Curriculum Vitae

John P. Burrows FRS

CURRICULUM VITAE - JOHN P. BURROWS FRS

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Professor Burrows is also a fellow of the Natural Environment Research Council: Centre for Ecology and Hydrology, Maclean Building,
Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB
United Kingdom.

Personal:

Born 16th August 1954, Whiston nr. Liverpool U.K.
British and German Citizen
Married

Education:

Ph.D., Trinity College, Cambridge University, U.K. 1975-1978
Ph.D. thesis title, "Study of free radical reactions by laser magnetic resonance."
Research Supervisor: Professor B. A. Thrush FRS.
M.A. Trinity College, Cambridge University, U.K. taken in 1979.
B.A.(Hons), Trinity College, Cambridge University, U.K- 1972-1975
West Park Grammar School St. Helens, Merseyside U.K. 1965-1971
Our Lady's and St. Joseph's RC Primary School, Prescot, Merseyside, U.K 1959-1965.

Employment:

(5) Science Director,
Natural Environment Research Council
Centre for Ecology and Hydrology
Maclean Building,

Benson Lane,
Crowmarsh Gifford,
Wallingford, Oxfordshire, OX10 8BB
United Kingdom
On a secondment from 01.12.2008 to 01.04.2010, after which Professor Burrows became a fellow of NERC: CEH now UK CEH 2010 to 2024.

(4) Professor (Chair Title "Physics of the Oceans and the Atmosphere") Faculty of Physics and Electrical Engineering, University of Bremen.
March 1992 to the present.

I have been a Guest Scientist at NASA-GSFC and University of Maryland since 1992 taking sabbatical leave at these institutions in 1995, and I am an adjunct Professor at the University of Maryland since 2006.

(3) Max Planck Institut für Chemie, Atmospheric Chemistry Department, (Director Prof. Dr. Dr. P. J. Crutzen F.R.S.) Research Scientist and then Research Group Leader): November 1981 to March 1992.

(2) Environmental and Medical Sciences Division, A.E.R.E. Harwell, Didcot, Oxfordshire, U.K.: Higher Scientific Officer,
and Guest Scientist at the Physical Chemistry Laboratory, Oxford University, March 1979 to November 1981 (within the group of Professor R. P. Wayne).

(1) Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, U.S.A.: Research Scientist, 1978 to1979 (within the group of the late Dr. H. E. Radford).

Scientific Societies:

Member of the following scientific societies: American Chemical Society (ACS), SPIE-The International Society for Optical Engineering, European Physical Society (EPS); Deutsche Physikalische Gesellschaft (DPG);

Life Member/ Fellow of the following scientific societies:
American Association for the Advancement of Science (AAAS), the American Geophysical Union (AGU), The International Academy of Astronautics (IAA); the European Geosciences Union, (EGU, International Commission of Atmospheric Chemistry and Global Pollution (iCACGP), the Royal Society, and the Leopoldina, the German National Academy of Science.

Awards, Honours, and Related:

1975-1978 Royal Society Gassiot Committee Research Student;
1992 Professor of Atmospheric and Oceanographic Physics at the University of Bremen;
1995 NASA Guest Scientist at the Laboratory of Atmospheres NASA GSFC;
1998 Distinguished Scientist Lectureship German American Scientific Committee (DAAD);
2003 Fellow of the AAAS;
2004 Fellow AGU;

2004 Distinguished Guest Lecture Royal Society of Chemistry – Environmental Chemistry Group;
2006 William Nordberg Medal COSPAR 2006;
2006 – present Adjunct Professor at the Department of Atmospheric and Oceanic Science, The University of Maryland, College Park, MD 20742,USA;
2006 EU GMES/CopernicusWorking Group 4, which recommended to the EU on the space segment required for GEOSS;
2007 Noble Lecturer, University of Toronto, Department of Atmospheric 2007 Physics and Environment Canada, 24-31st March 2007;
2007 NASA Group Achievement Award for outstanding achievements in the Intercontinental Chemical Transport Experiment conducted in the United States and Mexico. 10th May 2007;
2008 The Harold S. Johnston Lecturer University of California, Berkeley USA, Member of the International Academy of Aeronautics (IAA) 2008;
2010 Journal of Quantitative Spectroscopy and Radiative Transfer selected on its 50 anniversary a JQSRT Milestone Paper award to Burrows et al 1999 manuscript, January;
2008-2010 Guest member of high table at Christ Church Oxford;
2010-2024 Honorary fellow of the Natural Environmental Research Council: Centre for Ecology and Hydrology from 2019 UK Centre for Ecology and Hydrology;
2010 Member of the CEOS Carbon Task Force;
2012 Haagen Smit Prize presented by Atmospheric Environment, a premier journal of Elsevier Science, in recognition of outstanding 1991 contribution "The Nitrate radical: Physics, Chemistry and the Atmosphere" by Wayne et al;
2013 Vilhelm Bjerknes Medal by the European Geosciences Union, EGU;
2014 EGU Invited Speaker on the Atmosphere;
2015 IUGG Silver Medal and elected IUGG Fellow;
2016 EGU Alfred Wegener Medal and life member;
2016 Fellow of the Royal Society FRS;
2020 Member of the Leopoldina, the German Academy of Science;
2022 Honorary member for life of the International Association of Meteorology and Atmospheric Sciences (IAMAS) – international Commission on Atmospheric Pollution and Global Pollution (iCACGP).

International Projects of note:

EUROTRAC-PI in various projects1985-2003;
PI of different research projects within different consortia in all the EU Framework Research programmes, from the 1st to the current round;
Proposer, Principal Investigator-Lead Scientist of the GOME, (Global Ozone Monitoring Experiment) Project 1985 – 2020 end of mission;
Proposer, Principal Investigator and initiator of the SCIAMACHY, (SCanning Imaging Absorption spectrometer for Atmospheric CHartographY) Project.
Principal Investigator and initiator of the mission concepts GeoSCIA, GeoTROPE, GeoSCIA-Lite;
Chair of the SCIAMACHY Scientific Advisory Group, SSAG, established by ESA and the national space agencies of Germany, DLR, the Netherlands, formerly Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart (NIVR), now Netherlands Space Organisation (NSO) and Belgium Ministry of Space 1992- 2020 end of mission;

Founding Member and first scientific secretary of the GOME Scientific Advisory Group, GSAG, run by ESA and EUMETSAT 1990 to 2019;
Co-Investigator of the German French Merlin Experiment 2010 – present;
One of the Initiators and Proposers of the Space based Concepts for the measurement of the Greenhouse Gas: CarbonSat and CarbonSat Constellation; Following a peer review and in completion with 32 proposals CarbonSat was selected by ESA for its Earth Explorer 8 Phase A B1 studies in November 2010; The concept has now been selected for the EU Copernicus ESA CO2M mission
Initiator of the SCIA-ISS project concept;
Principal Investigator of the Effect of Megacities on the Transport and Transformation of Pollutants on the Regional to Global Scales EMeRGe, a DFG HALO project and international research consortium;

Community Service:
Scientific Reviewer of the Atmospheric Division of the NASA Langley Research Center 1997;
Member of the steering committee of IGAC (International Global Atmospheric Chemistry) Core Project of the IGBP (International Geosphere Biosphere Project) 2002 – 2008;
Co Proposer and Member of the scientific steering committee of the German Research Community Aircraft HALO (High Altitude Long duration) – 2000- 2020;
Member of the WMO - CEOS IGOS IGACO team and co-author of its recommendations 2002 – 2006;
Member of iCACGP (International Commission on Atmospheric Chemistry and Global Pollution) of IAMAS (International Association of Meteorology and Atmospheric Sciences), 2002 -2006; Officer and Secretary of iCACGP 2006 – 2010, President of iCACGP 2010-2014 and 2104-2018;
Member Scientific Steering Group of SPARC (Stratospheric Processes and their Role in Climate) a project of the WCRP (World Climate Research Programme) - WMO (World Meteorological organisation) -2003 – 2011, COSPAR SPARC Liaison 2012- 2020;
COSPAR Commission A – 1998 vice chair 2000 – 2008; COSPAR Member of national COSPAR Committee 2010 – present;
Member of Environmental Section of the European Physical Society – 2003 to 2016;
IGOS-IGACO member and an author of the IGACO Strategy document 2004,
Contributor to the quadrennial WMO UNEP Ozone Assessments a as co-author and reviewer 2002 –2020;
WMO-IGACO-Ozone group member, Advisor to GCOS 2004-2006;
Member of the Post-EPS Advisory Group for EUMETSAT 2005-2013;
Member of the EU Working Group - GMES Atmosphere Service and Space infrastructure of the service 2007 – 2009;
Member of the review board of the research programme of the Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency) 2008;
Member Advisory Board of the Leibniz Institute of Atmospheric Physics, Schlossstrasse, 618225 Kuehlungsborn Germany 2009-2016;
Member COSPAR Prize Committee 2008 – 2016;
Member AGU awards committee 2010- 2014;
Member EGU awards committee 2013-2020;
Reviewer of the DLR Research Programme 2013 – 2018;

Member of the Royal Society Selection Committee 5 2018-2020;
Member of Royal Society Future Leaders – African Independent Research (FLAIR) Fellowship committee 2018-2020;
Vice President of IAMAS 2019 to 2027;
Chair of the Academic Advisory, Committee of the Research Centre Environmental Change at Academia Sinica, Taiwan 2020-2026;
Member of the Copernicus Journal Atmospheric Chemistry and Physics PauL J. Crutzen Award committee 2022-2024;

Editorships:

Journal of Geophysical Research, Associate Editor 1998- 2002
Journal of Photochemistry and Photobiology A – Chemistry, Guest Editor 2003.
Advances in Space Research, Editor of Special Issues 1998- 2008
Atmospheric Physics and Chemistry 2001 – 2010, Associate Editor
Journal of Advances in Space Research, Associate Editor 2008 – 2015
Member of the Editorial Board Atmospheric Environment 2006 – 2011.
Advances in Measurement Techniques, Associate Editor 2008-2019
Member of the Editorial Board of the Progress in Earth and Planetary Science, PEPS, 2013- present.

Experience in Teaching:

I taught in a special needs school in Rainhill, Merseyside UK after completing my B.A. (hons) and before beginning my doctorate in 1978 and later in adult education in evening classes at the Volkshochschule Wiesbaden Germany from 1983-1983. During my time as a graduate student and postdoctoral scientist, I supervised undergraduates and taught practical undergraduates taking the Natural Sciences Tripos at Cambridge University and Part II students in Physical Chemistry at Oxford University 1975-1981. I have taught courses at the University level for the past 32 years in the following areas: a) 1991- 2005 Diploma in Physics, Diploma in Engineering and Diploma in Electrical Engineering – Courses: Physics for Engineers, Atomic and Molecular Physics; Atmospheric Physics; Atmospheric Chemistry; Remote Sensing; Optical Sensor; b) 2005-present M.Sc. Physics, M.Sc. Environmental Physics – Courses: Atomic and Molecular Physics, Atmospheric Physics, Atmospheric Chemistry.
I was one of the founders in 2000 of the first M.Sc. course in Germany focussing on "Environmental Physics: Atmosphere, Ocean, Land and Climate". I have been formally responsible for this course since 2004. I am also one of the leaders of the M.Sc. in Space Sciences and Technologies, which began in 2017.

Experience in the Supervision of graduate students for the Diploma in Physik, B.Sc., M.Sc. and Ph.D.:

A team comprising myself and my research group leaders have supervised ~ 120 students, who completed successfully the research projects for their Diploma in Physics, B.Sc. or M.Sc. degrees 1992- present.
I have supervised 110 graduate students within my research, who have completed successfully and been awarded the Doctor rerum naturalium, which is abbreviated to Dr. rer. Nat. and is equivalent to a Ph.D. or D.Phil. In addition, I have been a) the second reviewer and examiner of ~10 Dissertations for Dr. rer. nat. at the University of Bremen, and an external reviewer and examiner of Ph.D. / D.Phil. in the UK ((the University of

Oxford) the Netherlands (the University of Utrecht, the Free University of Amsterdam and the University of Eindhoven) and Sweden (Chalmers University). A majority of my doctoral students have embarked on academic and research careers. A number are now in senior positions at research and space agencies (NASA, ESA, DLR, EUMETSAT, ECMWF, South Korean NIER), a group have followed the calling of becoming teachers, and a similar group have successfully moved to industrial research and management.

Experience in the supervision and mentoring of postdoctoral scientists for their habilitation and promotion to a Professorship:

I have supervised eight postdoctoral scientists in my department, who successfully were awarded the German higher degree called habilitation or an honorary Professorship, one whom was awarded a DFG Leibniz Prize in 2021, another is an academic Dean. This group are now Professors at University Physics departments and/or Group leaders at Large Research Centres in Germany. Four additional post-doctoral scientists, who now also hold prestigious professorships in Ghana, the USA and China.

Research Interests and Motivation:

I am fascinated by the intricate interplay of biogeochemical, physical, and chemical processes that govern the behaviour of the Earth system. The latter comprises the sun, the earth's domains of the atmosphere, the ocean, the cryosphere and the land. The rapid growth of the earth's population, its longevity, and standard of living since the industrial revolution has resulted in the earth entering a new geological epoch called the Anthropocene. My research has been motivated by a desire to improve our understanding and knowledge of how the Earth system responds to both natural phenomena and the consequences of anthropogenic activity. Both scientific curiosity and the needs of environmental policymakers, who are tasked by society to achieve sustainable development, are addressed by my research.

My scientific interests and the motivation, described briefly above, led me initially to the study the kinetics and spectroscopy of atmospheric free radicals and key constituents in the laboratory. Physical, chemical and photochemical processes and mechanisms determine the composition of key atmospheric constituents. e.g. stratospheric ozone and short-lived climate pollutants (e.g. tropospheric ozone and aerosols) and their precursors. Subsequently, I realised that the accurate measurement of atmosphere constituents was a prerequisite required to improve our understanding of atmospheric physics and chemistry and to test the accuracy of atmospheric model and their predictions and projections. Consequently, I then began the development of instrumentation for field measurement campaigns using both in situ and remote sensing techniques from ground based and ship and aircraft borne sensors. This in turn led me to make pioneering contributions to earth observation science. These began with my development of the proposal in 1988 and subsequent leadership of projects. comprising SCIAMACHY (Scanning Imaging Absorption spectrometer for Atmospheric Cartography), which flew on ESA Envisat (2002 t 2012), and SCIA-mini, which later was renamed and became GOME (Global Ozone Monitoring Experiment) on ESA ERS-2 (1995-2011). The success of these missions led to the selection and development of GOME-2, the first instrument of its type, which flies on the ESA EUMETSAT Metope A, B and C series of operational meteorological satellites launched for numerical weather prediction, chemical weather and climate research.

Between 1997 and 2005, I developed and led with my scientific collaborators the GeoSCIA and GeoTrope proposals and concepts. This resulted in the selection by EU Copernicus, EUMETSAT and ESA in 2008 of Sentinel 4 for flight on the series of Meteosat Third Generation of satellites, which make diurnal measurements from geostationary orbits. I participated in the definition of the EU ESA Copernicus Sentinel 5, which builds on the heritage of SCIAMACHY, GOME and GOME-2 and will fly on the EUMETSAT Metop - Second Generation of satellites beginning in 2025. The SCIAMACHY development also led to the spin off OMI, which flies on the NASA AURA (2002- present and the ESA Sentinel 5 Precursor TROPOMI instrument.

One unique success of SCIAMACHY was the demonstration of the measurement the dry column mixing ratio of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4). This arose from my recognition that the absorptions in the overtone and combination vibrational rotational bands of CO_2 and CH_4 could be measured from space in the short wave infrared spectral region. In contrast to the thermal infrared solar similar sensitivity throughout the troposphere. These measurements, when combined with knowledge of the wind velocities or, the use of inversion techniques enables the surface fluxes of CO_2 and CH_4 to be measured top down from space.

In parallel to my involvement in the development of space instrumentation, together with my co-workers in Bremen, I developed the ground based DOAS (Differential Optical Absorption Spectroscopy) and the first Multi-Axial or MAX-DOAS instrument. This to the formation of BreDOM (BREmen's network of MaxDOAS (Multiple Axis DOAS) Measurements). In addition, AMAXDOAS (Airborne MAXDOAS) system was developed for the validation of SCIAMACHY and flew on the DLR Falcon aircraft. More recently the Airborne Imaging

My research and that of my students and co-workers has been in the fields of Biogeochemistry, Atmospheric Physics and Chemistry, Photochemistry, Photophysics and Chemical Kinetics. A particular highlight has been the development of in-situ and remote sensing measurement techniques to determine the amounts and distributions of trace atmospheric constituents, and their use as a tool for

- the study of air pollution, climate and chemistry interactions, the study of the stratospheric ozone layer, its destruction by ozone depleting substance and its response to the measures of the Montreal Protocol to ban and control ODS,
- the improvement of numerical weather and chemical weather prediction,
- the improvement of our knowledge of biogeochemical cycles,
- the establishment of a quantitative experimental basis for atmospheric, environmental and climatic change.

Following the recognition and definition of the new geological epoch the Anthropocene, a significant part of my research is dedicated to observing the changing Anthropocene and quantifying the impact of humankind on the earth system.

My most significant achievements in science:

I have made significant contributions over the past five decades in the following fields of atmospheric physic and chemistry, earth observation and earths system science:

Chemical kinetics of atmospheric free radicals and gas phase molecules:
a) experimental techniques

During my doctorate in Cambridge UK and post-doctoral study at the Harvard Smithsonian Center for Astrophysics I developed the discharge flow kinetic apparatuses coupled with laser magnetic resonance spectroscopy LMR. These apparatuses exploited the unique ability of LMR to measure free radicals and its high sensitivity and low detection limit. They were used to study the reactions of the atmospheric free radicals: hydroxyl (OH), hydroperoxyl (HO_2), the hydromethyl (CH_2OH), methoxy (CH_3O), nitric oxide (NO) and nitrogen dioxide (NO_2).

At Oxford University I developed an apparatus which coupled discharge flow with resonance fluorescence spectroscopy. This was developed for the study of OH and HO2 and chlorine atoms (Cl) and chlorine monoxide (ClO).

At the UKAEA in Harwell Oxfordshire and at the Max Planck Institute for Chemistry I developed and used the following kinetic experimental techniques

i) Modulated photolysis spectroscopy, which is an advance on molecular modulation spectroscopy. The modulated photolysis system was coupled with ultraviolet and visible spectroscopy and either tuneable diode laser absorption spectroscopy or matrix isolation Fourier transform spectroscopy;
ii) The photolysis of nitrous acid (HONO as a source of OH in Teflon chambers with product analysis by gas chromatography.

At the University of Bremen, I further developed the following techniques:

i) modulated photolysis technique
ii) time resolved flash photolysis, coupled with either grating spectrometers and Fourier transform spectrometers;
iii) Time resolved flash photolysis, coupled with spectrometers using 2D diode array detectors.

b) ***The studies of rate coefficients, photolysis frequencies, branching ratios and chemical mechanisms:***

The experimental techniques, described above were used to study the rate coefficients, branching ratios of key stratospheric and tropospheric reactions of free radicals and molecules in the gas phase.

The chemistry and photochemistry of the following free radicals and gas phase molecules were studied.

Free radicals: HOx (OH, HO_2), CH_3Ox (methoxy (CH_3O) methyl peroxy (CH_3O_2) and acetyl peroxy (CH_3COO_2) ClOx (Cl, ClO, chlorine dioxide isomers (OClO and ClOO) the chlorine dioxide dimer (ClOOCl)), BrOx (bromine atoms bromine atoms (Br) bromine oxide (BrO) bromine dioxide (OBrO)) IOx (iodine atoms (I), iodine monoxide (IO), iodeine dioxide (OIO), iodine monoxide dimer (I_2O_2) and higher iodine oxides) NOx (NO, NO_2), and the nitrate radical (NO_3).

Gas phase molecules: ozone (O_3), carbon monoxide (CO) dinitrogen tetraoxide (N_2O_4) dinitrogen pentoxide pentoxide (N_2O_5), chlorine nitrate ($ClONO_2$), Sulphur dioxide (SO_2), carbonyl sulphide (OCS).

Some highlights of this phase of my research were:
some of the first accurate measurement of the rate coefficients for the reactions of HO_2 with NO, O and OH; the discovery of the pressure dependence of the rate coefficient for the disproportionation of the HO_2 and its dependence on the concentration of water (H_2O); the study and mechanism of the reactions of OH with CS_2; the determination of the rate coefficients and branching ratios for the reactions of HO_2 and CH_3O_2 with ClO; the observation of the chlorine monoxide dimer from its the ultraviolet spectral region; the study of the products of the ClO and NO_2 reaction and the photolysis of $ClONO_2$; the study of the equilibrium between NO_2 NO_3 and N_2O_5; the studies of the kinetics of IO, OIO, I_2O_2 and higher oxides of iodine.

Spectroscopy of atmospheric free radicals and trace gases for use in atmospheric remote sensing

In addition to scientific curiosity about the structure of molecules, the motivation for these studies is to have high spectral resolution absorption cross sections and line parameters for use in atmospheric remote sensing.

a) *Experimental Techniques:*

For the study of short-lived free radicals, I developed experiments with double jacketed quartz cells / reaction vessels, which are coupled with flash photolysis and modulated photolysis to study short lived atmospheric free radical spectra in the solar spectral region from 200 to 3000 nm.

For longer-lived atmospheric radicals and trace gases, these are generated externally and then flowed quartz cells. These the temperature are controlled accurately from 180 to 350 K and the bulk gas pressure range from vacuum to 1.5 atmospheres. The absorption spectra are measured by either Fourier transform spectrometer or a UV Visible NIR grating spectrometer.

b) *Experimental Spectroscopic studies*

The spectra, of the free radicals and trace gases spectra measured by the SCIAMACHY GOME and similar were the targets.
The study of the absorption cross sections of Ozone(O_3), NO_2, N_2O_4, NO_3, BrO, OBrO, IO, OIO, ClO, OClO, IO OIO and higher oxides of Iodine.

Some highlights of this part of my research were as follows:
the discovery of an infrared band of NO_3 the visible spectrum of OIO; the accurate measurements of the absorption cross sections of key atmospheric constituents: O_3, NO_2, NO_3, BrO OBrO, ClO, OClO, IO, OIO etc.

c) *Theoretical spectroscopic studies*

The objective of these experiments was to generate “noise free” spectra for use in DOAS by fitting a quantum mechanical model for the molecule. The molecules ClO, chlorine, (Cl_2), bromine (Br_2), bromine chloride (BrCl) and RO_2 were studied and their spectra and absorption cross sections modelled.

The study of atmospheric composition using in situ remote ground based, ship borne aircraft borne and satellite borne instrumentation

My decision to begin to investigate from 1980s the changing composition of the atmosphere was motivated by the following:

- the scientific opportunities of the organisations, where I undertake my research.
- The fact that atmospheric scientists recognised in the 19th century if not earlier that accurate measurements of key atmospheric constituents are essential to improve our understanding the dynamical, physico-chemical, and biogeochemical processes which determine the composition of the atmosphere and the conditions for the biosphere and humanity.
- The need observations to test the ability of atmospheric models to simulate predict and project into the future the changes in the conditions within the atmosphere.
- The fact that human activity began to increase in the Holocene and has become a dominant force on the in the Anthropocene, the recognition in the 20th century that the consequence of human activity, through release of short lived and long-lived pollutants and their impact on the stability of the stratospheric ozone layer, air pollution/ quality, ecosystems, ecosystem services and climate change has led to the societal demand for sustainable development.
- The need for better knowledge of the solar spectrum and the role of the solar radiation and solar wind in initiating photochemical and chemical processes in the atmosphere and their impact on climate change.

The development and use of tuneable diode lasers for the study of tropospheric composition.

Tuneable diode lasers, which emit an intense beam of radiation in the thermal infrared coupled with long optical path cells provided in the 1980s some unique opportunities to measure tropospheric trace constituents. Ambient air drawn into the optical cell, having multipath optics to create typically an absorption path of several hundred meters for a base path of 1 or 1.5 m. The system I developed with colleagues successfully measured four trace gases from a selection of NO_2, Hydrogen peroxide H_2O_2, formaldehyde HCHO, CO and hydrogen chloride HCl. At the time we used this instrument in field campaigns measuring the trace gas composition in the marine boundary layer of the Atlantic Ocean. We observed the influence of the emissions pollutants from continental sources in particular from Africa and from ship in shipping lanes. In the North Atlantic marine boundary layer, the cleanest air appeared to be that which had travelled a long distance e.g. from the Caribbean. The TDLAS technique was later adapted at the MPI to be flown on aircraft.

The development of the peroxy radical detectors

Having studied HO_2 and some organic peroxy radicals, (RO_2) in the laboratory (e.g. CH_3O_2 and $CHCO.O_2$), I elected to make measurements of these radicals in the troposphere. Using the approach first proposed by D. Stedman, which uses the peroxy radical chemical amplification or PERCA technique, HO_2 and RO_2 are converted into NO_2 in a chemical reactor in which excess amounts of NO and CO are added. This is then followed by the specific detection of NO_2. The techniques required the development of sources of known amounts of HO_2 and RO_2 in an air flow to calibrate the response of the PERCA instrument.

Initially the Luminol NO_2 chemiluminescence reaction was used to detect NO_2. More recently a cavity ring down (CRD) detector was developed and deployed in the PERCEAS (Peroxy Radical Chemical Enhancement and Absorption Spectrometer), which was deployed on the DLR HALO (High Altitude LOng duration) research aircraft during the EMeRGe (Effect of Megacities on the transport and transformation of pollutants on the Regional to Global scales) campaign.

By deploying the PERCA and PERCEAS instruments in a series of campaigns over the past three decades, the presence of HO_2 and RO_2 and their role in atmospheric chemistry has been successfully studied. Our knowledge of the sources and sinks of HO_2 and RO_2 has been improved. In addition, our measurements of the HO_2 and RO_2 have provided evidence for the presence and the role of halogen oxides in the marine boundary. This explains the early morning initiation of photochemistry by the photolysis of Cl_2 and the production IO and BrO. IO is both a source of new particles and like BrO participates in chain reactions, which catalytically deplete O_3.

The development of Earth Observation science: passive remote sensing of tropospheric constituents and surface parameters using satellite and aircraft borne ship borne and ground based instrumentation.

Since 1984, I have devoted the largest part of my own energy and that of my research group to the development and use of remote sensing techniques to measure the amounts and distributions of atmospheric constituents (trace gases amounts, cloud and aerosol parameters) and land and ocean absorption (phytoplankton amounts, sun induced fluorescence etc.). We are investigating changes and deconvolving the origins of change i.e. natural phenomena or anthropogenic activity.

Satellite borne passive remote sensing: SCIAMACHY, GOME, EUMETSAT ESA GOME-2 GeoSCIA/ EU Copernicus ESA EUMETSAT Sentinel 4, EU Copernicus ESA EUMETSAT Sentinel 5, and CarbonSat/ EU Copernicus ESA EUMETSAT Sentinel 7 CO2M

a) *The beginning – SCIAMACHY and GOME*

Beginning in 1984, when starting a new research group in optical measurements at the Air Chemistry Department of the MPI for Chemistry in optical measurements at the instigation of its director, the late Professor P. J. Crutzen, I recognised that the differential optical absorption spectroscopy (DOAS), which had recently been developed by my then colleague the late Dr. Dieter Perner, could be used for the retrieval of trace gas column amounts from the measurements of upwelling radiances, which leave the top of the atmosphere and are measured by satellite instruments. To this end I developed with support from Paul and Dieter, a scientific team and an industrial partner (then Dornier now Airbus the SCIAMACHY (Scanning Imaging Absorption spectrometer for Atmospheric CHartographY) concept. I proposed in July 1988, as Principal Investigator, the SCIAMACHY instrument in response to the ESA call for instruments for its Polar Platform, which later was renamed Envisat. After a review, ESA selected SCIAMACHY for Phase A studies, in February 1989, as a national contribution to the Envisat payload, funded by the BMFT (German ministry for research and technology). SCIAMACHY was originally proposed as having two identical instruments, which measured alternately in nadir and limb viewing geometry and undertook solar and lunar occultation during sun or moon rise and set. During phase A studies, a Dutch industrial team joined the SCIAMACHY industrial team, funded by NIVR, now NSO. In Phase B the Belgian industry, funded by the Belgian Ministry responsible for space activity also joined the SCIAMACHY industrial consortium.

At this time, the interest in SCIAMACHY was coupled with the strategic need for European global measurements of stratospheric O_3 and key trace gases controlling its depletion, because Europe was about 30% responsible for the release of chlorofluorocarbons. This was recognised by ESA and led to a call for a small payload to make measurements of key atmospheric constituents from the planned ERS-2 (the second ESA Earth research Satellite). Space and spacecraft resource had been found by ESA for such an instrument, which needed to be built in four years. The building of this instrument was not allowed to delay the launch of ERS-2. I proposed SCIA-mini in response to this call. SCIA-mini was intended to make simultaneous measurements in the UV visible and near IR (232 to 783 nm) in limb and nadir viewing geometries. SCIA-min was then selected by ESA. However, after a short phase A study, SCIA-mini was descoped to make only nadir measurements and was renamed GOME (Global Ozone Monitoring Experiment). During Phase A study of Envisat, SCIAMACHY was descoped to be only one instrument, which made alternate limb nadir and solar in the NH or lunar in the SH occultation measurements. Both of these descopes were done to reduce the costs. The reason for the near simultaneous measurements in limb nadir is to be able to separate the stratospheric and mesospheric columns of trace constituents from the tropospheric columns. This was capability was lost for GOME.

I led, as Principal Investigator/Lead Scientist GOME and SCIAMACHY to their successful launches respectfully on ESA ERS-2 on the 20th April 1995 and on ESA Envisat on the 28th February 2002. GOME made successful measurements until ERS-2 was decommissioned in 2011whereas SCIAMACHY made successfully measurements until Envisat mysteriously failed on the Easter Sunday, 08 04 2012. Both GOME and SCIAMACHY were pathfinder satellite missions.

One key responsibility of a PI is to build a research team, which developed a majority of the scientific retrieval algorithms used in GOME and SCIAMACHY. This necessitated building a fast-radiative transfer models, which we named GOMETRAN and SCIATRAN. This was only possible with the unique capabilities of the key scientists, but in particular Vladimir Romanov, who joined my group in 1989 and has played a key role on our exploitation GOME, SCIAMACHY and subsequent missions.

Both GOME and SCIAMACHY were remarkably successful and made unique measurements. The nadir measurements although limited by data rate to have relatively poor spatial resolution demonstrated the ability to measure key tropospheric trace gases using the contiguous UV visible NIR measurements using DOAS and related inversion techniques. The retrievals of GOME delivered the following trace gas data products: the vertical profiles of O_3, total and stratospheric columns of NO_2, total and tropospheric columns of BrO, stratospheric column of OClO, the total column of formaldehyde, HCHO, and the total column of water vapour H_2O.

The improved performance of SCIAMACHY enabled in addition both IO and Glyoxal (CHO.CHO) to be measured. To a good approximation, these measurements represent the total tropospheric column, because the stratospheric concentrations both gases are small. The extended spectral coverage out to as far 2.38 micron measured in addition, the dry column mixing ratios of the greenhouse gases carbon dioxide (CO_2), XCO2, methane (CH_4), XCH4, nitrous oxide (N_2O), and the pollutant CO. Sun induced fluorescence, from the biosphere on the land and in the ocean is also retrieved well from SCIAMACHY.

The results for CO_2 and CH4 demonstrated for the first time that the XCO2 and XCH4 could be measured at sufficiently high precision that they can be used for the determination of surface fluxes i.e. emission and surface uptake/deposition. This represents a significant breakthrough.

The limb measurements of SCIAMACHY provide unique measurements of the vertical profiles of O_3, NO_2, BrO, Aerosol extinction and optical depth/thickness (AOD/AOT). The solar occultation measurements have been successful used for the measurement of the vertical profiles of O_3, NO_2, BrO, Aerosol extinction and optical depth/thickness (AOD/AOT).

The limb measurements of SCIAMACHY were exploited to prove very successfully the emissions by metals and mon metals from the mesopause to the lower thermosphere. For example, Na, Li, Ca, Mg, Mg+, Fe and many more emissions are readily observed. These originate from dust which ablates after entering the earth's atmosphere. These emissions are also exploited from the nadir measurements. The emissions of NO, $O_2(^1\Delta)$ and vibrationally and rotationally excited OH have been scientifically exploited to measure NO from solar proton events, retrieve O_3 profiles in the mesosphere and the temperature of the mesopause. The scattering signal has also been successfully used to measure noctilucent or polar mesospheric clouds.

b) *The first operational SCIAMACHY like operational mission: ESA EUMETSAT GOME-2*

I played a key role in helping to define GOME-2, which was selected by EUMETSAT for launches on the Metop platforms (A 2006-2022, B 2011-present, and C 2018-present). GOME-2 has somewhat higher spatial resolution, similar to SCIAMACHY and near daily coverage at the equator.

c) *GeoSCIA, GeoTROPE and EU Copernicus ESA EUMETSAT Sentinel 4 and geostationary constellations*

I led the development of The Geostationary Scanning Imaging absorption spectrometer GeoSCIA and the Geostationary Tropospheric Explorer, GeoTROPE concepts and proposals to the ESA and DLR calls between 1998 and 2005. The objective was to make geostationary measurements over Europe and Africa to provide diurnal variations of key tropospheric gases. There were different variants of GeoSCIA used including UV visible, NIR and SWIR bands similar to SCIAMACHY but optimised for high spatial resolution and signal to noise. The GeoTROPE concept included a GeoSCIA and a geostationary Fourier transform Interferometric Spectrometer, GeoFIS.

The GeoSCIA and GeoTROPE proposals and the related scientific and industrial studies were used by the EU Copernicus (formerly GMES) ESA and EUMETSAT to select a realisation of GeoSCIA as Sentinel 4 for MeteoSat Third Generation.

The idea of geostationary measurements has now been successfully achieved with the launch of the Korean Space Agency, KSA, Geostationary Environment Monitoring Spectrometer (GEMS) on 18^{th} February 2020. This has now been followed by the launch of NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) on the 14^{th} April 2020. The EU Copernicus ESA EUMESAT Sentinel 4 is now planned for launch on MeteoSat TG in 2024.

d) *EU Copernicus ESA EUMETSAT Sentinel 5*

As a Member of the EUMTSAT Post EPS advisory group (2006 to 2012). I defined specifically the specifications required for what is now known as EU Copernicus ESA EUMETSAT Sentinel 5 as part of Metop Second Generation. This is much closer to SCIAMACHY in terms of spectral coverage but with optimised spatial coverage and improved signal to noise. It is the follow on to GOME-2. The Metop-SG will have three series of platforms each having two 3 axis stabilised satellites and will measure from 2025 to 2040.

e) *CarbonSat to EU Copernicus ESA EUMETSAT Sentinel 7 CO2M*

From 2008 together with the industry partner OHB, my research group developed the CarbonSat and CarbonSat Constellation concepts. Building on the success and heritage of SCIAMACHY the objective is to make high spatial and diurnal sampling to invert XCO2 and XCH4 and thereby in combination with knowledge of the wind, retrieve surface fluxes of CH_4 and CO_2 . CarbonSat was investigated for flight on an ESA Explorer. This concept was then used and expanded on to create the EU Copernicus ESA EUMETSAR Sentinel 7 CO2M. I and my research group have provided unique scientific support to the development of this mission, which now comprises a small constellation of satellites. This mission is planned for launch by ESA in 2026.

f) *Other satellite systems which have befitted from GOME SCIAMACHY and related: OMI, TropOMI, OCO OCO-2 OCO-3, GOSAT GOSAT-2 and GOSAT-GW*

i) OMI (2004 – present on NASA AURA) and ESA Sentinel 5 Precursor (S5P) (2018 – present) are spin offs supported by NSO. These instruments focus of UV Visible measurements using the approach first developed for GOME and SCIAMACHY and target measurements at progressively much higher spatial resolution of O_3, NO_2 etc.

ii) Nadir Viewing
The following nadir viewing satellites successfully used the observation of NIR and SWIR bands first proposed for SCIAMACHY to measure XCO2 and XCH4: NASA OCO (failed at launch) OCO-2 (2016-present) and OCO-3 on ISS (2019- present) and JAXA Greenhouse Gases Observing Satellite (GOSAT) (2009- present), GISAT-GW (2018- present) GOSAT-GW

(launch 2024). The satellites are improving their spatial coverage and GOSAT-GW has added a channel for NO_2 similar to that on SCIAMACHY and CO2M.

iii) Limb viewing
The OSIRIS instrument on ODIN (201 to present), although proposed after SCIAMACHY, was independently developed by the CSA (Canadian Space Agency) and the SSA (Swedish Space agency). It like SCIAMACHY makes limb observations. The OSIRIS and SCIAMACHY tams have collaborated extensively in their exploitation of limb scattered measurements to retrieve trace gases and aerosol.

The ESA Altius mission is planned for launch in 2025 and is building on the heritage of SCIAMAHY in a novel small satellite approach.

Ground based shipborne and aircraft borne passive remote sensing

In support of the satellite missions described above and to evolve ground based, ship and aircraft borne observations of trace gases in the atmosphere, a series of DOAS instrument has been developed.

Ground based DOAS instruments were developed in Bremen and have operated continuously in Bremen (1993-present) in Svalbard at the AWI at the German and Norway bas in Ny-Aalesund. MAX-DOAS instruments were introduced from 1997 onwards. Measurements are also made in Athens and for some time at the UNEP building in Nairobi. These instruments operate in the Near UV and/or visible. They target the retrieval of trace gases O_3, NO_2, BrO, IO, OClO, SO_2, HCHO and CHO.CHO but also provide information about H_2O and aerosol. The MaxDOAS concept was developed in collaboration with the University of Heidelberg.

Our DOAS instruments are part of the network for the detection of atmospheric composition change NDACC, which began network operations as The Network for Detection of Stratospheric Change (NDSC) in January 1991. They have also been

DOAS and MAXDOAS instruments have been regularly used during ship campaigns. An airborne instrument AMAXDOAS was developed for the validation of SCIAMACHY. A current workhorse is the AIRMAP instrument which has successfully flown on aircraft to validate satellite data products in particular for S5P data products.

To measure XCO2 and XCH4 at high spatial resolution and to use this to determine the surface of CO_2 and CH_4 I initiated around 2006 the construction of the first MaMAP instrument, which is a Methane And carbon dioxide MAPper instrument. This at the time used a 1D diode array. This was deployed very successfully in a series of campaigns. It was used as a demonstrator for CarbonSat. It has also been successfully deployed to measure selected point sources of CO_2 and CH_4 around the globe. In 2016 I initiated the for our Greenhouse Gas Group the construction of family of MaMap-2D instruments.. This comprises a MaMap-2D-Light, which has successfully flown on light aircraft and on the DLR HALO. This instrument has one channel around 1.6 micron for CO_2 and CH_4 absorption measurements, and can be deployed. The MaMAP-2D which has two channels: one being at 1.6 micron and the second at 0,76 micron. This is an evacuated instrument and is now in its final phase of construction and testing.

The most recent addition to the MaMaP instrument family is CaMAP, which has a focus on carbon dioxide and methane. The first two channels are identical to MaMAP-2D but it also has an additional channel around 2 microns similar to SCIAMACHY. It is a demonstrator for EU Copernicus ESA EUMETSAT Sentinel 7 CO2M.

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In my career I had the good fortune to work for and with some outstanding scientists. Since I established my own research group, it my pleasure to supervise and mentor excellent graduate students and postdoctoral scientists. My team of sub group leaders have done an outstanding job for our department. Simiarly I thank our outstanding engineers and administrative staff, who toghther with the group leaders and senior scientists have helped me to run our department over the past three to four decades.