The Global Ozone Monitoring Experiment (GOME): Mission, Instrument Concept, and First Scientific Results

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Abstract

The Global Ozone Monitoring Experiment (GOME) is a new instrument aboard ERS-2. The main scientific objective of the GOME mission is to measure the global distribution of ozone and several trace gases which play an important role in the ozone chemistry of the Earth's stratosphere and troposphere, for example, NO_2, BrO, OClO, and SO_2. GOME measures the sunlight scattered from the Earth's atmosphere and/or reflected by the surface in nadir viewing mode in the spectral region 240-790 nm. For a 960 km swath width the size of one GOME ground pixel is 40 x 320 km^2 for the major part of the orbit. Global coverage is achieved in three days. Operational data products of GOME as generated by DLR-DFD comprise absolutely calibrated and geolocated earthshine radiance spectra, the spectral solar irradiance (level 1 products) and global distributions of total column amounts of ozone and NO_2 (level 2 products). In addition to these operational products, GOME has been shown to provide other important information about, for example, height resolved ozone, several minor (i.e. low concentration) trace gases, surface reflectance, solar variability indices, and aerosol information. The GOME scientific objectives, the instrument concept and results from the first 18 months of the GOME operation will be described briefly here.

Keywords: GOME, UV-visible, Spectrometer, DOAS, Ozone, Ozone chemistry

1. Introduction

Dramatic changes in atmospheric composition (e.g. Farman et al. 1985), their impact (e.g. IPCC 1991) and the need for global measurements of trace atmospheric constituents are well established (e.g. ESA 1991). The SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) instrument proposal (Burrows et al. 1988a) was prepared in response to these needs following an ESA call for instrumentation to fly on its polar orbiting platform, now known as ENVISAT-1, which is due for launch in 1999. The recognition of the relatively urgent need for accurate and long term global measurements of atmospheric trace species resulted in ESA issuing a call for ideas for an atmospheric constituent monitoring device for the second European Remote Sensing Satellite (ERS-2) in late 1988. In response to this call the SCIAMACHY scientists proposed a small scale version of SCIAMACHY under the name SCIAmini (Burrows et al. 1988b). This instrument was at a later stage after some modifications renamed GOME.

The purpose of this paper is to give a comprehensive overview of the GOME mission and to present the information that has been derived from its measurements during its first 18 months in space. In Chapter 2 an overview on the GOME project is given followed by a short description of the GOME instrument in Chapter 3. Chapter 4 describes the GOME mission objectives and in Chapter 5 GOME operational aspects, such as instrument measurement states and timelines, are covered. In Chapter 6 a short description of the GOME operational level 0-1 and level 1-2 processing algorithms is given. Chapter 7 summarises the outcome of the GOME geophysical validation phase and the main results of several activities to further improve the GOME data products covering the time period prior to the first official release (mid 1996) of GOME data products. In Chapter 8 a brief overview on "non-operational" GOME data products is presented indicating the full potential of the GOME mission. Finally, some conclusions are drawn in Chapter 9.

2. GOME Project Overview

From the outset of GOME it was clear that the development of a new instrument, including its accommodation on ERS- 2, was a challenging task taking into account the schedule constraints. Compared to many space and ground segment development programs, the time available for the development of the GOME instrument was extremely short. After its selection and a Phase A study involving scientists from University of Bremen, ESTEC and TPD the GOME instrument development was managed by an ESA/ESTEC team. The GOME industrial team comprised the Italian firms Officine Galileo (instrument Prime Contractor) and Laben (DDHU, EGSE), the Dutch firm TPD-TNO (optical concept, calibration unit, pre-flight calibration), Dornier, Germany (thermal-control subsystem), and British Aerospace (ATSR-DEU modifications). The German Deutsche Forschungsanstalt für Luft und Raumfahrt

(DLR- DFD) supported by the DARA developed with the help of the GOME scientists the operational GOME Data Processor (GDP). From its inception scientific experts have been involved in GOME data and algorithm development issues as well as calibration and validation aspects, mainly within the framework of the GOME Science Advisory Committee (GSAC) and its sub-committees.

3. The GOME Instrument

The GOME instrument (see e.g. ESA 1995 and Burrows et al. 1993) was designed to measure the solar radiation scattered back or reflected by the Earth's atmosphere- surface system in the spectral region 240-790 nm (UV-Vis- NIR) with a spectral resolution of 0.2-0.4 nm. Its basic concept was developed by H. Visser (TPD-TNO) and J P. Burrows during project Phase A. The ratio of earthshine and sunshine spectra in this spectral region contains information ("spectral fingerprints") about a variety of important atmospheric constituents (like O_3, NO_2, BrO, OClO, ClO, SO_2, HCHO, O4, O_2, H_2O, NO, NO_3). In addition, information about aerosols, clouds, and the Earth's surface spectral reflectance, which do not show narrow spectral features, can be derived utilising the broad spectral range covered by GOME. The relatively high spectral resolution enables the application of the DOAS (Differential Optical Absorption Spectroscopy) algorithm for trace gas retrieval. The DOAS method has been successfully applied to ground-based, aircraft and balloon-borne measurements for several years (see references in Burrows et al. 1993). GOME is the first opportunity to apply this technique for retrieval of trace atmospheric constituents from measurements of space-borne remote sensing instrumentation.

In the nadir observation mode (and when observing the moon) light enters GOME via the nadir scan mirror and is focused onto the entrance slit of the spectrometer by an anamorphous telescope formed by two cylindrical mirrors. The instantaneous field-of-view (IFoV) is 2.9o x 0.14o corresponding to an area of about 40 x 2 km^2 on the Earth's surface (with the longer dimension parallel to the flight direction, i.e. perpendicular to the scan direction). In order to cover the broad spectral range with the required resolution light entering GOME is split into four separate spectral bands by means of a pre-disperser prism, a channel separator prism and a beam splitter. Each of these four spectral bands is focused by means of optics and diffraction gratings onto four monolithic silicon linear detector arrays each comprising 1024 individual detector pixels. The main characteristics of the four spectral channels are:

Channel	Spectral coverage	Spectral resolution
	[nm]	[nm]
1	1A: 240 - 307	0.02
	1B: 307 - 316	
2	311 - 405	0.17
3	405 - 611	0.29
4	595 - 793	0.33

The detectors are cooled to 235 K by means of Peltier coolers in order to reduce the dark current and to improve the signal-to-noise ratio. To correct for effects caused by the polarisation sensitivity of GOME a small fraction of light polarised perpendicular to the main optical plane (parallel to the entrance slit) is reflected off the pre-disperser prism towards dedicated Polarisation Measurement Devices (PMDs). The PMDs consist of three broad band silicon diodes, whose spectral range covers the channels 2-4, respectively. Almost all on-board calibration facilities (except the LEDs which illuminate the detector arrays to monitor the pixel-to-pixel variability) are contained in a dedicated Calibration Unit, comprising the Pt/Cr/Ne hollow cathode gas discharge lamp (spectral calibration) and the sun viewport (diffuser plate, shutter, sun view mirror, transmission mesh).

4. Mission Objectives

The measurement and retrieval objectives of the GOME mission are as follows (see e.g. Burrows et al. 1993):

a) Radiation measurements: the solar irradiance, the earthshine radiance, and moon spectra

b) Trace gas retrieval: global measurements of total columns of O_3, NO_2, BrO, H_2O; OClO and ClO (under ozone hole conditions), NO (above 40 km), SO_2 (under polluted conditions and following volcanic eruptions), HCHO (under polluted conditions), and ozone profiles

c) Clouds: cloud cover and cloud top height, cloud reflectance

d) Surface properties: albedo and surface spectral reflectance

e) Aerosols: vertical optical depth in troposphere and stratosphere

The primary measurements of GOME are the earthshine radiance and the solar irradiance from 240-790 nm. Trace gas total column amounts are retrieved from these primary measurements utilising their characteristic spectral absorption (e.g. the ozone Huggins and Chappuis bands) or emission features (e.g. NO gamma-bands). In the special case of O_3 vertical profiles can be derived by inversion of the radiance measurements between 240 and 400 nm using algorithms similar to those developed for NASA's SBUV instruments. Cloud information can be derived from the spectral reflectance measurements inside and outside the oxygen bands and from the (sub-pixel) PMD measurements. Surface and aerosol information may be retrieved from their broad-band effects on the upwelling radiance.

5. GOME Operations

On 21 April 1995 ERS-2 was launched with GOME on board. After ERS-2 reached its orbit GOME underwent a number of successful functional tests of the various subsystems. In the initial time period the Peltier cooler was not activated to allow sufficient time for the outgassing of the Focal Plane Assemblies. The switch-on of the coolers, and the first performance assessment, occurred approximately one month after launch. The commissioning phase started mid 1995. One of the major findings during this phase was that under certain circumstances (high scene albedo) saturation of the visible channels occurred when using the nominal 1.5 s integration time. As a consequence the integration time for some part of the orbit was reduced to 0.375 s. This lead to a smaller ground pixel size (one quarter of the nominal 320 km across-track pixel length) and also to a loss of ground coverage. This problem was solved by successfully introducing a software patch allowing on-board co-adding of earthshine spectra. This patch was uplinked in March 1996. Since then GOME achieves global coverage at the equator in three days (and much faster at higher latitudes). During the illuminated part of the orbit GOME mainly performs nadir measurements. In addition solar observations are performed once a day. Moon observations are performed whenever the moon is visible for GOME (periods of several days spread over the year). On the dark side of the orbit GOME performs calibration measurements, such as spectral calibration, LED, and dark signal measurements. One (across-track) scan cycle of GOME lasts 6 s, 4.5 s for the forward scan, and 1.5 s for the backscan. The maximum possible swath width is 960 km, leading to three (nominal) GOME ground pixels (East, Nadir, West) with an area of 40 x 320 km^2 each (except for channel 1A, see below). If the solar zenith angle is larger than 85 degrees an integration time of 6 s is selected instead of 1.5 s resulting in a ground pixel size of about 40 x 960 km^2. Due to the large dynamic range of the signal below about 320 nm caused by increasing ozone absorption, channel 1 is divided into two virtual channels (1A and 1B) to optimise the signal-to-noise ratio by selecting a larger integration time in channel 1A. Therefore, most of the channel 1A spectra are obtained using an integration time of 12 s. The PMDs measure one polarisation component of the incoming light with a much higher spatial resolution (40 x 20 km^2) but at a lower spectral resolution.

6. Operational Processing of GOME Data

The algorithm development of GOME was led by the GOME Data and Algorithm sub-Group (GDAG) of the GOME Science Advisory Committee (GSAC) comprising scientist from several institutions (e.g. SAO, KNMI, SRON, RAL, IASB, MPI für Chemie, University of Heidelberg, RIVM, University of Bremen), and experts from ESA and DLR. Retrieval of geophysical information from the GOME raw measurements can be divided in two separate steps: the conversion of the raw data into spectrally and radiometrically calibrated and geolocated spectra (level 0-1 processing), and retrieval of geophysical parameters, mainly atmospheric trace constituents, from the calibrated spectra (level 1-2 processing). This paper gives a short overview of the algorithms. Details can be found elsewhere (Balzer et al. 1996, Spurr et al. 1996).

Level 0-1 processing

Level 0-1 processing can be divided into two calibration tasks: the spectral calibration and the radiometric calibration. The radiometric calibration comprises:

Adjustments of the level 0 data to account for leakage current, straylight, FPA noise (which is related to the voltage controlling of the Peltier coolers), and the detector pixel-to-pixel variability (using on-board LED measurements). The polarisation correction: This is the most complex part of the radiometric calibration. The purpose of the polarisation correction is to transform the measured signal into a signal that would have been measured if the same light intensity would have been detected with unpolarised light. The algorithm makes use of the main channels and PMD data, the measurements in the spectral overlap areas between adjacent main channels, and of the instrument polarisation sensitivity as measured during the pre-flight calibration phase. Using this information a detector pixel dependent polarisation correction factor can be derived which performs the required transformation. In addition the polarisation below 300 nm is assumed to be known from Rayleigh single scattering calculations (see Stammes et al. in ESA 1996). Finally, the signal in binary units per second is converted into a radiance by using the bi-directional scattering distribution function (BSDF) of the calibration unit (sun diffuser) and the radiance response function of the instrument. Both functions have been determined during pre-flight calibration. In addition the scan mirror angle dependence is taken into account.

The spectral calibration is performed using regular in-flight measurements with the spectral calibration lamp which is also used, for example, for diffuser plate monitoring.

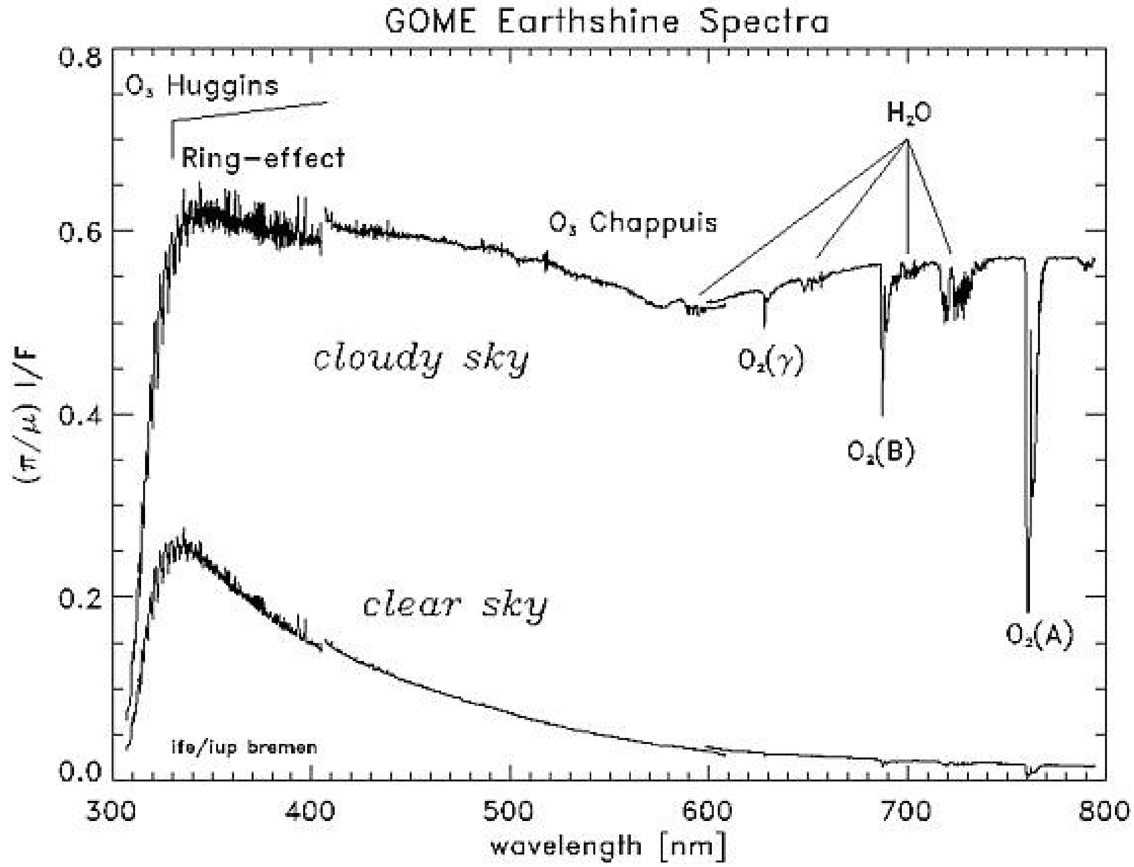

Figure 1: Sun-normalised earthshine spectra (or spectral reflectivities), as measured by GOME. I denotes the earthshine radiance, F the solar irradiance, and u the cosine of the solar zenith angle.

Level 1-2 processing

Level 1-2 processing comprises mainly four different algorithm steps:

ICFA (Initial Cloud Fitting Algorithm): this algorithm determines an estimate of the fraction of clouds contained in each single GOME ground pixel from the GOME channel 4 spectral reflectance measurements in and around the oxygen A-band. The cloud top height is assumed to be known (derived from the ISCCP cloud climatology database).

DOAS (Differential Optical Absorption Spectroscopy) algorithm: this algorithm determines, for each absorber within the given spectral window, a slant column amount (units: number of molecules per unit area) by least-squares fitting the measured optical depth to a linear combination of reference absorption cross-section spectra of trace gases and a Ring reference spectrum (to account for the filling-in effect of Fraunhofer lines). Essentially, only differential structures are considered as broad band features are filtered out by subtracting a low order polynomial. Appropriate reference spectra for ozone, NO_2 and "Ring" have been measured with the GOME FM instrument during the pre- flight calibration phase by the

University of Bremen. To improve the relative spectral alignment of the different spectra small shifts and squeezes maybe performed if necessary using a non-linear least-squares method.

AMF (Air Mass Factor) algorithm: to derive the desired vertical trace gas column, the slant column, obtained from the DOAS algorithm, has to be divided by an appropriate dimensionless air mass factor describing the enhancement of the absorption due to the slant path viewing geometry and the solar elevation. This factor is obtained by radiative transfer model (RTM) simulations. AMFs are determined on-line neglecting the multiple scattering of light. The single scattering AMFs are currently corrected using an AMF multiple scattering correction table, which has been generated off-line with the radiative transfer program GOMETRAN developed at the University of Bremen (Rozanov et al. 1997). The AMFs are calculated for both cloud free and completely cloudy scenes.

VCD (Vertical Column Density) algorithm: This algorithm calculates the desired trace gas vertical columns using the results from the previous three algorithms. The unknown column below the cloud level is derived from climatological profiles. The dependence of the AMF on the scan angle is also taken into account.

7. Validation of Operational Data Products

The first GOME data was released to the validation campaign participants during September 1995. The GOME Validation Campaign Final Results Workshop took place on 24-26 January 1996 in Frascati, Italy. This workshop was successful and provided a consistent picture of the quality of the GOME data products (ESA 1996). In addition, it resulted in detailed recommendations concerning further improvements of the quality of the GOME data.

For the level 1 data product (V0.5, V0.6) a good wavelength stability was found and a high instrument precision. The radiance/irradiance ratio is accurate within the ozone retrieval window and facilitates meaningful total ozone column retrieval using the DOAS technique. One problem identified was that the solar irradiance levels differ from spectra obtained from other sensors (e.g. SOLSPEC and SOLSTICE on UARS) by up to 15% in the UV and by up to 5% in the visible part of the spectrum. This effect seems to be partially due to UV- degradation caused by extended solar exposure, partially due to air-to-vacuum effects on the instrument response function. A substantial improvement was achieved by correcting the pre-flight response function using on ground thermal vacuum measurements and in-flight measurements with the spectral line lamp. Nevertheless, further work on this area is necessary and has already been initiated. Furthermore, discontinuities in the radiance measurements were detected between channels. This effect is caused by the serial readout of the detector array diodes which results in different diodes viewing slightly different ground scenes. A simple correction procedure using sub-pixel PMD measurements has been proposed by the University of Bremen and was successfully tested on GOME data.

Concerning the level 2 ozone product (V1.20, V1.21) it was concluded that the slant column fitting works very well in the UV range. For solar zenith angles (SZA) less than 75 degrees the differences between ground validation data and GOME results were in the order of a few percent, the main problem being in the air mass factor (AMF). SZA above 75 degrees had not been considered at that stage due to the missing multiple scattering correction of the AMFs for high solar zenith angles. In the meantime, the multiple scattering correction tables have been extended up to 92 degrees solar zenith angle using a more advanced version of the radiative transfer code GOMETRAN taking into account effects caused by spherical geometry. One of the latest changes of the GDP before the operational generation of GOME ozone products (V2.0) was the selection of a more representative wavelength to calculate the AMF for the ozone UV fitting window (325-335 nm). Studies performed at the University of Bremen have shown that using 325 nm rather than the centre wavelength is a much better choice. This significantly improved the accuracy of GOME ozone values, especially for SZAs above 80 degrees.

The latest comparison of GOME Data Processor (GDP) V2.0 ozone data with ground based Dobson and Brewer measurements and the SAOZ network (Jul-Dec 1996) shows good agreement up to solar zenith angles of 70 deg (mean difference)

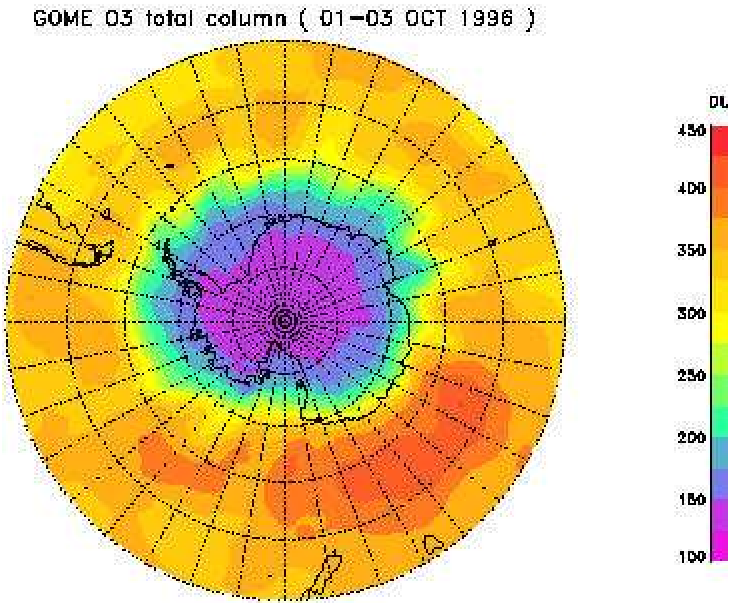

Figure 2: Total ozone column amount at the beginning of October 1996 as measured by GOME. The ozone hole, defined by ozone values below 220 DU, completely covers Antarctica.

The validation of the NO_2 total column, also part of the officially released operational GOME data products, is still in a preliminary stage. This is explained by several reasons: (i) GOME validation activities focused on ozone, the main operational level 2 data product, (ii) the number of ground based stations measuring NO_2 is rather small compared to the well established global networks of stations measuring ozone, and (iii) the significant and variable amount of tropospheric NO_2 not detected in most of the ground based measurements, which focus on monitoring the stratospheric amount. This explains, at least partially, the fact that the GOME NO_2 total columns are in general significantly higher than the ground based measurements. However, it has to be noted that the sensitivity of the NO_2 AMF with respect to the tropospheric column, especially for low albedos, presently seems to lead to an overestimation of the derived NO_2 total column. Nevertheless, important information concerning, for example, the longitudinal NO_2 variability is already contained in the NO_2 slant columns (see Figure 3). Clearly GOME is observing *tropospheric* NO_2 (as well as tropospheric SO_2, see Figure 5), which represents an important new dimension for remote sensing.

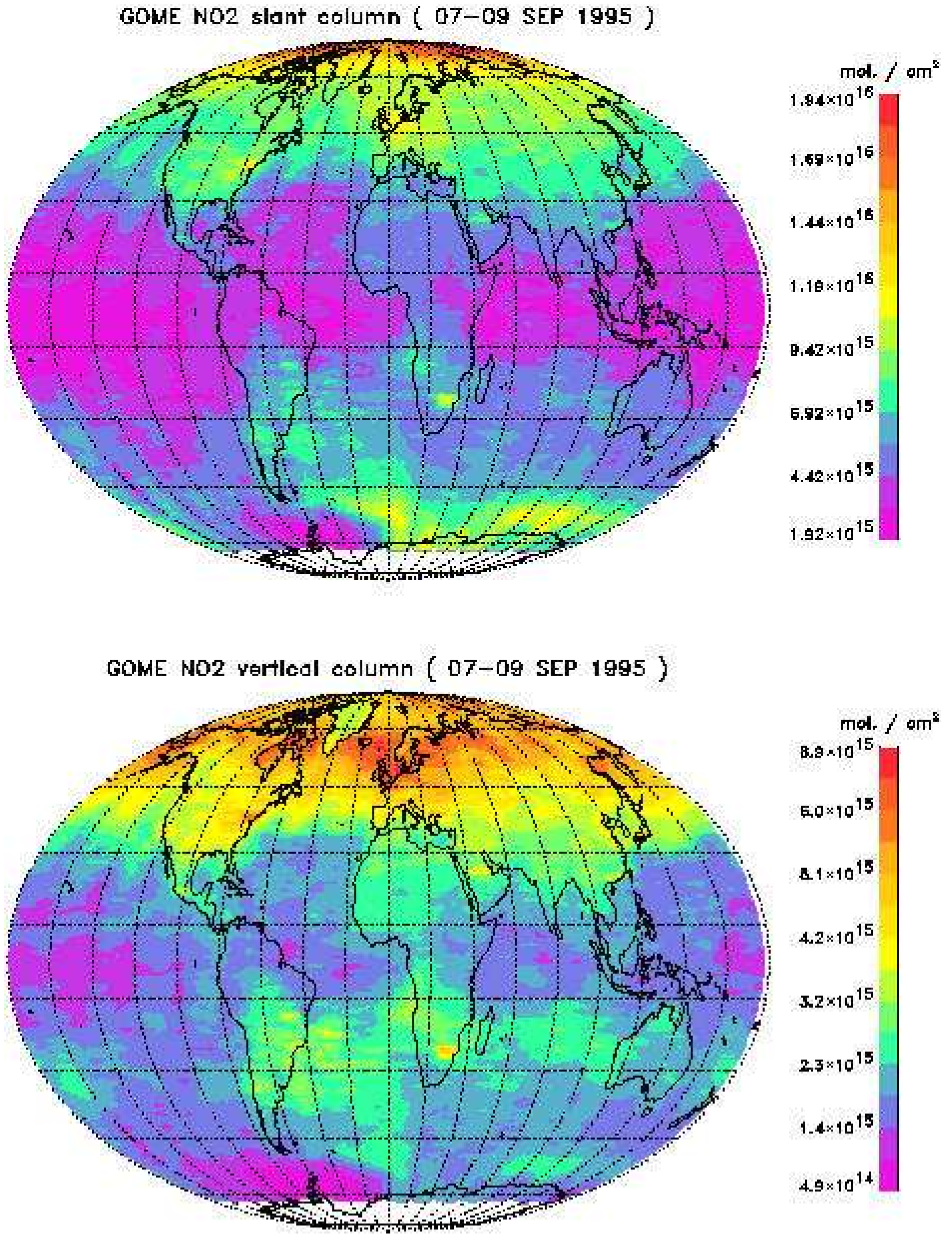

Figure 3: Global GOME NO_2 measurements (averaged): (a) NO_2 slant columns, (b) NO_2 vertical columns. Clearly visible are enhanced NO_2 concentrations over industrialised areas and in regions where significant pollution of the atmosphere results from biomass burning.

8. Non-Operational Data Products

In addition to the data products generated on a regular basis operationally from GOME, a large and growing scientific community is working successfully on algorithms to exploit the full potential of the GOME data. These activities comprise: retrieval of height resolved ozone information (see e. g. de Beek et al., this issue), retrieval of several trace constituents which also play an important role in atmospheric chemistry (like OClO, BrO, SO_2, etc., see Eisinger et al., this issue), information about clouds and aerosols, the polarisation state of the back scattered light, the monitoring of the variability of the sun (Weber et al. 1996), the analysis of the moon spectra, etc. A detailed description of these activities is outside the scope of this paper - only two examples of results obtained at the University of Bremen and at AWI, Potsdam, can be shown here (see Figures 4 and 5).

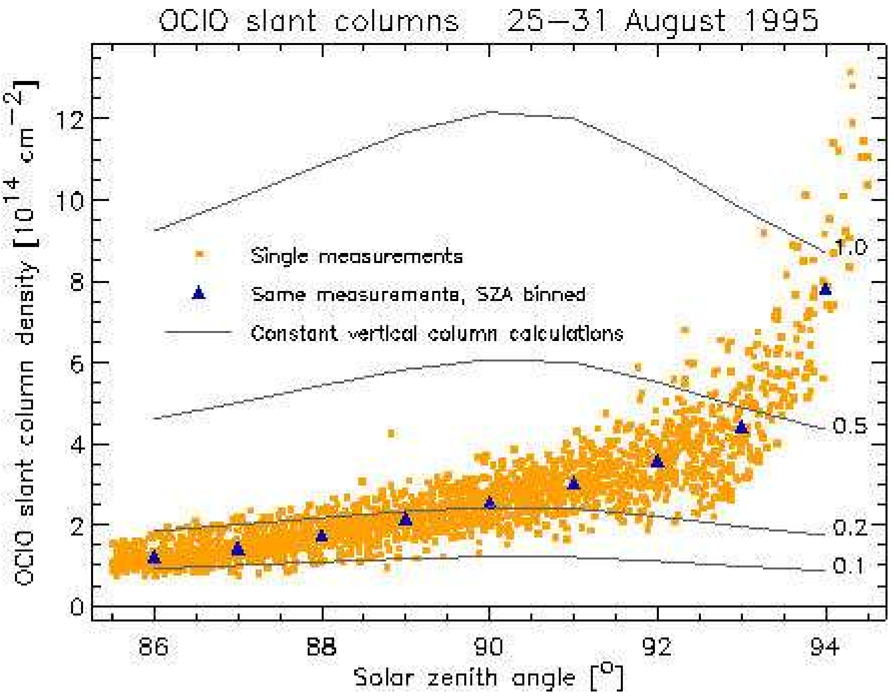

Figure 4: OClO slant columns derived from GOME measurements over Antarctica. The solid lines show slant columns that have been computed with the radiative transfer model GOMETRAN assuming different vertical columns in the model atmosphere.

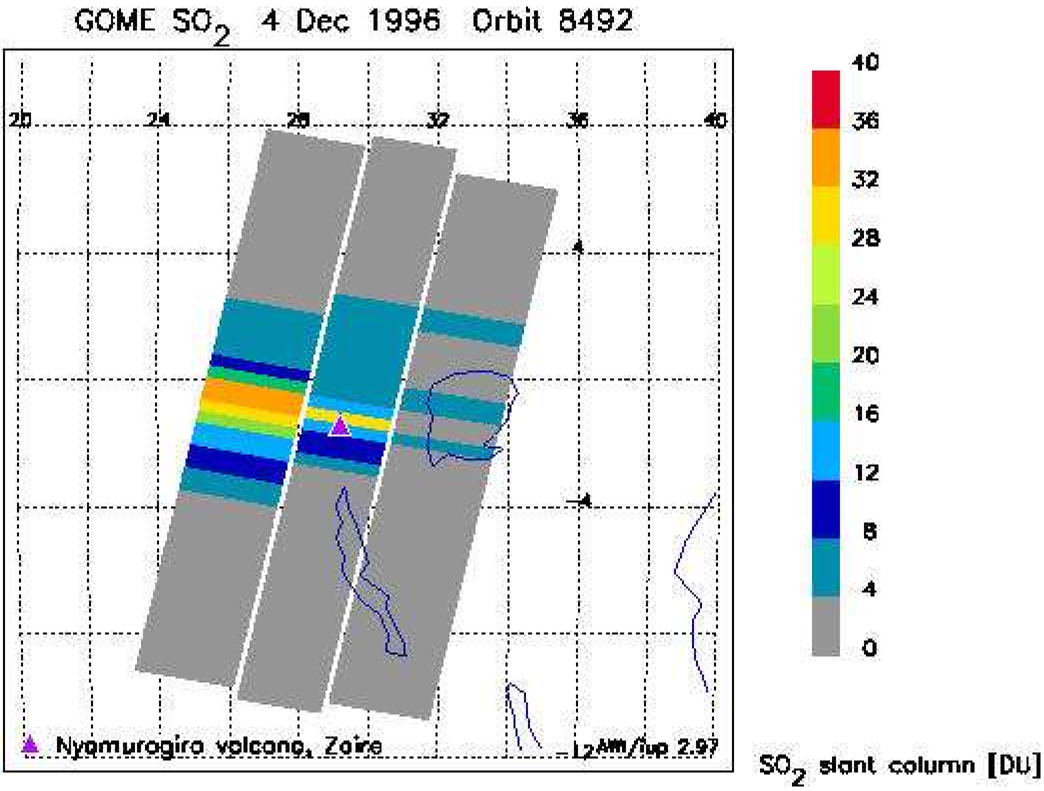

Figure 5: Preliminary GOME SO_2 measurements following the eruption of the Nyamuragira volcano, Zaire, Africa, beginning of December 1996.

9. Conclusions

In summary GOME is the first of a new generation of passive UV-visible-NIR remote sounding instruments, whose aim is to monitor atmospheric constituents. The simultaneous observation of a wide spectral region at moderate spectral resolution enables trace gases as well as aerosol, cloud and surface parameters to be retrieved from the upwelling radiance measured at the top of the atmosphere. GOME has successfully passed its initial validation phase and demonstrated its ability to provide valuable information about the state of the Earth's atmosphere. A growing scientific community is working on the development of algorithms to make full use of GOME's capacities and results achieved up to now are very encouraging. In line with the experience gained from other space sensors, continuous improvement of the quality of the data is necessary and will enable GOME to make an optimal contribution to such important and challenging issues as, for example, long-term trend analysis of atmospheric composition. The latter is a prerequisite for a better understanding of the global change issue.

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