\text{SO}_2$ release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors

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Pinatubo SO$_2$ cloud seen from TOVS - 3 separate instruments provide unprecedented temporal resolution
<table>
<thead>
<tr>
<th>Sensor</th>
<th>This Paper</th>
<th>Previous Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial SO₂ mass (Mt)</td>
<td>18 ± 4⁴</td>
<td>20 ± 6</td>
</tr>
<tr>
<td>SO₂ e-folding time (days)</td>
<td>25 ± 5</td>
<td>35 ± 11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>TOMS</th>
<th>SBUV⁵</th>
<th>MLS⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19 ± 4⁴</td>
<td>12 – 15</td>
<td>17³</td>
</tr>
<tr>
<td></td>
<td>23 ± 5</td>
<td>24 ± 5</td>
<td>33³</td>
</tr>
</tbody>
</table>

⁴Bluth et al. [1992].
⁵McPeters [1993].
⁶Reed et al. [1993], uncertainty unknown.
⁷Initially released SO₂ mass includes SO₃ sequestered in ice and SO₂ converted to sulfate during the rise of volcanic plume.
SO$_2$ from AIRS

- Atmospheric Infrared Sounder (AIRS)
- New research spectrometer (>2300 channels)
- EOS- Aqua platform
- Many new possibilities to study volcanic gases
### FACTS ABOUT AIRS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size:</td>
<td>stowed: 116.5 x 80 x 95.3 cm</td>
</tr>
<tr>
<td></td>
<td>deployed: 116.5 x 158.7 x 95.3 cm</td>
</tr>
<tr>
<td>Mass:</td>
<td>177 kg</td>
</tr>
<tr>
<td>Power:</td>
<td>220 W</td>
</tr>
<tr>
<td>Data Rate:</td>
<td>1.27 Mbps</td>
</tr>
<tr>
<td>Spectral Range:</td>
<td>IR: 3.74 - 15.4 μm</td>
</tr>
<tr>
<td></td>
<td>Vis/NIR: 0.4 - 1.0 μm</td>
</tr>
<tr>
<td>Channels:</td>
<td>IR: 2378</td>
</tr>
<tr>
<td></td>
<td>Vis/NIR: 4</td>
</tr>
<tr>
<td>Aperture:</td>
<td>10 cm</td>
</tr>
<tr>
<td>Instrument Field of View:</td>
<td>IR: 1.1° (= 13.5 km @ nadir)</td>
</tr>
<tr>
<td></td>
<td>Vis/NIR: 0.2° (= 2.3 km @ nadir)</td>
</tr>
<tr>
<td>Swath Width:</td>
<td>99° (= 1650 km)</td>
</tr>
<tr>
<td>Scan Sampling:</td>
<td>IR: 90 x 1.1°</td>
</tr>
<tr>
<td>Pointing Accuracy:</td>
<td>IR: 0.1°</td>
</tr>
<tr>
<td>Thermal Control:</td>
<td>IR detectors: active cooler @ 60 K</td>
</tr>
<tr>
<td></td>
<td>Passive radiator @ 150 K</td>
</tr>
<tr>
<td></td>
<td>Electronics @ ambient</td>
</tr>
<tr>
<td>Prime Contractor:</td>
<td>British Aerospace Systems</td>
</tr>
<tr>
<td></td>
<td>(formerly Lockheed-Martin)</td>
</tr>
<tr>
<td>Responsible Organization:</td>
<td>Jet Propulsion Laboratory</td>
</tr>
</tbody>
</table>
AIRS SO$_2$ for Anatahan

7.3 µm SO$_2$ feature

Theoretical calculation using Modtran

7.3 µm image
Compared with MODIS

![Graph showing temperature difference vs. wavenumber](image-url)
AIRS Manam 2004.10.24.040 Time:03:59UTC
μ-window: Matrix inversion +H₂O
Mass = 0.0093 Tg  Area = 8496 km²  Max SO₂=132.7DU
Aqua/MODIS 2004/298 03:55 UTC Bands 1–4–3 (true color) 250m
AIRS Manam 2004.10.24.163 Time:16:17UTC
μ-window: Matrix inversion +H₂O
Mass= 0.0145 Tg  Area= 36524 km²  Max SO₂= 47.1DU
Montserrat (TOMS) 13 July 2003

Orbit 37512
JUL 13, 2003

Iterative SO2
EARTH PROBE TOMS

NASA

Volcano Remote Sensing Workshop
Montserrat (AIRS ΔBTD) 13 July 2003
UV-IR comparison
Map showing the flight path of the NASA DC-8 travelling from NASA Dryden to Kiruna, Sweden on 26-28 February 2000. The position of the Hekla volcanic cloud at 1115 UT on 28 February 2000 based on MODIS imagery (Rose, 2003) is shown. The aircraft encountered the volcanic cloud at 0510-0518 UT at 10.4 km asl on 28 February.
SOLVE (NASA DC-8) *in situ* SO$_2$ measurements and MODIS retrievals show good agreement

Integrated across plume:

SOLVE = 248 ppmV

MODIS = 241 ppmV
Conclusions

• There are a variety of platforms operating at different spatial and temporal resolutions and in different regions of the spectrum.

• Each sensor has distinct advantages and disadvantages with significant overlap between the applications, enabling cross-platform validation.

• Interferences between ash, sulfate, ice and SO2 must be considered

• UV sensors are limited by the availability of light

• Robust SO2 monitoring from space is a few years away
SO$_2$ remote sensing at Volcanoes

Redundant precise methods exist
Low atmospheric background of SO$_2$
Absorption in atmospheric windows
Comparative results on several methods
Optimal environmental conditions for each method
Quantitative algorithms require more steps and inputs