SMASH overview and related ash projects at University of Oxford

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EODG,
ORAC team,
SMASH team
SMASH overview

Summary of SMASH products delivered:

- GOME-2 SO$_2$ amount (DLR)
- OMI SO$_2$ height (assimilation) (FMI)
- MODIS VIS & TIR ash and SO$_2$ (INGV & CGS)
- IASI ash and SO$_2$ (OE retrieval and fast) (Oxford)

Validation case study:
Together SMASH & SACS-2

Eyjafjallajökull: April_May 2010
Grimsvötn: May 2011

Earlinet: ash AOD & height
Aircraft: ash AOD & height, (if time concentration, $r_{\text{eff}}$)
Brewer spectrometer: SO$_2$ column
CALIPSO: ash AOD & height

Thessaloniki (SACS-2)

Etna 2011_2013
INGV (SMASH)

IR camera: ash source altitude
FLAME: SO$_2$ total amount
MODIS Ash and SO$_2$ retrievals

New MODIS-TIR Products
Ice detection/retrievals and SO$_2$ correction

INGV

Credit: Corradini, Merucci (INGV), Di Nicolantonio, Cacciari (CGS)
See poster P-12

Standard MODIS-TIR products

Kasatochi (Alaska) 2008
MODIS-Aqua
9 August 2008, 00:50 UTC

Eyjafjalla (Iceland) 2010
MODIS-Terra
19 April 2010, 14:55 UTC

New MODIS-TIR-VIS Products
Ash Detection and Retrievals

INGV

Table:

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<thead>
<tr>
<th></th>
<th>Ash Mass</th>
<th>Effective Radius</th>
<th>AOD</th>
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<tr>
<td>Standard MODIS-TIR products</td>
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The validation concerns the IASI, MODIS, GOME-2 SO\textsubscript{2} mass retrieved. Test cases selected are the 2011 Mt. Etna paroxysmal activities, Italy (lava fountains) using ground SO\textsubscript{2} flux measurements from FLAME monitoring network.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Date Time</th>
<th>SO\textsubscript{2} Mass Max (tons)</th>
<th>SO\textsubscript{2} Mass Min (tons)</th>
<th>D Error Sensor/Ground</th>
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<tr>
<td>FLAME</td>
<td>10/04/2011 10.05-12.30</td>
<td></td>
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<tr>
<td></td>
<td>10.05-12.47</td>
<td>5714 ÷ 3455</td>
<td>5753 ÷ 3479</td>
<td>-</td>
</tr>
<tr>
<td>MODIS</td>
<td>10/04/2011 12.30</td>
<td>4946 ÷ 3656</td>
<td>-</td>
<td>- 3%</td>
</tr>
<tr>
<td>IASI</td>
<td>10/04/2011 19.42</td>
<td>6049 ÷ 4517</td>
<td>+ 19%</td>
<td></td>
</tr>
<tr>
<td>GOME-2</td>
<td>11/04/2011 07.44</td>
<td>3496 ÷ 2506</td>
<td>- 32%</td>
<td></td>
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</tbody>
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Credit: C. Spinetti (INGV)
SO2 emission inversion for the 2011 Grimsvötn eruption using the OMI satellite observations

- The atmospheric SO2 release in the 2011 Grimsvötn eruption is reconstructed with inverse modeling:
  - OMI SO2 column observations assimilated into the SILAM dispersion model
  - 4D-Var algorithm yields temporal and vertical emission profiles
  - emission top constrained by in-situ observations; no prior information on emitted amounts
- ~200 kt SO2 emitted mainly between 10-12 km ASL, shown below:

The simulated (after inversion) and observed SO2 column density (DU) in May 22-24, 2011

Credit: Julius Vira (FMI)
IASI - SO₂

CAL_LID_L1-ValStage1-V3-01.2010-05-07T13-57-06ZD

IASI - CALIPSO ~ 3h difference
IASI SO₂ - Puyehue-Cordón Caulle eruption  5 - 30 June 2011
The total SO$_2$ mass present in the atmosphere is obtained summing all the values of a regularly gridded map of SO$_2$ amounts. Points are separated by ~12 hours.

Nabro produces the largest amount of SO$_2$ plume observed by IASI with a maximum of up to ~2 Tg of SO$_2$. SO$_2$ retrieved from IASI data. The values are the measured amount on a particular day and vary with volcanic emission, gas removal and satellite sampling. Points are separated by ~12 hours.
SO$_2$ vertical distribution

IASI SO$_2$ [Tg] - Nabro 12-23 June 2011

Altitude [km]

Julian day from 1 Jan 2011
SO$_2$ vertical distribution

IASI SO$_2$ [Tg] - Llaima 2-6 Jan 2008

IASI SO$_2$ [Tg] - Okmok 12-20 July 2008

IASI SO$_2$ [Tg] - Kasatochi 7-22 Aug. 2008

IASI SO$_2$ [Tg] - Dalaffilla 4-7 Nov. 2008
SO\textsubscript{2} Degassing

**Minimum error**

1 DU = 0.0285 g/m\textsuperscript{2}

Time series of the SO\textsubscript{2} column amount integrated over a box around Tungurahua. July – December 2007
ORAC Ash retrieval - VIS/NIR/TIR from AATSR on 6 May 2010

Particle type

11-12 microns - measured

Simulated 11-12μm BT/K

Optical depth

Effective Radius / microns

Altitude / km

Credit R. Siddans
SHIVA: Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash

to better understand the volcanic process that control eruptive activity.

Optimal estimation approach (Rodgers, 2000) to retrieve ash composition and possibly size from infrared spectral measurements. We will study ash formed from different magmas and at different stages of evolution within a volcanic plume.

one-to-one correspondence between refractive index spectra, compositions and remote sensing measurements.

ground and satellite retrievals ➔ ash type/composition (with different size distributions) to be compared with the geochemical and petrological analysis done on ash sample for the same volcanic plume.
From AOD and Reff we compute the total mass and mode radius.
- **SMASH** aims to improve source term characterisation by improving satellite retrieval of ash & SO2 from UV & TIR spectrometers and radiometers.
- Validation for Eyja, Girmm and Etna case study

- **IASI SO₂** scheme retrieves the **height and amount of SO₂** and provides a **comprehensive error budget for every pixel**.
- Retrieved uncertainties increase with the decreasing of altitude, nevertheless it is possible to retrieve information in the **lower troposphere and monitor volcanic degassing**.
- Thick ash can affect the retrieval, recognizable from cost >2
- Underlying **cloud don’t affect the retrieval**, cloud at the same altitude or above the plume mask the SO₂ signal.
- Comparison with other satellite retrievals is undergoing

- **ORAC** (radiometer and IASI) scheme retrieves **ash optical depth, effective radius** (from which mass and Mode radius are estimate), and **height**.
- Preliminary results show the possibility to exploit the IASI spectra in order to **discern between different ash model**.
- Full optimal estimation retrievals of ash is currently under development. The IASI ash retrieval scheme development will be carried out within the new NERC SHIVA and FP7 APHORISM projects.

This work has been supported by COMET+ (National Center for Earth Observation NCEO-NERC Geohazard theme), SMASH (ESA) and SHIVA (NERC).
ORAC Ash retrieval - VIS/NIR/TIR from SEVIRI on 6 May 2010

Credit R. Siddans
IASI is on board of METeorological OPerational satellite program (METOP-A and METOP-B), a European meteorological satellite that has been operational since 2007.

IASI is a Fourier transform spectrometer, that measures the spectral range 645 to 2760 cm\(^{-1}\) (3.62–15.5\(\mu\)m) with a spectral sampling of 0.25 cm\(^{-1}\) and an apodised spectral resolution of 0.5 cm\(^{-1}\). Radiometric accuracy is 0.25-0.58K. The IASI field of view (FOV) consists of four circles of 12 km diameter (at nadir) inside a square of 50 x 50 km.

It has a 2000 km swath and nominally can achieved global coverage in 12 hours (although there are some gaps between orbits at tropical latitudes). Radiances are collocated with the Advanced Very High Resolution Radiometer (AVHRR) that provides complementary visible/near infrared channel, for cloud and aerosol retrievals.
Bayesian theory -> OPTIMAL ESTIMATION  [Rodgers 2000]

Initial state estimate:  $x_0$  \textit{A priori:}  $x_a$

Run forward model:  $f(x_i)$

Compare to  \[ J = [y - f(x_i)]S_e^{-1}[y - f(x_i)] + \]
measurements (y):  \[ [x_i - x_a]S_a^{-1}[x_i - x_a] \]

Update state:  $x_i \rightarrow x_{i+1}$  (Levenburg-Marquardt)

Stop when:  □J is small, or when i is large.

NB Optimal estimation method provides \textit{error estimate} and quality control
SO₂ Retrieval scheme

State vector:
- Total column amount of SO₂
- Altitude H
- Thickness s
- Surface temperature Ts

Forward model: fast radiative transfer (RTTOV + SO2 RAL coefficients)

y is the measurement vector, x the state vector

\[ J = (y - F(x))^T S_y^{-1} (y - F(x)) + (x - x_d)^T S_a^{-1} (x - x_d) \]

S_y, is defined to represent the effects of atmospheric variability not represented in the forward model (FM), as well as instrument noise (cloud and trace-gases…).

The matrix is constructed from differences between FM calculations (for clear-sky) and actual IASI observations for wide range of conditions, when we are confident that negligible amounts of SO₂ are present.

y_s = F(SO₂=0)

Sy Computed with billions pixels

best estimate of stare vector: SO₂ amount, plume altitude, Ts

IASI simulated spectra

IASI measurements

OE retrieval

+ ECMWF profile (temperature, h2o, p, z)
linear error on the ‘true’ state obtained as:

\[ S_x = (K^T S_y^{-1} K + S_a^{-1})^{-1} \]

\[ A = S_x S_x^{-1} - S_a^{-1} \]

A priori values

SO2, H, s, Ts
Xa=[ 0.5, 400, 100, 290]
DXa=[100, 1000, 1, 20]
SO$_2$ plume mass [Tg]

20 April 30 April 10 May 20 May

- **IASI**
- **GOME-2**
- **OMI**
- **AIRS**

Phase III

OMI, AIRS (Thomas and Prata, ACP 2011)  GOME-2 (Rix et al, JGR 2012)  
[Carboni et al ACP 2012]
AATSR visible/near-ir false colour image on 6 May 2010

MSG visible/near-ir + “dust” false colour images (12 UT) (not map-projected)
Ash composition from thermal infrared spectrometer

relationship between ash features and styles of explosive activity.

- **Basaltic** ➔ **Andesitic** ➔ **Rhyolitic**

Increasing \( \text{SiO}_2 \)%

Extinction coefficients obtained for ice, volcanic ash (Peters, 2012), pumice, andesite, \( \text{H}_2\text{SO}_4 \), quartz, obsidian.

FTIR spectra measured at Masaya volcano in Nicaragua (Mike Burton).
The main plume appears at about 15 km but descends to about 12 km quite quickly. The plume to the south is much lower - typically around 5 km in altitude.