Global Ozone Monitoring Experiment

Interim Science Report

GOME01

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G O M E

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CONTENTS

FOREWORD

The Origins of GOME

Ozone, although a minor constituent of the atmosphere, is a very important atmospheric gas because changes in its amount and distribution in the stratosphere and troposphere:

— control the amounts of biologically harmful ultraviolet radiation reaching the surface of the Earth, and

— contribute to the radiative balance of the atmosphere and hence to the so-called 'greenhouse effect'.

There is therefore a clear need to monitor the abundance and distribution of ozone and to study the processes that control its production, destruction and distribution.

It was this need that led to the proposal that consideration should be given to the addition of an ozone instrument to the payload of the ERS-2 satellite, namely the GOME (Global Ozone Monitoring Experiment), a passive instrument intended to monitor absorption by trace gases in the solar spectrum. From these data the distribution of ozone and some other important atmospheric constituents will be derived. The GOME has the potential to monitor ozone in both the troposphere and the stratosphere.

The GOME is a simplified version of SCIAMACHY, which has been selected to fly as part of ESA's first Polar Platform Mission as an Announcement-of-Opportunity instrument (*Burrow et al. 1988*).

The Aims of the Report

To obtain final confidence in the scientific validity of the GOME for its inclusion in the ERS-2 mission, the Agency, in addition to carrying out a technical feasibility study, asked a group of scientists to review the scientific objectives and capabilities of the GOME. This is their report.

The report covers not only the scientific rationale and objectives underlying the GOME but also assesses its actual capabilities with annexes containing summaries of some of the calculations underlying this assessment. This report includes consideration of topics such as calibration and data processing as well as reviewing other experiments (intended to study the chemical composition of the atmosphere) which are planned to fly before the end of the century. This serves to set the GOME into the overall context of atmospheric chemistry studies.

This report has been prepared by the members of the GOME Scientific Advisory Group. Amongst the scientists who have assisted were :

- Professor J. P. Burrows (Germany)
- Dr K. V. Chance (USA)
- Dr A. P. H. Goede (Netherlands)
- Professor R. Guzzi (Italy)
- Dr B. J. Kerridge (UK)
- Dr C. Müller (Belgium)
- Dr D. Perner (Germany)
- Professor U. Platt (Germany)
- Dr J.-P. Pommereau (France)
- Dr W. Schneider (Germany)
- Dr R. J. Spurr (Germany)
- Dr H. van der Woerd (The Netherlands).

The Agency would like to acknowledge its indebtedness to all of them for their efforts.

EXECUTIVE SUMMARY

In recent years it has become increasingly apparent that the chemical composition of the atmosphere is changing on a global scale; there is strong evidence to suggest that human activity on the planet is partly responsible for this change. Ozone plays a central role in tropospheric and stratospheric chemistry. It is largely responsible for stratospheric heating through the absorption of biologically harmful ultraviolet radiation (below 330 nm), it determines to a large extent the oxidative capacity of the troposphere, and it is an important 'greenhouse' gas. Issues such as the springtime ozone hole observed over the Antarctic stratosphere and potential global climate warming, have helped to focus world wide attention on global atmospheric change.

There is a clear need to increase our understanding of the central processes involved in atmospheric chemistry, and it is vitally important to monitor and investigate global budgets of ozone and other chemically important trace gases. Ground-based observations provide only a limited picture of the distribution of these gases, and satellite measurements are required for global concentrations.

Following the adoption by ESA of a long-term Earth observation programme in 1987, a passive spectrometer instrument (SCIAMACHY – SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) was proposed for the 1998 ESA Polar Orbiting Platform (*Burrows et al. 1988*). The GOME (Global Ozone Monitoring Experiment) instrument is a scaled down version of SCIAMACHY; it is intended for inclusion on the ERS-2 satellite due for launch in 1994. The present document is a detailed scientific report on the GOME project.

The introductory chapter describes the scientific rationale behind GOME. The main function of the instrument is to obtain global measurements of total column amounts of ozone. GOME will also be able to measure column amounts of a variety of trace gases. Other special functions include the derivation of stratospheric and tropospheric ozone profiles, and the investigation of absorptions of selected trace gases in special circumstances (high pollution troposphere events, the ozone hole, etc.). In order to place the GOME project within the context of atmospheric field research, a brief summary of previous and current satellite and ground-based observations is presented.

The second chapter deals with the capability of the GOME instrument. The GOME detectors are arrays of photodiodes, and the spectral resolution is fairly high (0.2-0.4 nm) over a range of 240-790 nm, divided into four channels. The instrument's spatial resolution varies from approximately 40×40 km2 (smallest pixel size) to 40×320 km^2. GOME uses a moving mirror mechanism to scan across the satellite track (typically, three detector pixel readouts per scan). The along-track satellite velocity is approximately 7.5 km/s, and with a polar orbiting period of 100 minutes, global coverage can be achieved in three days with the largest pixel size. The instrument is designed to operate in the nadir viewing mode. The chapter continues with a catalogue of the GOME observations expected for each target trace gas, and some remarks on the measurement of extinction and scattering data for tropospheric and stratospheric aerosols. Variable height clouds and sub-pixel cloud cover present problems of data interpretation; however the ATSR-2 instrument (also planned for the ERS-2 mission) might provide additional information on pixel cloud discrimination. There is a possibility of a 'synergism' between the two instruments.

GOME mainly uses the DOAS (differential optical absorption spectroscopy) technique to observe scattered atmospheric radiation from the Sun. A single species spectrum is carefully aligned with a reference attenuation-free solar spectrum. The two spectra are then ratioed, and spectral features due to solar Fraunhoffer lines, atmospheric scattering and terrestrial features are filtered out; the resultant differential attenuation spectrum contains the desired narrow trace gas signatures. The DOAS approach has been used with great success in the measurement of trace gas spectra from ground-based, balloon- and aircraft-borne instruments. The GOME will be the first space-borne instrument to fully exploit this technique. In addition, ozone profiles can be determined from the inversion of backscattered ultraviolet intensities (the BUV approach). This was developed for the TOMS/SBUV instruments, and GOME will therefore be able to provide continuity with the successful global ozone monitoring experiments of the 1980's.

Chapter 3 deals with data retrieval. In the DOAS method the determination of slant column amounts of target gases is from least squares fitting between the observed differential absorption spectrum and a laboratory reference spectrum. Overhead columns are then inferred from theoretical

knowledge of : a) atmospheric scattering as a function of wavelength and zenith angle; b) vertical profile shape; and c) photochemically induced variations along the optical path.

Total vertical column amounts can only be retrieved above a certain scattering or reflecting altitude; this depends on the wavelength of the radiation and the solar zenith angle. This means that GOME will be most effective for stratospheric measurements at high latitudes, whereas at mid- and low-latitudes, important tropospheric observations can also be made. Determination of the base height for total column measurements using near-ultraviolet and visible wavelengths is achieved principally from the analysis of absorption features of O_2 and O_4. Scientific studies are necessary to evaluate the effectiveness of retrieval methods. This typically involves modelling the radiative transfer process in the atmosphere, and testing the sensitivity of column amounts to assumed trace gas profile shapes, aerosol/cloud distributions and multiple scattering regimes. Many more investigations are possible, and a summary of on-going sensitivity studies is given in Annex 2.

Calibration and verification of GOME is vital to the effective performance and ultimately the scientific output of the instrument (Chapter 4). Accurate radiance data must be correctly calibrated against a radiometric source, both before launch and during operation. Pre-launch radiometric calibration requires the construction of a functional bread-board to simulate actual observation, a laboratory comparison with the flight model instrument response, and a final check of the payload just prior to launch. During flight, calibration can be performed either with an internal lamp or with an external source (sun or moon).

One of the advantages of the DOAS technique (over the traditional BUV approach) is that it does not depend on the radiometric stability of a diffuser plate (its bi-directional reflectance distribution function is used to convert an irradiance source into a radiance source for the instrument). However it does require accurate wavelength calibration and this can be obtained from a good instrumental extra-terrestrial solar spectrum. Clearly, it is important to have the best calibration strategy, and several options will be discussed and evaluated. It is also necessary to check the quality of data during operation (validation), and for this, campaigns are needed to correlate data from ground-based and aircraft/balloon-borne instrumentation with simultaneous observations from GOME.

During operation, GOME will produce a continuous stream of data, and it is important to have an effective and efficient data system (Chapter 5). Data will be organised into five levels of data products: from levels 0 and 1 (raw telemetry and calibrated pixel data, respectively), level 2 (geophysical parameters), to levels 3 and 4 (concentration maps). All GOME data will have to be archived, and the data system must be able to process and store large volumes of data in real time. It must also provide easy access for all users of GOME products, and long-term storage will be necessary for climate studies.

In conclusion, it is clear that GOME will make an important contribution to the global monitoring of the atmosphere. It provides a unique opportunity for the European science community to increase our knowledge of the atmosphere, and to enhance our understanding of its physical and chemical behaviour.

1. INTRODUCTION

1.1 The Role of Ozone

The atmosphere, land and sea form a coupled system in which physical, chemical and biological processes all take place. In the troposphere and middle atmosphere, the most important biochemical cycles essential to life occur. The middle atmosphere is coupled with the underlying and overlying atmospheric regions through the exchange of momentum, energy and chemical constituents. It is also the place in which radiative, photochemical and dynamical processes are closely linked.

Ozone is continuously formed and destroyed in the atmosphere and at any point its concentration reflects the dynamic balance between these two processes. The majority of the atmospheric burden of ozone resides in the stratosphere where its abundance is controlled by a variety of catalytic chemical cycles involving NOx (NO and NO_2), ClO_x (Cl and ClO) and HO_x (H, OH and HO_2) species.

In the stratosphere, increased levels of NO_x, ClO_x or BrO_x (Br and BrO), which arise from increasing emissions of their tropospheric source gases (e.g. N_2O, CFCs and halons), lead via a variety of catalytic destruction cycles to an enhanced rate of removal of ozone. In addition, during the polar winter and spring, the formation of polar stratospheric clouds (PSCs) leads to the removal of oxides of nitrogen and simultaneously provides the surface required for the heterogeneous production of photochemically labile chlorine species. The resultant reactions of these gases lead to a decrease in ozone over Antarctica in the austral spring, commonly known as the 'ozone hole' (Fig. 1.1).

In the troposphere ozone plays a variety of important roles. There are two known sources of tropospheric ozone: transport from the stratosphere and photochemically induced production. Dependent on the composition of the local air mass, in particular the amount of NO_x, ozone can either be produced or removed from the troposphere. Ozone oxidises a variety of hydrocarbons but more importantly the tropospheric photolysis of ozone results in the formation of the hydroxyl radical. This is the most important tropospheric oxidising agent. The amount of tropospheric ozone is therefore a good indicator of the photochemical state of an air mass.

Over the last few decades man's activities have directly and indirectly influenced the chemical processes that occur in the atmosphere and there is now evidence that the chemical composition of the troposphere and middle atmosphere is changing on a global scale. The concentrations of CO_2, CH_4 and N_2O are currently increasing at rates ranging from 0.2% to 5.0% per year. Those of CFC-11 and the halons are increasing at an even faster rate.

These changes, in part, reflect the natural metabolism of the biosphere and in part a broad range of human activities, industrial and agricultural (including biomass burning).

As there is already much concern about present and future perturbations in the composition of the Earth's atmosphere and associated changes in climate, there is a need to investigate the fundamental mechanisms which control the physical and chemical processes in the troposphere and middle atmosphere.

1.2 The State of Knowledge

To understand the elementary processes which determine the physical and chemical behaviour of the atmosphere, detailed measurements of the amount and distribution of trace atmospheric constituents are required. In addition to monitoring ozone itself, it is necessary to measure the concentrations of other trace gases and understand their role in regulating the photochemistry of ozone. Concentrations of these gases, present only in parts per billion (e.g. NO_x), control the abundance of ozone (concentrations of the order of parts per million). In order to have complete datasets, integrated and complementary measurements must be made using instrumentation on the ground, on ships, on aircraft and on satellites.

Using measurements from ground-based and satellite-based instruments, ozone trends have been analysed from 1964 to the present. The results of these analyses are reported in the International Ozone Trends Panel Report (*R.T. Watson et al. 1988*).

Analysis of data from the ground-based Dobson instrument network, over the period from 1969 to 1986, after allowing for any effects due to solar cycles or the Quasi Biennial Oscillation (QBO), show that the decrease in the total column amount of ozone in the northern hemisphere lies in the range 1.7% to 3.0%. During the winter season the decrease is more pronounced, ranging from 2.3% to 6.2%. The most recent analysis of the TOMS data, covering the eleven-year period from November 1978 to November 1989, shows a global average total ozone decrease of 2.9% ±1.3% (*Herman et al. 1990*).

On the other hand, the global trends in the vertical distribution of ozone, obtained from satellite analysis of data from the Stratospheric Aerosol & Gas Experiment (SAGE), show an average decrease of ozone at 40 km of about 3%. In the same period ground-based instruments (Umkehr) show a decrease in concentration of 9% at the same altitude (*Herman et al. 1990*). These values agree within the range of their errors but leave a large band of uncertainty.

An intercomparison of ozone trend measurements with simulation models shows a large discrepancy. Furthermore, accurate data are needed to analyse and resolve this dilemma. Ground-based measurements alone are not sufficient, being too limited in scope. In fact, space-based measurements of atmospheric constituents are essential as they generate global distributions of the abundances of many of the important species. Only measurements made from space can provide a global view of the gaseous envelope surrounding the Earth.

Although a number of tropospheric pollutants such as CO_2, CFC-11, CFC-12 and N_2O can be monitored adequately by ground stations (they are uniformly mixed in the troposphere) many others with a shorter photochemical lifetime cannot. This is because their global distributions are affected by the local pattern of sources and sinks and by meteorology. For these gases, which include O_3, satellite measurements are needed to investigate their budgets and to monitor global trends.

In general, the instruments used up to now in space to monitor atmospheric gases have been conventional spectrometers whose spatial sampling can be controlled by imaging the entrance slit using either 'push-broom' scanning to view down through the atmosphere or else fixed, limb viewing scanning which provides altitude profiles at high resolution. The most significant previous, current and planned missions are summarised in the following paragraphs.

1.3 Previous and Established Missions

US Programme

The American scientific community benefits from approximately 20 years of experience in the application of satellite instrumentation to the study of atmospheric chemistry. The most pre-eminent instruments are listed below:
(a) BUV (Backscatter Ultraviolet) flew on Nimbus-4 (1970) and was the forerunner of the SBUV and TOMS instruments. It measured ozone by observing back scattered ultraviolet radiation.
(b) LRIR (Limb Radiance Inversion Radiometer) flew on Nimbus-6. It measured ozone between 10 km and 60 km by monitoring broad-band infrared emissions. It was the forerunner of LIMS.
(c) Nimbus-7 (1978 to present), a satellite flying with five instruments in polar orbit providing global coverage:
   (i) TOMS (Total Ozone Mapping System) measures total column ozone in nadir employing six ultraviolet channels and an across-track scanning mirror ($\pm 51°$). Figure 1.1 shows examples of ozone maps produced from TOMS data. In Fig. 1.1b, four days in (austral) spring 1989 are compared to show the 1989 ozone hole progression; in Fig. 1.1a, October monthly means for ten years give an indication of long-term trends in the ozone hole.

   (ii) SBUV (Solar Backscatter Ultraviolet), a nadir viewing instrument with 12 channels between 255 nm and 340 nm, measures stratospheric ozone profiles and total column amounts. Both SBUV and TOMS measure backscattered solar ultraviolet radiation and have operated continuously up to now. Unfortunately, absolute radiometric calibration is affected by the degradation (blackening) of the diffuser plate with time, yielding unreliable trend measurements. However, recent advances in the processing algorithm used to calculate ozone from the TOMS data are less affected by diffuser plate drift and appear to produce much more dependable results.
   (iii) LIMS (Limb Infrared Monitor of the Stratosphere) measured O_3, H_2O, HNO_3 and NO_2 in thermal emission. The lifetime of this 6-channel radiometer was limited to six months by the methane-cooled detector.
   (iv) SAMS (Stratospheric and Mesospheric Sounder) measured CH_4, N_2O and H_2O by using a limb sounding pressure-modulated radiometer employing interference filters in the 7-200 micron region. During four years of successful operation (1978-1982) it provided gas profiles between 28 and 58 km with 8 km resolution. This instrument was made by the University of Oxford in the UK.
   (v) SAM-II (Stratospheric Aerosol Measurement) is designed to provide extinction measurements (at 1 micron) of stratospheric aerosol in polar regions with a vertical resolution of 1 km. (*McCormick et al. 1979*).
(d) SME (Solar Mesospheric Explorer, 1983) contained limb scanning instruments for the measurement of O_3(50-90 km) and NO_2(20-40 km).
(e) SAGE-I (Stratospheric Aerosol and Gas Experiment) launched on the Atmospheric Explorer Mission, AEM-2 (1979-1981), views in the limb and has measured O_3, NO_2 and aerosols. SAGE contains a spectrometer which measures during solar occultation in four different wavebands (lying in the 0.38 micron - 1.00 micron range). The use of this technique, which requires a relative calibration only to measure optical densities, makes the SAGE one of the most important instruments for the measurement of O_3 profiles. The method is limited by sampling (i.e. only certain latitudes are accessible at a given time of year). Its successor, SAGE-II, launched in 1984 on ERBS (Earth Radiation Budget Satellite) and still working, has seven channels measuring H_2O in addition to the gases listed above.
(f) TOVS/HIRS2 (TIROS Operational Vertical Sounder)

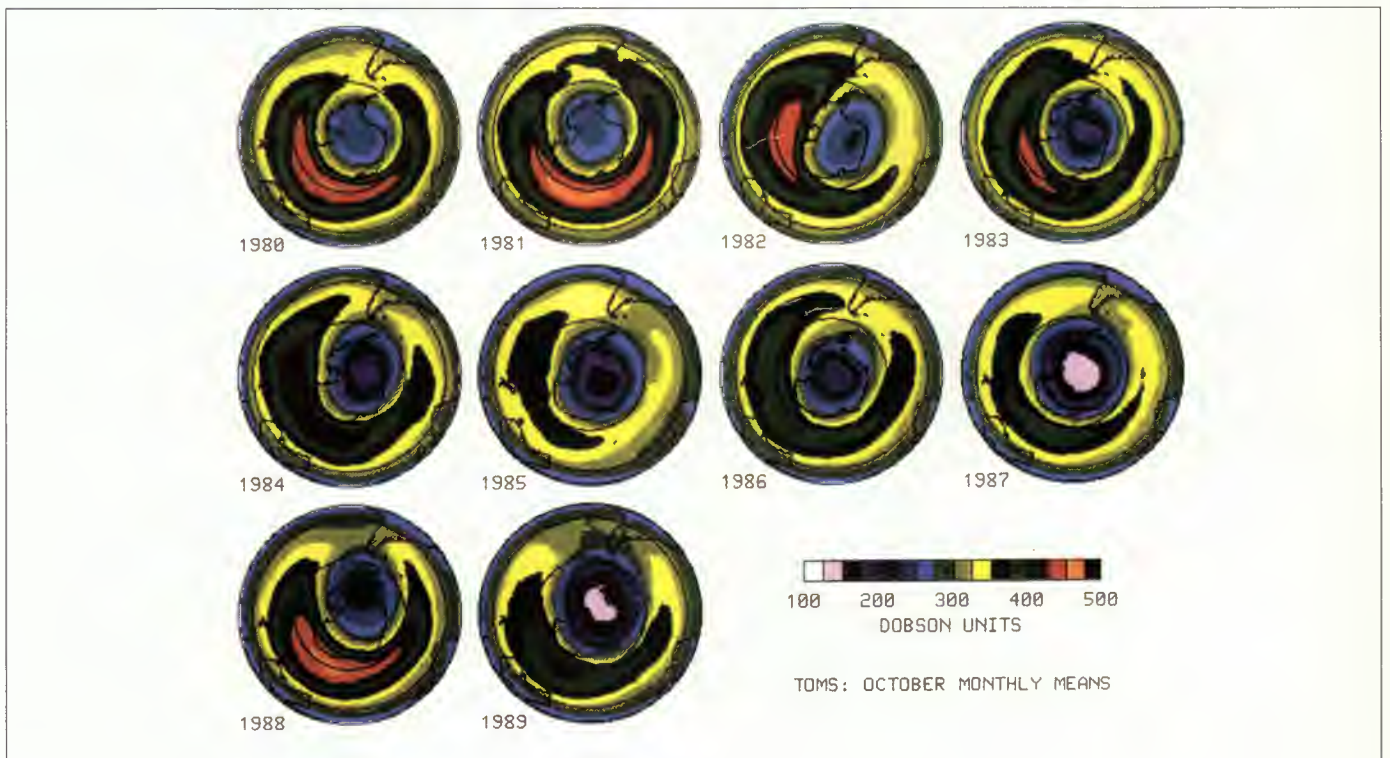**Nimbus-7 TOMS total ozone maps.**

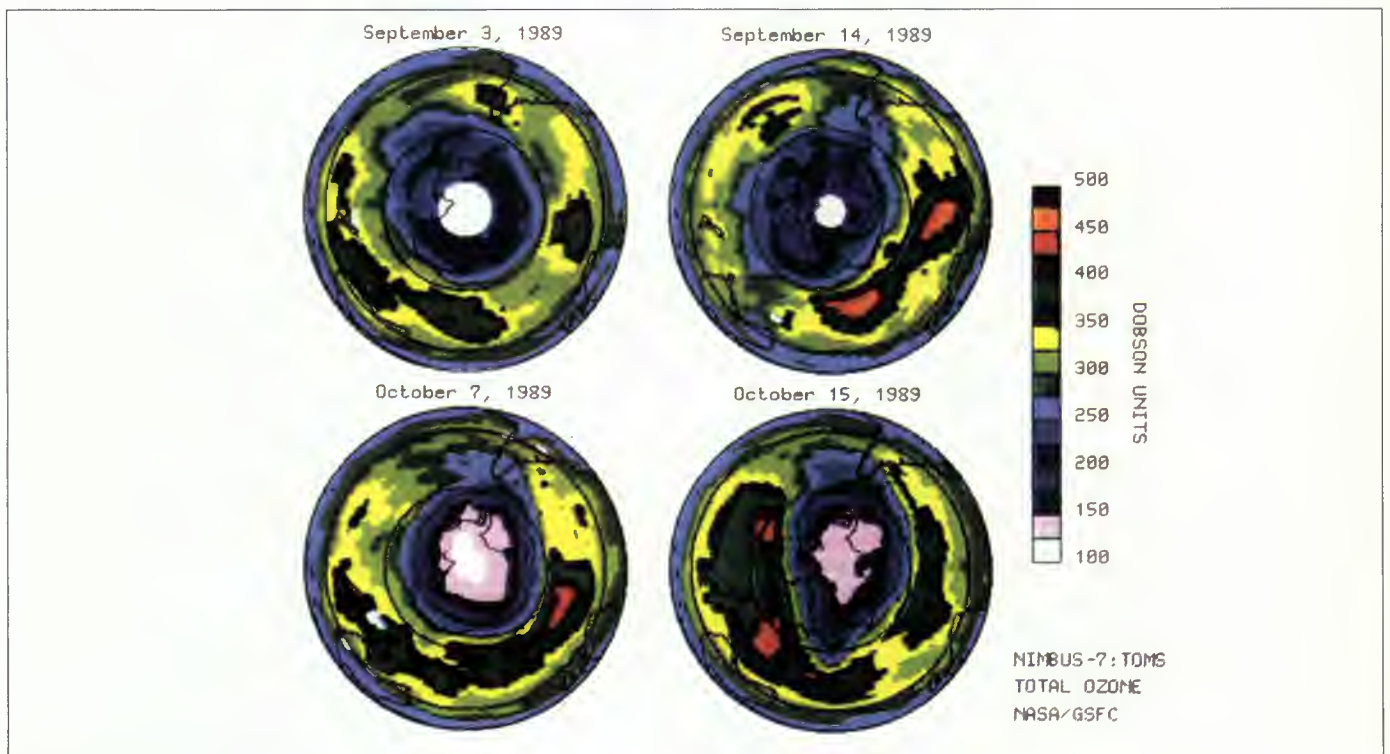Figure 1.1 (a) October 1980-1987 monthly means of total ozone.

Figure 1.1 (b) . The development of the ozone hole in 1989.

is currently operational on the NOAA TIROS-N satellites. It has flown on some 11 satellites. Infrared radiometers (with channels at 9.71 micron, 11.11 micron and 14.99 micron) are used to measure total ozone (to accuracies of 6-10%) and for polar stratospheric cloud mapping at regional scales. Although less accurate than TOMS and SBUV, this technique gives ozone columns for night time and polar winter regions where the backscatter ultraviolet technique cannot be used.

(g) SBUV/2 (Solar Backscatter Ultraviolet Radiometer: Version 2) flies on NOAA operational satellites. Currently the SBUV/2 is flying as an operational instrument for total ozone and vertical profiles on NOAA-9 (launched in 1984) and NOAA-11 (launched in 1988). Problems were experienced with the diffuser plates and currently no data is available from either instrument though work continues on correction procedures.

(h) Space Shuttle missions are limited both in time (missions last less than two weeks) and in latitudinal coverage (between 50° N and 50° S). Two relevant instruments have flown to date:

(i) MAPS (Measurements of Air Pollution from Shuttle) flew on the Space Shuttle in 1981. It made tropospheric CO measurements at 4.7 micron in nadir using a gas-filter correlation radiometer.

(ii) ATMOS (Atmospheric Trace Molecules by Spectroscopy) flew on Spacelab-3 (1985) and on a recent Shuttle (1992). It was a limb viewing interferometer using high-resolution Fourier transform and covering the spectral range from 2.2 micron to 16 micron. Many spectra were measured in sun occultation during its six-day mission. Data on approximately 25 gases have been published to date. Analyses continue.

(iii) SSBUV (Shuttle Solar Backscatter Ultraviolet Radiometer) is a Shuttle version of the SBUV/2 instrument and will have flown three times beginning in 1989. It will continue to fly throughout the lifetime of the SBUV/2 programme, possibly to the year 2000.

(i) AVHRR (Advanced Very High-Resolution Radiometer) measures aerosol on the NOAA Polar Orbiting Operational Environmental Satellites (POES).

(j) VISSR (Visible Infrared Spin Scan Radiometer) measures aerosol on the NOAA Geostationary Environmental Satellites (GOES).

Soviet Programme

Infrared radiometers similar to the TOVS have flown on board a series of Meteor satellites.

The MIR station has flown instruments which have made some ozone (MIR-O_3) and NO_2 profiles but these data have not yet been published outside the Soviet literature. These data have not been used in recent trend analyses, but have been published and confirm the conclusions of the ozone trends panel report.

Japanese Programme

The EXOS-C flew on board OZHORA in 1985-87. This instrument measured the vertical distribution of ozone by solar occultation in the ultraviolet.

1.4 New Missions

US Programme

The NASA programme contains the UARS (Upper Atmospheric Research Satellite) and the ATLAS (Atmospheric Laboratory for Application and Science) missions. Both have been flown on board the Space Shuttle (in September 1991 and March 1992, respectively). TOMS follow-on missions are planned by NASA for 1993 (Earth Probe) and beyond.

For the mid-1990s and beyond, the EOS (Earth Observation System) programme has been defined using polar platforms planned as part of the US programme and offering opportunities for both NASA research instruments and NOAA operational payloads. (For a more precise account of the current EOS programme, readers are recommended to consult the NASA EOS Reference Handbook 1991). The advanced TIROS-N with GOMR (Global Ozone Monitoring Radiometer), which will supplant SBUV-2, will also be launched in the mid-1990s.

(a) The UARS (Upper Atmospheric Research Satellite) contains four instruments for atmospheric chemistry:

(i) CLAES (Cryogenic Limb Array Etalon Spectrometer) contains 4 etalons and 8 prefilters in the 3.5 micron, 6 micron, 8 micron and 12.7 micron wavelength range. The limb is imaged onto a cryogenically cooled array.

(ii) ISAMS (Improved Stratospheric and Mesospheric Sounder), the successor to SAMS, employs filter radiometry and pressure modulation techniques in the 4.6 micron to 16.6 micron (mid-infrared) band. Some multiplexing is achieved by 4-element detector arrays, cooled to 80 K (instrument provided by the UK).

(iii) MLS (Microwave Limb Sounder) is a 3-channel (63, 183 and 205 GHz) heterodyne limb sounder. The 183 GHz radiometer was supplied by the UK.

(iv) HALOE (Halogen Occultation Experiment) employs gas-filter correlation radiometer

techniques in solar occultation in the infrared (2.4 – 10.2 micron).

(b) The ATLAS (Atmospheric Laboratory for Application and Science) mission contains three instruments for atmospheric research, two of which (GRILLE and ATMOS) have already flown. In addition it includes MAS (Mm-wave Atmospheric Sounder) which, like MLS, is a limb sounder employing heterodyne detection techniques, in this case around 61, 62, 63, 183, 184 and 204 GHz. It will measure pressure, temperature, ozone, water and ClO profiles.

(c) GOMR (Global Ozone Monitoring Radiometer) will be flown aboard the Advanced TIROS-N satellite. GOMR is intended as an operational instrument for making long-term ozone measurements. It has two subsystems: an ultraviolet nadir and side-scanning sounder drawing on TOMS technology and a SBUV-2 instrument. The nadir sounder will provide cross-track scanning of total ozone column amounts and the SBUV-2 instrument will provide stratospheric profiles and total column amounts of ozone.

European Programme

The ESA long-term (1987–2000) Earth observation programme was adopted during the 1987 ministerial level meeting in The Hague, providing Europe for the first time with the opportunity for an integrated atmospheric research programme from space. Four instruments addressing the chemistry and dynamics of the stratosphere and the tropo-sphere are presently considered for flight on the first European polar orbiting Earth observation mission – Envisat-1 – scheduled for launch in 1998.

The GOME is intended to bridge the gap between now and Envisat-1. It has been approved for flight on ERS-2 (1994) and is intended to provide an early start to European atmospheric chemistry studies.

On a national level, initiatives have been taken by France (GLOBSAT) and Germany (ATMOS) for dedicated missions on atmospheric research and climate studies. Belgium and France have been the driving force behind the GRILLE spectrometer which flew on Spacelab-1 (1983). This instrument had a high resolution in the infrared (2 micron to 10 micron) and measured vertical profiles of CO, CO_2, NO, NO_2, CH_4, N_2O, HCl, HF and O_3. Both SAMS and ISAMS were built by the UK.

Russian, Soviet Union, Commomwealth of Independent States Programmes

The Soviet Union does not appear to have an integrated atmospheric space science programme, rather instruments and existing facilities are adapted to carry out environmental studies.

The first flight of a new upgraded TOMS instrument is planned on board the Soviet Meteor-3 spacecraft scheduled for launch in August 1991. Unlike the sun-synchronous orbit of Nimbus-7, the Meteor-3 orbits will be subjected to precession with a period of 225 days (WMO 1989). This means that the coverage will not be uniform and so adjustments will have to be made for diurnal variations.

MIRAS, a Belgo-Franco-Russian Grille infrared spectro-meter (see section 1.3) has been accepted for flight on the MIR-2 space station in 1995 as has Ozon-Mir from the University of Saint-Petersburg – a solar occultation instrument operating in the region 0.25-1.04 micron.

Japanese Programme

NASDA has based its long-term Earth observation programme on polar orbiting platforms scheduled for launch in the late nineties. Prior to this the Japanese climate satellite ADEOS is scheduled for a 1995 launch. This contains six Announcement-of-Opportunity sensors, four of which address the atmospheric chemistry questions. These are TOMS (US, see section 1.3), IMG (Ministry of Trade and Industry), ILAS and RIS (Environment Agency):

(a) IMG (Interferometric Monitor of Greenhouse Gases) is a nadir looking interferometer (with a resolution of 0.1 cm^{-1}) working in the (4-16 micron) waveband for CO_2, CH_4 and N_2O observations.

(b) ILAS (Improved Limb Atmospheric Spectrometer) is a limb scanning (10-60 km) spectrometer working in three wavebands, namely 753-784 nm, 4.1-6.9 micron and 7.3-11.8 micron.

(c) RIS (Retroreflector In Space) is a corner cube retro-reflector (diameter 50 cm) reflecting ground-based laser light (0.3-14.0 micron); it is intended to measure O_3, CFC, CO_2 etc. by absorption.
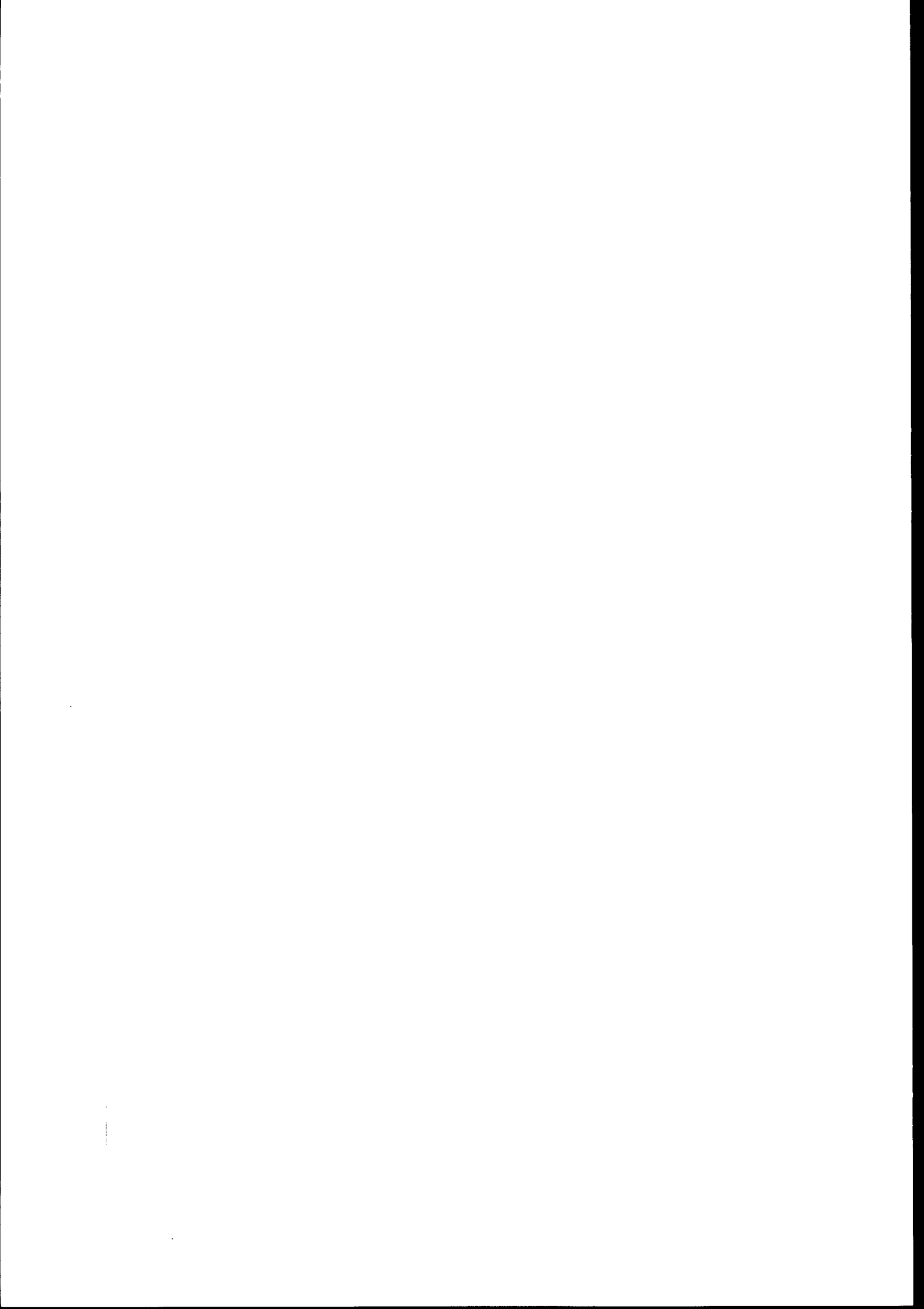
1.5 General Mission Objectives

The general scientific objectives of the GOME mission may be summarised as follows:

(a) To improve understanding of the processes controlling global bio-geochemical cycles in the troposphere and stratosphere.

(b) To monitor natural and anthropogenic changes in the composition of the atmosphere, e.g. O_3.

The primary measurement objectives of the GOME are the measurement of total column amounts and stratospheric and tropospheric profiles of ozone.

In addition it is intended to measure column amounts of H_2O and other gases involved in ozone photochemistry like NO_2, OClO, BrO and possibly ClO in anticyclonic conditions, plus pollutants like SO_2 and HCHO. The GOME will also be used to investigate the distribution of atmospheric aerosol and clouds-plus-surface spectral reflectance.

2. SCIENTIFIC CAPABILITIES OF THE GOME

2.1 The GOME Heritage

Conceptually, GOME is a spectrometer which observes solar radiation scattered from the atmosphere or from the earth's surface at moderately high resolution (approximately 0.2-0.4 nm) in the near ultraviolet, visible and near-infrared between 240 and 790 nm (Fig. 2.1).

The primary measurement technique to be employed by GOME will be differential optical absorption spectroscopy (DOAS). The GOME will be the first space borne experiment which will fully exploit the potential of this technique for remote sensing of trace atmospheric gases.

DOAS is already a well established technique; measurements of a variety of trace gases have already been made using DOAS from ground-based, balloon-borne and aircraft-borne instruments. Especially in the last decade, discoveries made by such DOAS measurements have contributed greatly to improving our understanding of the chemistry of the stratosphere and troposphere. For example DOAS was used for the analysis of the pioneering measurements of Noxon and coworkers which established the broad latitudinal and seasonal variations of NO_2 (*Noxon 1975, Noxon 1978, Noxon et al. 1978, Noxon et al. 1979*). These workers also used DOAS in discovering the anomalous behaviour of NO_2 at high latitudes in winter (the 'Noxon Cliff'). Vertical profiles of O_3, NO_2, NO_3, O_4 and H_2O have been derived from balloon-borne DOAS measurements by solar and stellar occultation. The effectiveness of the DOAS technique has been assessed during large coordinated field campaigns in the US and in Europe (BIC in 1982 and 1983, MAP/GLOBUS in 1983 and 1985) by comparison with other available remote and in-situ measurements, including validated satellite data (*Pommereau et al. 1987, Robbins et al. 1988, Roscoe et al. 1990* and *Chu & McCormick 1979*).

Recently ground-based and aircraft-borne observations of O_4, NO_2, OClO, O_3, BrO and NO_3 using DOAS techniques have been made in polar regions to study the 'ozone hole' depletion mechanism. DOAS spectrometers have been installed in the Arctic and Antartic since 1988 for monitoring these constituents, providing the first opportunity to validate high latitude satellite observations (*Mount et al. 1984, Sanders et al. 1987 and 1989, Pommereau & Goutail 1988a, b & c, Carroll et al. 1989, Solomon et al. 1989, Pommereau et al. 1989, Wahner et al. 1989a & b*).

During the spring of 1990 European scientists used the DOAS technique applied to ground-based instruments as part
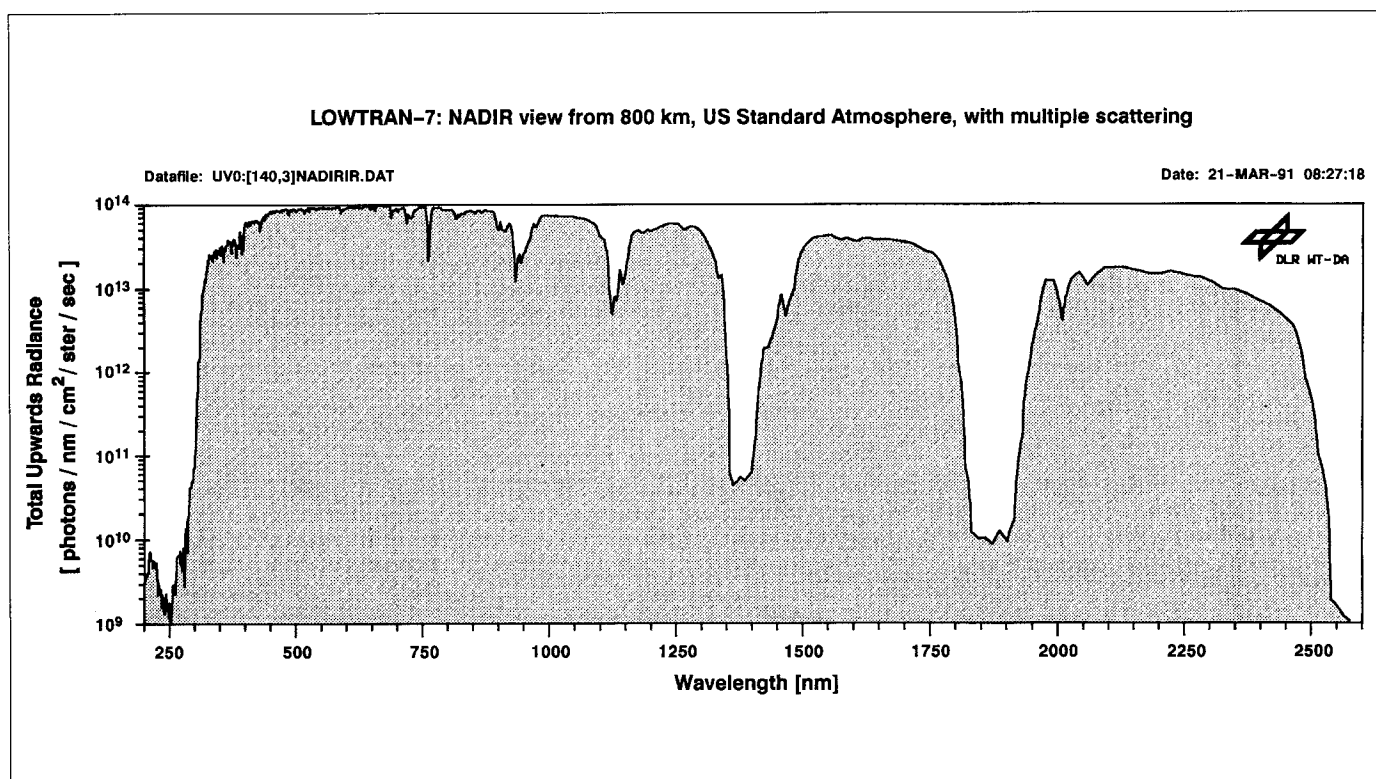

Figure 2.1. Lowtran-7. Nadir view from 800 km, US standard atmosphere, with multiple scattering, between 200 and 2600 nm.

of the Arctic Ozone Campaign. They found evidence for enhanced OClO and BrO amounts which could be a potential early warning signal for O_3 depletion over northern Europe (*Perner et al. 1990*).

Ultraviolet spectroscopy exploiting DOAS has been recognised as one of the four techniques (besides lidar, FTIR and microwave), which must be used at each of the seven stations comprising the recently agreed international network for the detection of stratospheric changes.

The term DOAS was originally applied to long path tropospheric measurements made using a lamp or laser as the light source. This method was developed in Europe by Perner, Platt & co-workers and has been successfully used to measure a variety of tropospheric constituents e.g. NO_2, NO_3, OH, SO_2, HCHO, HONO and O_3 (*Platt & Perner 1980, Platt et al. 1980, 1981, 1984, Perner et al. 1985, Hübler et al. 1984*).

The second approach to be used with the GOME for the retrieval of total column amounts and profiles of O_3 is the backscattered ultraviolet (BUV) technique. This technique was proposed by *Singer & Wentworth (1957)* and successfully applied for ozone retrieval from the BUV on Nimbus-4 and the SBUV and TOMS on Nimbus-7 (*Heath et al. 1975*). The TOMS-SBUV instruments have functioned for 13 years on Nimbus-7. The TOMS inverts the backscattered radiation at six selected wavelengths between 310 and 380 nm to produce a total ozone amount while SBUV uses 12 wavelengths between 255 and 340 nm to determine stratospheric profiles of O_3 (see section 1.3), as well as total ozone amounts.

The design of GOME is such that it measures at high spectral resolution throughout the wavelength regions monitored by both the TOMS and SBUV instruments. The GOME can therefore be used to retrieve O_3 column amounts and profiles in a manner similar to that employed by TOMS and SBUV. This is important as it provides continuity with two instruments which have been monitoring O_3 globally throughout the last decade, enabling DOAS and BUV to be directly compared.

2.2 The GOME Instrument

2.2.1 The Basic Concept

The basic concept underlying the GOME (Fig. 2.2) is that of a grating spectrometer operating from 240 to 790 nm (i.e. ultraviolet/visible/near-infrared) with a moderately high spectral resolution over the whole range (between 240 and 400 nm it will be approx. 0.2 nm; between 400 and 790 nm it will be approx. 0.4 nm).

Its main mode of operation will be nadir viewing but it will also be able to look at the sun and the moon so that an absolute radiometric calibrations will be possible. This means that the GOME will be able to retrieve ozone distributions with the traditional backscatter approach as well as the more novel DOAS technique.

As an instrument, the GOME can be described as a double spectrograph which predisperses light at a prism and then produces a spectrum using a set of holographic replicated gratings. At the heart of the GOME are its detectors. It is the combination of the optical arrangement and the use of array detectors in the GOME that enables the simultaneous measurement of the earth's backscattered and reflected spectrum between 240 and 790 nm to be made.

Photodiode arrays have a high quantum efficiency, are lightweight and ideal for recording spectra. Their use in GOME removes the need to have a moving grating to obtain a wavelength scan. Similar devices have been used successfully on a number of satellite instruments (e.g. Voyager and SPOT).

The random access diode array has been selected as the standard detector for GOME. These detectors are arranged in six bands which cover the 240-790 nm spectral region. The integration time of each band can be individually selected. This feature can be used to optimise signal to noise in different regions of the spectrum. Figure 2.1 is an impression of the GOME instrument, showing the arrangement of its optics and detectors.

The GOME is a scaled down version of SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography), the spectrometer proposed in response to the Announcement of Opportunity for the first ESA polar platform mission. SCIAMACHY is currently undergoing Phase-B studies for that mission. Work in support of SCIAMACHY has helped formulate GOME.

From the outset, an overall restriction was placed on the specification of GOME; namely that it must be possible to include it on ERS-2 without compromising either the basic satellite instrumentation or the mission's time schedule. This ruled out the possibility of flying SCIAMACHY itself.

2.2.2 Spatial and Temporal Resolution

The instantaneous image of a GOME detector pixel at the earth, which corresponds to the highest spatial resolution available to the GOME, is oblong and has an area of about 40×1.7 km. The GOME will record data by collecting photons from the atmosphere as this image (or field of view) is scanned across the satellite track. It will be possible to vary the overall spatial resolution of the GOME (i.e. pixel size) between 40×40 km and 40×320 km (see Figure 2.3).

There are two conflicting requirements underlying the choice of pixel size:

i) Small image size – This favours cloud detection as clouds lying in the field of view of the GOME will be recognisable by their characteristic high albedo and by the measurements of O_2 and O_4 absorption. Ideally each pixel should either have no clouds present or else it should be totally cloud covered. The smaller the pixel the more likely this is.

ii) Large image size – This favours global coverage as it will be achieved with the minimum number of orbits. This points to the use of the largest pixel.
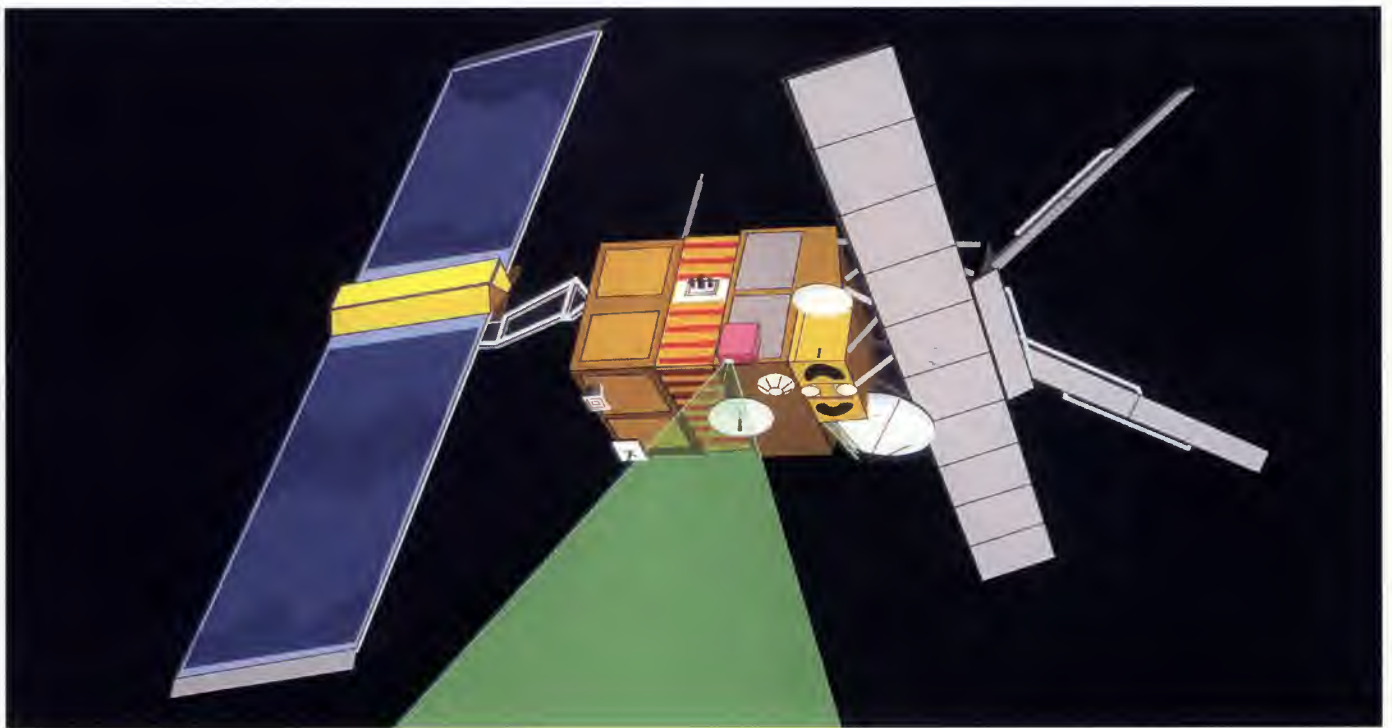
Figure 2.2 (a) Artist's impression of the GOME flying on ERS-2

290-405 240-295   400-605 590-790
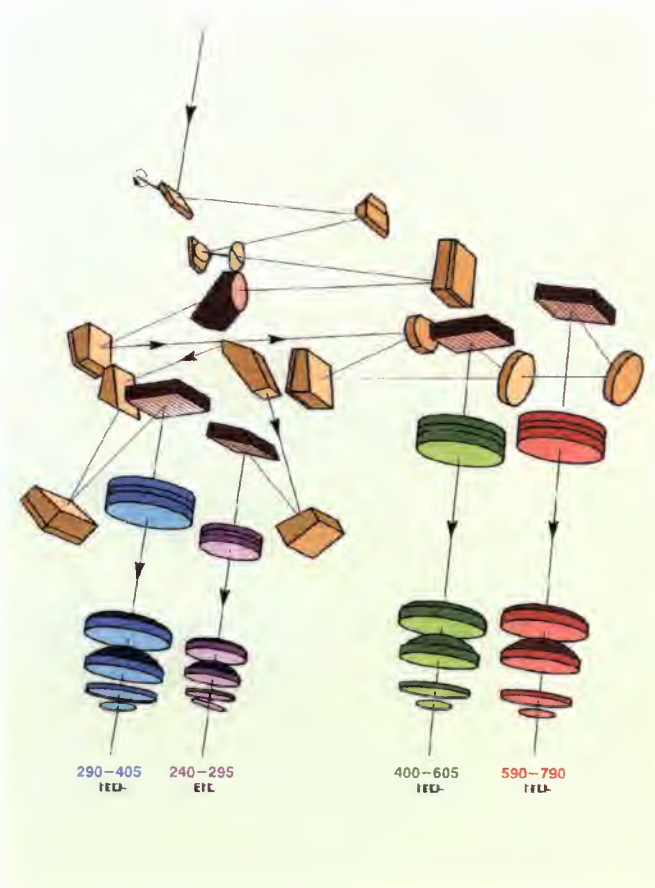IED   EIE   IED   IED

Figure 2.2 (b) Schematic diagram showing the optical layout inside the
GOME Instrument.

The GOME employs a mirror mechanism which scans across the satellite track with a maximum scan angle that can be varied from ground control. For a typical scan three readouts are envisaged. Using this scan mechanism the influence of cloud cover on the retrieval of data can be investigated at the beginning of the GOME mission. Thereafteranoptimised scan and readout strategy will be selected.

ERS-2 will fly in a sun-synchronous orbit at an altitude of 780 km with a local crossing time (at the equator) of approximately 10.30 h (descending mode). The corresponding orbital period will be about 100 mn, so with its maximum swath of 960 km across track, the GOME should give complete coverage of the globe at the equator in approximately three days.

As the observations will always be made at the same local time the GOME will not be able to detect any diurnal variations.

2.2.3 The GOME Spectral Channels

The GOME has four different spectral channels each of which has been chosen to observe different species anddifferent spectral features:

i)   Channel 1 (240-295 nm): absorption due to the Hartley band of O_3 and NO emission are the dominant features.

ii)   Channel 2 (290-405 nm): a variety of target species absorb in this region e.g. O_3 (Huggin's band), O_4, NO_2, HCHO, SO_2, BrO and OClO.
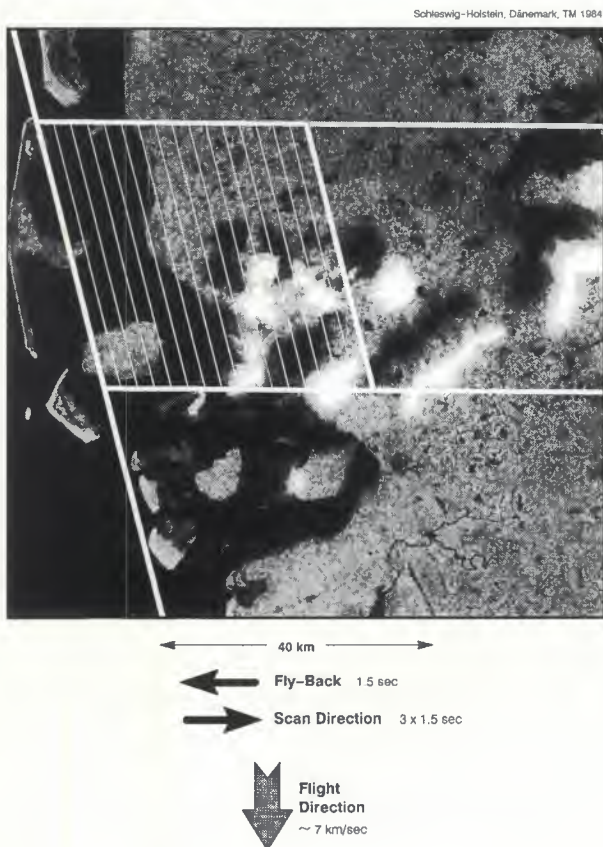
Figure 2.3 (a.i) The GOME scan pattern: high-resolution mode with 40 km swath.

Figure 2.3 (a.ii) High-resolution mode with 120 km swath.

iii) Channel 3 (400-605 nm): the target molecules for this region are NO_2, OClO, O_2, O_3 (Chappius band), O_4 and H_2O.

iv) Channel 4 (590-790 nm): the target molecules are O_3 (Chappuis band), NO_3, H_2O and O_2.

The combination of channels 2 to 4 can be used to make measurements of O_2 and O_4 column amounts which yield information about radiation penetration depths and cloud top heights. Also the backscattered light provides information about atmospheric aerosol and polar stratospheric clouds. Figure 2.3 illustrates the type of data that should be provided by the GOME.

2.2.4 The Polarisation Channels

As the optical throughput of the GOME can vary with the level of polarisation of the incoming light (which is not constant), it has been decided to measure its polarisation as a function of wavelength using silicon detectors. To make these measurements, reflection from the second surface of the pre-disperser will be used as this surface is oriented almost at the Brewster angle and consequently will only reflect that part of the light which is polarised perpendicular to the incidence plane.

Light from the pre-disperser prism will be directed onto a three-element silicon detector by means of an off-axis parabolic mirror and a flat folding mirror. The three detector elements will sense different spectral parts of the spectrum. They will be made of the same substrate. The overall characteristics of this polarising device are summarised below in the following table:

Channel	Wavelength range(nm)	Detector width (mm)	Expected signal na
1 (UV)	292-402	1.58	0.7
2 (visible)	402-597	0.913	2.8
3 (red)	597-790	0.357	2.8

In addition it will be possible to obtain further information on the polarisation of the incoming light by comparing channel outputs in regions where there will be spectral overlap.

2.2.5 The Calibration Unit

The requirements for radiometric accuracy mean that in-orbit radiometric intensity and wavelength calibration will

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Figure 2.3 (b) The GOME scan pattern: global mode.

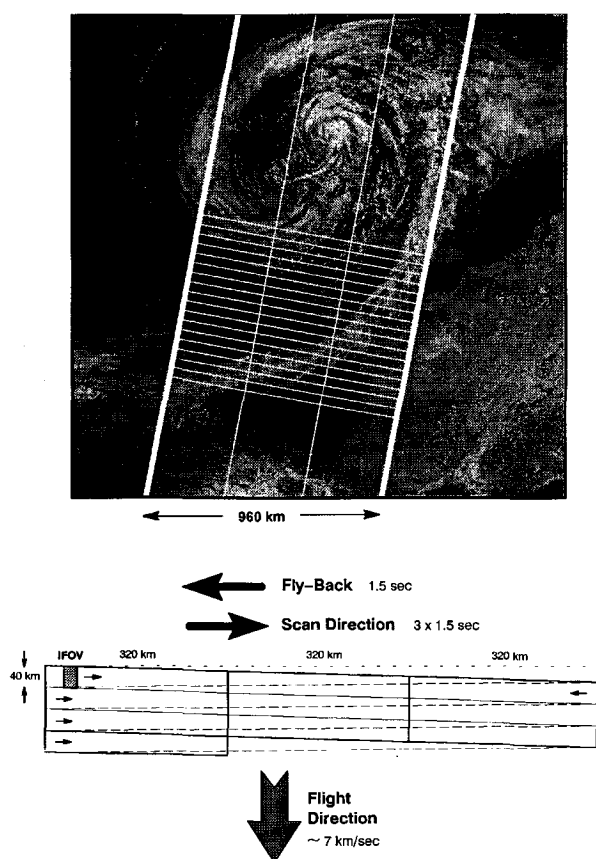both be essential. For the former it is proposed to use both the Sun and the Moon. As the intensity of sunlight could damage the instrument, the Sun will not be viewed directly via the scan mirror, but instead a second input aperture will be used. This will allow the Sun to be viewed for about 30 seconds in each orbit. Light entering this aperture will be directed via a flat mirror onto a sun diffuser and thence to the scan mirror.

From previous experiments it is known that exposure to sunlight (probably acting on spurious cantaminants) could degrade the diffuser plate, thereby undermining its use for calibrating the GOME. It has therefore been decided to include a cover in the design of the 'Sun path' to protect the diffuser during periods when sun calibration is not in progress. Further protection from sunlight may also be necessary so the installation of a mesh in front of the diffuser plate, to provide further attenuation, is also being considered.

Additional in-orbit radiometric intensity calibrations will be carried out by viewing the Moon using the same optical path as that used for observing the Earth. This is feasible as light intensities are much lower. The lunar light will be reflected directly by the scan mirror onto the entrance slit.

This calibration mode will be strongly affected by the fact that the Moon's diameter (as viewed by the GOME) will be much larger than that of the entrance slit. Only a fraction of the Moon's surface will be seen and only when three quarters of its

surface is illuminated. Furthermore, views of the Moon will only be available on a limited number of occasions, unevenly spread over the year. The implications of this are being studied.

Wavelength calibrations will also be required. This need can be partly met by observing known lines in the solar and lunar spectra but in addition a hollow cathode Pt/Cr/Ne lamp will be included in the GOME to act as an internal calibration source. This lamp will emit at least six lines in each of the GOME's spectral channels. Its output will be directed onto a ground surface which will illuminate the entrance slit of the GOME spectrometer when the scan mirror is at a particular orientation.

The wavelength calibration lamp can also be used to help monitor the characteristics of the sun diffuser at the wavelengths emitted by the lamp. This serves to illustrate the basic philosophy underlying the GOME's calibration system, namely not to rely on any one single technique but rather to use a composite of techniques, seeking to exploit individual strengths while at the same time seeking to minimise the impact of individual weaknesses.

A schematic diagram of the calibration unit is given in Figure 4.1. The calibration unit (CU) is located at the upper left corner of the optical bench.

2.3 The Scientific Objectives of GOME
2.3.1 Trace Gas Measurements by GOME

As indicated earlier, a primary scientific aim of GOME is the measurement of total column amounts of those gases which absorb between 240 and 790 nm by the differential optical absorption spectroscopy (DOAS) technique. In the special case of O_3, stratospheric and tropospheric profiles will also be derived.

A list of target molecules for GOME is shown in Table 2.1. The list is divided into two categories:

    i)   Trace gases for which GOME will obtain global coverage.

    ii) Trace gases where observation by GOME is dependent on circumstances.

The latter category includes gases which in a clean unperturbed atmosphere have very low concentrations, but which can achieve moderately high concentrations under certain circumstances e.g. SO_2 or HCHO in a polluted troposphere or ClO and OClO in the lower stratosphere during 'ozone hole' episodes.

In addition to the known absorptions due to the gases listed in Table 2.1, other structured features are known to be present in the part of the atmospheric spectrum that will be observed by the GOME (*Wahner et al. 1989a, 1989b*). Hopefully during the lifetime of the GOME project, some of these features will be identified.

The category selected for each trace gas in Table 2.1 reflects both instrumental limitations and the atmospheric variability
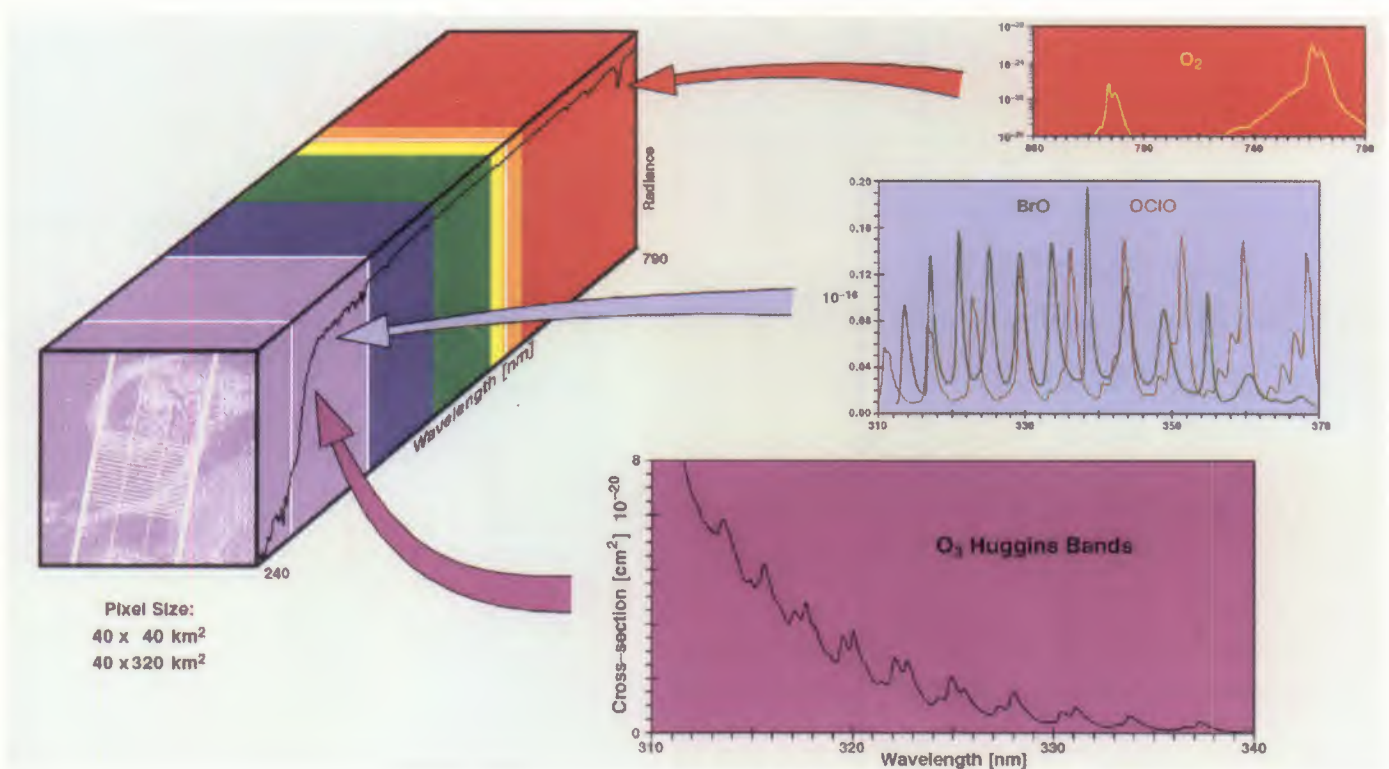
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Figure 2.4. Molecular absorption features in the total upwelling radiance.

of these gases. In Table 2.2 the various parameters that can be expected to be observed by the GOME are summarised. Details of the methods used to estimate the GOME's ability to measure trace gases, plus a detailed description of the sensitivity studies that have been performed, are provided in Annexes 1 and 2.

Each of the target species will now be considered in turn:

i) Ozone (O_3)

O_3 is measured in a variety of ways by GOME. The total column amount can be derived either from the Chappuis bands or else from the Huggins bands (as for TOMS). The vertical profiles can be inferred either from the temperature-dependent Huggins band or else from the 240-310 nm region (as for SBUV).

The O_3 measurements made by GOME will couple the high intrinsic precision of DOAS (as used in SME or as achieved in single wavelength absorption spectroscopy by SAGE-I and II) with a global coverage comparable to that of TOMS (at slightly lower spatial resolution dependent on scan strategy). TOMS ozone hole measurements are shown in Figure 1.1.

ii) Nitric Oxide (NO)

The NO band emissions between 255 and 300 nm will be used by GOME to deduce amounts of NO above 40 km. This emission results mainly from absorption by NO around 225 nm. The derivation of profiles of NO above 40 km from these measurements will be investigated. SBUV has detected no emission.

iii) Nitrogen Dioxide (NO_2)

NO_2 is another ideal candidate for observation by GOME DOAS type measurements as it has a strong banded absorption spectrum throughout the 330-700 nm region with a maximum between 400 and 450 nm.

In the remote marine troposphere, the amounts of NO_2 are low, except close to storm clouds associated with the presence of severe lightning. However, over or near continents (e.g. Europe), due to industrial pollution (fossil fuel combustion) or biomass burning, NO_2 concentrations are often high.

In the stratosphere, NO_2 concentrations are generally high, except in the polar spring where denitrification of the stratosphere appears to be an important precondition for ozone depletion in the lower stratosphere (ozone hole).

GOME will make global measurements of total column amounts of NO_2 and investigations will be undertaken to determine whether the stratospheric and tropospheric contributions can be separated.

iv) Bromine Monoxide (BrO)

BrO is formed in the stratosphere as a result of the photochemically induced decomposition of naturally occurring methyl bromide (CH_3Br) and anthropogenically produced halocarbon compounds (the halons). It takes part in several cycles which can catalytically destroy ozone.

The concentration of BrO in the stratosphere is lower by several orders of magnitude than its chlorine analogue ClO. Under ozone hole conditions, BrO reacts with ClO to produce

in part Br and OClO and thereby participates in one of the two major mechanisms which have been identified as responsible for ozone destruction in the lower stratosphere during the austral polar spring. Again the GOME will be used to measure column amounts.

v) Water Vapour (H_2O)

The H_2O column amounts observed by GOME will be dominated by the tropospheric burden of H_2O, which yields information about the interaction between the oceans and climate. The correlation between sea-surface temperatures derived from the along-track scanning radiometer (ATSR-2) and water-vapour columns derived from the GOME should prove scientifically interesting.

vi) Oxygen (O_2 and O_4)

Absorptions due to O_2 and O_4 should be readily observed by the GOME. It is intended to use them to determine penetration depths in the atmosphere. As the O_4 concentration is proportional to the square of the O_2 concentration it is a good indicator of tropospheric penetration of solar radiation.

vii) Sulphur Dioxide (SO_2)

In clean air, the column amount of SO_2 is low, both in the troposphere and in the stratosphere. It is therefore unlikely that SO_2 will be observed by GOME under such conditions even with averaging. However SO_2 does occasionally achieve high concentrations in the troposphere, though these episodes do not usually last very long (e.g. during pollution episodes or after volcanic eruptions). SO_2 has already been observed by TOMS in such circumstances.

viii) Formaldehyde (HCHO)

Due to its low level of concentration in the troposphere, the measurement of HCHO in the unperturbed atmosphere by a single GOME observation is borderline (see Annexes 1 and 2).

However, averaging several GOME spectra together may enable HCHO to be detected in the clean atmosphere, though at lower spatial resolution than for O_3.

However, HCHO, which is produced during the photochemically induced oxidation of hydrocarbons, often achieves moderately high concentrations (e.g. during biomass burning and anticyclonic pollution episodes in the northern hemisphere). Under these conditions HCHO may be observable by the GOME. HCHO is a key intermediate in the tropospheric oxidation of hydrocarbons. Knowledge about its global distribution will provide new insights into tropospheric chemistry.

ix) Chlorine Dioxide (OClO)

The abundance of stratospheric OClO only becomes significant during ozone hole conditions when its column amount increases by a factor of approximately 50-100. OClO

is rapidly photolysed during the day and therefore its nighttime concentration is larger than its day-time concentration. OClO should be observed by the GOME in polar regions during spring (at twilight) and, with lower precision, during the day.

x) Chlorine Monoxide (ClO)

ClO has strong banded absorptions in the ultraviolet (265-320 nm) but its spectrum is masked by absorptions due to O_3. However, its concentration increases by more than one order of magnitude in regions of stratospheric O_3 depletion. Under such conditions, the GOME may be able to observe it.

xi) Nitrogen Trioxide (NO_3)

NO_3 absorbs strongly in the visible part of the spectrum and is photolysed. Consequently its day-time concentration is very low. Only under twilight conditions may NO_3 prove to be observable by the GOME.

2.3.2 Cloud Top Heights

The penetration depth of light in the atmosphere should be determined by the GOME from observations of O_2 and O_4 absorption. The concentration of O_4 is dependent on the square of the amount of O_2 present and is therefore a sensitive measure of tropospheric penetration depth. The combination of the O_2/O_4 penetration depth and the measurement of the wavelength dependence of albedo will be used to determine the presence of clouds and to estimate cloud top heights. In addition polarisation detectors will be used to increase the spatial resolution of the cloud measurements.

The heights of polar stratospheric clouds (PSCs; see Section 2.3.3), which play an important part in the O_3 depletion mechanism thought to be responsible for the production of the Antarctic ozone hole, should also be measurable by the GOME using the same technique (they were first identified by SAM II measurements at 1 mm). However, PSCs are relatively diffuse and therefore care will be necessary in the quantification of the GOME PSC observations.

2.3.3 Observations of Aerosol Distributions
a) Stratospheric Aerosol and Polar Stratospheric Clouds

Figure 2.5 shows a picture of PSCs taken at Kiruna (N. Sweden). For stratospheric aerosols or polar stratospheric clouds (PSCs), a suitable approach for GOME would be to use a method which has been demonstrated for balloon limb observations. This requires first the determination of the phase function of the aerosol scattering efficiency at several wavelengths. Subsequently a model of the same parameter is used in a data fitting procedure to find a compatible size distribution. The extinction and scattering data are then inverted in terms of aerosol loading. This method will be investigated for GOME nadir observations of stratospheric aerosol.

In the absence of tropospheric haze, identification of stratospheric aerosol and PSCs should not be difficult.

Figure 2.5 Solar stratospheric clouds at Kiruna, North Sweden.

However, the presence of tropospheric aerosol will reduce the sensitivity of GOME to stratospheric aerosol and PSCs.

b) Tropospheric Aerosol

Tropospheric haze will be more difficult to monitor because of the stronger influence of Rayleigh scattering in the troposphere. Fortunately it is extremely time dependent. This should allow the high spectral resolution of the GOME instrument, combined with its spatial resolution, to be used to study image contrasts and hence to characterise the nature of haze in terms of natural phenomena.

For example, sand storms and their impact on radiative transfer have never been monitored on a global scale. Since they occur mainly in dry regions where clouds should be absent, the GOME should readily detect them.

The same reasoning applies to forest fires which release large quantities of soot to which, for decades, the blue moon phenomenon has been attributed. Identification of these 'clouds' and their continuous observation will lead to an assessment of the effects of these largely local phenomena on the global atmospheric system.

c) Retrieval

For temperate middle latitudes, where both cloud formation and transport are quasi-permanent features, simulation of data and tests of inversion algorithms will have to be conducted in order to try to separate water droplets, clouds, ground albedo and tropospheric 'dry' hazes.

The fitting and iteration process will be similar to the scheme proposed for the stratospheric and upper-atmospheric aerosol. However the inversion of tropospheric aerosol data will not be as valid in this region of the atmosphere since Mie theory is not such a good approximation in the presence of aspherical absorbing particles. Moreover, the presence of multiple scattering will further complicate the radiative transfer.

2.3.4 Possible Synergy between GOME and ATSR-2

The along-track scanning radiometer (ATSR-2), which will also fly on ERS-2, is a nadir viewing instrument with infrared and visible channels primarily designed to measure sea-surface temperature and other surface properties. Its scan pattern will provide 1×1 km images of cloud cover.

The ATSR-2 images should therefore provide a very powerful method of discriminating cloud-free GOME pixels from those containing sub-pixel cloud. In the case of complete cloud cover a consistency check may also be possible by comparison of GOME effective scattering heights with ATSR2 cloud top temperatures.

The spectral resolution (0.2-0.4 nm) and polarisation (broad band) information on the backscattered flux of solar radiation available from the GOME may prove to be of use in

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identifying the scattering medium giving rise to ATSR-2 signals in the four broad band (20 nm) visible channels. This would be useful for tackling the problem of near surface aerosol contamination and would also allow joint studies of surface phenomena.

2.4 Overall Conclusions

The tropospheric measurements (O_3, NO_2 and HCHO) of the GOME will be unique and in the foreseeable future will only be surpassed by the SCIAMACHY instrument, which is an advanced version of the GOME. In the stratosphere several important trace gases (e.g. NO_2, BrO, OClO and ClO) in addition to O_3 are observed by the GOME.

The GOME will provide both continuity with existing O_3 monitoring satellite instruments (such as TOMS and SBUV) and simultaneously it will enable the use of the differential optical absorption spectroscopy (DOAS) for the remote sensing of trace gases from space to be tested. This method promises to supersede TOMS and SBUV as the standard measurement method for O_3 observations from space.

The GOME instrument will provide the European scientific community with an early opportunity to study independently the atmospheric trace gases in the troposphere and stratosphere.
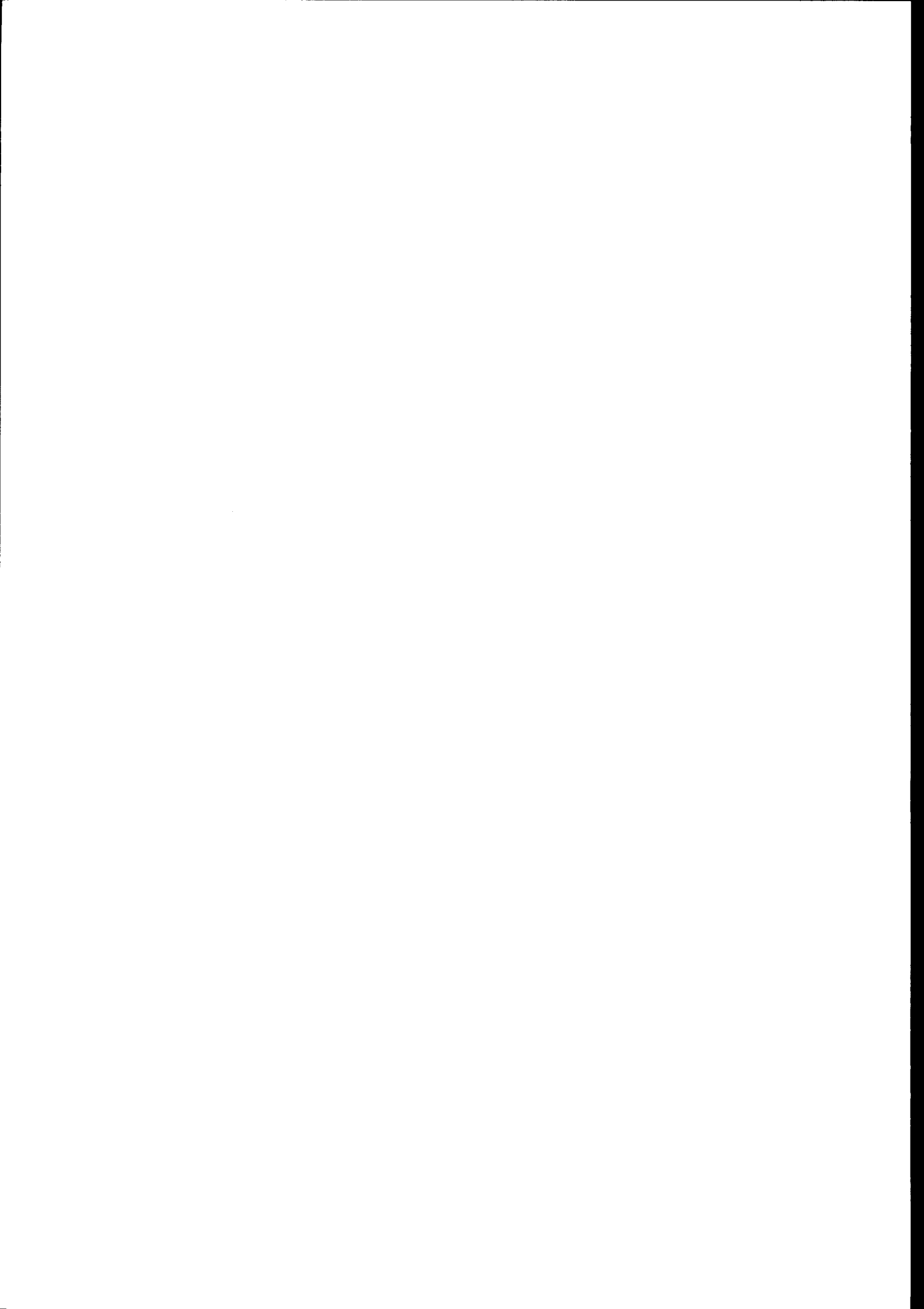
Table 2.1. Target molecules for GOME

Global Coverage	Partial Coverage or Occasional Observation	
SPECIES	SPECIES	QUALIFICATION
O_3	SO_2	tropospheric pollution; volcanic events
NO (above 40 km)	HCHO	tropospheric pollution; biomass burning
NO_2	OClO	twilight ozone hole conditions
BrO	BrO	ozone hole conditions
H_2O	ClO	ozone hole conditions
$O_2 - O_4$	NO_3	twilight conditions i.e. close to the terminator
Aerosols	PSCs	

Table 2.2. Quantities Retrieved from GOME Observations

Species	Retrievable Quantity[1]	Wavelength (nm)	Notes-Applications
O_3	Profile (S, T)	240-350, 480-680	
O_2	Column (S, T)	690, 760	Cloud tops/boundary layer
O_4	Column (T)	360, 380, 477, 516, 630	Cloud tops/boundary layer
H_2O	Column (S, T)	500-790	
HCHO	Column (T)[2]	310-360	Biomass burning; tropical vegetation
SO_2	Column (T)[2]	290-310	Industrial pollution; volcanos
NO	Column (S, M)	255-280	Above 40 km in emission
NO_2	Column (S, T)	300-600	Lightning, combustion
ClO	Column (S)[3]	300-310	Polar regions in spring
OClO	Column (S)[3]	320-420	Polar regions in spring
BrO	Column (S)	310-345	

Notes:

1 - S = stratosphere; T = troposphere; M = Mesosphere.

2 - Observable in regions with relatively high concentrations.

3 - Observable in perturbed 'O$_3$ hole' regions.

3. DATA RETRIEVAL

3.1 Introduction

Reflected or scattered sunlight observed in nadir from orbit includes the signatures of atmospheric scattering by air molecules and aerosols plus absorption by many of the trace species, which sometimes depend on temperature. It also includes the spectral signatures of reflecting surfaces: clouds, vegetation, soils, sea etc. The mixing of many features of various origins makes the measurement of atmospheric trace species by absorption impossible where only a limited number of spectral channels are available. In particular this is true in the troposphere.

Ozone retrievals using the BUV technique have concentrated on wavelengths where scattering occurs above the tropopause. The GOME has the necessary spectral coverage and resolution to retrieve vertical profile information down to the lower altitudes and also to determine total column amounts of a number of other gases by discriminating their spectral signatures using a method known as Differential Optical Absorption Spectroscopy (DOAS).

The name DOAS originates from tropospheric remote sensing measurements made by Perner, Platt and co-workers (e.g. *Platt & Perner 1980*. Figure 3.1 explains the DOAS method as applied to the measurement of ozone via absorption in the Huggins bands. Figure 3.2 shows the three absorption bands of ozone which will be used by the GOME for atmospheric measurements : Hartley (210-300 nm), Huggins (300-340 nm) and Chappuis (420-700 nm).

3.2 Determination of Total Column Amounts by the Differential Optical Absorption Spectroscopy Technique

The DOAS technique proposed for the GOME derives directly from the one developed for the interpretation of zenith sky observations made from the ground. The retrieval approach for satellite geometry involves two steps :

    (i) Derivation of slant column heights;

    (ii) Conversion to vertical column and determination of base heights.

(i) Derivation of slant column heights

— Each single spectrum is first carefully aligned in wavelength onto a reference or control spectrum which has been obtained by looking directly at the sun and which is therefore free of atmospheric attenuation. The alignment is performed by correlation, taking advantage of the presence of large Fraunhofer structures in the solar spectrum. A precision corresponding to a wavelength shift of 1/100 of a detector pixel is ideally required.

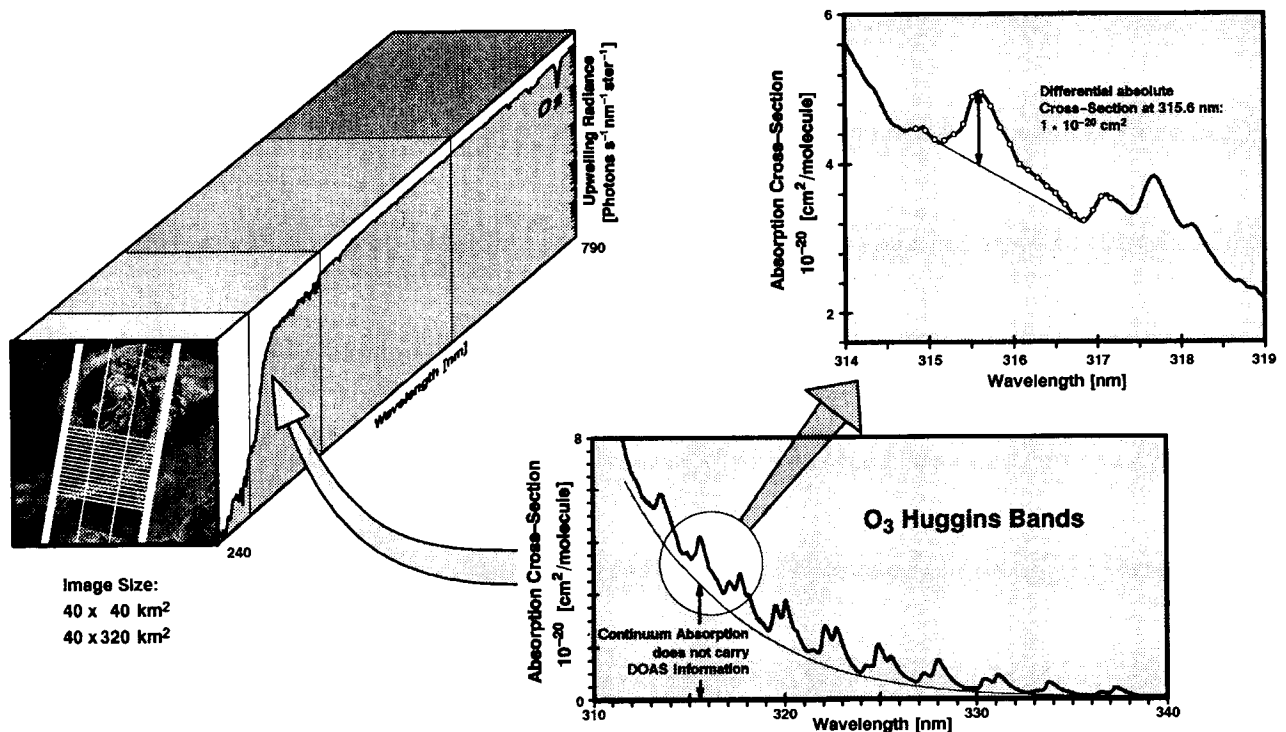— The two spectra (i.e. the observed and the reference) are

Figure 3.1 Schematic representation of differential optical absorption spectroscopy (DOAS) applied to the GOME
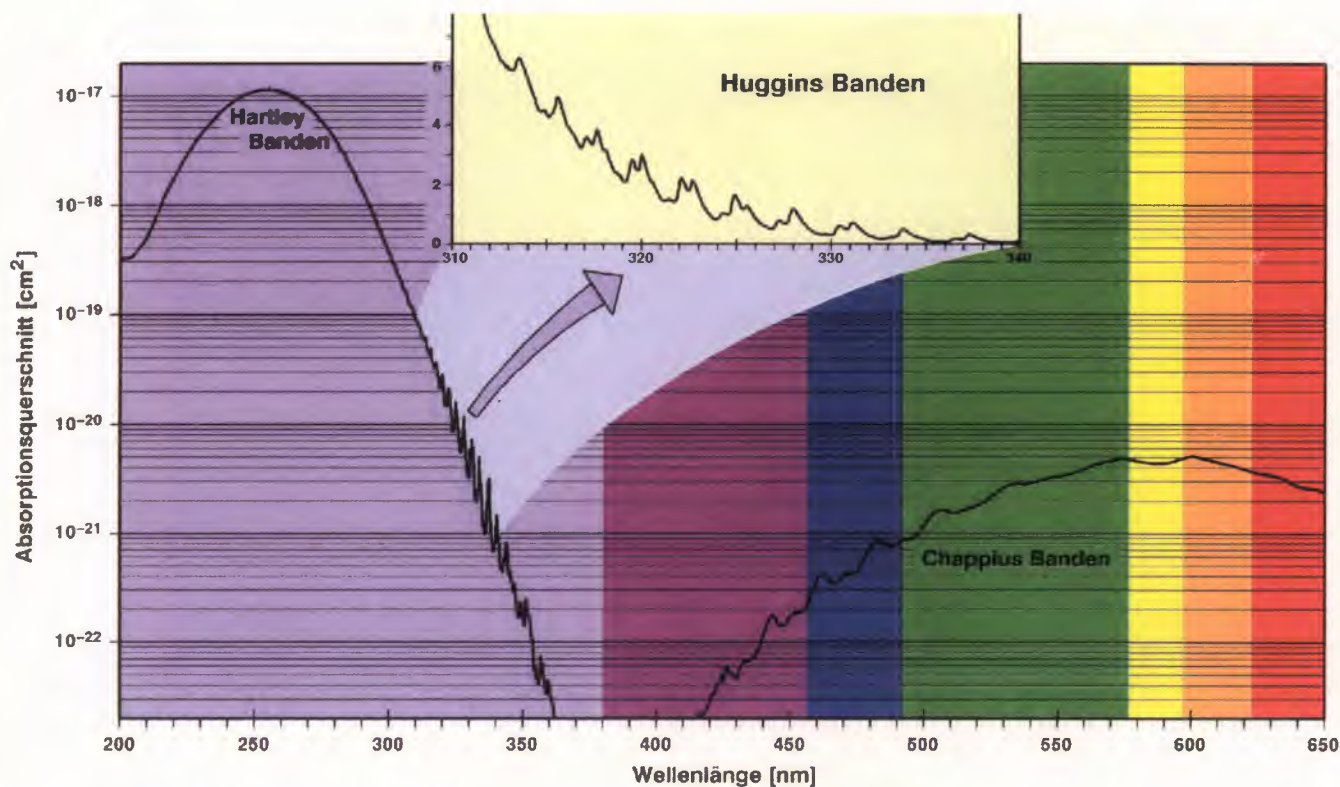
Figure 3.2 The absorption spectrum of ozone: Hartley, Huggins and Chappuis bands.

then ratioed. The logarithm of the ratio is the absolute atmospheric attenuation spectrum. This contains broad band features (due to Rayleigh & Mie scattering and surface signatures) and narrow ones which correspond mainly to absorption by atmospheric traces. The former are removed by subtracting the absolute attenuation spectrum, filtered at broad bandpass (typically 20-30 nm) from itself, resulting in a differential attenuation spectrum in which only narrow features remain (of the order of 10-20 nm wide).

— The slant column densities of the various constituents are then calculated by least squares fitting of the differential attenuation spectrum and absorption cross sections of constituents measured in the laboratory. This can be done either by an iterative process or by global fitting, in selected spectral regions corresponding to the largest features of each species. In order to be selective, a minimum of two or three successive characteristic features must be covered for each species.

— An alternative method, which should be investigated, involves fitting at all wavelengths to obtain slant column densities of a number of species simultaneously. In this case it might be possible to include solar calibration information as input to the fitting process instead of ratioing the spectra as above.

After removal of the narrow band absorptions it is always possible to study broad band atmospheric and ground features (see Fig. 3.2).

A limitation to the precision with which slant columns can be derived comes from the relative filling-in of the solar Fraunhofer lines due to scattering in the atmosphere. This effect is known as the Ring effect after its discoverer. It is due to primarily Raman scattering in the atmosphere. It can be almost completely removed empirically either by correlating the attenuation spectrum with the original solar spectrum or else by measuring the polarization of the scattered spectrum (the Raman component is unpolarised). After such treatment, only signatures near the largest Fraunhofer lines, 7 or 8 in the GOME spectral range are still significant. It is advisable not to use these narrow spectral regions for the determination of faint absorptions.

Generally, the DOAS technique can be used to measure total column densities without any need for an absolute radiometric source. The accuracy is generally quite high (a few percent). For example a series of narrow band features are found at 350, 460, 490, 505 and 530 nm (see Fig. 3.2). When looking at the atmosphere at a zenith angle of 180°, their amplitude is of the order of 4% to 8%. As GOME is expected to be sensitive to absorptions of the order of 10^{-4} this is large enough to enable total column density measurements to be made with a precision of approx. 1%.

(ii) Conversion to Vertical Column and Determination of Base Heights

Having measured the slant column density of a gas with the DOAS technique, the next step in the retrieval process is to

determine total columns above the reflecting or scattering level. This requires knowledge of the altitude of this level. It can be measured directly when the scattering surface is a reflecting cloud or the surface of the Earth, but has to be calculated from the (known) sun zenith angle, for the case of scattering in clear air. Due to the strong wavelength dependence of scattering, the average scattering altitude increases rapidly with decreasing wavelength and increasing solar zenith angle.

The altitude at which radiation is scattered in the Earth's atmosphere is controlled by Rayleigh scattering. This increases strongly with decreasing wavelength (wavelength raised to the power minus four) and increasing solar zenith angle. Its magnitude can be calculated by a radiative transfer model which includes multiple scattering. At high sun, radiation at wavelengths shorter than 300 nm does not reach the Earth's surface. At low sun, in polar regions in winter for example, much of the visible radiation is scattered before reaching the ground. An average scattering layer can be defined which depends only on the wavelength and the solar zenith angle.

This is illustrated by Figure 3.3 which shows how the altitude of the average scattering layer varies with season and

wavelength. Because of ozone absorption in the ultraviolet and Rayleigh attenuation at all wavelengths, the altitude of the scattering layer increases rapidly at large solar zenith angles. At wavelengths below 310 nm the light observed at nadir is always scattered above the tropopause and therefore provides a good measurement of total stratospheric ozone at all latitudes in the summer hemisphere and at latitudes lower than 35° in winter. It should be possible to measure tropospheric ozone simultaneously in the same region by observing the 325 to 340 nm spectral region.

At high latitude in winter, the ultraviolet light does not penetrate down to the tropopause and therefore ozone measurements are not possible at these altitudes poleward of 50 to 55°. In the range 240-340 nm (via the Hartley-Huggins bands of ozone), they must be replaced by measurements in the visible in the Chappuis bands centred around 500 nm. These should be sensitive enough for this because of the large air mass factor (Fig. 3.4). Compared to previous instruments, GOME will be able to increase by 10° to 15° in latitude the area in which the ozone hole can be monitored. Below 45° to 50° the NO_2 column density as measured from its absorption at 450 nm, includes tropospheric NO_2 and consequent

Figure 3.3 Altitude of the average scattering layer of sunlight in the ultraviolet and the visible when observed from an heliosynchronous orbit at noon for (a) summer and (b) winter. Calculated by steps of 5 km of latitude for a standard atmosphere and constant ozone, NO_2, aerosols and humidity profiles representative of 60° N in winter. Discontinuities in the curves come from the assumed aerosols and dust concentration profiles. These have minima at 8 km in the model.

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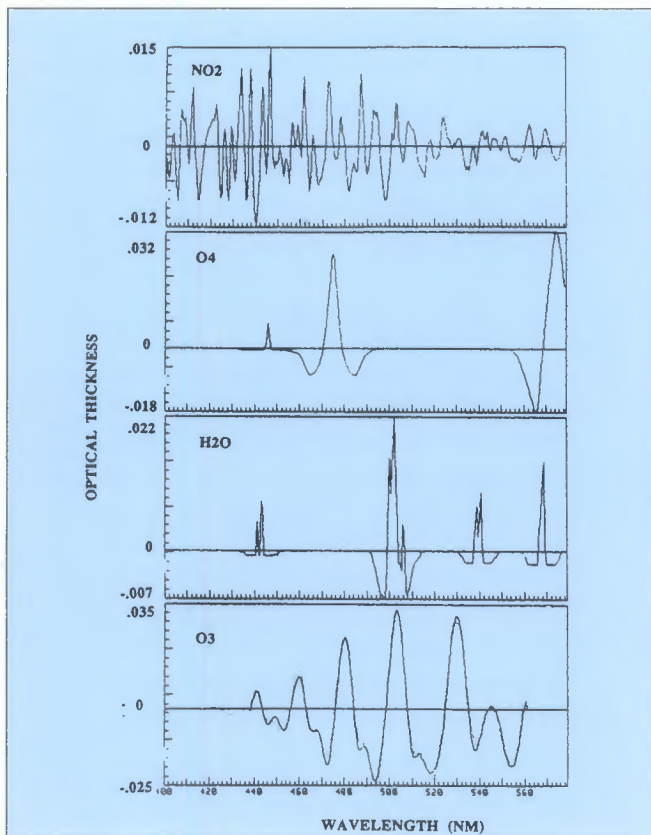Figure 3.4. NO_2, O_4, H_2O and O_3 signatures observed from the ground using a 0.1 nm resolution spectrometer looking at zenith in the visible for a clear day, at 90° sun zenith angle, after removing the broad-band pass signal by filtering and subtracting the four constituents sequentially by an iterative method. Solid lines are atmospheric signals; dotted lines are laboratory absorption cross-sections.

tropospheric pollution. Conversely at high latitudes the absorption around this wavelength will be weighted towards stratospheric NO_2. The rapidly changing airmass factor makes the observations sensitive to the stratospheric distribution of NO_2 in polar winter.

Knowing the altitude of the scattering level allows the computation of the ratio between the slant column densities of measured species and corresponding vertical columns above the scattering level. It is not possible to get any information below this scattering level, so for each species at a given wavelength there will be a minimum altitude below which no data will be available. This will vary depending on latitude and season.

When the radiation penetrates the atmosphere down to the ground or cloud top, the scattering altitude will be replaced by a reflecting altitude which can be measured directly by observing the O_2 and O_4 molecule slant column densities. Strong O_2 bands are present in the visible and the near infrared while O_4 bands are located in the visible and the near ultraviolet. At large solar zenith angles, the latter can also be used to make direct measurements of the scattering levels at 360, 477 and 576 nm. It therefore provides a check on the radiative transfer model.

With this approach it should be possible to measure the altitude of cloud tops directly without any need for assumptions on emissivity or temperature (as is required in the infrared). At 576 and 476 nm, the O_4 absorption bands should be extremely sensitive to the altitude of the polar stratospheric clouds (PSCs) reflecting the light in the stratosphere, while the light at 360 nm (another O_4 absorption band) will be scattered at upper levels and therefore not affected. Differential measurements of O_4 at two wavelengths should provide a powerful method for measuring the altitude of PSCs. The GOME should be able to distinguish between cirrus clouds and PSCs in the polar winter.

Because the scattering or reflecting altitude depends on the solar zenith angle (except for ozone and NO which can be always measured in the ultraviolet), the GOME may be characterised as a tropospheric trace gas constituents instrument at mid-latitudes but a predominantly stratospheric instrument at high latitudes. Thus at mid-latitudes and in the tropics, the low solar zenith angle will make the GOME rather insensitive to stratospheric trace species with the notable exception of ozone. The main products will be tropospheric total column amounts of pollutants, that is plumes of large cities, industrial areas, bush fires etc. and stratospheric ozone. At high latitudes the large solar zenith angle will make the GOME sensitive to stratospheric trace species. However, the altitude of the scattering layer in the upper troposphere will make the GOME insensitive to pollution at lower altitudes.

The orbit of ERS-2 will enable the GOME to have a dense geographical coverage. This is illustrated by Figure 3.6, which, with the exception of H_2O which is located near the surface, gives a good idea of what should be observed in nadir viewing from the GOME on ERS-2 during winter in polar regions. The ozone Chappuis bands present significant narrow band features (typically 10 nm wide) convenient for ozone measurements by DOAS without any assumption on aerosols or dust scattering. The amplitudes of all the above absorption features are in the range 2×10^{-2} to 5×10^{-2}.

These visible measurements of the GOME will make it possible, for the first time, to study ozone columns from space at high latitudes in winter near the terminator. For example at a 90° solar zenith angle the altitude of the scattering layer at 510 nm is at 10 km, still below the ozone layer. The GOME should provide reliable ozone data up to a solar zenith angle of 92°. This may be compared with the angle of about 82° available when observing in the ultraviolet. Therefore it should be possible to use the GOME to make observations 10° further poleward in winter than either TOMS or SBUV. This, coupled with its ability to measure ozone, NO_2, OClO, BrO, and the altitude of PSCs simultaneously, makes the GOME the best space-borne instrument available in the short term in orbit for studying polar ozone depletion.

3.3 Determination of Ozone Vertical Profiles

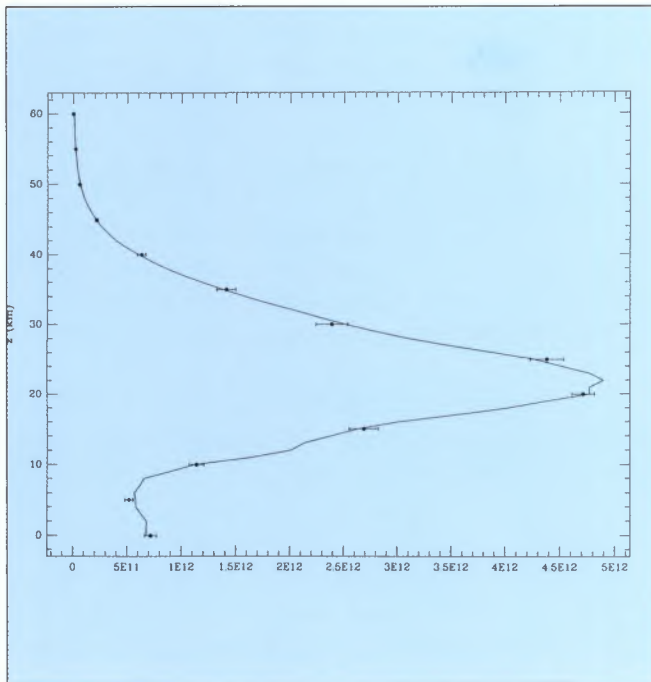Ozone is the principal absorber of solar radiation at

Figure 3.5. 'Non-linear least squares' retrieval of ozone from simulated GOME measurements in the Hartley, Huggins and Chappuis bands. The solid line is the O_3 profile used to synthesise measured spectra; error bars on the retrieved profile represent uncertainties due to measurement noise.

ultraviolet wavelengths above 200 nm and, together with molecular and aerosol scattering, it controls the penetration of solar radiation at ultraviolet wavelengths below 300 nm. By monitoring the intensity of solar radiation backscattered by the atmosphere at selected wavelengths, the BUV and SBUV instruments have determin l ed the ozone vertical profile in the stratosphere. The GOME will measure the backscattered ultraviolet spectrum over a broader range of wavelengths with higher spectral coverage. It should therefore permit the ozone vertical profile to be retrieved to lower altitudes and with higher vertical resolution (~ 5 km).

Ozone profile retrievals could also make use of the temperature dependence of the Huggins band which gives rise to detectable differences in spectral signatures and hence to profile information (Fig. A2.4).

Two independent studies of GOME's capability to retrieve ozone profiles have been undertaken. They have demonstrated that the temperature-dependent Huggins bands should be exploited as fully as possible, both to retrieve tropospheric profiles and to improve the precision and/or vertical resolution of stratospheric profiles. Ozone profiles retrieved at 5 km resolution from the ratio of simulated backscattered to direct sun spectra by applying a 'non-linear least squares' procedure to all ozone bands covered by the instrument and by applying an 'optimal estimation' procedure to the Hartley and Huggins bands only are shown in Figures 3.5 and 3.6 repectively.

LOWTRAN-7 was used as the radiative transfer model in both simulations, assuming nadir-viewing with overhead sun,

no clouds or aerosol and an average surface albedo of 0.3, and including multiple scattering and the temperature dependence of the Huggins bands. Synthetic measurements were generated in both cases using the most accurate available information concerning instrument properties such as etendue, optical and detector efficiencies and noise. However, in all other respects, the algorithms were developed independently.

In Figure 3.5, the solid line is the true profile used to synthesise measurements and error bars on the retrieved profile represent uncertainties due to measurement noise. In Figure 3.6, the solution error bounds are the combination of measurement noise with an 'a priori' uncertainty of ± 30% in volume mixing ratio. It should be noted that these are best case errors, since they do not include other uncertainties aasociated with the instrument (e.g. due to radiometric and wavelength calibration) or modelling atmospheric radiative transfer (e.g. clouds, temperature profiel and ozone spectroscopy). However, the potential of GOME to retrieve both stratospheric and tropospheric information has been clearly demonstrated. The effect of including the temperature-dependent Huggins bands can be judged from Figure 3.7 which used simulated measurements confined to the 255- 300 nm range.
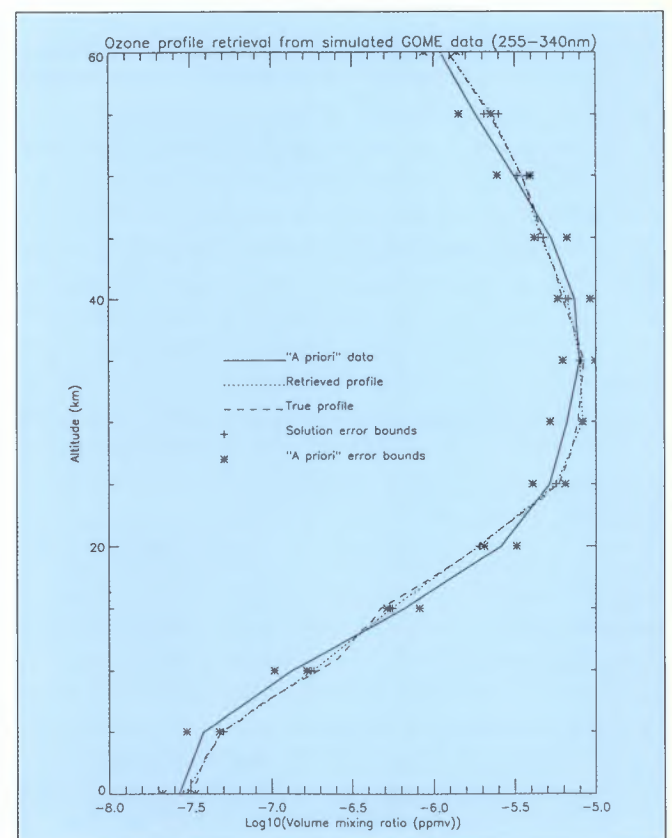

Figure 3.6. 'Optimal estimation' retrieval of ozone from simulated GOME measurements in the Hartley and Huggins bands. Solution error bounds are the combination of measurement noise with an a priori uncertainty of ±30% in volume mixing ratio.

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3.4 Determination of NO_2 Vertical Profile

If measurements of the backscattered spectrum can be made at wavelengths which are sufficiently diverse that the mean scattering height varies significantly, then a certain amount of profile information can be derived by DOAS. For example, at high zenith angles (high latitudes), the NO_2 column might be resolved into three layers from spectral measurements in the 350, 440 and 500 nm regions.

3.5 Scientific Studies and Data Validation

Scientific studies will be necessary for developing and updating the data retrieval scheme, including atmospheric spectroscopy and radiative transfer modelling of multiple scattering before launch and data validation after. Spectroscopic investigations include high-accuracy, full-resolution, measurements of molecular absorption cross-sections, their pressure and temperature dependence plus searches for new features. The database for absorptions in the ultraviolet/visible is poor compared to that for the infrared. For example, new water-vapour and hydrocarbon signatures have been recently discovered in the visible.

Other specific investigations include:
— the retrieval of the vertical distribution of ozone including
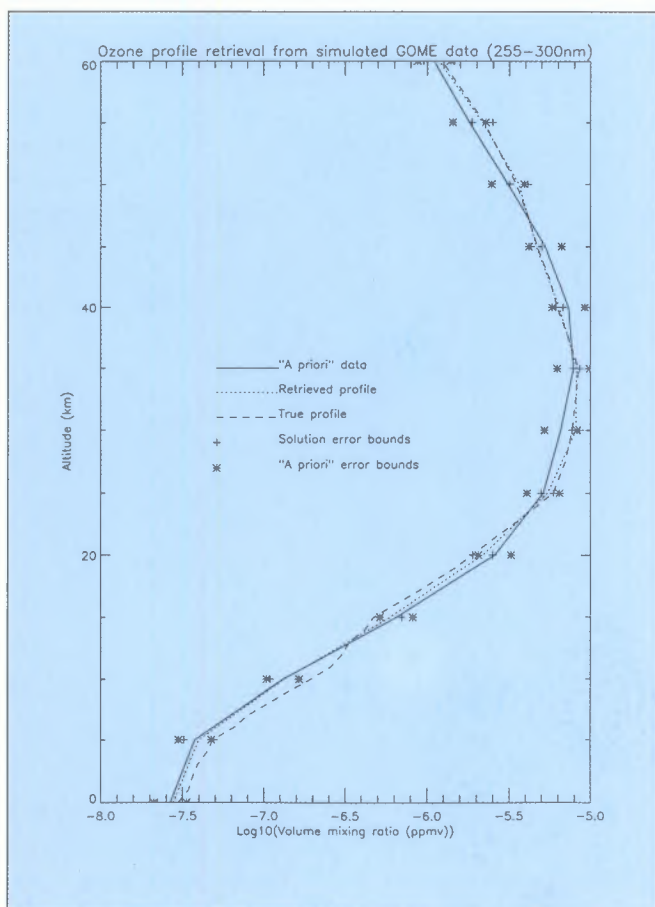

Figure 3.7. 'Optimal estimation' retrieval of ozone from simulated measurements in the Hartley band (255-303 nm) only.

(i) the temperature dependence of absorption cross-sections in the Huggins band; and (ii) an assessment of the improvement to vertical resolution that will be obtained with the GOME over SBUV from having a resolution of 0.2 nm available compared with the current 1.0 nm resolution.

— the quantitative assessment of the 'Ring effect' (*Granger & Ring 1962*); at the moment the smallest residual which can be achieved in ground-based measurements is of the order of 0.1%; permanent features are present which could be due to either residual Ring effect signatures or to unknown absorptions;

— the sensitivity of retrieved column amounts to assumed profile shapes and to twilight photochemistry along the optical path (NO_2, $OClO$, BrO, NO_3);

— the sensitivity of retrieved columns to assumptions about multiple scattering, aerosols and clouds;

— the quantitative assessment of PSC detection, i.e. is the optical depth sufficient? What is detected when the cloud is thin?

The availability of an instrument breadboard for observing the sunlight scattered at zenith from the ground prior to the launch, would enable certain aspects (DOAS and total column amounts) of the data retrieval process to be tested and evaluated over a wide range of solar zenith angles, except at wavelengths shorter than 300 nm which do not reach the ground. These results could possibly be compared directly to observations from similar nearby operational ground-based instruments.

Aspects of all the above studies, including ozone profile retrievals, improving the spectroscopic data base of atmospheric trace constituents, radiative transfer modelling, comparisons of ground-based ultraviolet/visible spectroscopic measurements with observations made from other satellites (TOMS, SBUV, SAGE-2, UARS) and ground-based observations of O_3, NO_2, NO_3, $OClO$, BrO, O_4, H_2O and PSCs, are in progress (answers to several of the above questions have been already obtained) within the framework of some European collaborative programmes such as:

— TOPAS (Tropospheric Optical Absorption Spectroscopy) for the troposphere in 1989-90, one of the EUROTRAC sub-projects grouping most of the European research institutes involved in the measurements of atmospheric trace species by ultraviolet and visible long path spectroscopy;

— a CEC/STEP project for the stratosphere (Interpretation of Stratosphere Monitoring by Ground-Based Ultraviolet and Visible Spectrometers) in 1990-91, which includes a ground-based network of ultraviolet visible spectrometers looking at zenith, direct sun and moon, and radiative transfer, photochemistry and dynamics modelling related to the observations.

The main objectives of the two projects are outlined in the Annex 3.

4. CALIBRATION AND EVALUATION OF THE GOME

4.1 General

In-flight data stability relies on precise design specifications which can only be checked by a verification and calibration process which follows the instrument from an early stage right up to and including flight. The basic objective is to ensure that the actual signals observed in space not only fall within the anticipated range, but in addition make possible temporal comparisons covering longer time spans than those appertaining to seasonal and latitudinal variations. To achieve this, many aspects of the instrument's performance must be characterised thoroughly under controlled conditions before flight as well as being monitored during actual operation.

4.2 Pre-launch Testing and Calibration

Amongst the most important instrument characteristics that must be determined under controlled conditions prior to launch, are radiometric response, wavelength response and field-of-view response, together with the diffuser bi-directional reflectance function. The response of the instrument to different polarisations is a particularly important variable.

The stability of the instrument's radiometric performance should be checked by repeated measurement with a special optical bench during ground testing. Provision of an early functional breadboard, using detectors and optics, as far as possible identical to the flight ones, will allow tests on the real sky at a mountain station (except for channel 1 for which no sunlight reaches the ground).

Mountain observatories have the advantage of already being well equipped for atmospheric observations, in terms of existing logistics and often of specialised atmospheric instruments. The sky conditions are monitored at these stations and sky radiances can thus generally be compared with theoretically computed radiances. The turbidity is usually low and clear conditions usually pertain from day to day in a single campaign. The blue sky conditions required for these tests are usually not encountered in sea-level urban laboratories. Furthermore, even if cloudy or highly turbid skies were used, their changing nature would prevent the constitution of a reference database.

The data obtained from the functional breadboard could be used as scientific data in its own right and be fed into the flight data algorithm to test it functionally and exercise the retrieval procedures. The simultaneous presence at the ground station of other instruments designed to measure the same end products as the GOME, as implemented in the present EEC
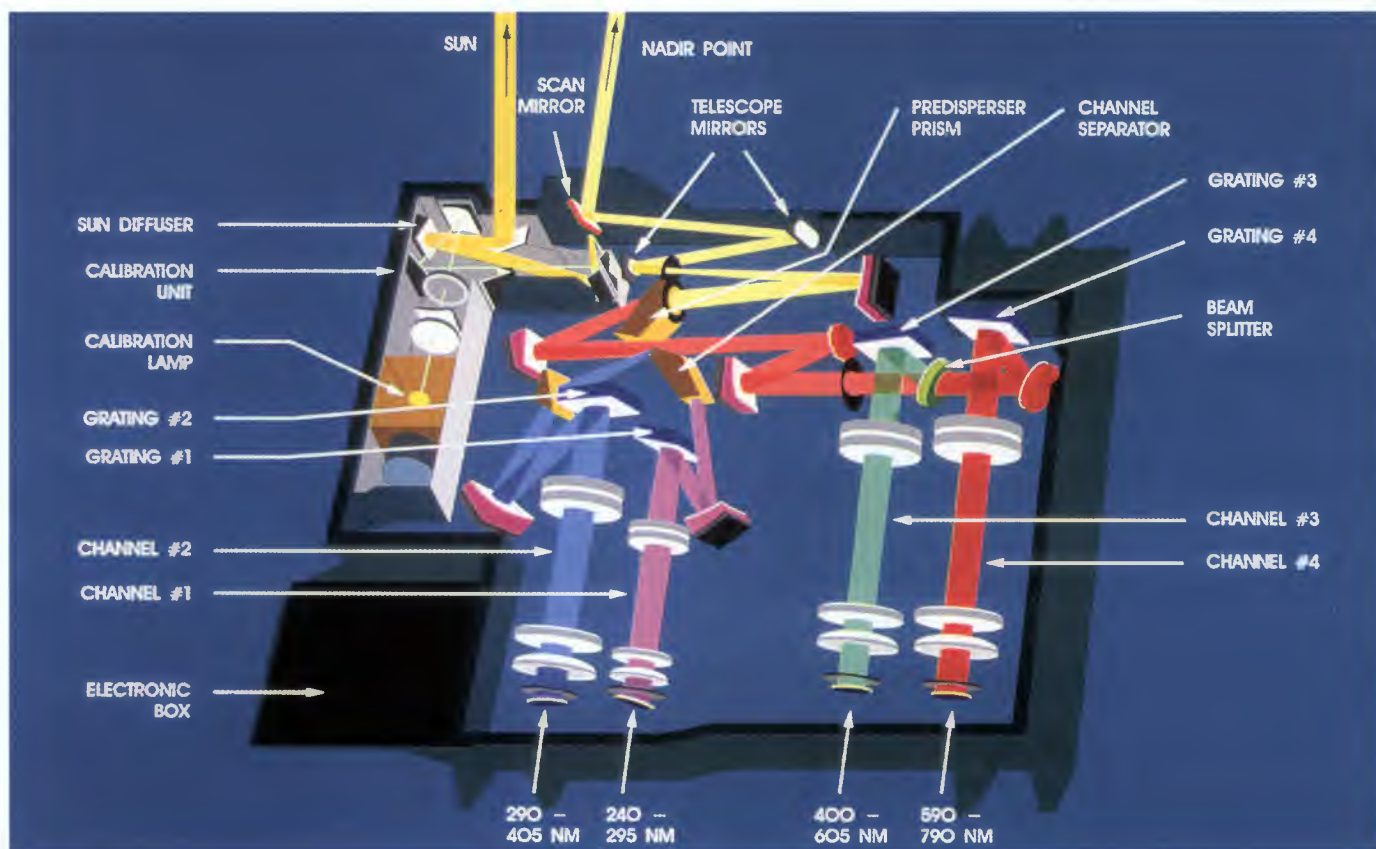

Figure 4.1. A schematic diagram of the GOME instrument highlighting the internal calibration system.
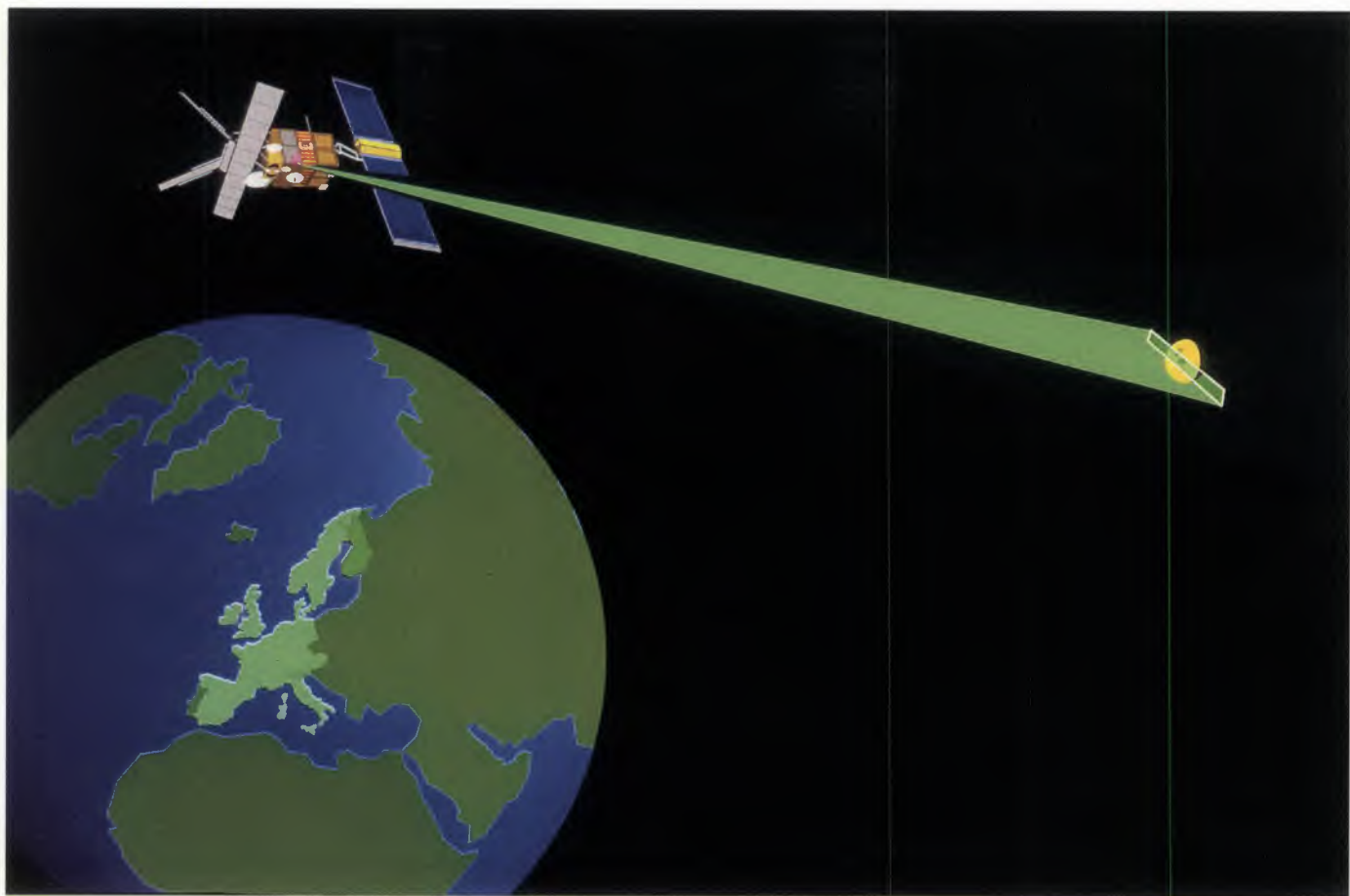
Figure 4.2. An artist's impression of the GOME in its moon calibration mode.

project of alpine ozone chemistry monitoring stations, will also facilitate the inter-comparison of the different techniques and prepare the flight 'ground truth' programme.

Once the functional breadboard has confirmed the theoretical evaluations of the signal, it should be compared with the flight model using the same calibration set-up, in the laboratory. Ideally, if this could be fitted in the integration calendar, the flight model should also be run in mountain station conditions in order to record its response to ground truth.

These rather straightforward sky tests do not preclude a realistic simulation of space conditions in a specialised test chamber of the flight model. In particular, it must be subjected to thermal vacuum tests in order to assess the thermal stability of the instrument under realistic conditions.

4.3 Post-launch Calibration

Once the satellite has reached its orbit and the payload has been activated, data quality and stability can be checked by the internal calibration lamp (Fig. 4.1), as well as by viewing external sources. The GOME is intended to point at both the sun and the moon (Fig. 4.2) for this reason.

Its low albedo makes the full moon a pale grey reflector whose luminosity is weaker than that of the Earth in most spectral regions. Also because of geometric restrictions, the moon can be seen only as '¾ moon' during certain periods of the year. Special studies still have to confirm whether the required 1% accuracy can be achieved with these restrictions. The advantage of the moon as a calibration source is that it uses the same optical path within the GOME as that used to observe in the nadir, albeit with the entrance slit only partially filled.

The use of the sun as a calibration source is not easy. Firstly, the sun provides a source whose intensity is several orders of magnitude higher than those expected in the other modes of viewing. Secondly, despite the fact that all instrument components should be able to withstand direct solar radiation, degradation will be much faster in the full sun.

The GOME requires both radiometric and wavelength calibration with the sun being used as a stable radiometric source. Of the various alternatives available, the use of a diffuser plate to attenuate the solar radiation to acceptable levels was selected as the best option.

Diffuser plates used in TOMS/SBUV are known to be susceptible to degradation. This could compromise a BUV-type retrieval technique which requires an absolute radiometric calibration. However, it would have a negligible influence on

the DOAS-type retrieval technique which only requires reference to a good quality extra-terrestrial solar spectrum viewed through the instrument.

Given the importance of the diffuser option, every effort will be made to ensure that *(i)* degradation is minimised, and *(ii)* it is monitored. For the latter it is intended to view a spectral line calibration lamp with and without the diffuser.

The use of an internal calibration source, in principle the simplest solution, has risks of its own. The first is that it involves putting an extra-mechanical system in the optical path which could fail and prevent the observation of the external signal. The second is that its long-term stability is not guaranteed. Every conceivable solution (viz redundancy) leads to more complexity and more risk. Even well-known laboratory standard lamps have never been properly tested in weightlessness. Furthermore, their lifetimes have always been limited, in particular if they have to deliver significant UV output.

The GOME contains a calibration lamp to provide a wavelength calibration. For this, problems associated with stability should not be serious. While several lamp types can be used at wavelengths over 300 nm, the choice of sources becomes very limited below this. A Pt/Cr/Ne hollow cathode lamp, as flown on several US missions, provides a number of spectral lines spanning the whole GOME wavelength range. Although in the UV they are not very strong, they should suffice for the purpose envisaged.

The use of a 'white lamp', in addition to a spectral line source, would be highly desirable as this would permit artificial spectral features to be eliminated, such as those caused by pixel-to-pixel variations in the detector response and etalon structure arising from contamination. However, only one calibration lamp can be accommodated in the GOME.

It is intended that combining the sun, the moon and an internal lamp, plus reference to laboratory spectra, should provide the means of checking instrument degradation. They should also provide the means to verify the radiometric and wavelength calibrations used for the interpretation of the data.
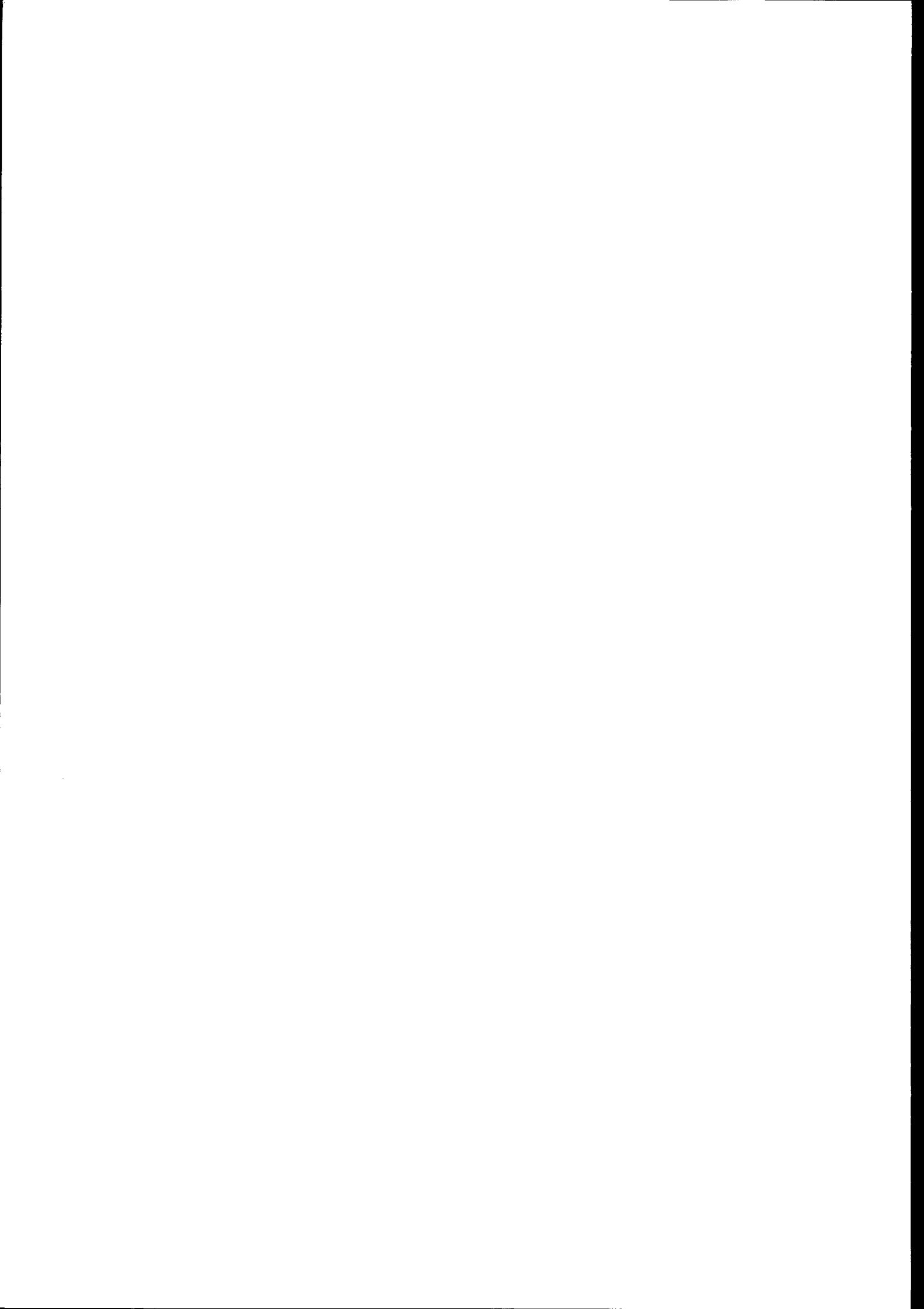
4.5 Validation

During flight, overpasses of atmospheric observatories should be used to check data quality by comparing the data retrieved from the GOME with the best that can be obtained from ground-based instruments. It would be also desirable to organise, whenever possible on such occasions, mini-campaigns involving the simultaneous use of all the relevant instruments at a selected ground station(s). Such comparisons would serve to highlight the correlative measurements needed to improve the GOME scientific output.

The data gathered during these validations should also be used to extend the GOME database to constituents not covered by the GOME primary objectives as well as to cross-check the inversion algorithm. Any significant disagreement between ground-based and the GOME data will obviously necessitate thorough checks of the GOME's functioning. The GOME functional breadboard should be operated at stations selected for the 'ground truth' programme and the instrument compared with the other instruments. The comparison of these data with the results obtained simultaneously by the flight model will provide another opportunity to check for artefacts in the performance of the instrument and its data processing system. In the long term, this will also enable any drifts due to mechanical or optical degradation to be identified.

Another source of validation data will be observations made by instruments on other satellites. Here the emphasis will have to be on geographical distribution and variability since common views will be very rare.

4.6 Conclusion

The outlined calibration and validation programme for the GOME is very ambitious and will require careful planning. Up to now it has only been matched by the first two years of the Nimbus-7 flight where an extensive programme of correlative observations relating to the entire payload was carried out.

5. DATA PLAN

5.1 Introduction

The GOME instrument will produce a continuous stream of data at a maximum rate of about 40 kb/s. For climate studies it will be necessary to make provision for their long-term storage. In addition there is a clear requirement for global coverage, unlike some earth observation instruments where only parts of the globe are studied. Thus, all the basic GOME data will have to be archived, corresponding to an accumulation rate of several gigabits per day over several years of operation. This implies the need for a data system that can handle, process and store this volume of data at a 100% duty cycle.

In order to make effective use of the GOME data, the data system needs to provide convenient access to the user communities of the GOME data products including the catalogue of observations, calibration data, databases, modelling and data analysis codes. For some applications of the data acquired by the GOME instrument, raw data or even processed data products will need to be delivered within a very short time period after reception by the appropriate ground station. Such a situation might arise when GOME data are needed to optimise operating parameters or in support of aircraft or balloon campaigns. For example the TOMS-SBUV data has proven to be a valuable tool for vortex detection and for fine tuning mission (aircraft) operation plans for 'ozone hole' measurement campaigns. This system was able to provide fully processed ozone maps in the region of interest within two hours after the observations had been made.

5.2 Data Products

In order to process the large amount of transmitted data in a consistent way, data are organised as data products of different level. For GOME the following definitions may be adopted:

Level 0.0 — Raw data as transmitted by the satellite telemetry system; this will consist of raw science data, instrument housekeeping data, header information, transmission quality flags;

Level 1.0 — Spectra which have been calibrated radiometrically and with respect to wavelength, complete with all header information (universal time, orbit, attitude etc.); all values are converted to physical units and geographical coordinates by applying the appropriate geometrical transforms using spacecraft ephemeris;

Level 2.0 — Atmospheric physics data, i.e. trace gas column amounts, ozone mixing ratio profiles, penetration depths mapped on a geographical grid corresponding to measurement strategy. Level 2 processing includes the bulk of the GOME analysis since it encompasses virtually all radiative transfer calculations and the application of the retrieval algorithm;
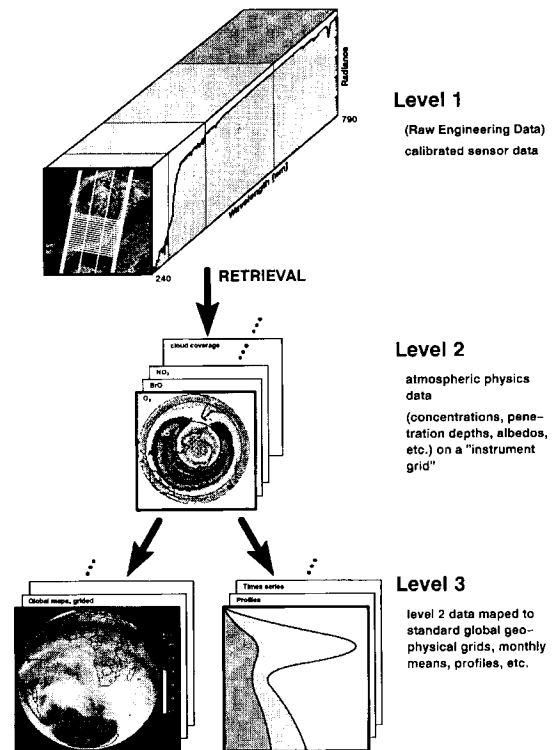

Figure 5.1. The GOME data product levels

Level 3.0 — Maps of ozone on standard pressure surfaces and trace gas column amounts selected by base height; some constituents, such as those that are observable only in ozone-depleted regions or the polluted troposphere, will have only partial global maps in the Level 3 dataset;

Level 4.0 — Model output or results from analyses of lower level data, especially variables, which are not directly measured by the GOME instrument, but instead are derived from GOME data augmented by measurements from other sensors, ground measurements, aircraft measurements or balloon campaigns; processing of Level 2 or 3 data into Level 4 data would not usually be performed at the main data centre but by specific research groups though later it might be archived in the main data centre;

Figure 5.1 illustrates the general concept of data product definitions.

5.3 The Ground Segment

The GOME data will be multiplexed into the ERS data stream and handled using the ground segment already developed for ERS. The data will be included in the ATSR-2 telemetry stream.

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Operation of the ERS instruments is performed by the Mission Management & Control Centre (MMCC) at ESOC in Darmstadt. It is responsible for executing the Mission Operation Plan (MOP). Via the Tracking Telemetry & Command (TTC) station in Kiruna, uplink contact with the ERS space segment is maintained. Data may either be downlinked directly (=1 Mbit/s) or, by employing the on-board data recorder (6.5 Gbit), dumped at each orbit crossing (]100 mn) of the receiving ground station. Several ground stations (Kiruna, Gatineau, Prince Albert, Maspalomas, Fucino) are responsible for data reception. These ground stations generate several types of data streams:

— Fast-Delivery (FD) products directly to the participating national centres and ESA establishments using terrestrial and satellite links. FD data include engineering products which are essentially small quantities of raw data;
— Received High-Rate (HR) and Low-Bit Rate (LBR) telemetry data, on High-Density Data Tape (HDDT) sent to the Processing and Archiving Facilities (PAFs), in some cases following transcription to Optical Disc;
— Extracted ATSR data supplied directly to the instrument provider on tape.

It is gathered that it is not foreseen to provide Fast-Delivery GOME data products, except for the engineering products consisting of small amounts of extracted raw data.

In addition to its use for monitoring the performance of the instrument, the FD data channel is required to deliver data which can be processed in support of campaigns. For example during defined periods in the ozone cycle for providing an early warning of occurrence and for monitoring the formation of the Arctic and Antarctic springtime ozone holes (one week characteristic time) where the normal data delivery time would be too long (2 weeks to 1 month).

Supporting the ground stations are the PAFs which process the HR and the LBR data and generate off-line (OL) products. They are also responsible for long-term archiving of data. PAFs are situated at Oberpfaffenhofen, Brest, Farnborough and Matera. They are coordinated by the Earthnet ERS Central Facility (EECF) at ESRIN in Frascati. The EECF offers various user facilities and products.

For the GOME a 'central' processing PAF will be required which will perform the 'operational' retrieval of the GOME data into a limited number of products such as global total ozone maps, global maps of ozone on standard pressure surfaces, maps of some other trace gases, global maps of cloud coverage and cloud height, and certain other standard products. These data products may be distributed by this 'central' PAF to the other PAFs and directly to the user community.

In addition there will be a need for some user groups to have access to the Level 1 products in order to generate special data products (at Level 2 or higher). Level 1 products would also be required by specialists who wish to investigate alternative retrieval algorithms. It is desirable that in such cases adequate cooperation with ESA and the central PAF be maintained in order to ensure their validity.

Table 5.1 Estimated code and data throughput requirements for the GOME

	Level 1	Level 2	Level 3	Level 4	Archiving*
Data generated (kb/s)	40	1 to 10	0.5 to 5	0.5 to 5	40 to 60
Processing (kFLOP/s)	20	100	10	50	10
Lines of code (x 1000)	4	15	3	10	45

[* including testing and validation]

6. CONCLUDING REMARKS

It is clear from the foregoing parts of the report that there is an urgent need for an instrument to observe ozone and other gases involved in ozone photochemistry in the period covered by ERS-2. (Further insights are provided in Annex 3 which compares the GOME with existing and planned instruments). It is also clear that the concept of the GOME is very attractive. The GOME should produce unique data as there is no other instrument available on its time scale which duplicates its capabilities. The GOME fills a slot in the observing strategy and could well become the prototype of future ozone monitoring instruments.

The high spectral resolution combined with a wide spectral range is particularly important as it means that, in addition to applying the traditional backscatter approach (viz SBUV), the GOME can also use another retrieval technique. This is differential optical absorption spectroscopy (DOAS) which allows ozone data to be obtained without recourse to absolute radiometric calibration.

The GOME is noteworthy for its robust calibration system which does not depend on one technique but seeks to exploit several. These include views of both the sun (via diffuser plate) and the moon as well as an internal source. Both radiometric and wavelength calibration will be possible.

Calculations show that the GOME should be capable of viewing several important species in addition to ozone, in both the stratosphere and the troposphere+ (see Table 2.2). In the case of ozone it should be possible to derive profiles as well as column densities. Furthermore, its ability to detect aerosols coupled with its direct view of the poles, place the GOME in the position to make a very significant contribution to polar ozone chemistry. It is an important response to the request of the International Ozone Trends Panel *(WMO 1990a)* for better data.

ANNEX 1

DATA RETRIEVAL AND SIGNAL-TO-NOISE CALCULATIONS

1. RETRIEVAL OF TRACE GAS AMOUNTS

There are two methods by which GOME can retrieve ozone total column amounts.

i) GOME DOAS

The application of this method of retrieving information on the distribution of trace atmospheric gases from a satellite borne spectrometer is one of the main scientific objectives of GOME. One of the primary advantages of DOAS is that it does not require an absolute radiometric calibration.

The basis of the method lies in the identification of 'finger-print' banded spectral features of a gas. From the GOME observations of the optical density (OD) and a knowledge of the corresponding differential absorption cross-section (laboratory determinations) of such a feature, the column amount, Ic, can be determined via the Beer Lambert law:

$$\Sigma l = OD/\sigma$$

where $OD=ln(I_0/I)$ and I and I_0 are the transmitted and incident light intensity respectively. In the ultraviolet and visible parts of the spectrum a number of important trace gases (e.g. O_3 and NO_2) have readily identifiable features.

ii) GOME BUV

The use of radiometric measurements of the wavelength dependence of the back scattered ultraviolet radiation to determine both the amount of O_3 and its vertical profile were first proposed in the late 1950s. Several experiments using this approach have been flown in space, the most famous being the SBUV and TOMS instruments aboard the Nimbus-7 satellite, which have produced the pictures of 'ozone holes' (Figs. 2.3 and 2.4).

The total amount or vertical profile of O_3 is calculated by inversion of the observed flux of light at selected wavelengths in the ultraviolet. The disadvantage of this approach is that it depends on the BRDF of the diffuser plate used to establish the radiance calibration of the instrument.

The GOME records the backscattered ultraviolet radiation in the same wavelength region as the SBUV and TOMS instruments, and it is proposed to use GOME data in this region for the retrieval of O_3 total column amounts and vertical profiles.

This is important for two reasons. Firstly it provides continuity with TOMS and SBUV instrument measurements and secondly it allows a direct comparison to be made between total column ozone derived from this wavelength region with that derived by the DOAS technique in the visible region.

2. SIMULATION OF GOME OBSERVATIONS

In order to estimate accurately the detection limits for the measurement of atmospheric trace gas species in nadir viewing geometries, it is necessary to simulate the type of data that should be obtained by the GOME. For this purpose the LOWTRAN-7 computer program has been used. This program was developed by the AFGL for the simulation of atmospheric transmission. It includes single and multiple scattering routines and a variety of different model atmospheres can be used. A simple way to estimate the sensitivity of individual GOME-DOAS retrievals for the determination of total column amounts of target molecules is to evaluate the signal-to-noise ratios (S/N) for GOME-DOAS observations and then to compare these with anticipated column absorptions in nadir viewing. This was done with the aid of the LOWTRAN-7 program which was used to calculate the flux of photons reaching the GOME instrument.

For clean and polluted air conditions latitudes of 55°N (or S) were used at the spring equinox. However, for ozone hole conditions a latitude of 70° at the spring equinox was selected. Estimated column absorptions due to banded absorption features of the target molecules are listed in Tables A1.1.

In Tables A1.2 the column absorptions for the different trace gases are compared with the noise calculated for a 1.5 s observation at highest resolution available to GOME (i.e. two detector pixels 0.24 nm in channels I and II and 0.4 nm in channels III and IV). The signal-to-noise estimates for a single readout are then tabulated.

It is important to point out that if there are N bands of an absorber, then sensitivity for retrieval of a trace gas is increased by $(N)^{1/2}$. So for gases with many absorptions, this improves the precision further. Co-adding observations is equivalent to integrating on the chip for longer periods (i.e. increasing the integration time). Both approaches reduce the GOME noise at the expense of the spatial resolution. These techniques improve the sensitivity of the GOME.

Examples of the usefulness of co-adding GOME data for 30 s are given for night time NO_3 and ClO in Tables A1.2. Although NO_3 absorption at night is still below the detection limit, (i.e. the S/N $\approx$ 1), the ClO example emphasises the power of this technique.

Table A1.1a. GOME-DOAS Estimated Column Absorptions for a Clean Unpolluted Atmosphere (nadir viewing at 55°N with a 10.00 a.m. equator crossing at the spring equinox). SZA=60.2°.

Gas	Wavelength Range	Column Amount	Differential Absorption Cross Section Range	Atmospheric Column Absorption at GOME detector pixel (0.12 or 0.2 nm)
	nm	$c_i l$ cm^{-2}	σ_i cm^2	$(1+\sec(SZA))c_i l\ \sigma_i$
O_3 (Huggins bands)	310-350	$9.2\times E^{18}$	$(0.5\text{-}10)E^{-20}$	$(0.14\text{-}2.8)$
O_3 (Chappuis bands)	400-700	$9.2\times E^{18}$	$(0.1\text{-}4)E^{-21}$	$(2.8\text{-}110)\times 10^{-3}$
NO_2	330-500	$3\times E^{15}$	$(0.5\text{-}3)E^{-19}$	$(4.5\text{-}27)\times 10^{-4}$
NO_3	600-700	$5\times E^{13}$	$(1\text{-}1.8)E^{-17}$	$(1.5\text{-}2.7)E^{-3}$
NO_3	600-700	$1\times E^{13}$	$(1\text{-}1.8)E^{-17}$	$(3.0\text{-}5.4)E^{-4}$
NO_3	600-700	$1\times E^{12}$	$(1\text{-}1.8)E^{-17}$	$(3.0\text{-}5.4)\times 10^{-5}$
H_2O	500-790	$6.6\times E^{22}$	$(1\text{-}10)E^{-26}$	$(2.0\text{-}20)\times 10^{-3}$
O_2	500-790	$3\times E^{24}$	$(1.6\text{-}24)E^{-26}$	$(0.15\text{-}2.2)$
O_4	350-700	-	-	$(3.8\text{-}60)\times 10^{-3}$
HCHO	320-350	$2\times E^{15}$	$(1\text{-}6)E^{-20}$	$(0.52\text{-}3.2)\times 10^{-4}$
ClO	305-320	$1.5\times E^{14}$	$(8\text{-}2)E^{-19}$	$(3.2\text{-}0.75)\times 10^{-4}$
BrO	320-380	$1.5\times E^{13}$	$(0.6\text{-}1)E^{-17}$	$(2.3\text{-}3.9)\times 10^{-4}$

Table A1.1b. GOME DOAS Estimated Column Absorptions for a Polluted Atmosphere (nadir viewing at 55°N with a 10.00 a.m. equator crossing at the spring equinox). SZA=54°.

Gas	Wavelength Range	Column Amount	Differential Absorption Cross Section Range	Atmospheric Column Absorption at GOME detector pixel (0.12 or 0.2 nm)
	nm	$c_i l$ cm^{-2}	σ_i cm^2	$(1+\sec(SZA))c_i l\ \sigma_i$
SO_2	305-320	$5\times E^{16}$	$2E^{-19}$	2.6×10^{-2}
HCHO	320-350	$5\times E^{15}$	$(1\text{-}6)E^{-20}$	$(1.74\text{-}9.1)\times 10^{-4}$
NO_3	600-700	$1\times E^{14}$	$(1\text{-}1.8)E^{-17}$	$(3.0\text{-}5.5)\times 10^{-3}$

Table A1.1c. GOME-DOAS Estimated Column Absorptions for Ozone Hole Conditions (nadir viewing at 70°N with a 10.00 a.m. equator crossing at the spring equinox). SZA=54°.

Gas	Wavelength Range	Column Amount	Differential Absorption Cross Section Range	Atmospheric Column Absorption at GOME detector pixel (0.12 or 0.2 nm)
	nm	$c_i l$ cm^{-2}	σ_i cm^2	$(1+\sec(SZA))c_i l\ \sigma_i$
OClO	320-440	$1.0\times E^{13}$	$(0.1\text{-}1.3)E^{-17}$	$(0.44\text{-}5.7)\times 10^{-4}$
OClO	320-440	$3\times E^{13}$	$(0.1\text{-}1.3)E^{-17}$	$(0.13\text{-}1.7)\times 10^{-3}$
OClO	320-440	$1.5\times E^{14}$	$(0.1\text{-}1.3)E^{-17}$	$(0.66\text{-}8.6\times 10^{-3}$
ClO	305-320	$1.5\times E^{15}$	$(8\text{-}2)E^{-19}$	$(5.3\text{-}1.3)\times 10^{-3}$
BrO	320-380	$2.5\times E^{13}$	$(0.6\text{-}1)E^{-17}$	$(6.6\text{-}11)\times 10^{-4}$

1) The wavelength range is the range where the gas absorbs and where differential absorption cross sections can be estimated. No estimate for O_4 column amounts have been made here, instead the strength of the absorptions has been estimated from atmospheric observations.

2) The polluted tropospheric scenario assumes a 1 km tropospheric layer of 20 ppb of SO_2 and 2 ppb of HCHO.

3) The values for the column amounts of OClO, BrO and ClO for 'Ozone hole conditions' are taken from recent measurements. The two values of OClO represent daytime and twilight conditions. The daytime amount of OClO is much lower than the other because it is rapidly photolysed by visible light.

Table A1.2a. GOME DOAS Estimated Signal-to-Noise Ratios for an Unpolluted Atmosphere (nadir viewing at 55°N for an ERS-2 orbit with a 10.00 a.m. equator crossing at the spring equinox)

Gas	Wavelength Range nm	Atmospheric Column Absorption (0.12 or 0.2 nm) $(1+\sec(SZA))c_i l\ \sigma_i$ OD	GOME Noise Level OD	Signal-to-Noise Ratio S/N
O_3 (Huggins bands)	310-350	(0.14-2.8)	$10\text{-}3.2E^{-4}$	2800-440
O_3 (Chappuis bands)	400-700	$(2.8\text{-}110)\times10^{-3}$	$2E^{-4}$	14-550
NO_2	330-500	$(4.5\text{-}27)\times10^{-4}$	$(3\text{-}2)E^{-4}$	1.5-9
NO_3 (30 s at night full moon)	600-700	$(1.5\text{-}2.7)E^{-3}$	0.04	0.07
NO_3 (Twilight)	600-700	$(3.0\text{-}5.4)E^{-4}$	$6E^{-4}$	1
H_2O	500-790	$(2.0\text{-}20)\times10^{-3}$	$2E^{-4}$	10-100
O_2	500-790	(0.15-2.2)	$2E^{-4}$	$750\text{-}1.1\times10^{-4}$
O_4	350-700	$(3.8\text{-}60)\times10^{-3}$	$2E^{-4}$	19-300
HCHO	320-350	$(0.52\text{-}3.2)\times10^{-4}$	$(5.6\text{-}3.2)E^{-4}$	0.1-1
ClO	305-320	$(3.2\text{-}0.75)\times10^{-4}$	$(80\text{-}5.6)E^{-4}$	0.04-0.13
ClO (with a 30 second average)	305-320	$(3.2\text{-}0.75)\times10^{-4}$	$(4\text{-}1)E^{-4}$	0.75
BrO	320-380	$(2.3\text{-}3.9)\times10^{-4}$	$(5.6\text{-}3)E^{-4}$	0.4-1.3

Table A1.2b. GOME DOAS Estimated Signal to Noise Ratios for a Polluted Troposphere (nadir viewing at 55°N for an ERS-2 orbit with a 10.00 a.m. equator crossing at the spring equinox)

Gas	Wavelength Range nm	Atmospheric Column Absorption (0.12 or 0.2 nm) $(1+\sec(SZA))c_i l\ \sigma_i$ OD	GOME Noise Level OD	Signal-to-Noise Ratio S/N
SO_2	305-320	2.6×10^{-2}	$(80\text{-}5.6)E^{-4}$	3.3
HCHO	320-350	$(1.5\text{-}9.1)\times10^{-4}$	$(5.6\text{-}3.2)E^{-4}$	0.26-2.8
NO_3 (30 seconds nighttime full moon)	600-700	$(3.0\text{-}5.5)\times10^{-3}$	0.04	0.08-0.14
NO_3 (Twilight)	600-700	$(3.0\text{-}5.5)\times10^{-3}$	$6E^{-4}$	5-9

Table A1.2c. GOME-DOAS Estimated Signal-to-Noise Ratios for Ozone Hole Conditions (nadir viewing at 70°N for an ERS-orbit with a 10.00 a.m. equator crossing at the spring equinox)

Gas	Wavelength Range	Atmospherc column Absorption (0.12 or 0.2nm) $(1+\sec(SZA)\,c_i l$	GOME Noise	Signal-to-Noise Noise Ratio S/N
OClO (daytime)	320-440	$(0.44\text{-}5.7)\times10^{-4}$	$(5.6\text{-}2)E^{-4}$	0.2
OClO (twilight)	320-440	$(0.13\text{-}1.7)\times10^{-3}$	$(17\text{-}6)E^{-4}$	0.3
OClO (nighttime)	320-340	$(0.66\text{-}8.6)\times10^{-3}$	0.06	0.01 - 0.14
ClO	305-320	$(5.3\text{-}1.3)\times10^{-3}$	$(80\text{-}5.6)E^{-4}$	0-7-2.3
ClO (with a 30 second average)	305-320	$(5.3\text{-}1.3)\times10^{-3}$	$(4\text{-}1)E^{-4}$	13.3-13
BrO	320-380	$(6.6\text{-}11)\times10^{-4}$	$(5.6\text{-}3)E^{-4}$	1.2-3.66

As for Tables A1.1 but note that the atmospheric column absorption at detector pixel level have been calculated with the following assumptions:

i) for clean unperturbed and polluted air conditions the photon flux reaching the telescope in 1.5 sec has been estimated from a LOWTRAN7 calculation for 55°N (or 55°S) at the spring equinox;

ii) for ozone hole conditions the photon flux reaching the telescope in 1.5 sec has been estimated from a LOWTRAN-7 calculation for 70°N (or 70°S at the spring equinox;

iii) the pixel resolution has been assumed to be 0.1 nm over the range 240-400 nm and 0.2 nm over range 400-790 nm;

iv) telescope area is to be 5 cm^2, the slit field of view 1 x 10^5 sterad, the optical throughout 0.115 (240-400 nm) or 0.2 (400-790) and the detector quantum efficiency 0.5.

Averaging for longer than 1.5 s reduces spatial resolution but increases the signal-to-noise ratio and sensitivity.

ANNEX 2

SENSITIVITY STUDIES FOR CONSTITUENT MEASUREMENTS

SUMMARY

Sensitivity studies are presented for the GOME nadir measurements of atmospheric composition. Constituent profile information is determinable in some cases by differential penetration of backscattered light at different wavelengths (as in TOMS-SBUV), and by the variable temperature structure of some molecular absorptions. Height resolution is limited to 8-10 km from differential penetration and 5 km in favourable cases using temperature structure.

The quantities retrieved from GOME measurements include:
— Total column amounts of O_3, O_4, O_2, H_2O, NO_2, HCHO, SO_2, ClO, OClO, and BrO; the column of NO above the ozone layer.
— Stratospheric profiles of O_3; the profile of tropospheric O_3, at limited altitude resolution. Stratospheric O_3 profile information, discrimination between stratospheric and tropospheric O_3 columns, and tropospheric O_3 profile information is derived from the temperature dependences of the absorption features and from the wavelength-dependent back scattering of ultraviolet light.
— Clouds and aerosols. GOME will obtain data providing information on stratospheric and tropospheric aerosols. Stratospheric aerosol measurements include background aerosol, Junge layer, and polar stratospheric clouds (PSCs); tropospheric aerosols, including clouds, sand winds, and soot from forest fires.
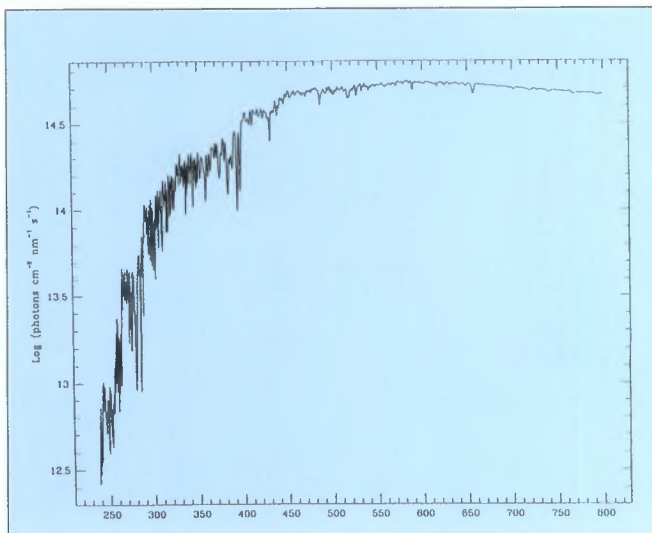
A2.1. INTRODUCTION

To gauge the capabilities of the GOME instrument, the sensitivity of the retrievals of the concentrations of molecular species concentrations as functions of altitude, have been studied under a wide variety of geographic conditions. The calculations were performed for nadir viewing and included expectations of detector quantum efficiency and noise performance as well as instrument etendue and optical throughput (derived from the Phase-A instrument study).

The calculations used atmospheric concentration profiles derived from the MPI Mainz global 1-D and 2-D models (*C. Bruhl, R. Hennig & P. Crutzen*, private communication) for both clean and polluted air in daytime conditions. Additional information on night time NO_3 was derived from *Norton & Noxon [1986]*. Constant mixing ratios were assumed for CO_2 (340 ppm) and O_2 (20.95%).

Spectra for the simulations are taken from the best available sources including digitally acquired electronic spectra obtained in the laboratory at MPI Mainz. For each individual molecule allowance was made for potential interference from other absorbing species. Confirmation of the O_4 spectrum was provided by a 1.0 airmass high resolution visible solar spectrum from Kitt Peak National Observatory (KPNO) (*courtesy of R. Kurucz*).

An integration time of 2 seconds was assumed throughout but in reality, in many cases, increased sensitivity could be obtained by longer averaging at the sacrifice of spatial resolution. A limitation in pressure altitude corresponding to 60 km

Figure A2.1 The LOWTRAN7 solar source function over the GOME spectral measurement range.
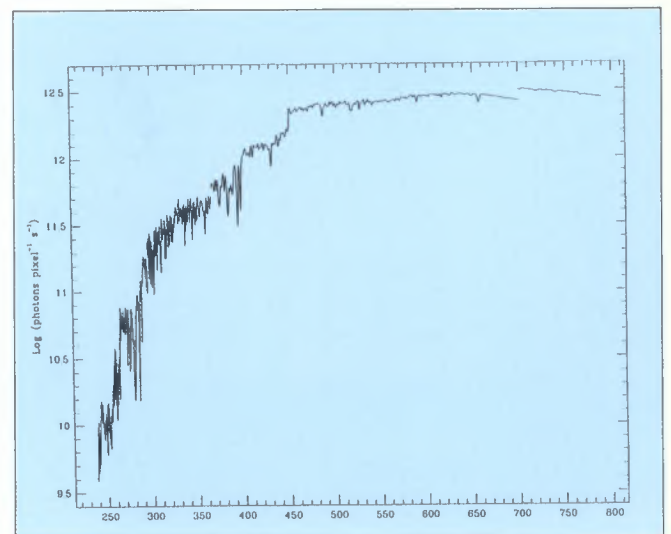

Figure A2.2 The solar spectrum that would be observed by the GOME, based on the LOWTRAN7 solar source spectrum and including the instrument etendue, optical throughout, detector quantum efficiency and beam dilution.
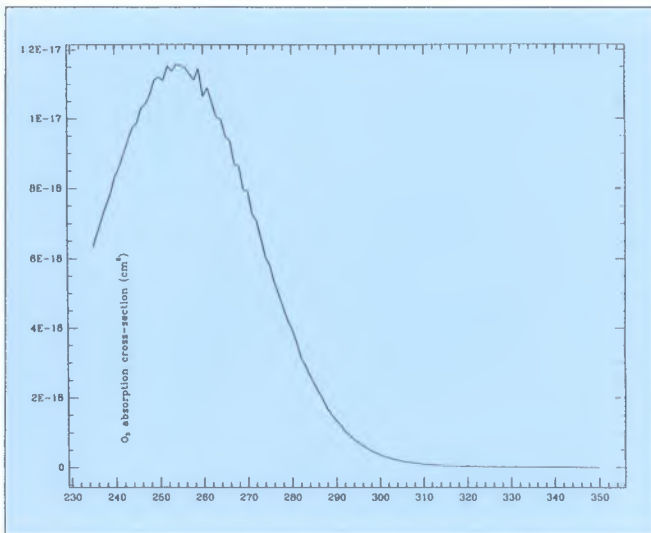
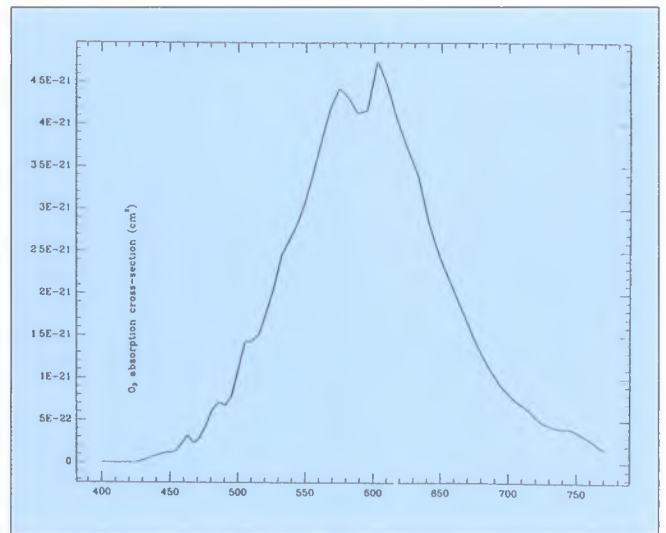Figure A2.3 a) Absorption cross sections for the Hartley and Huggins bands

Figure A2.3 b) Absorption cross-sections for the Chappuis bands.

was imposed reflecting the limitation of the model calculations to the stratosphere and troposphere.

Calculations of geometries were performed with multilayer, curved-shell models (including refraction) to provide line of sight column densities as functions of temperature, pressure, and altitude. Also used in the calculations was the AFGL LOWTRAN7 code (with multiple scattering), the Smithsonian Astrophysical Observatory line-by-line radiance code [*Chance & Traub, 1987*] and code written specifically for this study. Most calculations were made assuming an average albedo for the Earth of 0.3. The effect of surface spectral reflectance on the measurements was investigated. This will be discussed later in more detail.

The 2-D model results used in the calculations were those for January 1, with global coverage extending from 85°S to 85°N, which samples a very representative set of the Earth's atmospheric conditions. Most calculations were done at 35°N, which corresponds to a solar zenith angle of 63.4° for a 10:00 satellite crossing time. The effect of other solar zenith angles on measurements, including those in polar regions, was investigated in some detail. This is also discussed later.

The solar illumination source function used in these studies was the one from LOWTRAN7. Aerosol and molecular scattering were also derived from LOWTRAN7. Measurement capabilities were calculated assuming a lower limit of 1% for measurement precision reflecting the difficulty of
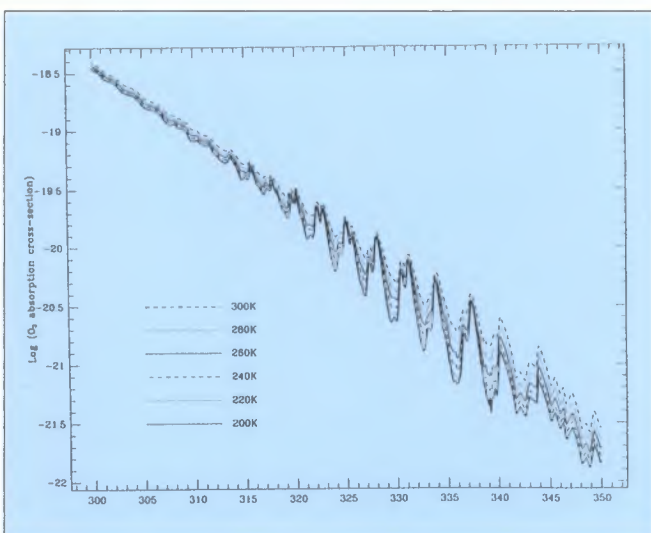

Figure A2.4a. The absorption cross sections of ozone, as a function of temperature, in the part of the Huggins band having a discrete vibrational structure.
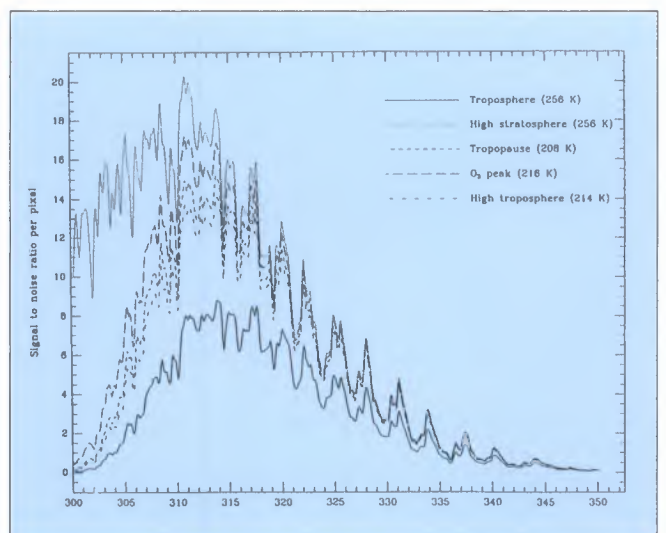

Figure A2.4b. The sensitivity of the ozone spectrum as measured by the GOME, at GOME's spectral resolution, for 1% changes in the total ozone column at various levels in the atmosphere. Derived using the full multiple scattering formulation of LOWTRAN7.
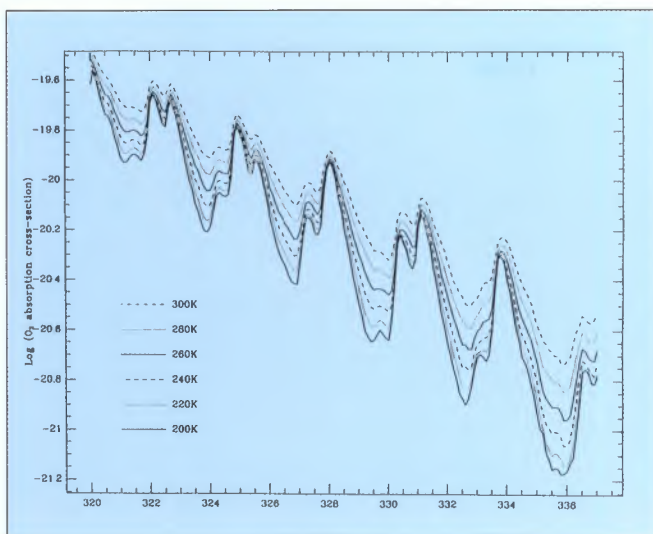
Figure A2.4c. Similar to Figure A2.4a but for a more restricted part of the Huggins bands and with a full calculation of the temperature dependence of the bands.
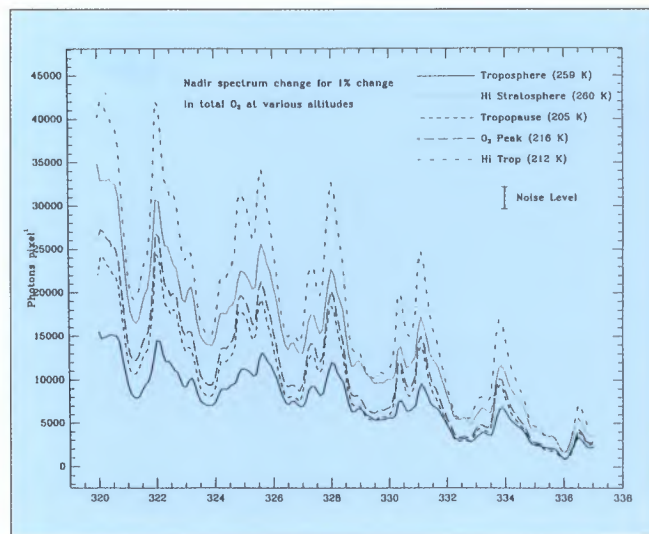

Figure A2.4d. Similar to Figure A2.4b, but with the Figure A2.4c data input.

making more precise measurements and uncertainties associated with instrument calibrations. This could well prove to be overly pessimistic as much higher precisions may be achieved in practice. The GOME should be capable of contributing to the monitoring of long-term trends in global O_3.

Figure A2.1 shows the LOWTRAN7 solar source function over the GOME measurement range. Figure A2.2 shows the solar spectrum as it would be measured by GOME, including the etendue, optical throughput, detector quantum efficiency (normalised to photons-pixel-sec for the various detector channels) and the beam dilution (18% of the instrument field of view is filled by the sun when the GOME views the central part of the solar disk).

A molecule by molecule discussion of the retrieval studies follows. The results are summarised in Table A2.1. These results were derived from the 1 January, 35°N studies, implying a solar zenith angle of 63.4°, as mentioned previously. For most molecules they are valid for solar zenith angles of up to at least 80°.

A2.2. MOLECULES IN AN UNPOLLUTED ATMOSPHERE

Ozone (O_3)

Concentrations were retrieved from the GOME observations using the ultraviolet (Hartley and Huggins) bands and the visible (Chappuis) bands. The absorption cross-sections for these bands are shown in figure A2.3a-b. Precise determinations of column O_3 were obtainable from Chappuis band measurements. Observations of signals in the ultraviolet bands, using knowledge of penetration depth as a function of wavelength to obtain stratospheric profile information, has become a standard technique for satellite ozone measurements

(e.g. by the SBUV instruments). With the current instruments differential penetration is measured using a number of discrete wavelength channels that are much broader than the GOME's spectral resolution. With the GOME this type of measurement can be included as a subset of its O_3 measurements.

A strength of the GOME instrument is that it should provide extensive maps of tropospheric ozone. Some determinations of tropospheric O_3 in tropical regions have been made in recent studies by subtracting stratospheric O_3, measured by the SAGE instrument, from TOMS total ozone measurements [*Fishman, 1988*]. The GOME includes the ultraviolet bands used in past and present satellite instruments for measuring O_3, but affords continuous coverage of the region above
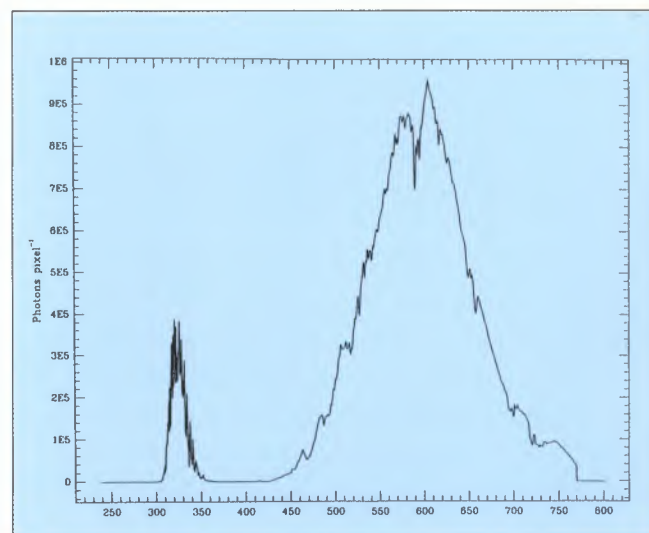

Figure A2.5a. The change (in photons per pixel for a two/second integration time) in the GOME nadir spectrum associated with a 20% reduction in the total column of ozone above the tropopause, symmetric about the ozone peak. This is intended to simulate moderate ozone hold conditions.
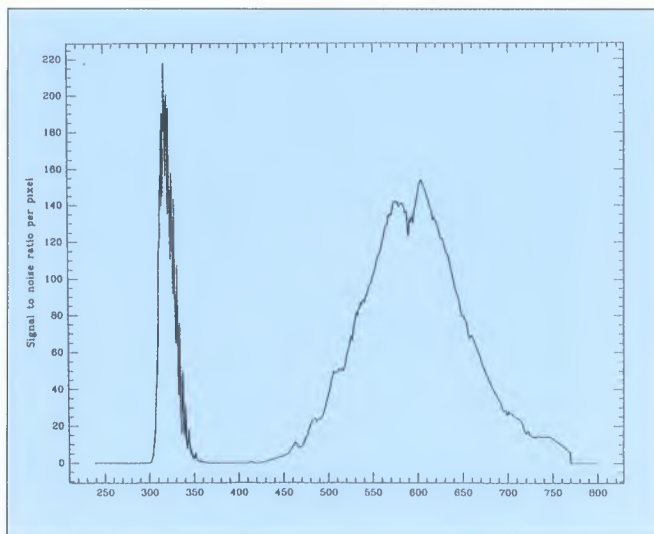
Figure A2.5b. The corresponding signal-to-noise ratios that should be achieved by the GOME.

Figure A2.6. $(O_2)_2$ in a solar spectrum observed at sunset at the Kitt Peak National Observatory, USA.

240 nm, and at significantly higher resolution. This provides leverage in the retrieval of tropospheric ozone profiles due in part to the temperature-dependent structure of the Huggins bands (see recent measurements by *Bass & Paur, 1985* and by *Yoshino et al., 1988*).

The Huggins bands have discrete vibrational structure between 300 and 350 nm, with features having widths significantly less than 1 nm. This is the sharpest vibrational structure of any electronic band of O_3 that has been studied. It has strong temperature dependence due to the presence of thermally excited vibrational levels in the electronic ground state. It is this temperature dependent structure that provides a spectral signature for tropospheric ozone. This takes the form of weak
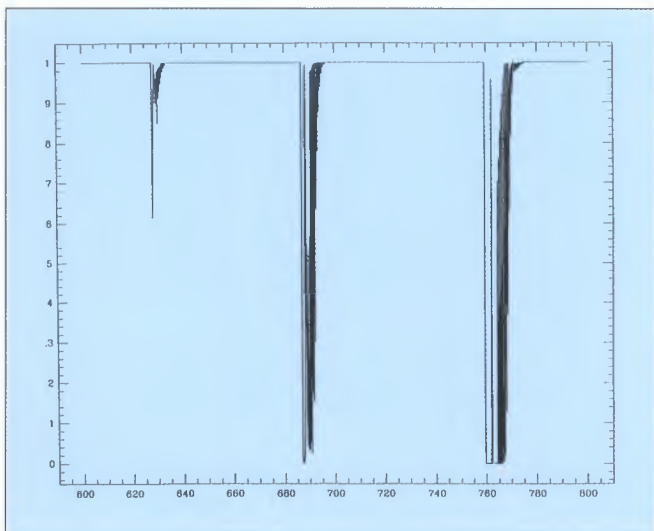
band absorptions located between the stronger absorption peaks which are due to absorption from O_3. The variation of the O_3 spectrum with temperature may be viewed as forming part of a reference set of spectra to be matched to the observed spectrum.

Generally, tropospheric ozone is significantly warmer than stratospheric ozone at any altitude in the stratosphere where there is significant O_3. This makes it possible to obtain tropospheric O_3 column amounts from instruments with the resolution and sensitivity of GOME. However, the determination of the complete vertical profile of O_3, including the troposphere requires the development of a sophisticated algorithm.

Figure A2.4a shows absorption cross-sections of O_3 in the

Figure A2.7. The absorption spectrum of oxygen (O_2) between 600 and 800 nm at nadir at the GOME spectral resolution.
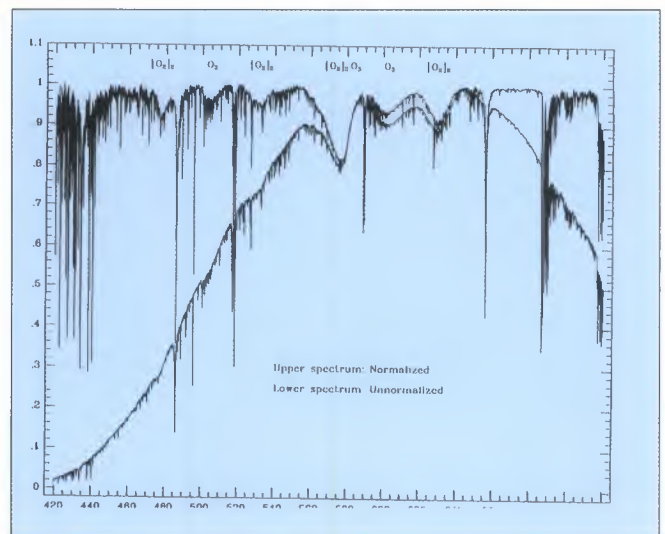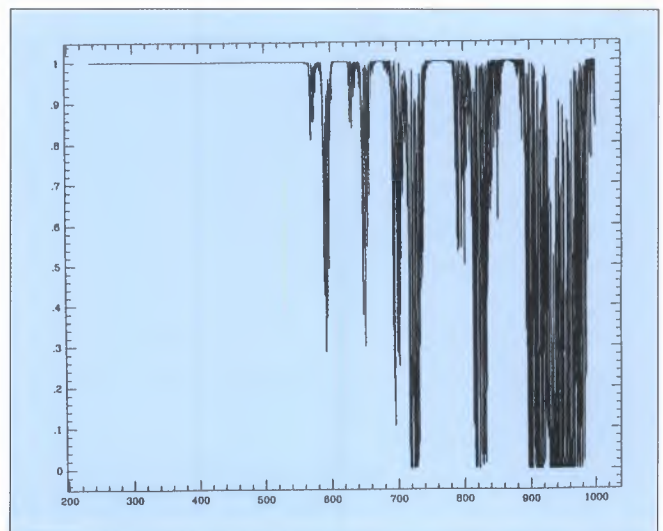

Figure A2.8. The absorption spectrum of water vapour (H_2O) at nadir between 200 and 1000 nm.
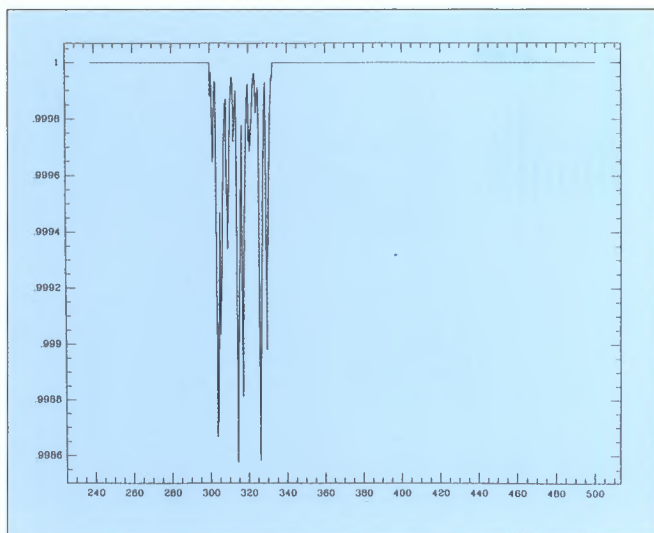
Figure A2.9. The absorption spectrum of formaldehyde (HCHO) at nadir between 240 and 500 nm for moderate atmospheric pollution i.e. an enhanced HCHO column of 5.0×10^{15} cm^{-2} with standard 35 geometry.

relevant part of the Huggins bands for the range of temperatures encountered in the atmosphere. Figure A2.4b shows the sensitivity of the nadir spectrum as measured by the GOME, at the GOME resolution, for 1% changes in total ozone column at various levels in the atmosphere. The sensitivity is represented by the signal to noise ratios per pixel that can be achieved in 2 seconds of averaging time by the GOME in measuring these 1% differences at different altitudes.

Figures A2.4c and A2.4d show similar calculations for the 320-337 nm region alone. This is the most important part of the spectrum for distinguishing O_3 contributions from different levels in the atmosphere using the temperature dependence of the Huggins bands. Figure A2.4b was derived using the full multiple scattering formalism of LOWTRAN7 to show the main characteristics of the radiance changes due to variations in ozone distribution with temperature. It does not, however, fully model the temperature dependence of the bands.

Figure A2.4d was derived using a simpler, single scattering radiance code that did allow the full calculation of the temperature dependence of the Huggins bands. Note differences in spectral structure in Figure A2.4d (as compared with Figure A2.4c) due to the changes in the O_3 spectrum with temperature. Note also the offset due to differential penetration for similar temperatures but different altitudes (e.g. troposphere and high stratosphere, high troposphere and O_3 peak). The sensitivity studies indicate that the GOME should achieve a precision of at least 1% of the total column amounts for retrieval of O_3 with a 5 km vertical resolution throughout the stratosphere and troposphere.

In more recent studies (i.e. after the GOME sensitivity

studies had formally ended) it has proved possible to implement the LOWTRAN7 radiance code with both multiple scattering and the temperature dependence of the O_3 Huggins bands. It has additionally proved possible to imbed this code in a non-linear least squares retrieval programme to begin testing ozone retrievals in a more rigorous fashion (see Section 3.2 and Figures 3.1 and 3.2).

The ability of the GOME to measure polar ozone depletion has also been considered. The calculations were performed using a solar zenith angle of 80°, appropriate to 80°N/80°S at the equinox. Moderate ozone hole conditions were simulated by removing 20% of the total column ozone from the atmosphere above the tropopause, symmetric about the ozone peak. Figure A2.5a shows the change in the GOME nadir spectrum for this amount of ozone depletion, in photons-pixel for 2 seconds of integration time. Figure A2.5b shows the signal to noise ratio that should be achieved by the GOME to measure this difference. In its nadir mode the GOME should be able to measure polar ozone depletion over the full geographic coverage of the orbit.

In summary, the GOME should be able to determine ozone column densities quite accurately (to better than 1% precision); significantly better than SBUV. It should also be able to clearly distinguish between tropospheric O_3 and stratospheric O_3 and provide moderate (1% of total column ozone) profile information in the troposphere. The GOME should be able to make precise measurements of polar ozone depletion to at least 80° latitude; probably further. The ozone measurements of the GOME should not be subject to long-term degradation of the type suffered by SBUV-TOMS, as discussed further in the instrumentation section.
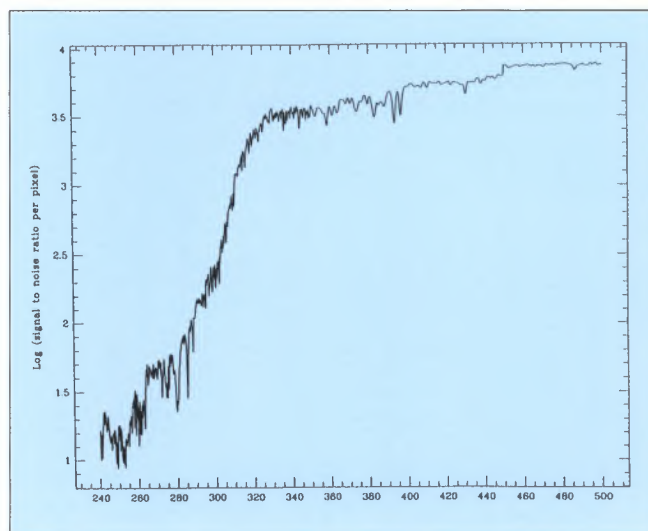

Figure A2.10. The signal-to-noise ratios of the sulphur dioxide (SO$_2$) signal between 240 and 500 nm for moderate pollution in the boundary layer (i.e. 20 ppbv with standard 35 geometry).
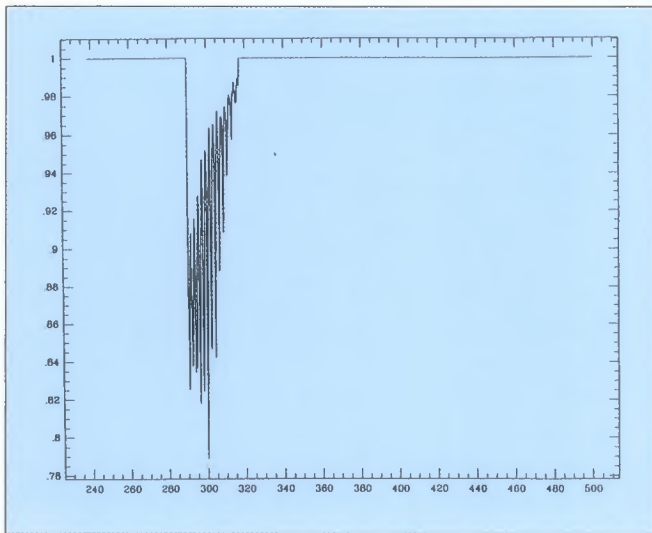
Figure A2.11. The absorption spectrum of sulphur dioxide (SO_2) at nadir between 240 and 500 nm for moderate pollution in the boundary
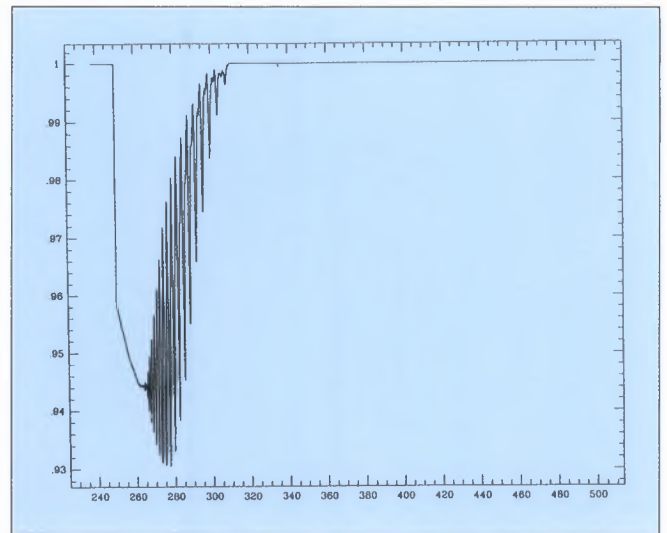

Figure A2.12. The absorption spectrum of chlorine monoxide (ClO) at nadir between 240 and 500 nm under moderate ozone hole conditions

Oxygen (O_4)

Quantitative laboratory O_4 spectra were not available for sensitivity studies. However, as O_4 is quite prominent in the solar spectrum observed from the ground (see Figure A2.6 , courtesy of R. Kurucz), it should be observable at high precision by the GOME (note that following the van der Waals notation it is called $(O_2)_2$ in the Figure). As O_4 is a van der Waals molecule (or a collision complex), and thus has a concentration strongly dependent upon temperature and pressure, it is a useful diagnostic for cloud top and boundary layer height.

Oxygen (O_2)

Penetration depth determinations from O_2 provide information

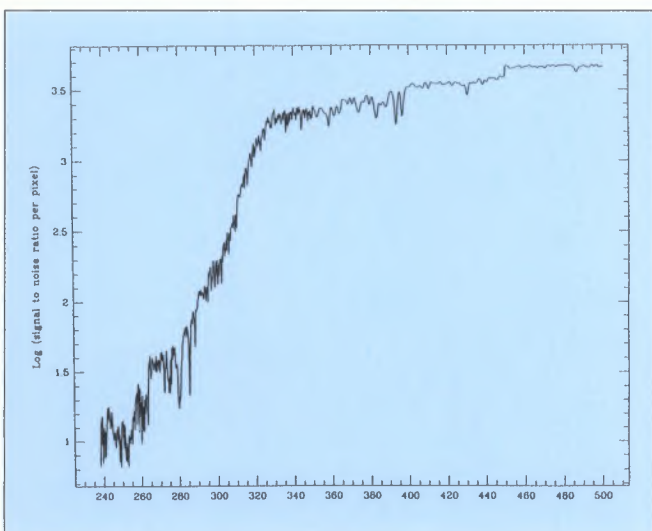**Figure A2.13.** The signal-to-noise ratios of the chlorine monoxide (ClO) signal between 240 and 500 nm for a nadir spectrum and an 80° solar zenith angle under moderate ozone hole conditions i.e. assuming a chlorine monoxide absorption of 1.5×10^{15} cm^{-1}.

about cloud and boundary layer heights. O_2 absorbs very strongly in the atmosphere, mainly near 690 and 760 nm so O_2 column measurements should have a precision of 1%, the projected limit for strong absorbers. Figure A2.7 shows O_2 absorption for a nadir spectrum at the GOME resolution.

Water Vapour (H_2O)

This absorbs strongly between 700 and 1000 nm, as shown in Figure A2.8. H_2O should be retrievable from the GOME observations with an accuracy of 1%, corresponding to the limit of the GOME technique applied to absorption between 700 and 790 nm.

Nitric Oxide (NO)

The GOME should be able to measure NO using the (1,4), (1,6) and (0,3) gamma bands which fluoresce between 255 and 280 nm (as determined in model sensitivity studies by *Frederick & Abrams (1982)*). The gamma band emission provides a means to derive column amounts for NO above the level where O_3 absorbs strongly (approximately above 40 km).

Nitrogen Dioxide (NO_2)

Concentrations of NO_2 should be retrievable from ultraviolet/visible absorption between 300 and 600 nm. NO_2 has been observed in the stratosphere using limb-scattered light in this wavelength range by SME and by balloon measurements (*Mount et al., 1983, 1984; McElroy, 1988*). Under typical clean air mid-latitude conditions GOME should be able to measure the total column amounts of NO_2 with an accuracy of the order of 1%, which corresponds to a value of 3×10^{13} cm^{-2} i.e to an average tropospheric mixing ratio of 1.6 pptv. Tropospheric mixing ratios of NO_2 vary between approximately 10–40 pptv in clean air and 10 to 100 pptv in polluted air.
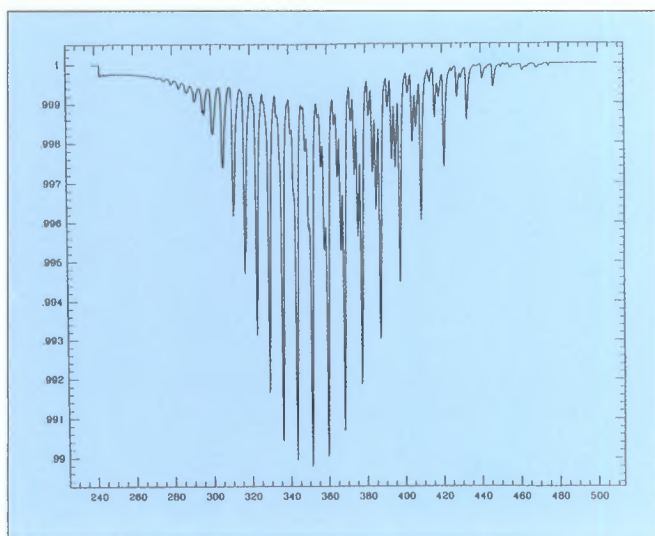
Figure A2.14. The absorption spectrum of chlorine dioxide (OCIO) at nadir between 240 and 500 nm assuming a chlorine dioxide absorption of 1 x 10^{-2} cm $^{-1}$ corresponding to moderate ozone hole conditions.

The NO_2 absorption features are known to be temperature-dependent and is the subject of current high-resolution laboratory studies (*G. Fiocco*, private communication). If it transpires that the temperature dependence of the spectrum provides a substantial spectroscopic signature for warm NO_2, then this could be used by the GOME to distinguish tropospheric column amounts from stratospheric column amounts thereby providing maps of tropospheric NO_2 pollution.

A2.3. MOLECULES IN A POLLUTED ATMOSPHERE

Formaldehyde (HCHO)

This absorbs between 250 and 360 nm, with its strongest absorption between 300 and 350 nm. Figure A2.9 shows this portion of the HCHO absorption spectrum for a concentration of 1.6×10^{16}; corresponding to the nadir concentration along the viewing path for the standard 35° geometry with an enhanced HCHO column of 5.0×10^{15} (moderate pollution). The short wavelength absorption is strongly obscured by O_3 absorption but there is a clearly discernible contribution between about 300 and 350 nm. This window is very dependent on the total O_3 concentration, the viewing geometry, the temperature and concentration of tropospheric O_3 (increased absorption by warm tropospheric ozone will further obscure the HCHO). In these circumstances HCHO should be measurable in the nadir view, chiefly at low latitudes.

The sensitivity for HCHO measurements with this concentration as determined by reference to Figure A2.10, which shows the calculated signal/noise ratios per pixel for this nadir geometry, is 5. Thus it should prove possible to observe moderately enhanced HCHO with modest precision. Major pollution should be readily measured. This signal/ noise ratio was determined using only the portions of the HCHO spectrum

close to 350 nm which remain reasonably unobscured by O_3. The sensitivity increases by as much as a factor of 2 under conditions of low amounts of column O_3.

Sulphur Dioxide (SO$_2$)

This absorbs between 290 and 315 nm and should be observable by the GOME in a polluted troposphere when amounts of tropospheric ozone are low. For a tropospheric concentration of 20 ppbv (moderate pollution in the boundary layer) quantitative comparison of Figure A2.11, which shows the SO_2 spectrum, with Figure A2.10, which shows the nadir signal to noise ratios per pixel, gives a signal/noise ratio of 60 (i.e. better than 2% precision), but this is highly variable, depending on the O_3 concentration. SO_2 in normal background concentrations will not be observable.

A2.4. OZONE HOLE MOLECULES

Chlorine Monoxide (ClO)

This absorbs between 220 and 310 nm (Fig. A2.12) but is strongly masked by ozone absorption. The sensitivity limit for the GOME will vary from about 10^{13} to 10^{15} cm $^{-2}$ depending on the ozone concentration so the GOME cannot be expected to be able to detect ClO under normal conditions. However, unusually high ClO concentration coupled with low O_3 concentration (which will improve the detection limit substantially), as found in the Antarctic ozone 'hole' (*de Zafra et al. 1987*) should make ClO columns observable.

An absorption spectrum of ClO calculated using a representative O_3 hole concentration of 1.5×10^{15} cm $^{-2}$ is shown in Figure A2.12. Comparison with a synthesis of the nadir spectrum at an 80° solar zenith angle, under moderate ozone
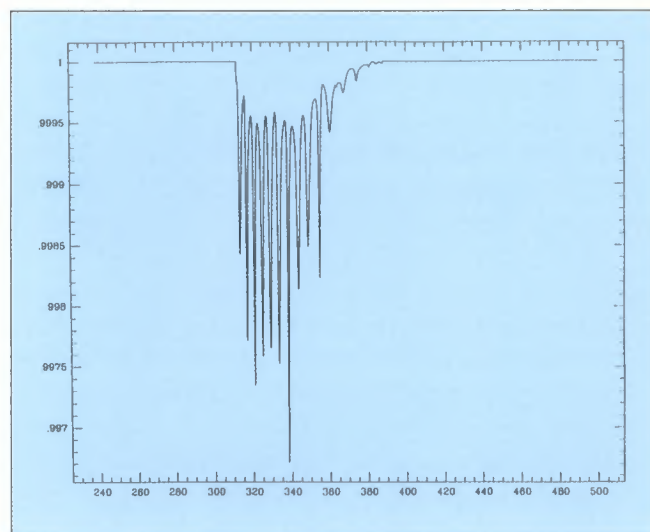

Figure A2.15. The absorption spectrum of bromine monoxide (BrO) at nadir between 240 and 500 nm for a nadir concentration of bromine monoxide of 2.5 x 10^{13} cm $^{-2}$ corresponding to moderate ozone hole conditions.
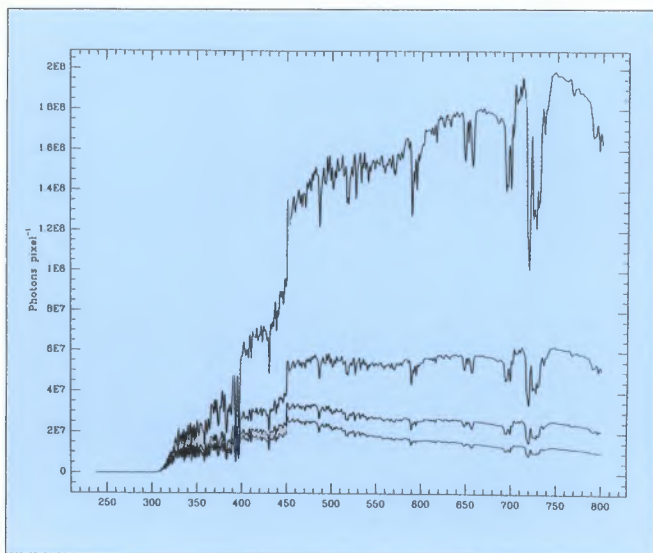
Figure A2.16. The 35°N nadir reflected solar spectrum for albedos ranging from 0.03 to 1.0 calculated using the LOWTRAN7 radiance code including multiple scattering. The calculations are for photons per pixel with 2-s integration times.

hole conditions (Fig. A2.13), gives a precision for ClO column measurements of 10%.

Chlorine Dioxide (OClO)

OClO is formed in the atmosphere from the reaction of BrO with ClO and destroyed by photolysis. Absorption occurs strongly between 280 and 440 nm. The structured absorption between 320 and 420 nm has been used to observe OClO at night over Antarctica in spring (column densities of 1×10^{14} molecule cm^{-2} (*Solomon et al., 1987; Solomon et al., 1989*). Using the synthesised nadir spectrum for moderate ozone hole conditions (Fig. A2.13) and assuming a OClO absorption of 1×10^{14} cm^{-2}, corresponding to twilight concentrations (Fig. A2.14), a 2% measurement precision was obtained for OClO. For a typical daytime concentration (2×10^{13} cm^{-2}) it should be possible to measure OClO to 10% precision.

Bromine Monoxide (BrO)

This has been measured in the Antarctic spring using its ultraviolet absorption (*Solomon et al., 1989*). Figure A2.15 shows the absorption of BrO for a nadir concentration of 2.5×10^{13} cm^{-2} for the assumed ozone hole geometry. By comparing this with the synthesised nadir spectrum, it follows that it should be possible to measure column densities of BrO with a precision of 10%. Under normal stratospheric conditions, the BrO column density is 1.5×10^{13} cm^{-2}, implying that the GOME's global measurements (mapping of BrO) should have a precision of 15%.

A2.5. SURFACE REFLECTANCE AND SOLAR ZENITH ANGLES STUDIES

The absolute radiometric calibration of the GOME

instrument will provide new global information about surface spectral reflectance in the range 300-790 nm. Although the spatial resolution of GOME is limited, this data will be very useful scientifically. Further studies of the retrieval of the reflectance measurements by GOME will be made during Phase B. For the GOME, considerations of surface reflectance and solar zenith angle are linked. Increases in path due to larger solar zenith angle can offset decreases in light levels due to lower reflectance for measurements made at wavelengths that penetrate fully to the ground. The increase in path length can also degrade measurements of tropospheric molecules made at shorter wavelengths (e.g. O_3) due to increased loss of tropospheric information because of increased Rayleigh scattering in the stratosphere. The standard conditions used for the sensitivity studies (ie 35°N; 63° solar zenith angle; albedo = 0.3) are fairly stringent in the sense that, for the set of molecules to be observed by the GOME, the results will not be radically changed by the use of lower surface reflectance or other solar zenith angles. The main impact would be on tropospheric measurements.

Figure A2.16 shows the 35°N nadir spectrum for albedos ranging from 0.03 to 1.0 calculated with the LOWTRAN7 radiance code including multiple scattering. The calculations are for photons per pixel with 2 seconds of integration time. With decreasing wavelength, Rayleigh scattering from atmospheric molecules becomes increasingly large compared with ground reflection. Figure A2.17 shows the nadir spectrum assuming an albedo of 0.3 for a range of latitudes from 5°N with a solar zenith angle of 40° (top) through to a latitude of 65°N with a solar zenith angle of 88° (bottom), spaced every
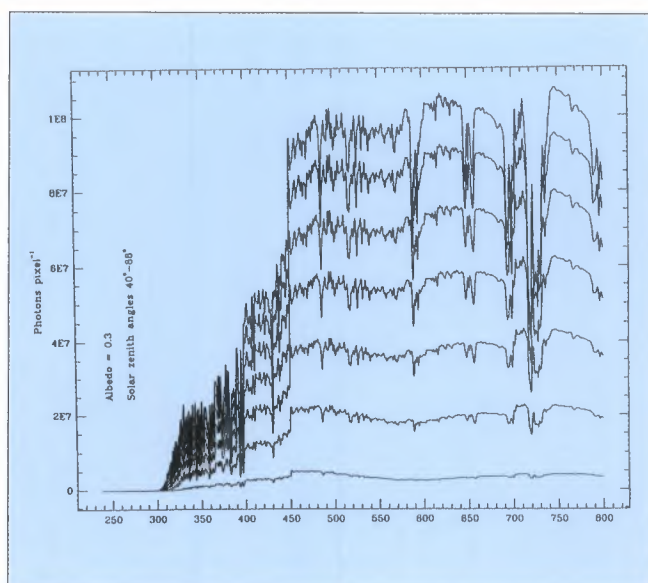

Figure A2.17. Reflected solar spectra for an albedo of 0.3 for a range of solar zenith angles from a latitude of 5°N with a solr zenith angle of 40° (top) through to a latitude of 65°N with a solar zenith angle of 88° (bottom), spaced every 10° in latitude

10° in latitude. The 55°N spectrum with a solar zenith angle of 80° (second from bottom) is about the largest solar zenith angle that should be measured by the GOME. These calculations also have been made in photons per pixel assuming 2 seconds of integration time.

Surface reflectances and solar zenith angles differing from those included in the standard conditions will have their greatest impact on observations of tropospheric O_3 made at 320 nm. At the standard 35°N (63 ° solar zenith angle), 13% of the light measured by the GOME will be reflected from the ground. For an albedo of 0.1, this decreases to 3.6% and the precision of the measurement of tropospheric O_3 is a factor of 2 lower. Losses in tropospheric O_3 information are partly compensated for by increased solar zenith angle as the light at the red end of the Huggins bands has significant penetration to quite high solar zenith angles.

Tropospheric NO_2, which may be measurable with modest precision in the standard conditions, depending on the temperature structure of the spectrum, absorbs in a wavelength range where Rayleigh scattering is not a major problem. Sensitivity to tropospheric NO_2 varies roughly as the square root of the reflectance. Measurements of the tropospheric columns of HCHO and SO_2 will suffer with decreased reflectance. HCHO sensitivity will increase almost linearly with the increased path due to higher zenith angle up to quite large angles because of the long wavelength extent of the spectrum. SO_2 sensitivity changes with zenith angle will be small.

Predictions for ClO, OClO, and BrO column measurements were calculated for a high solar zenith angle (80 °), appropriate to measurements by the GOME in ozone hole conditions. ClO is measured at such short wavelengths that changes in surface reflectance are not a serious consideration in measurement sensitivity; variability in O_3 has a much more serious impact. ClO will generally be seen at high solar zenith angles, so that sensitivity versus zenith angle is not an important issue. OClO is also generally seen at these high zenith angles. Its measurement is more sensitive to surface reflectance as the spectrum extends well beyond 400 nm. Fortunately, the climatology of OClO is such that measurements will generally only be possible in regions of high surface reflectance; exceptions occur when the ozone hole conditions extend over ice-free ocean waters. However, even in these conditions, the strength of the absorption in the 300 – 350 nm range safeguards the measurement sensitivity. The spectrum of BrO has its major absorption in the 300 – 350 nm range, long enough for O_3 absorption not to be a serious problem and short enough to ensure that lower surface reflectance will not seriously hamper the measurements. BrO measurement under normal conditions (i.e. away from O_3-depleted polar regions) will decrease as the path length decreases due to lower solar zenith angle.

A2.6. AEROSOL STUDIES

The presence of aerosols in climatic models leads to increased energy absorption in the stratosphere and to a cooling of the troposphere. More recently, the Antarctic ozone hole phenomenon has been explained by the conversion of HCl to ClO by heterogeneous reactions on the surfaces of polar stratospheric clouds.

The GOME instrument should obtain aerosol data during its normal usage. Its high spectral resolution should permit gases and aerosols to be distinguished. It should also allow the characteristics of column aerosols to be studied. Proper treatment of aerosols in the inversion process also increases the accuracy with which the column densities of gases can be derived. The simulation and verification of the various types of spectral signatures from different aerosols are an integral part of the GOME data system development plan.

a) Stratospheric Aerosols

Stratospheric aerosols have been extensively studied from balloon and space for the past 30 years. The measurements have revealed spherical particles in the stratosphere composed of a mixture of sulphuric acid and water. These are divided between layers of large particle size, the Junge layer (typical size 0.15 mm), and a background layer of aerosols of significantly smaller size (aprox. 0.05 mm). However, in the polar stratospheric clouds associated with the Antarctic ozone hole, particle sizes larger than 1 micron have been conjectured. Other types of suspended particles also exist in the upper atmosphere from meteoric decay. Little is known about them except that they have large imaginary refractive indexes due to their metallic cores. The resulting increase in the Mie scattering efficiencies makes them more observable (cf. published visual observations from space and balloon data reports). The GOME, through observation of these latter particles, may help resolve the present controversy surrounding the geophysical impacts of small meteorites and comets.

b) Tropospheric Aerosols

The high spectral resolution of the GOME instrument, combined with its spatial resolution, should facilitate the study of image contrast and hence to the characterisation of the nature of tropospheric haze in terms of natural phenomena. For example, sand winds have never been monitored on a global scale. As they occur by definition mostly in dry regions, the absence of clouds should make the GOME an almost perfect sensor for them. The GOME should also detect soot from forest fires to which for decades the blue moon phenomenon has been attributed. Identification of these 'clouds' and their continuous observation will permit an assessment of the effects of these largely local phenomena on the global atmospheric system.

Table A2.1 Quantities Retrieved from GOME Observations

Species	Retrievable Quantity*	Wavelength (nm)	Notes-Applications
O_3	Profile (S, T)	255.-350, 480-680	
O_2	Column (S, T)	690, 760	Cloud tops; boundary layer
O_4	Column (T)	475, 530, 560, 630	Cloud tops; boundary layer
H_2O	Column (S, T)	700-790	
HCHO	Column (T)**	310-360	Biomass burning; tropical vegetation
SO_2	Column (S, T)**	290-310	Industrial pollution; volcanos
NO	Column (S, M)	255-280	Above 40 km in emission
NO_2	Column (S, T)	300-600	Lightning; pollution
ClO	Column (S)***	300-310	Polar regions in spring
OClO	Column (S)****	320-420	Polar regions in spring
BrO	Column (S)	310-345	

NOTES:
* S = stratosphere; T = troposphere; M = mesosphere
** Observable in regions with relatively high concentrations
*** Ozone hole conditions
**** Observable in perturbed 'O_3 hold' regions

ANNEX 3

COMPARISON OF THE GOME WITH EXISTING & PLANNED INSTRUMENTS

A3.1 Introduction

Measurement of the distributions (total column amounts and vertical profiles) of trace gases from satellite borne instruments is a relatively new science with measurements spanning only the last twenty years. Over this period NASA and NOAA have launched instruments on several satellites whose aim was to investigate stratospheric O_3 and a few of the more important stratospheric gases (e.g. instruments on NASA's Nimbus-4, 6 and 7, and NOAA-9 and 11).

The global coverage and the duration of observations has often been limited and the overlap between measurements made by successive instruments poor. This state of affairs has arisen for a variety of reasons (e.g. limited launch opportunities, delays in launch, failure of certain instruments, etc). Nevertheless the impact on our understanding of the atmosphere, obtained from these measurements has been significant, and as a result our knowledge of the chemical behaviour of the earth's atmosphere has improved dramatically.

In Section 1.3 previous and current instruments were described. Here, in the following sections, the instruments will be considered in terms of their ability to realise the scientific objectives of the GOME.

A3.2 Previous Trace Gas Measurements from Space

a) Ozone (O_3)
i) BUV, SBUV and TOMS

Ozone has been measured by several instruments using the Backscattered UltraViolet (BUV) technique (*Singer & Wentworth 1957*): the BUV instrument on Nimbus-4 (*Heath et al. 1975*) launched in 1970 and by the SBUV and TOMS instruments on Nimbus-7 launched in 1978. In addition NOAA has placed two SBUV-2 instruments into orbit on NOAA-9 (launched in 1984) and NOAA-11 (1988).

The SBUV approach yields stratospheric profiles and total column amounts while that of the TOMS yields total cross track column amounts of ozone producing a global map every 24 h. The measurements obtained have been investigated by the NASA International Ozone Trends Panel (*WMO 1990a*) who concluded that, due to the degradation of the SBUV diffuser plate used for radiometric calibration, the SBUV measurements could not be used for long-term trend assessment. The same problem exists for the TOMS data though this can be compared with the Dobson ground network.

For the SBUV new internal analysis techniques are being developed for the correction of diffuser plate degradation which it is hoped will enable stratospheric ozone profiles (from SBUV) and total column amounts of ozone (from TOMS as well as from SBUV/2) to be produced which will be suitable for trend analyses. SBUV/2 instruments were flown on NOAA-9 (1984) and NOAA-11 (1988). No data is currently available from either though it is hoped that some will soon be made available (see previous paragraph). NOAA-9 had diffuser plate problems and NOAA-11 showed time dependent bias with respect to both Nimbus-7 and ground-based measurements.

ii) SAGE

Solar occultation at a single visible wavelength has been used by SAGE I on the Atmospheric Explorer Mission II from February 1979 to November 1981 (*McCormick et al. 1984*) and by SAGE II on the Earth Radiation Budget Satellite from October 1984 to present (*Cunnold et al 1989 and 1991*). This instrument relates the absorption in the Chappuis band to column amounts and yields stratospheric O_3 profiles. The Ozone Trends Panel (*WMO 1990a*) considered the SAGE measurements to have the highest precision for trend analysis. However, the sampling of SAGE measurements is limited to two profiles per orbit which severely restricts spatial and temporal coverage.

iii) SME

Differential ultraviolet absorption between two fixed wavelengths (265 and 297 nm) has been used to monitor O_3 in the mesosphere between 50 and 70 km by the ultraviolet spectrometer on the Solar Mesospheric Explorer from January 1982 to December 1986 (*Rusch et al 1984*). In addition SME has used a near infrared spectrometer to monitor airglow and to determine O_3 densities from 50 to 90 km (*Thomas et al. 1984*).

iv) LRIR and LIMS

Mid infrared broad band emission has been successfully used by two instruments, LRIR on Nimbus-6 and LIMS on Nimbus-7 (October 1978 to May 1979), to measure O_3 profiles between 10 and 60 km. The short lifetime of these experiments reflects the need to keep the detectors cooled to very low temperatures.

The different techniques for the measurement of O_3 have various systematic and random errors. Furthermore, altitude ranges, global coverage and operational lifetimes are quite varied. As a consequence only the SBUV, TOMS and the SAGE data have been chosen to be used for trend analysis (*WMO 1990a*). The former has the advantage of being composed of 13 years of continuous data.

The SAGE technique, which used absorption spectroscopy, has the advantage that it is does not require a radiometric calibration (unlike SBUV or TOMS data).

By applying the DOAS technique to light backscattered and reflected from the atmosphere, the GOME will combine the advantages of the SBUV-TOMS technique (e.g. global coverage) with those of SAGE technique (e.g. high precision of absorption spectroscopy measurements and no requirement for an absolute radiometric calibration). More detailed comparisons of the GOME with SBUV-TOMS, SAGE and SME are given below.

b) Nitrogen Dioxide (NO₂)

Stratospheric NO_2 has been measured by three instruments from space:

(i) by solar occultation at a single visible wavelength by SAGE I from February 1979 to November 1981 and by SAGE II from October 1984 to the present;

(ii) by differential optical absorption spectroscopy at a set of fixed wavelengths on SME (*Mount et al. 1984*);

(iii) by mid-infrared broad band emission: LIMS on Nimbus-7, from October 1978 to May 1979 (*Russell et al. 1984*).

The above three instruments were able to determine vertical profiles of NO_2 in the mid and upper stratosphere. However none were able to measure NO_2 in the lower stratosphere where a significant amount of the species resides. No total column measurements were made.

The total column measurements of the GOME should provide global information about both stratospheric (upper and lower) and tropospheric NO_2.

c) Nitric Oxide (NO)

Above 90 km vertical profiles of NO have been measured using band fluorescence at 215 nm by the UVNO experiment on the Atmospheric Explorer D satellite. In addition detection of NO band fluorescence at 255 nm by the SBUV instrument has been used to determine the latitudinal and seasonal variation of the column amount above 40 km (*Fredericks & Serafino 1985*).

By virtue of its higher spectral coverage and resolution the GOME should provide superior information on NO band emissions between 250 and 300 nm compared with that available from SBUV. The observation of several bands of NO may also yield information on the vertical structure of the NO amount above 40 km. Although the vertical range and resolution of the NO measurements by the GOME do not match the measurements to be undertaken by UARS, the GOME will provide useful information on NO in the post UARS period.

d) Water Vapour (H₂O)

Atmospheric H_2O is measured by several meteorological satellites. Measurements of H_2O by the GOME are dominated by the tropospheric amount. Nevertheless the GOME should provide useful information on latitudinal and seasonal variations in tropospheric H_2O for cloud free regions; this information is coupled to sea surface temperature and is therefore relevant to investigations of the global 'green house' effect.

e) Chlorine Monoxide (ClO), Bromine Monoxide (BrO) and Chlorine Dioxide (OClO)

ClO, BrO and OClO all play crucial roles in the mechanism controlling the 'ozone hole' phenomena. The global distribution of ClO between 80°N and 80°S above 20 km has been measured by the Microwave Limb Sounder (MLS) on UARS and the Millimeter Atmospheric Sounder (MAS) on Atlas.

However, MLS and MAS were not designed to measure ClO in the lower stratosphere and, due to bandwidth limitations, the accuracy of measurements in the region below 20 km has still to be determined. In ozone hole regions in spring, ClO has been shown to have elevated concentrations below 20 km. The GOME should be capable of measuring ClO under such conditions and it is therefore likely that the GOME will provide important new information about ClO amounts. The GOME will make the first observations of BrO and OClO from space.

f) Formaldehyde (HCHO) and Sulphur Dioxide (SO₂)

There have been no remote sensing instruments which have been designed to provide global measurements of SO_2 and HCHO. Both SO_2 and HCHO have relatively short atmospheric lifetimes and consequently in the clean atmosphere have low concentrations. In photochemically induced pollution episodes in cloud free regions (e.g. high-pressure regions over Europe in summer), elevated concentrations of tropospheric HCHO are obtained over large areas. High concentrations of SO_2 occur as a result of fossil fuel burning and volcanic eruptions. Under such conditions the GOME may measure total column amounts of HCHO and SO_2. (MLS has measured the global distribution of SO_2 in the wake of Mount Pinatubo which erupted in 1991.)

A3.3 Current and Planned Trace Gas Measurements

A number of satellite missions, which plan to include atmospheric constituent measurements, have been proposed: UARS, ADEOS, the NASA TOMS follow-on missions and the NASA and ESA Polar Platforms. As indicated earlier, some of these have already been implemented.

a) UARS

The Upper Atmospheric Research Satellite (UARS) is a very important mission for the study of atmospheric chemistry. Launched in September 1991, its mission is planned to last approximately two years, so it is unlikely that UARS will provide data after 1993.

One of the primary objectives of UARS is to study the chemistry of the middle and upper stratosphere and the mesosphere (i.e. above 25 km), which is where the ozone layer was perceived to be most at threat from the use of chlorofluor carbon compounds at the time of UARS' conception (i.e. pre-ozone hole).

The geometry of limb sounding in conjunction with the UARS orbit (57° inclination) provides overall global coverage from 82°N to 82°S. The following limb sounding instruments on UARS measure ozone and other trace gases:
i) Microwave Limb Sounder (MLS) — millimetre wavelength emission (observes only one hemisphere);
ii) Improved Stratospheric and Mesospheric Sounder (ISAMS) — mid-infrared broad band emission;
iii) Cryogenic Limb Array Etalon Spectrometer (CLAES) — mid-infrared narrow band emission (lifetime 18 months, observes only one hemisphere);
iv) Halogen Occultation Experiment (HALOE) — mid-infrared broad band solar occultation (limited geographical coverage).

The vertical resolution of the measurements will be between 2 and 3 km but the horizontal resolution will be low, typically 500 km.

b) ADEOS

The Advanced Earth Observing Satellite (ADEOS) is proposed by the Japanese Space Agency and is planned to fly in 1995. Its atmospheric instruments, namely IMG, ILAS, RIS and TOMS, have been described in Section 1. ADEOS will also fly the Ocean Colour and Temperature Scanner (OCTS) and the Advanced Visible and Near-Infrared Scanner (AVNIR).

Both OCTS and AVNIR are broadband instruments aimed at the studying the surface of the earth. However ADEOS does include a TOMS instrument and two infrared atmospheric scanners.

c) The NASA TOMS follow-on missions

As the original TOMS instrument flying on board Nimbus-7 is now well over its anticipated functional lifetime, NASA plans to launch follow-on instruments.

One was launched on the Russian Meteor-3 spacecraft in August 1993. Unfortunately this has an orbit which precesses with a period of 223 days. This makes interpretation of the data and comparison with previous missions difficult.

A TOMS instrument has also been selected to fly on a small US Explorer class satellite in 1993 and also on the Japanese ADEOS satellite (1995).

d) The NASA and ESA EOS Polar Platforms

Although these will provide the next generation of instruments for earth observation, they will not fly until the late 1990s. They will therefore not be discussed further here.

A3.4 Comparison of the GOME with related instruments
A3.4.1 Introduction

For differential absorption measurements the modern multichannel device described here (ie the GOME) is in many respects superior to the 'limited channel' existing instruments e.g. SBUV, TOMS, SAGE and SME. For example, in order to measure NO_2, SME used six pairs of wavelengths to measure a normal, inverted and null absorption in the 430 to 450 nm region (Mount et al., 1984). Similarly the measurement of atmospheric aerosol abundances from the inversion of the scattered light by the large number of wavelengths available to the GOME will be much improved over the limited number of wavelengths used in SAGE-2.

The measurement of O_3 by SBUV-TOMS instruments has recently been investigated by the Ozone Trends Panel (*WMO 1990a*). The report of this panel highlights the need for better measurements of atmospheric trace gases and the limitations of the TOMS-SBUV instruments.

The multichannel approach to the measurement of differential absorption proposed here provides a very flexible instrument, which should make possible accurate measurements of the composition of the atmosphere. Additionally the observed spectra will be useful for the land usage and oceanographic communities.

A3.4.2 SBUV-GOME Comparison

SBUV is a double monochromator instrument flown on Nimbus-7 which measures the Earth's backscattered radiation in twelve wavelengths between 255 and 340 nm. SBUV has a spectral resolution of 1 nm and takes approximately 32 seconds for a complete scan of these twelve wavelengths. In each of the twelve, 1 nm wide, SBUV channels, light is collected for 1 second. The field of view of the SBUV is $11.3° \times 11.3°$ and the area of the slit is approximately 0.3 cm². The quantum efficiency of the SBUV photomultiplier detector is estimated to be 0.25 in the ultraviolet.

The GOME is also a double monochromator system which observes backscattered and reflected light between 240 and 790 nm. In the SBUV region between 255 and 340 nm the GOME has 850 0.1 nm pixels simultaneously observing the atmosphere.

In order to compare the two instruments the relative performances of the instruments (i.e. spectral coverage and signal-to-noise ratios) needs to be assessed. As no details of SBUV noise are available for calculation purposes, the read out noise has been assumed to correspond to that of a diode array, i.e. 1500 electrons in 1.5 second at the SBUV photocathode.

The signal to noise ratio of both devices was calculated from equations A3a and A3b:

$$S/N = (F_E^2/(F_E^2 + N_c^2))^{1/2} \qquad \text{A3a}$$

51

$F_E = F_p.A.\Omega.T.Q.t.R$ electrons per pixel per second   A3b

where F_p is the flux of photons (photons $ster^{-1} nm^{-1} s^{-1}$) at the instrument calculated using LOWTRAN 7; N_c is the number of electrons which are noise (approximately 1500 electrons per read out); A is the effective area of the entrance slit (SBUV approximately $0.2 cm^2$), or telescope (for the GOME with standard optics $5 cm^2$ or with anomorphotic optics $1 cm^2$ in channel 1 and channel 2; $0.5 cm^2$ in channel 3 and channel 4); Ω is the solid angle of the field of view (SBUV 3.9×10^{-2} sterad, the GOME with standard optics 1×10^{-5} sterad, or with anomorphotic optics 1.25×10^{-4} sterad); T is the optical throughput (for the GOME assumed to be 0.1 but calculated to be 0.15 (UV) and 0.2 (visible), for SBUV assumed to be 0.1); Q is the quantum efficiency of the detectors (the GOME diode array 0.5; SBUV 0.25); t is the averaging time at each wavelength (SBUV 1 s, 50% chopped, for the GOME 30 s); R is the resolution in nm per detector pixel (SBUV 1 nm; the GOME 0.1 nm).

To compare the values of S/N obtained for the two instruments as calculated above, the GOME data must be summed to form 1 nm averages. This can be done in two ways:

a)   Groups of 10 pixels (1 nm) can be read out at the 12 SBUV wavelengths which leads to:

$(S/N(1 nm))_{GOME} / (S/N)_{SBUV} \approx 1.2$

b)   Alternatively each 0.1 nm pixel can be read out individually which leads to

$(S/N(1nm))_{GOME} / (S/N)_{SBUV} \approx 0.4$

From the above it is clear that the calculated 1 nm average signal to noise ratios of GOME and SBUV are comparable. However SBUV has a very limited spectral resolution having only twelve 1 nm measurements between 255 and 340 nm whereas the GOME has 850 0.1 nm measurements in the same region. The GOME should therefore be able to retrieve O_3 profiles with improved precision.

A3.4.3 Comparison of GOME and TOMS

The TOMS instrument is a single monochromator with a fixed grating and a variable exit slit, enabling it to scan through six wavelengths between 312.5 and 380 nm. Its field of view is 3×3 and it has 1 nm resolution. A TOMS measurement takes 0.2 second.

The performance of TOMS (i.e. its S/N) was calculated using equations A3a and A3b assuming that A is $0.2 cm^2$, T is 0.15, Q is 0.25, t is 24 ms and R is 1. The level of electron noise in the TOMS' signal was estimated from the minimum S/N. This is 39 close to the terminator 84°N and is estimated to be equivalent to 400 electrons in 0.2 second. At the six TOMS

wavelengths between 312.5 and 380 nm, if the GOME were read out every 0.2 second, then:

$(S/N(1 nm))_{GOME} / (S/N)_{TOMS} \approx 1$

However, due to data rate limitations, the current read out strategy for the GOME implies a read out every 1.5 second.

For the GOME it will be possible to vary the scan angle. Although the smallest scan option of the GOME is compatible with the spatial resolution of TOMS, global coverage by the GOME with this scan strategy takes longer to achieve than TOMS. Increasing the scan angle in the GOME decreases the spatial resolution and global coverage is obtained more quickly.

In conclusion the performance of the GOME appears to be slightly better than TOMS but due to data rate limitations in the GOME, it does not obtain global coverage as quickly.

A3.4.4 Comparison of GOME with SAGE and SME

SAGE I, SAGE II and SME all determine gas amounts by absorption spectroscopy. The three instruments have limited global coverage for different reasons.

SAGE I and SAGE II are solar occultation instruments which determine the vertical profile (between 10 and 50 km) of O_3 from absorption measurements at a single wavelength in the visible Chappuis bands of O_3. The Ozone Trends Panel (*WMO 1990a*) concluded that the absolute accuracy of O_3 measurements by SAGE I and SAGE II is about 6% to 9%. However the stability (or ability to detect changes) was 2% to 7% for SAGE I and 1.3% to 4% for SAGE II. Of the data currently available, the SAGE O_3 profiles have been recognised to be the most accurate and reliable (*WMO 1990b*).

SME observed the atmospheric limb scattering and used two wavelengths (265 and 297 nm) in the Hartley band of O_3 to determine O_3 profiles from 50 to 70 km. Due to its orbit and viewing strategy it mainly obtained data over North America. SME demonstrated the use of limb DOAS measurements for O_3 but as it was mainly aimed at the mesosphere it cannot be directly compared with the GOME.

The GOME is a differential optical absorption spectrometer with high spectral resolution and coverage which views the atmosphere in nadir. The Beer Lambert law relates column amount $C_i l$ to absorption via:

$$OD = \ln (I_o/I)_n = \Sigma_i (l.c_i.\sigma_i)$$ A3c

where OD is the optical depth, I_o is the incident radiation and I is the transmitted radiation at wavelength n, l is the absorption path length, c_i is the concentration of component i and σ_i its absorption cross section. For narrow banded molecular features, the above equation can be simplified to the following:

$$OD_d = \ln (I_{max}/I_{min}) = \sum_i (l.c_i.\sigma_{id}) \qquad\qquad A3d$$

where OD_d is the differential absorption between the maximum transmission, I_{max}, and the minimum transmission, I_{min}, of the absorption band of species i and σ_{id} is its differential absorption cross section.

The retrieval algorithms of SAGE I and II use equation A3c, whereas those of SME and of GOME adapt equation A3d.

Due to the high photon fluxes obtained in solar occultation it is unlikely that the inherent signal-to-noise within the GOME will be as high as that in SAGE I and II. However, the spectral coverage in the GOME is much superior to that in SAGE I and II and the GOME should be capable of making global measurements on relatively short time scales which SAGE cannot.

A3.4.5 Comparison of GOME and SCIAMACHY

GOME is an experimental device, whose design is based on some of the concepts developed for SCIAMACHY. The underlying objective in designing the GOME has been to define an instrument which marries a sufficiently worthwhile subset of the scientific objectives taken from the SCIAMACHY project with the necessity to manufacture such a device in the short time available before the planned launch of ERS-2.

As compared to SCIAMACHY, the GOME will have only a nadir viewing capability, a much smaller wavelength range and a restricted data rate. Nevertheless the GOME should provide global measurements of the total column amounts of several important trace gases (e.g O_3 and NO_2).

The primary advantage of the GOME over SCIAMACHY is that it can be manufactured in a very short time and will therefore be able to fly in 1994. It will enable many of the ideas underlying SCIAMACHY to be assessed.

ANNEX 4

EUROPEAN PROGRAMMES RELATING TO THE GOME

A. INTERPRETATION OF STRATOSPHERE MONI-TORING BY GROUND-BASED ULTRAVIOLET AND VISIBLE SPECTROMETERS (CEC/STEP-0013-M, 1990-91)

It is proposed to monitor ozone and several related stratospheric constituents (NO_2, OClO, BrO, PSCs) from the ground by ultraviolet and visible spectrometers. A network covering all latitudes from Northern to Southern Polar Regions is presently being deployed by the participating European institutions. The first operational measurements started in January 1988.

This network will be used for photochemical investigations, observations of polar ozone depletion, PSC detection, long term monitoring of constituents, early detection of changes of atmospheric composition and validation of satellite observations,

The specific objectives of the programme are:

(1) to ensure the homogeneity and accuracy of the data both in space and time, by the development of common data reduction and archiving processes, by intercomparisons and improvements of calibration methods;

(2) to increase the scientific return of the measurements and the accuracy, by appropriate model simulations of the atmospheric radiative transfer, photochemical reactions and large scale transport.

Recently funding for a follow-on project has been provisionally agreed by the EEC for 1992-93 within programme Environement 1990-1994. The title of the EEC project is 'Stratospheric Climatology using UV-Visible Spectroscopy' (SCUVS). The coordinator is Dr T. Jorgenson of the Danish Meteorological Institute, Copenhagen, Denmark.

B. TOPAS (Tropospheric OPtical Absorption Spectroscopy). EUROTRAC SUBPROJECT N° 12 1989-92

It is the intention of the participating institutes to cooperate in the development of DOAS techniques within the EURO-TRAC frame to:

— develop high-performance instruments capable of simultaneous observation of several atmospheric constituents;

— improve the sensitivity of the technique by at least one order of magnitude (minimum detectable optical thickness of 1×10^{-4});

— improve the calibration procedures;

— develop instruments for localised measurements, for use on the ground and mobile platforms (ships, aircraft);

— intercompare the techniques and their performances during dedicated field campaigns;

— make the new developments commercially available.

The multi-constituent measurements, performed by the techniques developed in the TOPAS subproject, should make an important contribution to the success of other EUROTRAC programmes. For instance they can provide measurements of key species essential for the understanding of the reaction cycles and transport processes responsible for the generation of OH, O_3 and acidity in the troposphere.

ANNEX 5
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ANNEX 6
LIST OF ACRONYMS

ADEOS	Advanced Earth Observing Satellite	GRILLE	(name of French spectrometer)
AEM	Atmospheric Explorer Mission	HALOE	Halogen Occultation Experiment
AFGL	Air Force Geophysics Laboratory	HIRS	High-resolution Infrared Sounder
AMAS	Advanced Microwave Atmospheric Sounder	ILAS	Improved Limb Atmospheric Spectrometer
ANSI	American National Standards Institute	IMG	Interferometric Monitor of Greenhouse gases
ATLAS	Atmospheric Laboratory for Application and Science	ISAMS	Improved Stratospheric and Mesospheric Sounder
ATMOS (i)	Atmospheric Molecules by Spectroscopy	KPNO	Kitt Peak National Observatory
(ii)	Atmospheric and Ocean Surface Satellite (Germany)	LBR	Low Bit Rate
		LIMS	Limb Infrared Monitor of the Stratosphere
ATSR	Along-Track Scanning Radiometer	LRIR	Limb Radiance Inversion Radiometer
AVHRR	Advanced Very High Resolution Radio-meter	MAP/GLOBUS	Middle Atmospheric Programme Global Budget of Stratospheric trace constituents
AVNIR	Advanced Visible and Near Infrared scanner	MAPS	Measurement of Air Pollution from Shuttle
BIC	Balloon InterComparison	MAS	Millimetre-wave Atmospheric Sounder
BS	Browse Service	Meteor	Russian meteorological satellite
BUV	Backscattered UltraViolet	MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
CFC	Chloro-Fluoro-Carbon		
CLAES	Cyrogenic Limb Array Etalon Spectro-meter	MIR	Russian space station
		MIRAS	Mid Infrared Absorption Spectrometer (Franco-Belgian instrument)
DOAS	Differential Optical Absorption Spectro-scopy	MLS	Microwave Limb Sounder
EEC(CEC)	European Economic Community	MMCC	Mission Management and Control Centre
EECF	European ERS Central Facility	MOP	Mission Operations Plan
EOS	Earth Observation System	MPI	Max-Planck Institut (Mainz, Germany)
EPOP-M1	European Polar Orbiting Platform Mission M1	NASA	National Aeronautics and Space Adminis-tration
ERBS	Earth Radiation Budget Satellite	NOAA	National Oceanic and Temperature Scanner
ERS-1, ERS-2	Earth Resources Satellite (Versions 1, 2)	OCTS	Ocean Colour and Temperature Scanner
ESA	European Space Agency	OD	Optical Depth
ESOC	European Space Operations Centre	Ozhora	Japanese Satellite
ESRIN	European Space Research Institute	OZTP	Ozone Trends Panel
ESTEC	European Space Research and Technology Centre	PAF	Processing and Archiving Facilities
		PCS	Product Control Service
EUROTRAC	European experiment on Transport and transformation of environmentally relevant trace Constituents in the troposphere over Europe	POES	Polar Orbiting operational Environmental Satellite
		PSC	Polar Stratospheric Clouds
		QBO	Quasi-Biennial Oscillation
EXOC	(Japanese satellite instrument)	RIS	Retroreflector in Space
FR	Fast Rate	ROSIS	Reflective Optics System Imaging Spec-trometer
FTIR	Fourier Transform Infrared		
GAP	Global Activity Plan	S/N	Signal-to-Noise
GLOBSAT	Global Satellite for atmospheric measure-ments (France)	SAGE	Stratospheric Aerosol and Gas Experiment
		SAM	Stratospheric Aerosol Measurement
GOME	Global Ozone Monitoring Experiment	SAMS	Stratospheric And Mesospheric Sounder
GOMR	Global Ozone Monitoring Radiometer	SBUV	Solar Backscattered Ultra-Violet

SCIAMACHY	Scanning Imaging Absorption Spectro-meter	TTC	Tracking Telemetry and Command
SME	Solar Mesospheric Explorer	UARS	Upper Atmospheric Research Satellite
SPOT	Système Probatoire d'Observation de la Terre	UVNO	Ultra-Violet Nitrous Oxide
STEP	Science and Technology for Environmental Protection	VIS/IR	Visible/Infrared
		VISSR	Visible Infrared Spin Scan Radiometer
TIROS	Television and InfraRed Observations Satellite	kbit, Mbit, Gbit	— kilobits, Megabits, Gigabits
TOMS	Total Ozone Mapping System	km, cm, nm	— kilometre, centimetre, nanometre
TOPAS	Tropospheric Optical Absorption Spec-troscopy	ppb	— parts per billion
		s, sec	— second
TOVS	TIROS Operational Vertical Sounder	ster	— steradian (unit of solid angle)
		1-D, 2-D	— one-dimensional, two-dimensional