The Global Ozone Monitoring Experiment (GOME)

Since the middle of the 1980s it became clear that in order to improve our understanding of the chemical, physical, and dynamical processes governing the behaviour of the atmosphere, global knowledge about the abundance and distributions of the important trace constituents involved in ozone chemistry is required. For relatively short-lived species, such as ozone, the only feasible method of obtaining global information about their distributions is from instrumentation aboard orbiting satellite platforms. Such knowledge is unique, essential in establishing the predictive capability of our current models of the atmosphere and complementary to the important information gathered from the network of ground-based, ship, aircraft and balloon borne measurements.

In response to this need, the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) project was initiated at the Max-Planck-Institute for Chemistry (MPIfC), Mainz, Germany, and submitted to ESA by a group of European scientists in 1988 as a candidate for flight on the European Polar Platform now known as ENVISAT (Environmental Satellite). The SCIAMACHY proposal was selected as a national German and Dutch industrially funded contribution to the ESA-ENVISAT project. At a later stage the Belgian government joined the SCIAMACHY funding consortium. In November 1988, ESA decided to launch another space-borne instrument to start long-term monitoring of atmospheric constituents four years ahead of the scheduled ENVISAT launch in 1999. A call for proposals for this instrument to be added to the second European Remote Sensing satellite (ERS-2) as the only new instrument which has not been part of the preceding ERS-1 mission was announced. A small scale version of SCIAMACHY termed SCIAmini was proposed by the SCIAMACHY scientists for this flight opportunity and ultimately selected for a feasibility study. After some modification of design to accommodate the requirements of the integration onto the ERS-2 platform, the renamed Global Ozone Monitoring Experiment (GOME) was born and approved by the ESA council in June 1990.

The limited time (1990-1993) available for the assembly of GOME prior to the launch of ERS-2 necessitated a close collaboration between scientists, the ESA-ERS-2 team and the industrial consortium, selected to build GOME. The optical design of GOME was made by this group, based upon preliminary work done at the MPIfC and the Dutch firm TPD-TNO for the SCIAMACHY project. The GOME industrial consortium, having Officine Galileo as prime contractor, included Laben (main electronics and electrical interface to ERS-2), the TPD-TNO (optical concept, calibration unit, pre-flight calibration), Dornier, Germany (thermal control subsystem), and British Aerospace (joint usage of the Along-Track Scanning Radiometer digital electronic interface). The industrial consortium was led by P. Dubock and his successor A. Hahne from ESA-ESTEC as the GOME project manager. The GOME Science Advisory Group (GSAG), headed by C. Readings (ESA, chairman) and J. P. Burrows (U. of Bremen, lead scientist), was subsequently established by ESA to advise on the GOME development. The German Space Agency (DARA) subsequently agreed to support the development of the operational GOME Data Processor (GDP) at the German Remote Sensing Data Centre of the DLR (DLR-DFD) in Oberpfaffenhofen. The DLR-DFD GDP became part of the ESA's official Data Processing and Archiving Facility (DPAF) of GOME managed by ESA/ESRIN, the latter responsible for the public delivery of the official GOME level 1 and level 2 data products. After much effort by all of the above mentioned, the GOME instrument was delivered, tested and calibrated on time. ERS-2 was launched aboard Ariane 4 from Kourou, Fr. Guyana, on April 20, 1995.

GOME Heritage and Objectives

The GOME instrument concept was developed from experience using the Differential Optical Absorption Spectroscopy (DOAS) technique for the detection of atmospheric trace gases as applied to the ground based zenith sky measurements. However it has similarities with BUV (Nimbus 4), SBUV (Nimbus 7), TOMS (Nimbus 7, Meteor-3, ADEOS and Earth Probe), SSBUV and SBUV-2 (NOAA-9,11). Like SBUV, GOME is a double monochromator, but uses diode array detector technology to observe simultaneously the extra-terrestrial solar spectrum or the up-welling earthshine radiance.

GOME is a passive remote sensing instrument for the global observation of ozone and selected atmospheric constituents. It determines its information about both stratospheric and tropospheric constituents from UV-visible and near-IR measurements of the extra-terrestrial solar output and the up-welling earthshine radiance at the top of the atmosphere (TOA).

Division of these two measurements yields an angular dependent atmospheric spectral reflectance, which contains information about the absorption and scattering properties of the earth's atmosphere and its surface. Appropriate inversion of such information enables the amounts and distributions of those constituents to be retrieved.

The potential constituents which might be measured by GOME can be separated into those which have a major or minor impact on the radiative transfer of light through the atmosphere. A major impact is made by absorption of O_3 in the Hartley and Huggins bands, O_2 and H_2O, aerosol scattering, and surface reflectivity, whereas a relatively minor impact is made by the absorption by O_3 in the Chappuis bands, NO_2, BrO, OClO and H_2CO (formaldehyde), and SO_2. The molecular species observed within the spectral range covered by GOME are listed in Table 1.

The GOME Instrument

A schematic diagram of the GOME instrument is shown in figure 1. It comprises a scan mirror system, a calibration unit, and a spectrometer. Light backscattered from the Earth or light (solar irradiance, lamp spectra) from the calibration unit is collected by the scan mirror and reflected towards an off-axis parabolic mirror which focuses light onto the entrance slit of GOME's spectrometer.

Wavelenhth coverage/ spectral resolution:	Channel 1: 240-316 nm/0.20 nm Channel 2: 311-405 nm/0.17 nm Channel 3: 405-611 nm 0.29 nm Channel 4: 595-793 nm/0.33 nm
Dispersive elements:	prism (predisperser) and 4 holographic gratings
Detectors:	4 Reticon Si diode linear arrays (1024 pixel each channel) 3 broadband Polarization Monitoring Devices (295-397 nm, 397-580 nm, 580-745 nm)
Field of view (FOV):	2,9° x 0.143°
Viewing mode:	• Nadir (acros track scan angle max. ± 31°) • Polar (static scan angle at 45°) • Solar (with diffuser plate) • Lunar (scan angle 75-85°) • Pt/Ne/Cr lamp: - with diffuser plate (monotoring optical degradation) - direct (wavelengt calibration) • Telescope (dark current)
ERS-2 orbital parameter:	near polar (98.49 deg. inclination), sun-syncronous (10:30 UTC mean equator crossing time), 100 min period, 785 km mean altitude
Measurement techniques:	DOAS (trace gas), profile retrieval (03) cloud and aerosol retrieval, surface and TOA reflectivity, 11 yr solar cycle variability
Major trace gases:	O_2, O_4, O_3, NO_2, H_2O
Minor trace gases:	ClO, BrO, OClO, SO_2, NO_3, H_2CO

Table 1

After entering the spectrometer, light is collimated and directed towards a prism which forms two spectra. The first is obtained from an internal reflection in the prism at the Brewster angle and is therefore polarised at an instrument defined orientation. This minor beam directed towards the polarisation monitoring devices (PMDs), which consists of an array containing three fast broadband Si detectors which measure the light in three bands between 300 and 800 nm, which roughly correspond to the wavelength range covered by the three long-wave spectral channels (see Table 1). The main beam leaves the prism and is then directed and split to the four spectral channels of GOME using a band separator prism, reflective and transmissive optics, and four holographic gratings as secondary dispersive elements. A lens configuration in each spectral channel produces a flat focused image in the focal plane of the instrument, where light is detected by monolithic self scanning linear silicon photodiode array detectors having 1024 detector pixels. In this manner light between 240 and 790 nm is simultaneously detected at a spectral resolution of approximately 0.2 nm or 0.4 nm respectively for the regions 240-400 nm and 600-800 nm.

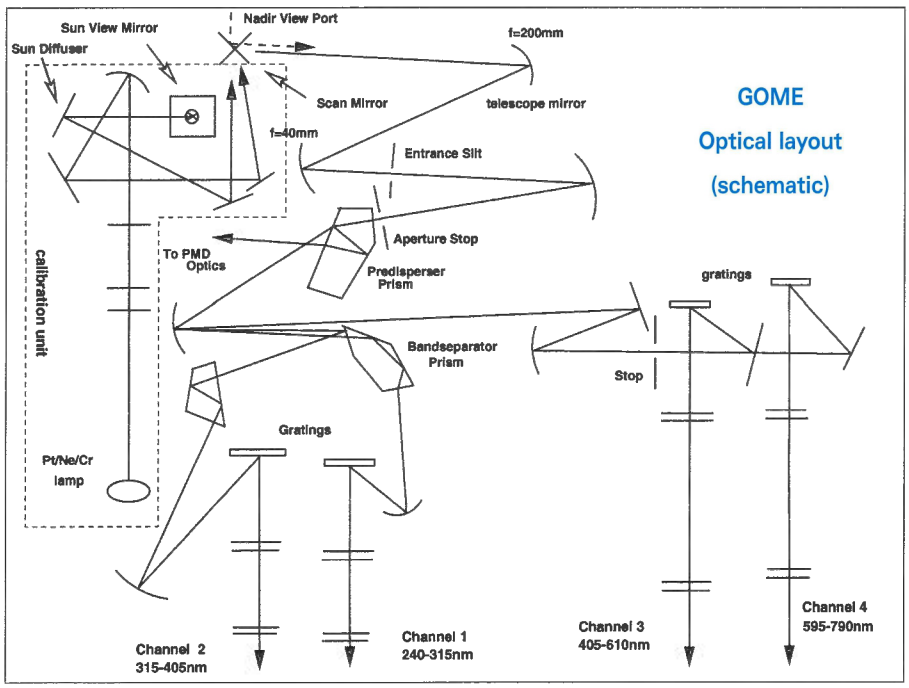

Figure 1 - Schematic instrumental set up of GOME. The GOME instrument is a double monochromator with four spectral channels. Attached to the spectrometer is a calibration unit housing a Pt/Cr/Ne hollow cathode discharge lamp and the fore optics for solar viewing. Not shown is an additional mirror which directs the lamp light to the solar diffuser plate for diffuser reflectivity monitoring.

In order to optimise the signal to noise ratio, part of the detector array in channel 1 of GOME (band 1A) are read out more slowly than those of band 1b and channels 2 to 4. However the PMD devices are read out 16 times faster than the channel 2 to 4. The combined PMD and array detector measurements yield information about the polarisation of the incoming light and enable the instrument polarisation response to be accounted for. In addition the PMDs may provide information about cloud cover and the top of atmosphere (TOA) albedo at a higher spatial resolution than the spectral data.

The GOME calibration unit houses a Pt-Cr-Ne hollow cathode emission lamp and a diffuser plate. The former is used to spectrally calibrate the GOME spectra; the latter enables the direct observation of the sun. Degradation of the diffuser plate due to extended exposure to the harmful UV radiation in space is monitored using the line lamp. Finally at various times of the year observations of the moon above the atmosphere are made. Combining the observations of the line source, the solar and lunar spectral measurements and the pre-flight characterisation measurements permits a periodic update of the in-flight radiometric calibration of GOME.

GOME observes the atmosphere in nadir viewing geometry and the light collection mirror scans typically ±32° in 4.5 sec in across-track direction followed by an 1.5 sec back-scan. Channels 1b to 4 are read out typically every 1.5 sec, channel 1A is read every 12 sec, and the PMDs every 93 ms.

The ERS-2 satellite follows a near polar sun-synchronous orbit with a mean equator crossing in a descending node of 10.30 a.m. local time. An orbit takes approximately 100 minutes and in one day 14 orbits are completed. The maximum scan angle of 32° results in global coverage every three days at the equator, every two days above 50°, and every day above 65°. The various observation modes of GOME are summarised in Table 1.

After launch GOME was not switched on until after about a month when it had thoroughly been outgassed. In its first month of life, the functional performance of GOME was tested. Routine measurements began in July 1995. For the period between July 1995 and March 1996 a provisional read out strategy was used whereby only the last quarter of the 1.5 sec data stream for channel 1b to 4 was down-linked to avoid saturation of the diode arrays. Since March 1996, the spectra have been co-added for the full 1.5 sec.

GOME Operational Data Products

The data products developed within the GDP at DLR-DFD Oberpfaffenhofen comprise the so-called Level 1 (backscattered earthshine spectra and solar irradiance) and Level 2 (total columns of O_3 and NO_2, fractional cloud cover) products. During operational level 0 to 1 processing GOME signals are converted to the geo-located radiances or solar irradiance. In level 1 to 2 processing the radiance and irradiance data are used to retrieve information about atmospheric constituents using the DOAS technique. The algorithms used in the operational GDP has been developed by scientists from the Universities of Bremen (J. P. Burrows) and Heidelberg (U. Platt), the Smithsonian Astrophysical Observatory (K. Chance), Royal Dutch Meteorological Institute, KNMI, (P. Stammes), and the DLR-DFD (W. Balzer).

One of the major activities during the commissioning phase (July 1995-June 1996), following the launch of GOME, was the validation of the total ozone and NO_2 products with the network of global ground-based measurements. In addition to the groups just mentioned in the algorithm development, the Institut d'Aéronomie Spatiale de Belgique (IASB) (P. Simon) and KNMI (H. Kelder) were actively involved in the validation efforts. Following the recommendations from the Final Geophysical Validation Workshop in Frascati, Italy, January 24-26, 1996, further improvements in the data quality of the level 1 and level 2 data products were achieved.

GOME Results

Many research groups in Europe and USA are working on the scientific exploitation of the global spectral data sets from GOME. A few highlights shall be given here and the reader should forgive that the GOME science presented here is weighted towards the work done at the University of Bremen. It shall not diminish the valuable contribution from other scientific groups mentioned earlier.

Total Ozone and NO_2

The dramatic development of the Antarctic ozone hole between September and December 1996, shown as monthly means, can be observed in figure 2. In September 1996, the ozone hole extended to an area of about 20x106 km², which is nearly the size of the North American continent and similar in magnitude to the previous records observed between 1992 and 1995. By December the ozone levels almost recovered to normal levels. In the bottom of figure 2 a similar dramatic decrease of ozone is observed during the arctic spring in early April 1997, after an unusual late cold stratospheric period, where the minimum temperature in the polar vortex at the 475K potential temperature surface (ca. 19 km height) went slightly below the PSC I threshold of 195K. Although the lowest value of the total ozone reached during the first days in April did not go below 250 DU, which is almost a factor of two higher than the minimum observed during the Antarctic spring, the ozone gradient observed from the area outside the vortex to within is on the order of 150 DU, which amounts to nearly a 40% loss of ozone. The percentage is about the same by comparing the monthly means from March 1979-1982 observed by TOMS to the monthly mean in March 1997. It is interesting to note that during the same time in middle Europe the ozone levels also dropped to values near 250 DU during the first days in April 1997. The latter phenomena is probably of dynamical and meteorological origin since a high pressure system moved across Europe during that time and was separated from the vortex by an ozone ridge.

Considerable reduction in NO_2 columns up to 60% can be observed within the polar vortex in the Arctic region in early April 1997 (figure 3, top). Several explanations for the mechanism of the NO_2 loss are possible, of which i) the heterogeneous reaction $N_2O_5(g)+H_2O(s)\rightarrow 2HNO_3(s)$, removing the daytime reservoir of NO_2, ii) the gas-phase reaction $NO_2+OH+M\rightarrow HNO_2+M$, requiring sunlight (as in April) to produce sufficient OH radicals and low temperatures, and iii) the temperature dependence of the N_2O_5 photolysis, causing a slowdown of NO_2 formation at lower temperatures, may be the most relevant ones. Further studies using the global data retrieved from GOME, including the minor trace gases BrO, OClO, and ClO, and considering the particular dynamics of the vortex may shed some more light in the chemical pathways leading to the observed ozone and NO_2 loss inside the vortex. It is also possible that dynamical aspects may explain the observed ozone loss. In figure 3 (bottom) enhanced tropospheric emission of NO_2 is observed in the Northeast of the USA, the industrial area around the metropolitan area of Sao Paulo and Rio de Janeiro in South America, and in Middle Europe.

Ozone Vertical Profiles

In the wing of the Huggins band of ozone below 320 nm ozone absorption increases exponentially with decreasing wavelength. At the same time the scattering height increases, which provides important information of the ozone column density as a function of height. The use of an inversion scheme to derive height resolved ozone information from the radiance measured at the top of atmosphere (TOA) using a nadir viewing space instrument has been successfully demonstrated with the series of SBUV (Solar Backscatter UV) and SBUV/2 sensors operating in the UV/visible spectral range. A similar BUV technique, called FURM (FUll Retrieval Method), has been optimised for the GOME retrieval to obtain a global 3D ozone distribution. This work is done in collaboration with the Rutherford Appleton Laboratory.

OClO over Antarctica (minor stratospheric trace gases)

Measured slant column of OClO as a function of solar zenith angle were observed by GOME during the Antarctic spring 1995 as shown in

figure 4. Since for high solar zenith angles between 86° and 94° the air-mass factor (AMF) remains nearly constant, it can be safely assumed that the vertical column similarly increases with SZA. This SZA dependence of the column amount is a measure of the diurnal variation of OClO related to the rapid photolysis assuming a similar variation of vertical and slant columns at high SZA. Similarly, the higher the solar zenith angle in August, the closer the chlorine dioxide measurements move towards the polar vortex centre, where enhanced local OClO production may occur. Between July and middle September enhanced OClO diurnal variation can be observed, while starting in October the OClO levels fall off near or below the detection limit. At low ClOx background levels, OClO correlates well with ClO, however, above a certain threshold OClO becomes a rather poor indicator of the ClO levels. Nevertheless, the measurements presented support the indicator role of OClO distinguishing between low (background) and medium/high (disturbed) ClO cases, switching to high levels once ClO concentrations exceed a certain threshold.

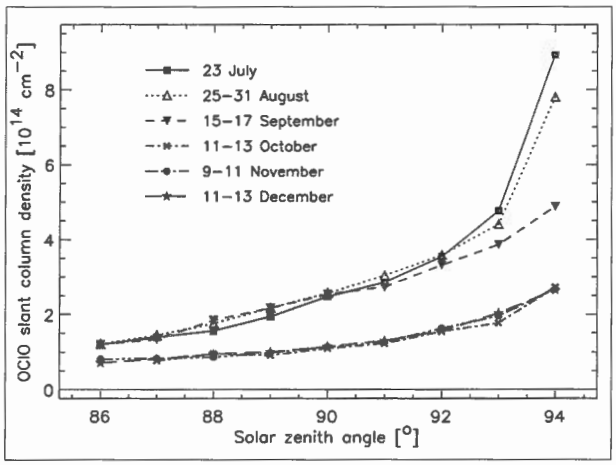

Figure 4 - Antarctic OClO diurnal profiles from July to December 1995. Measurements have been binned into 1° steps and averaged. The detection limit of OClO is reached at a slant column of about 1x10^{14} cm^{-2}.

Volcanic SO_2 (tropospheric trace gases)

Sulphur dioxide released from volcanic eruptions can then be oxidised and combines with water to form stratospheric sulphate aerosols. Heterogeneous reactions on aerosols can affect global ozone chemistry and alter the radiation budget.

GOME observed SO_2 from an eruption of the Nyamuragira volcano in the Democratic Republic of Congo (former Zaire), a shield volcano near the border of Rwanda. The eruptions started on December 1, 1996, and four days later the plume reached an altitude of 12 km, which is still well below the tropopause at tropical latitudes. Figure 5 displays SO_2 slant columns derived from the GOME radiances during the twelve days following the first reported eruption. In order to visualise the extent of the volcanic SO_2 plume, three day composites of observed GOME orbits giving full surface coverage in the region around the volcano are shown. A rough estimate of the total column amount can be obtained by dividing the measured slant column by a factor of two.

The maximum SO_2 slant column of 54.7 DU was observed on the first day of the eruptions on December 1, 1996. On this day a SO_2 cloud was already observed stretching up to 2000 km westwards (10° E) from Nyamuragira, which may be explained by early SO_2 emissions normally expected to precede the major eruptions. Most of the SO_2 emission was transported to the west, which is consistent with mean wind directions in Nairobi and Bangui observed in December 1981 at 10 km altitude. Adding up all the contribution of SO_2 within a given three day period leads to an estimated lower limit of a few hundred kilotons for the December 1996 eruption, which is much lower than the 3Mt observed by the TOMS (Total Ozone Monitoring Experiment) in the December 1981 eruption.

Clouds

The absorption in the O_2 A-band is currently used to estimate the fractional cloud cover observed within a GOME ground pixel. Depending on the fractional cloud cover a correction to the total columns of O_3 and NO_2 for the missing column below the cloud is applied. Advanced cloud detection algorithms will also make use of the three PMDs, which can be associated to the basic colours blue (PMD1: 295-397 nm), green (PMD2: 397-580 nm), and red (PMD3: 580-749 nm) and colour-mixed to produce a true colour image of the earth as seen in figure 6. Each PMD covers a surface of 40x20 km^2 and allows the investigation of partially cloud cover and surface reflectivity at a high spatial resolution. The goal of the advanced cloud algorithm is to combine the information provided by the PMDs, spectral information from the O_2 and O_4 absorption to derive in addition to the fractional cloud cover, optical depth and/or cloud top pressure.

The series of new European UV/visible remote sensing instruments, starting with GOME/ERS-2, SCIAMACHY/ENVISAT (launch in 1999) and the second generation GOME on the European operational meteorological satellite METOP (launch in 2002) will provide the necessary long-term continuity in global atmospheric measurements and monitoring and will be a valuable complement to the US Mission to Planet Earth (MTPE) programme. For further details on the GOME project and science, interested readers may check the WWW-pages at http://www-iup.physik.uni-bremen.de/ifepage/gome.html.

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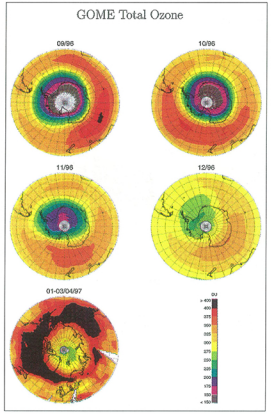
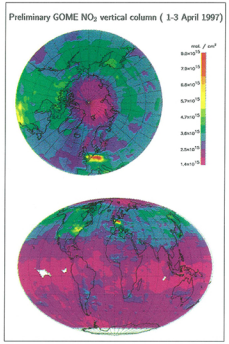
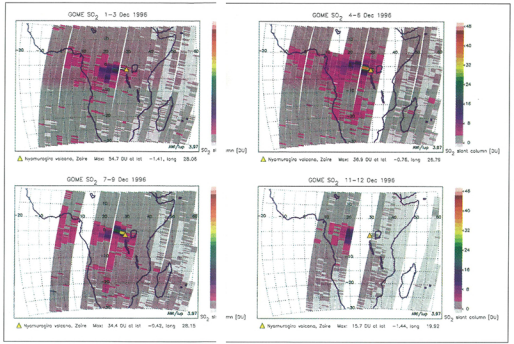
The Global Ozone Monit ring Experiment (GOME)





◀ **Figure 2**
Global ozone measured by GOME. Top and Middle: Evolution of the Antarctic ozone hole between September 1996 and December 1996. Ozone values are calculated monthly means. Bottom: Three day composite ozone distribution from 1-3 April 1997 indicating an ozone loss of up to about 40% inside the polar vortex.



▲ **Figure 3**
Global GOME NO_2 measurements averaged over the three day period between April 1 and April 3, 1997: NO_2 vertical column in the arctic polar region (top) and in the equatorial region (bottom).

▲ **Figure 6**
RGB image produced from the PMD measurements.

▲ **Figure 5**
Plume evolution of the volcanic eruption of the Nyamuragira volcano in the Democratic Republic of Congo (former Zaire) starting on December 1, 1996, based on SO_2 detection by GOME.