

**EOS IDS Volcanology Team
Data Product Document
Product # 3289**

**Volcanic SO₂ -
High and Moderate
Spatial Resolution**

**Version 3
November 6, 1995**

**Vincent J. Realmuto
Jet Propulsion Laboratory
(vince@vulcano.jpl.nasa.gov)**

Table of Contents

1. Introduction	1
1.1 Algorithm and Product Description	1
1.2 Document Scope	1
1.3 Relevant EOS Documents	1
2. Overview and Background Information	1
2.1 Experiment Objective	1
2.2 Historical Perspective	2
2.3 Instrument Characteristics	3
2.3.1 ASTER	3
2.3.2 MODIS	3
3. Algorithm Description	3
3.1 Theoretical Description	3
3.1.1 Estimates of Error	5
3.2 Practical Considerations	5
3.2.1 Operation of Procedure	5
3.2.2 Input Data Requirements	6
3.2.2.1 High-Resolution Mapping	6
3.2.2.2 Moderate-Resolution Mapping	7
3.2.3 Output Data Products	7
3.2.3.1 High-Resolution Maps	7
3.2.3.2 Moderate-Resolution Maps	8
4. Constraints, Limitations, and Assumptions	8
5. References	11
6. Appendices	12
Appendix A: Transmission Through Atmospheric Path Containing SO ₂	12
Appendix B: Example of Output from XMAP_SO2	13
Appendix C: XMAP_SO2 On-line Help Documentation	16

List of Tables

Table 1. Description of ASTER Channels	9
Table 2. Description of MODIS Channels	10

1. INTRODUCTION

1.1 Algorithm and Product Identification

This document describes an algorithm for the mapping of SO₂ in volcanic plumes using data acquired by the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) and the Moderate Resolution Imaging Spectrometer (MODIS). Both instruments are currently scheduled for a 1998 launch on the AM-1 Earth Observing System (EOS) platform. This data product is number 3289, Volcanic SO₂ (High and Moderate Resolution), produced by the Global Assessment of Active Volcanism Interdisciplinary Science (IDS) Team. This team is led by Dr. Peter J. Mouginis-Mark of the University of Hawaii at Manoa.

1.2 Document Scope

This document contains a brief description of the physical principals involved in the estimation of SO₂ concentrations in a volcanic plume from measurements of the ground radiance transmitted through the plume. A detailed discussion of radiative transfer theory is beyond the scope of this document; Goody and Yung [1989] and Stephens [1994] contain thorough discussions of this topic.

The following sections contain an overview of the remote sensing of volcanic plumes, a discussion of the operation of a procedure designed to estimate the SO₂ abundance and an example resulting from the application of the estimation procedure to image data acquired over the Puu Oo vent, Kilauea Volcano, Hawaii. The background material and operating instructions provided by this document will enable investigators to apply the SO₂ estimation procedure to their volcanic field sites.

1.3 Relevant EOS Documents

Gillespie et al., Temperature Emissivity Separation Algorithm Theoretical Basis Document (ATBD-AST-03)

Guenther et al., MODIS Level 1B Algorithm Theoretical Basis Document (ATBD-MOD-01)

Menzel WP and Gumley LE, MODIS Atmospheric Profile Retrieval Algorithm Theoretical Basis Document (ATBD-MOD-07)

Palluconi et al, Atmospheric Correction Methods for ASTER Radiometry (ATBD-AST-04)

Wan Z, MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (ATBD-MOD-12)

Watanabe et al., Algorithm Theoretical Basis Document for ASTER Level 1 Data Processing (ATBD-AST-01)

2. OVERVIEW AND BACKGROUND INFORMATION

2.1 Experiment Objective

In the most basic terms, the objective of the experiment described in this document is to use satellite-based sensors to map, in two dimensions, the concentration of SO₂ in the plumes emanating from several select volcanoes. The ability to map SO₂ from space will be a valuable asset to volcano monitoring programs, since such measurements are often impractical or even danger-

ous to obtain. In addition, the repetitive coverage provided by satellite-based sensors will facilitate the determination of the baseline SO₂ flux levels of fuming volcanoes. The determination of baseline flux levels is an important goal of volcanologists, since research has indicated (cf. Section 2.2) that deviations (increases or decreases) from baseline flux levels have preceded documented eruptions.

2.2 Historical Perspective

The direct sampling of volcanic SO₂ plumes is not practical or safe in many field settings. Remote sensing of SO₂ in the ultraviolet (UV) and thermal infrared (TIR) spectral regions offers an alternative method for measuring volcanic plumes.

The introduction of the portable correlation spectrometer, or COSPEC, in the early 1970's [cf. Moffat and Millan, 1971] was soon followed by the application of these instruments to the study of volcanic SO₂ plumes [cf. Stoiber et al., 1983]. COSPEC instruments, which convert measurements of the UV sunlight transmitted through a plume into estimates of its SO₂ burden [Hamilton et al., 1978], have been deployed at a variety of volcanoes from a variety of stationary and mobile platforms [eg. Andres et al., 1993a, b; Caltabiano et al., 1994].

However, a COSPEC instrument can only view a small portion of a plume. The plume transects necessary to estimate flux rates are obtained by either traversing beneath a plume in a vehicle or panning across plume from fixed positions near the vent. Therefore, the estimation of spatial or temporal variations in the SO₂ content of plumes can involve considerable labor, logistical planning, and personal risk.

Satellite-based remote sensing is largely free of the limitations imposed by field logistics and safety. UV image data acquired with NASA's Total Ozone Mapping Spectrometer (TOMS) have been used to create small-scale, multitemporal maps of the maps of the SO₂ clouds from many recent explosive eruptions, including El Chichon [Krueger, 1983], Mauna Loa [Casadevall et al., 1984], Nevado del Ruiz [Krueger et al., 1990], Cerro Hudson [Doiron et al., 1991], Mount Pinatubo [Bluth et al., 1992a], and Mount Spurr [Bluth et al., 1992b].

Realmutto et al. [1994] have recently demonstrated that the multispectral TIR image data collected with NASA's airborne Thermal Infrared Multispectral Scanner (TIMS) could be used to map the SO₂ content of volcanic plumes. This estimation technique uses radiative transfer modeling to fit the radiance observed when the ground is viewed through an intervening volcanic plume. The TIR SO₂ estimation procedure will be modified to permit the input of data from ASTER [Kahle et al., 1991] and MODIS [Salomonson et al., 1989] in the EOS era.

The combination of ASTER and MODIS on the EOS AM-1 platform (scheduled for launch in 1998) will create a powerful tool for mapping volcanic SO₂. The ASTER data, with a spatial resolution of 90 m and a swath width of 60 km, are ideal for the mapping of small SO₂ plumes (such as the Puu Oo plume depicted in Appendix B). The MODIS thermal infrared data, with a spatial resolution of 1 km and a swath width of 2330 km, are ideal for synoptic maps of large SO₂ clouds produced by explosive volcanic eruptions. The ASTER and MODIS data will be complementary when the instruments are trained on the same plume or cloud; ASTER will provide detailed measurements of small areas of the target while MODIS will extend the ASTER measurements to the entire target.

The AM-1 platform will orbit the Earth 15 times per day, repeating the ground track every 16 days. This orbit will permit both ASTER and MODIS to collect detailed time-history data sets of dynamic plumes and clouds. The limited field of view of ASTER will require that the instrument look off-nadir to acquire these multi-temporal data.

2.3 Instrument Characteristics

2.3.1 ASTER

ASTER data will be the principal input for the SO₂ maps. A brief description of the characteristics of this instrument is found in this section; Kahle et al. [1991] provide a more detailed description. The specifications for the fourteen ASTER channels are listed in Table 1.

As indicated by Table 1, the ASTER instrument is actually a collection of three separate imaging subsystems, each operating in a separate spectral region. The visible and near-infrared (VNIR) subsystem features nadir and forward-looking telescopes to provide panchromatic stereographic coverage in ASTER Channel 3. These data are to be used in the construction of digital elevation models upon request (product AST14, parameter # 2828).

All three of the imaging subsystems will have cross-track pointing capability of at least 8°. The cross-track pointing, together with the 16-day repeat cycle of the EOS AM-1 platform, will enable ASTER to image virtually any point on Earth. Due to operational constraints, ASTER will probably acquire a maximum of 50 volcano images per year.

2.3.2 MODIS

Salomonson et al. [1989] provide a detailed description of the MODIS instrument. MODIS will scan 55° off-nadir, providing a imagery with a swath width of 2330 km. The instrument will have a duty cycle of 100%, meaning that it will collect data continuously (by comparison, the ASTER duty cycle is approximately 9%, or 9 minutes out of each 100 minute orbit). The specifications the 36 MODIS channels are listed in Table 2.

The efficacy and accuracy of the MODIS SO₂-mapping algorithm will be tested early in the AM-1 mission using data acquired over Mount Etna. Once the algorithm is validated, it will be applied in the event of a large, explosive eruption or when the appearance of an SO₂ plume or cloud is indicated by the Eruption Plume Thermal Alert (Volcanology Team Product #3288). An examination of the 15-year TOMS data archive (Bluth et al. 1993) suggests that an average of one volcano per year will explode with enough vigor to create high-altitude volcanic SO₂ clouds. Therefore, the use of MODIS data in the SO₂ mapping algorithm will be minor relative to that of ASTER data.

3. ALGORITHM DESCRIPTION

3.1 Theoretical Description

The thermal infrared (TIR) SO₂ mapping procedure is based on the MODTRAN radiative transfer code [Berk et al., 1989], which is used to model the TIR radiance perceived by an instrument as it views the ground through an intervening SO₂ plume. The general expression for this radiance is

$$L_s(\lambda, T_o) = \{ \epsilon(\lambda) B(\lambda, T_o) + [1 - \epsilon(\lambda)] L_d(\lambda) \} \tau(\lambda) + L_u(\lambda), \quad (1)$$

where T_o represents the temperature of the ground, $L_u(\lambda)$ and $L_d(\lambda)$ represent the ambient, or sky, radiance at the instrument and ground altitudes, respectively, and $\tau(\lambda)$ represents the spectra transmittance of the atmosphere. The ground radiance is the product of the Planck function, $B(\lambda, T_o)$, and the emissivity of the ground, $\epsilon(\lambda)$. This expression is only valid for vertical paths through the atmosphere; the angular dependencies of $\tau(\lambda)$, $L_u(\lambda)$, and $L_d(\lambda)$ have been omitted to simplify notation.

The MODTRAN inputs include $\epsilon(\lambda)$, which will be estimated from the multispectral radiance measurements, the altitudes of the ground and instrument, and the zenith angle defining the

line of sight between the instrument and ground target. MODTRAN calculates $L_u(\lambda)$, $L_d(\lambda)$, and $\tau(\lambda)$ from altitude profiles of barometric pressure, temperature, humidity, and atmospheric constituents. The altitude profiles can be selected from the several latitude- and season-dependent model atmospheres that are packaged with MODTRAN or entered manually. The altitude, thickness, and SO_2 content of a plume will be specified by modifying the constituent profile.

The presence of an SO_2 plume in the line of sight of a TIR sensor will modify the transmission term in Equation (1). The change in $\tau(\lambda)$ is illustrated in Appendix A, which depicts the transmission through a 4 km-long atmospheric column as calculated with MODTRAN. The solid and broken lines indicate the transmission through columns containing 0 and 23 g m^{-2} of SO_2 , respectively. Superimposed on Appendix A are the normalized spectral response functions for the six TIMS channels. The broad absorption feature of SO_2 affects the first three channels of TIMS, with the strongest absorption in TIMS Channel 2 (centered at $8.5 \text{ }\mu\text{m}$).

The five ASTER Thermal IR channels (Table 1) will be virtual duplicates of TIMS Channels 1, 2, 3, 5, and 6. In the case of MODIS, the SO_2 absorption features fall within Channels 28 and 29 (Table 2) while Channels 30, 31, and 32 are not affected by the presence of this molecule. Water vapor absorption of ground radiance in MODIS Channel 28 may limit the contribution of this channel to the SO_2 mapping algorithm, particularly in the case of low-altitude plumes or clouds.

The strength of the SO_2 absorption is a nonlinear function of many factors, including the concentration of SO_2 in the plume, thickness of the plume, temperature contrast between the plume and ground, and atmospheric pressure at the plume altitude. None of these model parameters are uniquely determined by the radiance measurements. Therefore, the estimation of SO_2 concentrations from measurements of ground radiance is a nonlinear, underdetermined inversion problem.

To create a more tractable inverse problem, information regarding the plume and surrounding atmosphere must be obtained from ancillary sources. Profiles of atmospheric pressure, temperature, and relative humidity can be obtained from radiosondes, climatological models, or atmospheric sounding instruments such as MODIS and AIRS. The temperature profile can be applied to the plume, assuming that it is in thermal equilibrium with the surrounding atmosphere. Profiles of standard atmospheric constituents are available within MODTRAN. The thickness and height of a plume can be estimated from cloud shadows, stereographic images (as provided by ASTER Channel 3), eye-witness observations, or COSPEC measurements. The net effect of this additional information is to reduce the number of model parameters in the inversion problem to the temperature of the surface and SO_2 concentration within the plume.

The inverse problem is still underdetermined, since there are a multitude of combinations of ground temperature and SO_2 concentration that will produce the same fit to an observed radiance spectrum. To achieve a unique solution to the inverse problem the temperature and SO_2 concentration are estimated in two separate steps. The first step is to estimate the ground temperature by fitting the observed radiance spectrum in a spectral region unaffected by SO_2 absorption (Appendix . The resulting temperature estimate is then used in an iterative estimation of SO_2 concentration using spectral channels that span the SO_2 absorption feature.

The estimation of SO_2 concentration is reduced to an over-determined inverse problem which is solved through method of least squares. The least squares inversion is the most time-consuming stage of the SO_2 estimation process, since a large number (> 20) of iterations are typically required to obtain a least squares solution. If MODTRAN were run at each iteration, it would be impractical to map SO_2 at each of the hundreds or thousands of pixels located beneath a plume.

To accelerate the SO_2 estimation process, MODTRAN is run only six times for each pixel location. The first run, for which the SO_2 concentration is zero, is used in the estimation of ground temperature. The next five runs feature increasing amounts of SO_2 . The results from all six runs are used to define a piecewise linear function describing the dependence of radiance perceived at the sensor on the SO_2 concentration of the intervening column of atmosphere.

The amount of SO_2 used in each run of MODTRAN is scaled from a maximum level input by the user at the initiation of the estimation procedure. The input level must be at least twice the

maximum level anticipated for the plume. The maximum SO₂ concentration was set at 1 g m⁻³ for the SO₂ map included with this document and this setting should be sufficient for most situations.

To further reduce the time required to map a plume, a binning algorithm has been implemented in the estimation procedure. Under the binning algorithm, the estimation procedure is only run if the attributes of the pixel in question are significantly different than those of pixels for which the procedure has previously been run. Otherwise the pixel in question is assigned the ground temperature and SO₂ concentration of the previously mapped pixel to which it is most similar.

The uniqueness of a new pixel is defined by the associated zenith angle, elevation, and radiance spectrum. These attributes must differ from those of the previously-mapped pixels within tolerance levels input by the user. Setting all three tolerance levels to zero overrides the binning algorithm, causing the estimation procedure to be run at every pixel.

3.1.1 Estimates of Error

The absolute accuracy of the SO₂ estimation procedure has yet to be determined. Using TIMS data acquired over Mount Etna, Sicily, Realmuto et al. [1994] inferred that the precision of the estimation procedure was 15%.

Tests with synthetic data sets indicate that use of a piecewise-linear approximation to describe the relationship between SO₂ concentration and ground radiance can result in overestimates of SO₂ concentrations of up to 10%. The errors appear to be independent of both the actual SO₂ concentration and the maximum SO₂ used to scale the approximation.

Tests of the binning algorithm indicate that the number of pixels at which the estimation procedure is run can be reduced by a factor of two. The tolerance levels for differences in zenith angle, elevation, and radiance spectrum were 0.60° (the fraction of the field of view covered by 5 TIMS pixels), 5 m (the vertical resolution of the optional DEM), and 0.05 W m⁻² sr⁻¹ m⁻¹ (square root of the sum of the squares of the difference in each TIMS channel), respectively.

Approximately 90% of the resulting SO₂ estimates were within ± 10% of the estimates obtained with the conventional estimation procedure, and there was no appreciable bias (less than -1%) in the SO₂ estimates obtained using the binning algorithm.

3.2 Practical Considerations

The current version of the SO₂-estimation procedure was developed on a Sun 4/80 (SPARCstation10) with 160 Mbytes of physical memory (RAM) and 435 Mbytes of virtual memory. The memory requirements of the estimation procedure are large, since the input radiance and emissivity and the output SO₂ column abundance and surface temperature data sets are held in memory during execution.

The estimation procedure is computationally-intensive as well, due to the multiple runs of MODTRAN required for a single output point. Execution times on the SPARCstation ranged between 9 and 15 seconds/pixel, with execution increasing with decreasing SO₂ concentration.

3.2.1 Operation of Procedure

An IDL-based application known as XMAP_SO2 has been developed to perform the SO₂-estimation procedure described in this document. The main functions of XMAP_SO2 are to (1) identify pixels that lie beneath an SO₂ plume, (2) identify pixels from which estimates of ground emissivity are to be extracted, (3) set up and execute the required MODTRAN runs, and (4) find the ground temperature and SO₂ concentration that yield the best (least squares) fit between the observed and modeled radiance spectra. A copy of the XMAP_SO2 on-line help documentation can be found in Appendix C.

The initial inputs to XMAP_SO2 are all image products. The first of these inputs is an index image from which the user can identify the SO₂ plume and surface materials that lie beneath the plume. The index image is typically a contrast-enhanced false-color composite of the image data under analysis. XMAP_SO2 provides a graphics user interface through which the user can

draw boxes over the image and designate if the pixels located within a box are to be used to extract radiance or emissivity spectra.

Multiband images containing radiance and emissivity values are the next inputs to XMAP_SO2. Radiance and emissivity spectra will be extracted from the corresponding images from the pixel locations specified on the index image. It is important that the index, radiance, and emissivity images are in spatial registration: these images can be derived from the same input data or registered via geometric transformation. The latter approach requires resampling, which invariably degrades the spatial resolution of the data.

The final input image is a digital elevation model (DEM). Ground elevation values will be extracted from the DEM at the pixel locations specified on the index image, so the DEM must be in registration with the index, radiance, and emissivity images. The input of a DEM is optional, but ground elevation is a mandatory parameter in the MODTRAN model. If no DEM is available, the user must enter a value for ground elevation.

Following the entry of the input images, the user must enter the altitude of the midpoint of the SO₂ plume, thickness of the plume, altitude of the sensor, and ground elevation (if no DEM is available). Due to constraints imposed by MODTRAN, the midpoint altitude cannot be lower than the sum of the ground elevation and plume thickness.

The user must enter altitude profiles of atmospheric pressure, temperature, and relative humidity. XMAP_SO2 resamples the altitude profiles using the values entered for midpoint altitude, plume thickness, ground elevation, and sensor altitude. The vertical resolution of the resampled profiles is symmetric about the midpoint altitude of the plume. The finest resolution, equal to the plume thickness, occurs at the midpoint altitude, with geometrically-increasing coarseness both above and below the plume.

The spectral response functions of the sensor used to observe the plume must also be input to XMAP_SO2. The output of each MODTRAN run is convolved with the spectral response functions to convert the model spectra, which have a spectral resolution of approximately 0.02 μm , to the TIMS spectral resolution, which is approximately 1 μm (Appendix A).

The selection of pixels for the extraction of emissivity spectra requires some photo-interpretation of the index image. The user must find exposures of the same surface materials that lie beneath the SO₂ plume in portions of the scene where they are in clear view of the sensor. Emissivity spectra can be extracted from a single pixel location or as an average over a rectangular region of interest. In general, an emissivity spectrum averaged over a large region of interest is preferable to a spectrum extracted from a single pixel location.

XMAP_SO2 can be run at a single pixel location or over a group of locations enclosed by a rectangular region of interest. In the region-of-interest mode, the plume midpoint altitude, plume thickness, sensor altitude, and maximum SO₂ concentration level cannot be changed once the estimation procedure is initiated. The ground elevation value can vary if a DEM is used, otherwise this parameter is also held constant over the region of interest.

3.2.2 Input Data Requirements

3.2.2.1 High-Resolution Mapping

As discussed in Section 2, ASTER data will be the data set for the SO₂-mapping at high spatial resolution (90 m at nadir). The algorithm will use AST03 (parameter # 2452), ASTER registered radiance at the sensor. The size of this data set is 243 Mbytes per 60 X 60 km ASTER scene.

The preparation of an emissivity image from AST03 requires that the radiance data be corrected for atmospheric effects. Prior to the launch of the EOS PM-1 platform in 2001, the primary source of profiles of atmospheric temperature and water vapor will be MODIS data product MOD30, atmospheric temperature (parameter # 3726) and moisture profiles (parameter # 3727). These profiles will be available at a spatial resolution of 5 km X 5 km. No more than 12 MODIS temperature and humidity profiles will be used to cover an ASTER scene. The MOD30 profiles

will be stored as data records containing 237 bytes; approximately 3 kbytes of MODIS product will be required per ASTER scene.

Following the launch of the EOS PM-1 platform in 2001, data collected with the Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU) experiment will be incorporated into the SO₂-mapping procedure. These relevant AIRS data products are the atmospheric temperature (AIR07, parameter # 1588) and humidity profiles (AIR05, parameter # 1828). The size of the AIRS data products has yet to be determined, but should be on the order of 1500 bytes/profile. In addition to MODIS and AIRS/AMSU data products, atmospheric profile data will be obtained from a variety of ancillary sources, such as radiosoundings, climatological models, and assimilation models.

ASTER will offer a surface emissivity data product, AST05 (parameter # 2124), which will be generated from AST09 (parameter # 3817), surface radiance using the methods and data sets described above. Given the Volcanology Team's objective of producing 22 high-resolution SO₂ maps per year, the use of AST05 as a time-savings measure will be considered. The addition of AST05, at 6 Mb per ASTER scene, will increase the input data volume to roughly 250 Mb/scene (including the MODIS and AIRS profiles). The use of AST05 will not eliminate the need for atmospheric profiles, as these data are required by the SO₂ estimation procedure.

The use of a DEM is optional in the SO₂ estimation procedure. However, an ASTER-derived DEM will contain information on plume height in addition to ground elevation. If the ASTER science team provides a DEM (Product AST14, parameter # 2828) for each volcano scene analyzed, the input data volume will increase by 35 Mbytes/scene.

3.2.2.2 Moderate-Resolution Mapping

MODIS data will be used for SO₂ mapping at moderate spatial resolution (1 km at nadir). Since large explosive eruptions are rare events (~ 1 per year), the use of MODIS data will be limited to six scenes per year. The mapping algorithm will use the data from five of the MODIS thermal infrared channels. It is not known at this time if MODIS data will be available by the channel.

Assuming that a MODIS thermal infrared scene will consist of 2000 rows X 2000 columns of 16-bit (2 byte) data, the data from a single channel will total 8 Mb. The input data volume from MODIS will be 240 Mb/yr. Each MODIS scene will require no more than 12 atmospheric profiles for processing, adding 216 Kb to the annual input data budget.

3.2.3 Output Data Products

XMAP_SO2 produces two output maps. The first is a map of SO₂ column abundance, the second is a map of ground temperature estimates for pixel locations at which the estimation procedure was executed. The latter data product is a useful gauge for the accuracy of the SO₂ estimates. If the ground temperatures appear to be unreasonable, given the local environmental conditions, then it is likely that the SO₂ estimates are also in error. Unfortunately, reasonable ground temperature estimates are only a necessary, rather than sufficient, criterion for accurate SO₂ estimates.

3.2.3.1 High-Resolution Maps

Output data volume will be considerably less than the input data volume. If the SO₂ column abundance and temperature maps are in 24-bit raster format, the size of the output products will be approximately 2.6 Mb/scene. Producing the final maps in an 8-bit color graphics format such as GIF or HDF will reduce the data volume to approximately 0.9 Mb/scene.

The observation plan for ASTER is to routinely image three volcanoes every other month, with an additional 4 scenes/year budgeted to cover eruptions. Assuming a production rate of 22 plume maps per year, the output data volume will be 57 Mb/year (20 Mb/year for GIF or HDF).

3.2.3.2 Moderate-Resolution Maps

Following the assumptions of the Section 3.2.2.2, each pair of maps derived from MODIS data will contain 12 Mb in 24-bit color format or 4 Mb in GIF (or HDF) format. Assuming a production rate of six map pairs per year, the output data volume will be either 72 Mb/year (24-bit color) or 24 Mb (GIF/HDF).

4. CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

The descriptions of the mathematics involved in creating the SO₂ maps are deceptively simple, since the most intense number crunching is performed by MODTRAN and IDL. Both software packages are available to the public, although MODTRAN is public domain software and IDL is commercial software. It is assumed that the Land Processes Distributed Active Archive Center (LP-DAAC) at the USGS EROS Data Center (EDC) will accept procedures written in IDL and that any users requesting copies of the procedure will have their own copies of IDL.

Table 1. Description of ASTER Channels

Specifications for ASTER Channels			
Subsystem	Band Number	Bandpass (μm)	Spatial Resolution (m)
VNIR	1	0.52 - 0.60	15
VNIR	2	0.63 - 0.69	15
VNIR	3	0.76 - 0.86	15
SWIR	4	1.600 - 1.700	30
SWIR	5	2.145 - 2.185	30
SWIR	6	2.185 - 2.225	30
SWIR	7	2.235 - 2.285	30
SWIR	8	2.295 - 2.365	30
SWIR	9	2.360 - 2.430	30
TIR	10	8.125 - 8.475	90
TIR	11	8.475 - 8.825	90
TIR	12	8.925 - 9.275	90
TIR	13	10.25 - 10.95	90
TIR	14	10.95 - 11.65	90

Table 2: Description of the MODIS Channels

MODIS Channel Specifications					
Band Number	Bandpass (μm)	Spatial Resolution (m)	Band Number	Bandpass (μm)	Spatial Resolution (m)
1	0.620 - 0.670	250	19	0.915 - 0.965	1000
2	0.841 - 0.876	250	20	3.660 - 3.840	1000
3	0.459 - 0.479	500	21	3.929 - 3.989	1000
4	0.545 - 0.565	500	22	3.929 - 3.989	1000
5	1.230 - 1.250	500	23	4.020 - 4.080	1000
6	1.628 - 1.652	500	34	4.433 - 4.498	1000
7	2.105 - 2.155	1000	25	4.482 - 4.549	1000
8	0.405 - 0.420	1000	26	1.360 - 1.390	1000
9	0.438 - 0.448	1000	27	6.535 - 6.895	1000
10	0.483 - 0.493	1000	28	7.175 - 7.475	1000
11	0.526 - 0.536	1000	29	8.400 - 8.700	1000
12	0.546 - 0.556	1000	30	9.580 - 9.880	1000
13	0.662 - 0.672	1000	31	10.780 - 11.280	1000
14	0.673 - 0.683	1000	32	11.770 - 12.270	1000
15	0.743 - 0.753	1000	33	13.185 - 13.485	1000
16	0.862 - 0.877	1000	34	13.485 - 13.785	1000
17	0.890 - 0.920	1000	35	13.785 - 14.085	1000
18	0.931 - 0.941	1000	36	14.085 - 14.385	1000

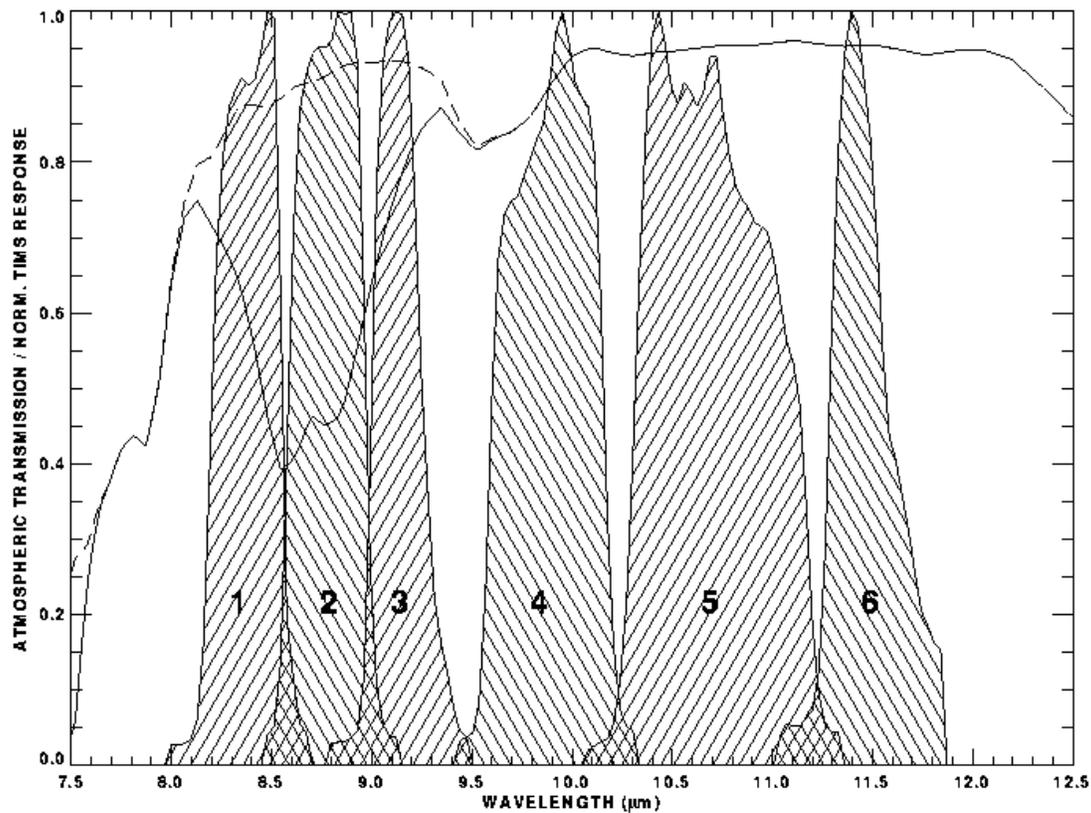
5. REFERENCES

- Andres RJ, Kyle PR, Chuan RL (1993a) Sulphur dioxide, particle, and elemental emissions from Mount Etna, Italy during July 1987. *Geol Rundsch* 82: 687-695
- Andres RJ, Rose WI, Stoiber RE, Williams SN, Matais O, Morales R (1993b) A summary of sulfur dioxide emission rate measurements from Guatemalan volcanoes. *Bull Volcanol* 55: 379-388
- Berk A, Bernstein LS, Robertson DC (1989) MODTRAN: a moderate resolution model for LOWTRAN-7. GL-TR-89-0122
- Bluth GJS, Doiron SD, Schnetzler CC, Krueger AJ, Walter LS (1992a) Global tracking of the SO₂ clouds from the June, 1991 Mount Pinatubo eruptions. *Geophys Res Let* 19: 151-154
- Bluth GJS, Scott CJ, Schoeberl M, Schnetzler CC, Krueger AJ, Walter LS (1992b) SO₂ cloud tracking from the June and August eruptions of Mount Spurr, Alaska. *Trans Am Geophys Union* 74: 614
- Bluth GJS, Schnetzler CC, Krueger AJ, Walter LS (1993) The contribution of explosive volcanism to global atmospheric sulphur dioxide concentrations. *Nature* 336: 327-329
- Caltabiano T, Romano R, Budetta G (1994) SO₂ flux measurements at Mount Etna (Sicily). *J Geophys Res* 99: 12,809-12,819
- Casadevall TJ, Krueger AJ, Stokes B (1984) The volcanic plume from the 1984 eruption of Mauna Loa, Hawaii. *Trans Amer Geophys Union* 65: 1133
- Chartier TA, Rose WI, Stokes JB (1988) Detailed record of SO₂ emissions from Puu Oo between episodes 33 and 34 of the 1983-1986 ERZ eruption, Kilauea, Hawaii. *Bull Volc* 50: 215-228
- Doiron SD, Bluth GJS, Schnetzler CC, Krueger AJ, Walter LS (1991) Transport of Cerro Hudson SO₂ clouds. *Eos Trans AGU*, 72, 489-498
- Goody RM, Yung YL (1989) *Atmospheric Radiation* (2nd Ed.). Oxford, New York, pp 1-519
- Hamilton PM, Varey RH, Millan MM (1978) Remote sensing of sulfur dioxide. *Atmos Environ* 12: 127-133
- Kahle AB, Palluconi FD, Hook SJ, Realmuto VJ, Bothwell G (1991) The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER). *Int J Imaging Sys Tech* 3: 144-156
- Krueger AJ (1983) Sighting of El Chichon sulfur dioxide clouds with the Nimbus 7 Total Ozone Mapping Spectrometer. *Science* 220: 1377-1379
- Krueger AJ, Walter LS, Schnetzler CC, and Doiron SD (1990) TOMS measurement of the sulfur dioxide emitted during the 1985 Nevado del Ruiz eruptions. *J Volcanol Geotherm Res* 41: 7-15
- Moffat AJ, Millan MM (1971) The applications of optical correlation techniques to the remote sensing of SO₂ plumes using sky light. *Atmos Environ* 5: 677-690
- Realmuto VJ, Abrams MJ, Buongiorno M-F, Pieri DC (1994) The use of multispectral thermal infrared image data to estimate the sulfur dioxide flux from volcanoes: a case study from Mount Etna, Sicily, July 29, 1986. *J Geophys Res* 99: 481-488
- Salomonson V, Barnes W, Maymon P, Montgomery H, Ostrow H (1989) MODIS: advance facility instrument for studies of the earth as a system. *IEEE Trans Geosc Remote Sens* 27: 145-153
- Stephens GL (1994) *Remote Sensing of the Lower Atmosphere*. Oxford, New York, pp 1-523
- Stoiber RE, Malinconico LL, Williams SN (1983) Use of the correlation spectrometer at active volcanoes, in *Forecasting Volcanic Events*, Tazieff H and Sabroux JC eds., pp 425-444, Elsevier, New York.

6. APPENDICES

Appendix A: Transmission Through Atmospheric Path Containing SO₂

Figure A.1 depicts the spectral transmission through two model atmospheric columns, as calculated with the LOWTRAN 7 radiative transfer code. The columns are vertical, with path lengths of approximately 4.5 km. The solid and dashed lines represent the transmission through columns containing 23 and 0 g m⁻² of SO₂, respectively. Also shown are the spectral bandpasses of the six TIMS Channels. The proposed ASTER TIR Channels are equivalent to TIMS Channels 1, 2, 3, 4, and 6.



Appendix B: Example of Output from XMAP_SO2

The XMAP_SO2 procedure was applied to TIMS data acquired over the Puu Oo vent of Kilauea Volcano, Hawaii. TIMS was flown over Puu Oo on 30 September 1988. To create the SO₂ column abundance map depicted in Figure B.1, the following parameters were used: (1) plume midpoint altitude of 1.10 km, (2) plume thickness of 0.250 km, (3) sensor altitude of 1.900 km, (4) ground altitude of 0.850 km, and (5) maximum SO₂ concentration of 1 g m⁻³.

The SO₂ column abundance map is the first map of the two-dimensional distribution of SO₂ within the Puu Oo plume. The map (Fig. B.1) clearly shows that the plume consists of four high-concentration puffs entrained in a low-concentration stream. This puffing behavior results in large variances in the flux rates determined with COSPEC data [Chartier et al., 1988]. The column abundances within the puffs range between 16 and > 32 g m⁻², while abundances in the surrounding stream range between 2 and 8 g m⁻². The SO₂ mapping procedure is the only technique that can map all of the puffs simultaneously, thus offering the opportunity to refine estimates of flux rates.

The spatial resolution of the TIMS data set depicted in Figure B.1 is approximately 3 m/pixel, which is a factor of 30 better than the spatial resolution of the ASTER thermal channels. Figure B.2 portrays the same SO₂ estimates resampled to the 90 m spatial resolution of ASTER. Three of the four high-concentration puffs can be recognized in the ASTER map, although the concentrations have been diluted (10 to 16 g m⁻² column abundance) by the larger footprint of ASTER. Assuming that the spectral and signal resolution of ASTER is similar to those of TIMS, ASTER should be able to map low-lying non-explosive (quiescent) SO₂ plumes of concentrations similar to the Puu Oo plume. The ability to map such plumes from space will be a boon to volcano monitoring programs.

Appendix C: XMAP_SO2 On-line Help Documentation

INTRODUCTION

XMAP_SO2 is a graphic user interface to the thermal infrared-based SO₂ estimation algorithm described in Realmuto et al. 1994 (JGR, v.99, pp. 481-488). The estimation algorithm utilizes the MODTRAN radiative transfer code to model the absorption of thermal infrared ground radiance observed when the ground is viewed through an intervening SO₂ plume.

The INPUTS to the MODTRAN model include the ground altitude, temperature, and emissivity, the altitude of the observing instrument, and the altitude and thickness of the SO₂ plume. MODTRAN must also be supplied with profiles of atmospheric pressure, temperature, and relative humidity. The graphic user interface of XMAP_SO2 provides prompts for both the MODTRAN parameters and interactive selection of ground pixels.

WIDGET #1

DESCRIPTION OF INPUTS

The first XMAP_SO2 widget prompts the user for the following input files:

RED: Red component of color-composite index image
or panchromatic index image

GREEN: Green component of color-composite index image
(optional)

BLUE: Blue component of color-composite index image
(optional)

The index color-composite image is used to identify (1) ground pixels beneath the SO₂ plume and (2) ground pixels outside the plume whose emissivity matches those beneath the plume. If the index image is panchromatic (black and white), the GREEN and BLUE input fields should be blank.

IRAD: Multiband Instrument Radiance Image (BSQ)

EMIS: Multiband Emissivity Image (BSQ)

DEM: Digital Elevation Model (optional)

The IRAD image contains the radiance observations that will be fitted by the MODTRAN model. The units of the radiance values in the IRAD image must be $\text{mW m}^{-2} \text{sr}^{-1} \text{m}^{-1}$. The EMIS image contains the emissivity estimates required to model ground radiance. The data values in the EMIS image range between 0 and 10,000; XMAP_SO2 converts them to real values ranging between 0.0 and 1.0 (recall that emissivity is a unitless parameter). Currently, the IRAD and EMIS images must contain 6 bands in a Band-Sequential (BSQ) format (samples, lines, bands). The pixels are in 16-bit integer format (IDL: 'INTEGER', VICAR: 'HALF').

The units of elevation in the DEM image must be meters. As with the IRAD and EMIS images, the DEM must be in 16-bit integer format. If a DEM is not available, the user must input an elevation value. Without a DEM, the elevation can not be changed within the region of interest selected by the user. Elevations entered manually must be in units of kilometers above mean sea level (MSL).

Currently XMAP_SO2 expects to find an ASCII VICAR label at the head of each input file. This label, which contains information on the dimensions and format of the image, can be read by dumping the image to the screen with the UNIX command "more". The VICAR software library is largely internal to JPL and future versions of XMAP_SO2 will permit the input of non-VICAR files.

WIDGET #2

DESCRIPTION OF PARAMETERS

The second XMAP_SO2 widget prompts the user for the following inputs:

PLUME MIDPOINT ALT: Altitude of midpoint of SO₂ plume (km MSL)

PLUME THICKNESS: Thickness of the SO₂ plume (km)

SENSOR ALTITUDE: Altitude of the sensor observing the plume (km MSL)

GROUND ALTITUDE: Altitude of the ground target (km MSL)

RADIOSONDE: File containing radiosonde-measured profiles of atmospheric pressure, temperature, and relative humidity

These four inputs set up the MODTRAN radiative transfer model. MIDPOINT ALT and PLUME THICKNESS are used to resample the RADIOSONDE profiles to an appropriate vertical resolution. *NOTE: MODTRAN REQUIRES THAT THE MIDPOINT ALT BE GREATER THAN GROUND ALTITUDE + PLUME THICKNESS.* Once the RADIOSONDE file is selected, the DEFINE ATMOSPHERE widget pops up to allow the user to specify the units and climatology model that will be used in the MODTRAN calculations. The SENSOR ALTITUDE and GROUND ALTITUDE are used to define the optical path through the SO₂ plume.

MAX SO2 CONC: Concentration level (mg/m³) used to scale the SO₂ vs. ground radiance function (defined by successive runs of MODTRAN).

SPEC. RESPONSE: Spectral response file for the TIR imaging instrument.

BOX LOCATION: Coordinates of Upper Left (UL) and Lower Right (LR) corners of rectangular region of interest.

BOX LOCATION is updated when mouse is used to draw a box. Each coordinate can also be entered by typing into the appropriate field.

ACTION MENU Items

- Recover SO₂: Start the SO₂ estimation algorithm. The abundance (g/m²) of SO₂ in the atmospheric column above the selected pixels will be estimated.
- Emissivity: Estimate the ground emissivity for the selected pixels. The estimates will be read from the EMIS image. If a BOX LOCATION has been specified, the emissivity will be the average of all the pixels enclosed by the box.
- Tolerance: Tolerance levels used in the binning algorithm. Setting all TOLERANCE levels to 0.0 overrides the binning procedure.
- Load Maps: Read in the Temperature and SO₂ column abundance maps created during previous runs of XMAP_SO₂. User is prompted for name of disk files every time this button is selected.
- View Maps: Spawn a map viewer widget in which the current SO₂ Abundance or Temperature Map is displayed.
- Save Maps: Save the current Temperature and SO₂ Abundance maps to disk. The user is prompted for the names of the disk files each time this button is selected.
- Zoom: Spawn a zoom widget from which regions of interest can be specified, and the estimation procedure can be initiated.
- Draw Box: Draw the box specified by UL and LR coordinates entered from the Zoom Widget or keyboard. If UL and LR are not changed after a box is drawn, the box will be erased by the next selection of DRAW BOX.
- Help: Spawn this Help Widget.
- Exit: Kill the current widget. This button does NOT kill XMAP_SO₂.

MODE OF OPERATION

Enter PLUME MIDPOINT ALT, PLUME THICKNESS, SENSOR ALTITUDE, and GROUND ALTITUDE. The default MAX. CONC, 1000 mg/m^3 , should be adequate for most applications. Next enter the RADIOSONDE and SPEC. RESPONSE file names.

The radiosonde file is a four-column ASCII file. The first column is altitude (km MSL), the next three columns contain atmospheric pressure, temperature, and water vapor content. The DEFINE ATMOSPHERE widget is used to specify the units used in the radiosonde profile for pressure, temperature, and water vapor.

The SPEC. RESPONSE file describes the spectral response of the TIMS scanner. Future versions of XMAP_SO2 will accept the spectral response functions of other scanners (such as MIVIS and ASTER). This TIMS file has seven columns. The first is wavelength in units of μm , the next six are the spectral responses of the six TIMS channels.

Select the Menu item LOAD MAPS if you wish to update a pair of maps created during a previous run of XMAP_SO2. Following selection of LOAD MAPS, all boxes drawn on the screen will be erased as the screen is updated.

Select a rectangular region of interest for emissivity extraction. Press the left mouse button to start the rectangle, move the mouse, and release the button to draw the rectangle. Press the middle mouse button to erase the last-drawn box. Alternately, the coordinates of the rectangle may be entered in the BOX LOCATION fields or selected in the Zoom Widget. A press of the right mouse button (when the cursor is in the view port) will draw a box defined in this manner.

Select the EMISSIVITY menu item and a plot of the extracted emissivity spectrum will appear in the plotting window below CURRENT RESULTS. Regardless of the number of boxes drawn on the screen, the emissivity will be extracted from the box whose coordinates appear in BOX LOCATION.

Select a rectangular region of interest for SO₂ recovery. Again, you may use the mouse, Zoom-Widget, or manual entry. The radiance measurements within the region of interest will be read from the IRAD image. Regardless of the number of boxes drawn on the screen, the SO₂ estimation algorithm will operate on those pixels within the box whose coordinates appear in BOX LOCATION.

Select RECOVER SO2 to begin the mapping procedure. The line, sample, zenith angle of observation, ground temperature (K), SO₂ concentration (mg/m^3), and SO₂ column abundance (g/m^2) estimates for every pixel within the window of interest will be reported. Upon completion, the time elapsed since RECOVER SO2 was selected will be reported in the MESSAGES box. *NOTE: THE SO₂ RECOVERY ALGORITHM RUNS AT A RATE OF AT LEAST 11 SECONDS PER PIXEL. THE SELECTION OF A LARGE WINDOW SIZE WILL RESULT IN LONG RUN TIMES.*

NOTE: THE PLUME THICKNESS, MIDPOINT ALT, AND EMISSIVITY PARAMETERS CANNOT BE CHANGED ONCE THE MAPPING ALGORITHM HAS STARTED. Therefore, you must assume that these parameters do not change within the window of interest that you choose.

XMAP_SO2 uses a binning algorithm to reduce the number of times that MODTRAN is run. At any given pixel, MODTRAN is run only when the attributes of the pixel are significantly different from those of the preceding pixels. The attributes compared by the binning algorithm are radiance spectrum, zenith angle, and elevation. The TOLERANCE levels for these comparisons may be set by the user. Setting all three TOLERANCE levels to zero overrides the binning algorithm, causing MODTRAN to be run at every pixel.

Tests of the binning algorithm were conducted on a 21 X 21 (441-pixel) region-of-interest (ROI). The tests indicated that use of the default TOLERANCE levels can reduce the number of MODTRAN runs by a factor of 2. As for approximation errors, 88% of the resulting SO₂ estimates were within the range -10% to 10%. There was no appreciable bias (less than -1%) in the approximated SO₂ estimates within the ROI.

The Zoom Widget can be used to define a region of interest, define an emissivity spectrum, or initiate the SO₂ estimation algorithm. Clicking the left mouse button within the zoom display window selects a point. Holding the left mouse widget down while dragging the mouse defines a rectangular region of interest. Clicking on the middle mouse button deletes the most recent ROI. Select GET EMISSIVITY to extract an emissivity spectrum; select RECOVER SO₂ to initiate the estimation algorithm.

The Temperature and SO₂ Abundance maps produced by selecting RECOVER SO₂ can be viewed by selecting VIEW MAPS. This selection spawns the MAP VIEWER widget. The maps are displayed in black and white, but they can be colored by selecting the PSEUDO COLOR button on the MAP VIEWER widget. The temperature and SO₂ abundance estimates at the cursor position are reported when the left mouse button is clicked within the MAP VIEWER screen.

Selecting SAVE MAPS will cause the Temperature and SO₂ Abundance maps to be written to disk. The user will be prompted for the disk file names. The temperature estimates will be saved as a VICAR file with 32-bit integer pixels (IDL:'LONG', VICAR:'FULL'). The temperature estimates are multiplied by 100 before conversion to integer to preserve two decimal places. The data values in the saved Temperature Map are therefore in the unusual units of "centi-Kelvins".

The SO₂ Abundance map will also be saved as a VICAR file with 32-bit integer pixels. The SO₂ abundance estimates are multiplied by 1000 prior to conversion to integer to preserve three decimal places. The data values in the saved SO₂ Abundance Map are therefore in units of mg/m².

Happy Mapping!!!