Measuring volcanic SO2 emission using IASI

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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.
**SO₂ linear** (v3)

It is mainly a ‘measurements’ of the SO₂ signal

- All IASI archive 2007-2014 analysed
- NRT data processing

Used for: (i) **plume detection**, (ii) **identify where there is a signal**

**SO₂ iterative** (all v1 and v3)

comprehensive error budget for every pixel

Require auxiliary data (ECMWF profiles), radiative transfer (RTTOV) called iteratively

Used for:

<table>
<thead>
<tr>
<th>Volcanic plume</th>
<th>study SO₂ mass and vertical distribution</th>
</tr>
</thead>
</table>

Retrieve:

- SO₂ column amount [DU]
- SO₂ plume altitude [mb, km]

**Result**

- (2)
- (3) **Low signal case: degassing, pollution**

Results are average in time

(1) Assume:

- SO₂ vertical profile, atmospheric profiles, Jacobian

(3) Assume:

- SO₂ altitude

Retrieve:

- SO₂ column amount [DU]
The optimal estimate of \( x \) taking into account total measurement error may be computed as:

\[
\hat{x} = x_0 + (K^T S_{y}^{tot} K)^{-1} K^T S_{y}^{tot} (y - \bar{y})
\]

\[
G = (K^T S_{y}^{tot} K)^{-1} K^T S_{y}^{tot}^{-1}
\]

\( S_{y}^{tot} \) is computed considering an appropriate ensemble of \( N \) measured spectra to construct an estimate of total measurement error variance-covariance \( S_{y}^{obs} \)

\[
S_{y}^{tot} \approx S_{y}^{obs} = \frac{1}{N} \sum_{i=1}^{N} (y_i - \bar{y}) (y_i - \bar{y})^T
\]

\[
\bar{y} = \frac{1}{N} \sum_{i=1}^{N} y_i
\]

[ Rodger 2000]

Create a generalized error covariance \( S_{y}^{tot} \) that contains not only the instrument noise, but noises due to interfering gases and broadband scatterers (using IASI spectra only).

NRT IASI-A SO2 linear – plume detection - Calbuco
(2) **SO$_2$ iterative - Retrieval scheme**

**State vector:**
- Total column amount of SO$_2$
- Altitude $H$
- Thickness $s$
- Surface temperature $T_s$

+ ECMWF profile (temperature, h2o, p, z)

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

**y** is the measurement vector, **x** the state vector.

$y = F(SO_2=0)$

$S_y(i,j) = \langle (y_{mi} - y_{si}) - (\bar{y}_{mi} - \bar{y}_{si}) \rangle \langle (y_{mj} - y_{sj}) - (\bar{y}_{mj} - \bar{y}_{sj}) \rangle$

$J = (y - F(x))^T S_y^{-1} (y - F(x)) + (x - x_a)^T S_a^{-1} (x - x_a)$

$S_y$ 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 SO$_2$ are present.

**best estimate of state vector:**
**SO$_2$ amount, plume altitude, $T_s$**

$y_s = F(SO_2=0)$

$S_y$ Computed with billions pixels
SO2 iterative – Bardarbunga
Scatter plot of IASI SO2 measurements, averaged within a distance of 200 km from the ground station, versus the daily SO2 column amount, measured from Brewer spectrometers. Different colours correspond to a different ground station. Black error-bars are the IASI average errors; dotted error-bars are the standard deviation of the IASI data within the selected distance. Black lines represent the ideal line $y=x$; dotted lines are the best fits with error in the best fit.
SO2 iterative – Height comparison with CALIOP

Note that underlying cloud doesn’t affect the retrieval.
SO2 iterative – Height comparison with CALIOP

Grímsvötn eruption
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.
VEI is a poor index of the potential height to which volcanic SO2 is injected. All of the eruptions in the tropics (except Nyamuragira, VEI 1,2), reached the tropopause.
May 2010, anyone know if something happen to IASI l1c data?

“18/05/2010 IASI lev 1C EO:EUM:DAT:METOP:IASIL1C change of format and content
From eumetsat web page – ‘product history’
(3) SO2 iterative – Ecuador monthly average - degassing

OMI – BIRA – N. Thyes

(3) SO2 iterative – Ecuador monthly average - degassing

OMI – BIRA – N. Thyes

Summary

SO2 linear: (AMT Walker et al 2011, JRL Walker et al 2012)
Very fast => global survey tool
⇒ show emission from volcanic eruptions, anthropogenic source and degassing.
  - IASI archive 2007-2014
  - NRT processing

SO2 iterative: (ACP Carboni et al 2012, ACP Carboni et al. 2016)
We use simultaneously cannel between 1000-1200 cm\(^{-1}\) and 1300-1410 cm\(^{-1}\) (v1 and v3 SO2 absorption band)
  - retrieve both column amount and altitude for volcanic plume.
  - we can study the plume vertical distributions, and evolution in time.
  - Volcanic degassing look promising (vs, OMI and ground data)

Thank you!

+ Lucy poster on IASI ash retrieval:
  Optical depth, effective radius (⇒ ash mass) and altitude
In clear and cloudy atmosphere (cloud below the plume)
SO$_2$ degassing

assumption: we know the altitude of the plume

Minimum error

considering 60 overpass a month => error reduced of $1/sqrt(60)$

1 DU = 0.0285 g/m$^2$

SO$_2$ monthly errors

<table>
<thead>
<tr>
<th>[km]</th>
<th>[g/m$^2$]</th>
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</thead>
<tbody>
<tr>
<td>11</td>
<td>9 $10^{-4}$</td>
</tr>
<tr>
<td>8.3</td>
<td>13 $10^{-4}$</td>
</tr>
<tr>
<td>6.4</td>
<td>17 $10^{-4}$</td>
</tr>
<tr>
<td>3.5</td>
<td>24 $10^{-4}$</td>
</tr>
<tr>
<td>1.5</td>
<td>73 $10^{-4}$</td>
</tr>
<tr>
<td>0</td>
<td>388 $10^{-4}$</td>
</tr>
</tbody>
</table>

Bagana - February 2008

IASI detect between 2 and 4 time more SO$_2$ then OMI for Bagana degassing on Feb. 2008

OMI monthly mean is produced with the Giovanni online data system, developed and maintained by the NASA GES DISC:
http://gdata2.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=omil2g
SO\textsubscript{2} mass [Tg]

SO\textsubscript{2} flux [Tg/s]