Infrared retrieval of SO_2 using high spectral resolution satellite data

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Introduction

A spectral gas matching algorithm has been developed (Prata and Bernardo, 2007) that can be used to identify specific gas species in the presence of other gases. A standard least squares estimation retrieval technique is applied to determine partial (or total) column abundances. The method is fast, easy to implement and requires little or no ancillary information. It is therefore ideal for use in an operational environment where timeliness is important and where resources may be limited. We illustrate the technique by using some examples from AIRS high spectral resolution satellite measurements of tropospheric SO_2 detection from volcanoes. The spectral matching technique for SO_2 has been used for 7.3 μm features of SO_2 (Figure 1), but the method is quite general and can be used for other gases and spectral regions, and using other high spectral resolution data (e.g. IASI).

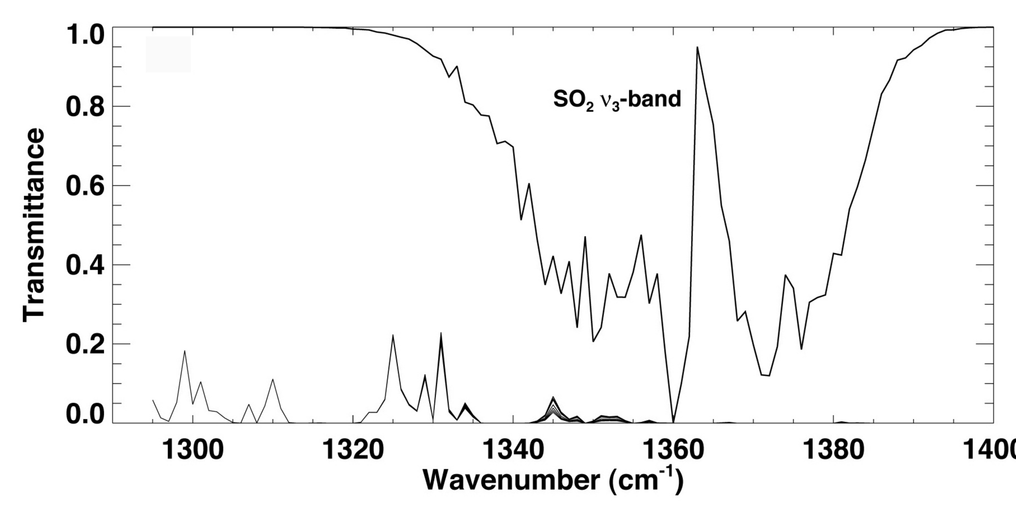

Figure 1. The 7.3 μm SO_2 absorption feature.

Retrieval scheme

The retrieval scheme is a two-step process. In the first step pixels that contain SO_2 are identified. In the second step a least squares procedure is used to find the amount of SO_2 in the pixel, based on off-line radiative transfer calculations. The upwelling radiance received by AIRS is assumed to consist of emission from the surface and from the atmosphere,

$$I_\nu = I_{\nu,s} + \int_0^\infty B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_1(z), q_2(z)...q_n(z)]}{\partial z} \right) dz, \quad (1)$$

$I_{\nu,s}$ is the radiance emitted from the surface, B_ν is the Planck function, ν is wavenumber (cm^{-1}), $T(z)$ is the temperature as a function of height z, τ is the transmittance and $q_i(z), i = 1...n$ are constituent profiles of SO_2,H_2O, CO_2, O_3 etc. The aim of the analysis is to retrieve the column abundance, u_1 of SO_2, which is related to the constituent profile by,

$$u_1 = \int_0^\infty q_1(z) dz. \quad (2)$$

The total column background atmospheric SO_2 in the absence of volcanic activity is typically less than 1 Dobson unit[1] (DU) (<0.2 DU in the boundary layer). We assume that the SO_2 lies in a layer at $z = z_1$ to $z = z_2$ (above the boundary layer) so that equation (1) can be written,

$$\begin{aligned} I_\nu \approx & \int_0^{z_1} B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_2(z)...q_n(z)]}{\partial z} \right) dz \\ & + \int_{z_1}^{z_2} B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_1(z), q_2(z)...q_n(z)]}{\partial z} \right) dz \\ & + \int_{z_2}^{\infty} B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_2(z)...q_n(z)]}{\partial z} \right) dz. \quad (3) \end{aligned}$$

The AIRS retrieval relies on being able to correctly identify pixels within the image granule that are affected by SO_2. To do this we assume that the transmission of radiation within this restricted band, for each pixel, follows the Beer-Bougier-Lambert law:

$$I'_\nu = I_{\nu,0} \exp \left\{ - \int_o^\infty k_\nu(z) q(z) dz \right\}, \quad (4)$$

where I'_ν is the radiance at wavenumber ν leaving the SO_2 layer measured at the satellite (term 2 in Eq. (3)), $I_{\nu,0}$ is the radiance entering the SO_2 layer from below and is equivalent to term 1 in (3), and k is the absorption coefficient.

Spectral Matching

By ratioing a target spectrum with a reference spectrum (from a reference pixel), the absorbance of the gas can be found by integration. The method of determining the optimal reference pixel relies solely on the degree of correlation between the absorbance spectrum computed from,

$$A_\nu = -Ln \left\{ \frac{I_{p_t,l_t}}{I_{p_r,l_r}} \right\} \text{ and } S_\nu = -Ln \left\{ \frac{I_s}{I_0} \right\},$$

where I_s is the synthetic radiance spectrum (1295−1405 cm^{-1}) with 100 DU of SO_2 and I_0 is the synthetic spectrum with background SO_2. I_{p_t,l_t} and I_{p_r,l_r} are measured AIRS radiance spectra (functions of ν–the reference to ν has been dropped for notational convenience) for the target pixel [p_t,l_t] and the reference pixel, [p_r,l_r], respectively, and p and l represent pixel and line number. The R^2 correlation is calculated from,

$$R = \frac{\frac{1}{n-1} \sum_{i=0}^{n-1} \tilde{A}_i \tilde{S}_i}{\sqrt{\frac{1}{n-1} \sum_{i=0}^{n-1} \tilde{A}_i^2} \sqrt{\frac{1}{n-1} \sum_{i=0}^{n-1} \tilde{S}_i^2}}. \quad (5)$$

The ordinates of the spectrum occur at discrete values of wavenumber, ν_i that are determined by the AIRS instrument characteristic, and n is the number of channels used ($n \approx 140$). $\tilde{A}$ and $\tilde{S}$ are the normalized measured and synthetic absorbance spectrums, defined as,

$$\tilde{A}_i = \frac{A_i - \min(A_i)}{\max(A_i) - \min(A_i)}, \tilde{S}_i = \frac{S_i - \min(S_i)}{\max(S_i) - \min(S_i)}.$$

Figure 2 illustrates the method for the 4 μm SO_2 band using AIRS data.

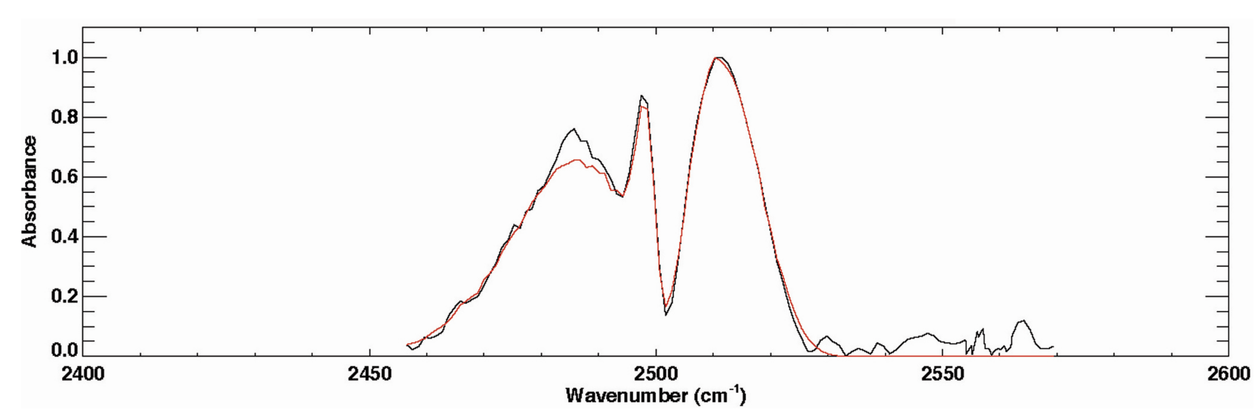

Figure 2. AIRS measured (black) and calculated (red) absorbance spectra for the 4 μm SO_2 band.

Examples

One of the most prodigious emitters of volcanic SO_2, Nyamuragira (1.41 °S, 29.20 °E, 3000 m ASL) has a long and well-documented TOMS (and now OMI) record of satellite measurements. Between 28 November 2006 and 4 December 2006, Nyamuragira produced a regional-scale SO_2 cloud that initially travelled westwards before recurving north and then east towards the Red sea. AIRS captured the SO_2 cloud during the whole week of activity. This is an interesting volcano to observe as most of the emissions reside in the lower troposphere, but the large quantities of SO_2 emitted make detection by many different satellite sensors feasible. Figure 3 shows the AIRS SO_2 retrievals for the period 28 November–3 December, 2006, averaged and re-binned to show the scale and extent of Nyamuragira's SO_2 cloud. The total SO_2 mass emission calculated from this map is about 0.44 Tg.

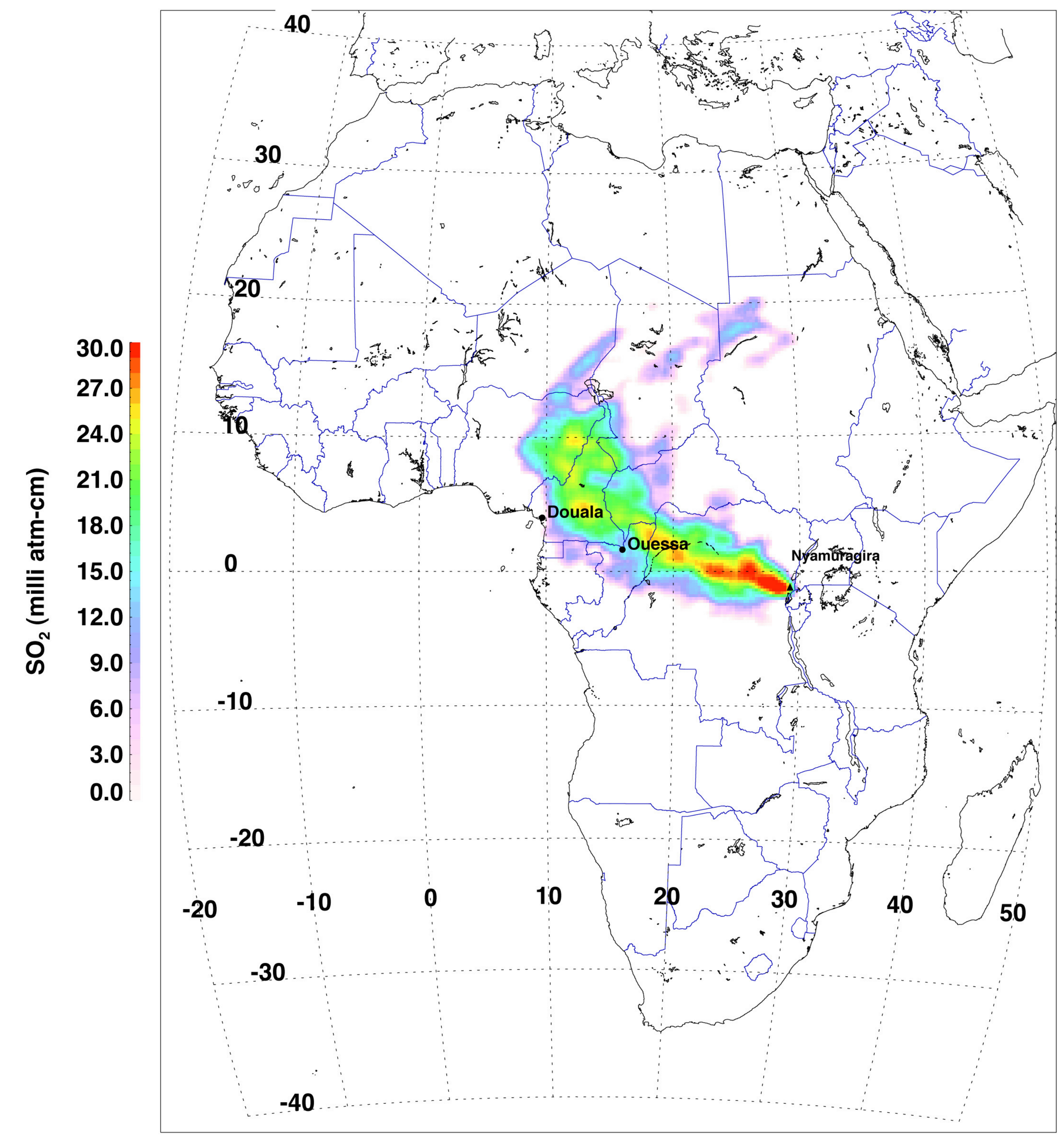

Figure 3. SO_2 emissions from the eruption of Nyamuragira during November–December 2006.

In late September 2007, Jebel al-Tair a Yemeni volcano in the Red Sea, unexpectedly erupted generating an SO_2 cloud that probably reached 11 km and eventually spread eastwards reaching Japan and the Pacific ocean. Figure 4 shows a single-granule AIRS retrieval for this eruption, illustrating the lack of interference from the hot desert surface radiation on the retrieval of SO_2 made at 7.3 μm

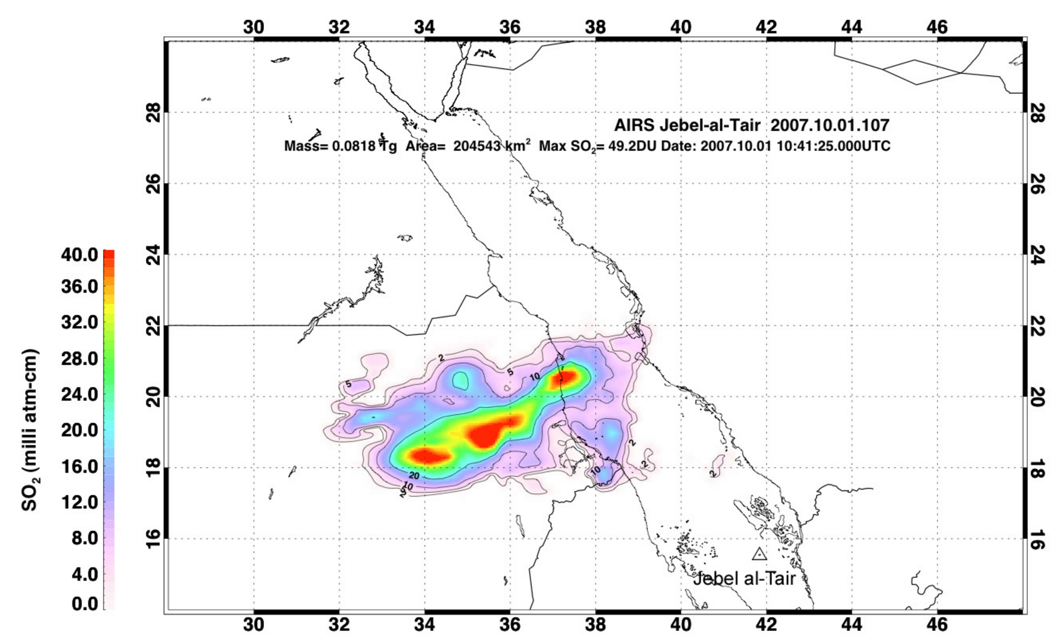

Figure 4. SO_2 emissions from the eruption of Jebel al-Tair in the Red Sea.

Conclusions

A retrieval scheme has been proposed for deriving the column SO_2 abundance from the 1362 cm^{-1} (7.34 μm) anti-symmetric stretch absorption ν_3-band using AIRS spectra. The scheme has an accuracy of about 6 D.U. ($\approx$1.6 x 10^{16} molecules cm^{-2}), mostly limited by errors in accounting for the background atmosphere, i.e. obtaining the reference pixel and reference spectrum. AIRS and IASI measurements provide a natural filter for identifying SO_2 in the UTLS, that may be climatically significant. With such high spectral resolution, AIRS and IASI will be able to "see" deeper into the atmosphere than any of the broadband infrared sensors (e.g. MODIS or HIRS). Inspection of AIRS spectra also shows that there may be vertical SO_2 height information. SO_2 absorption has also been identified in the AIRS spectra at 2460–2525 cm^{-1} and 1070–1125 cm^{-1}. Anthropogenic SO_2 release from industry in mainland China has been determined from 4 μm AIRS measurements (see Figure 5).

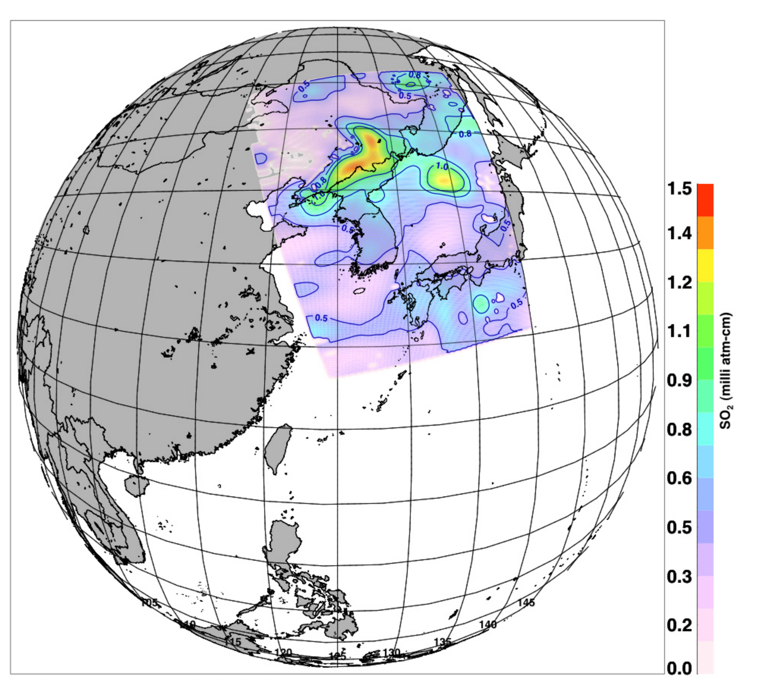

Figure 5. Lower tropospheric SO_2 derived from the AIRS 4 μm band on 6-June-2007. The high SO_2 abundance near the Korean peninsula.

Reference Prata, A. J. and C. Bernardo (2007), Retrieval of SO_2 column abundance from AIRS measurements, *J. Geophys. Res.*, **112**, D20204, doi:10.1029/2006JD007955.

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