SP-1257 (4)

ACECHEM - Atmospheric Composition Explorer for Chemistry and Climate Interaction

European Space Agency
Agence spatiale européenne

REPORTS FOR ASSESSMENT

THE FIVE CANDIDATE EARTH EXPLORER CORE MISSIONS

ESA SP-1257(4)
September 2001

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ESA SP-1257(4) – The Five Candidate Earth Explorer Core Missions –
ACECHEM – Atmospheric Composition Explorer for CHEMistry and climate interaction

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1 Introduction

The ESA Living Planet Programme includes two types of complementary user driven missions: the research oriented Earth Explorer missions and the operational service oriented Earth Watch missions. These missions are implemented via two programmes: the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme. The Earth Explorer missions are completely covered by the EOEP.

There are two classes of Earth Explorer missions. The Core missions are larger missions addressing complex issues of wide scientific interest. The Opportunity missions are smaller missions in terms of cost to ESA, addressing more limited issues. Both types address the research objectives of the Earth Explorers, which are being implemented according to well established mechanisms (ESA, 1998). The missions are proposed, defined, evaluated and recommended by the scientific community.

Core and Opportunity missions are implemented in separate cycles. A new cycle is started every four years. The missions are implemented per cycle. The two missions selected in the first cycle of the Earth Explorer Core missions are underway: the Gravity field and steady-state Ocean Circulation Explorer (GOCE) and the Atmospheric Dynamics Mission (ADM-Aeolus), scheduled for launch in 2005 and 2007, respectively. The first cycle of Earth Explorer Opportunity missions is also on-going and will result in the CryoSat and Soil Moisture and Ocean Salinity (SMOS) missions to be launched in 2004 and 2006, respectively.

This report concerns the second cycle of Earth Explorer Core missions. As a result of the second call for ideas for Earth Explorer Core missions, which was released in June 2000, five missions were selected in Autumn 2000 for the second step of the implementation mechanism, i.e. the assessment. These missions are ACECHEM (Atmospheric Composition Explorer for CHEMistry and climate interaction), EarthCARE (Earth Clouds, Aerosols and Radiation Explorer), SPECTRA (Surface Processes and Ecosystems Changes Through Response Analysis), WALES (WAter vapour Lidar Experiment in Space), and WATS (WAter vapour and temperature in the Troposphere and Stratosphere). Reports for Assessment have been prepared for each of these candidate missions.

These reports will be circulated among the Earth Observation research community in preparation for the 'Earth Explorers Granada 2001 User Consultation Meeting', which will be held in Granada/Spain at the end of October 2001. The consultation meeting is part of the evaluation of the candidates that should lead to the selection of three candidates for feasibility studies in 2002-2003 and further to the selection of the next two Earth Explorer Core missions to be launched in 2008 (Core-3) and 2010 (Core-4).

This particular 'Report for Assessment' is concerned with the ACECHEM (Atmospheric Composition Explorer for CHEMistry and climate interaction) mission. It was prepared by a Core mission Drafting Team consisting of four members of the ACECHEM Scientific Preparatory Group (SPG): Claude Camy-Peyret (University of Paris, France), Didier Hauglustaine (Laboratory of Climate and Environmental Sciences (Gif sur Yvette, France), Hennie Kelder (Royal Dutch Meteorological Institute, de Bilt, The Netherlands) and Brian Kerridge (Rutherford Appleton Laboratory, Chilton, United Kingdom). They were supported by the other members of the ACECHEM SPG, namely Bruno Carli (Institute for Research on Electromagnetic Waves, Florence, Italy), Klaus Künzi (University of Bremen, Germany), John McConnell (York University, Toronto, Canada) and Rolf Müller (Research Centre Jülich, Germany). Further scientific contributions to this report have been made by various other scientists, in particular by Jolyon Reburn and Richard Siddans (both Rutherford Appleton Laboratory, Chilton, United Kingdom), and Michiel van Weele (Royal Dutch Meteorological Institute, de Bilt, The Netherlands).

The technical content of the report (notably Chapter 6) has been compiled by Umberto del Bello, Ulf Klein, Jean-Loup Bézy and Pierluigi Silvestrin (ESA) based on inputs derived from the industrial pre-Phase A contractors. Einar-Arne Herland and Alberto Tobias should also be acknowledged for their time and effort in reviewing this document and Doris Reinprecht for preparing its publication.

Changes to the composition of the atmosphere are the primary cause of global climate change, but the processes whereby atmospheric composition and climate interact are not well understood. Existing and planned spaceborne atmospheric composition sounding missions mainly address the issues of stratospheric ozone depletion and tropospheric pollution. However, today it is clear that improvements in our ability to predict climate change and to improve understanding of the underlying atmospheric processes will only come about as a result of an integrated approach. Thus it is essential to study the troposphere and stratosphere together as a coherent unit, and to consider simultaneously the chemical, dynamical, and radiative processes involved, and their non-linear coupling. In particular, the region around the tropopause is of paramount importance for the interactions between composition and climate and for the mixing between the atmospheric layers.

The main goal of the ACECHEM mission is therefore to investigate the composition of the upper troposphere and the lower stratosphere (UTLS), its interaction with climate, and the impact of anthropogenic activities. In particular, four scientific objectives are addressed:

- The role of the UTLS region in the radiative forcing of climate and in climate-chemistry feedbacks.

- The importance of stratosphere-troposphere exchange in atmospheric chemistry and climate.

- Stratospheric change and its interactions with stratospheric chemistry and climate.

- Impact of pollution on the composition of the upper troposphere.

ACECHEM is the first space mission that will have the observational capabilities necessary for a focussed study of the UTLS region, and in particular of the upper troposphere, a region that is difficult to observe from space. ACECHEM will carry on a dedicated platform:

- the first limb-sounding millimetre-wave spectrometer optimised specifically for upper tropospheric observations through specification of spectral bands and resolution, vertical resolution, sensitivity and tomographic measurement strategy;

- the first limb-sounding mid-infrared spectrometer optimised specifically for upper tropospheric observations through specification of spectral resolution, horizontal sampling (along- and across-track) and vertical resolution;

- the first spaceborne limb-viewing cloud imager, to support tropospheric trace gas retrievals by precise determination of cloud and aerosol contamination in the spectrometers' fields of view.

ACECHEM will fly in formation with MetOp to exploit simultaneous and co-located nadir-viewing observations synergistically.

All the 'Reports for Assessment' follow a common general structure comprising seven chapters. Following this introduction, the report is divided into six chapters:

- Chapter 2 addresses the background and provides the scientific justification for the mission, set in the context of issues of concern and the associated need to advance current scientific understanding. It also addresses the potential societal benefit of the mission. It clearly identifies the potential 'delta' this mission would provide, highlighting its unique and innovative contribution.

- Drawing on these arguments, Chapter 3 summarises the scientific objectives.

- Chapter 4 derives geophysical observational requirements from the scientific objectives, identifies suitable observational techniques and quantifies the key mission and instrument requirements. This chapter also demonstrates the scientific performance of the mission, consistent with the technical concept described in Chapter 6.

- Chapter 5 provides an overview of the mission elements such as the space and ground segments and external sources required, and of the relation to other missions.

- Drawing on Chapter 5, Chapter 6 provides a summary description of the proposed technical concept (space and ground segments), establishes basic system feasibility and provides a preliminary assessment of the expected technical performances. It also identifies the major technical innovations compared with other existing and planned missions.

- Chapter 7 outlines programme implementation and risks. In particular, drawing on the previous chapters, Chapter 7 discusses ACECHEM in the international context.

2 Background and Scientific Justification

In this chapter the underlying science justifying a future Earth Explorer core mission to sound atmospheric composition from space is presented. This mission will investigate the impact of anthropogenic activities on atmospheric composition and chemistry, and the interactions between chemistry and climate.

After an introduction of the general rationale for the mission and a survey of global change in atmospheric composition, the scientific background with respect to radiative, dynamical and chemical processes is discussed. Specific scientific issues arising from the discussion are outlined. The response of ACECHEM to these as well as to societal concerns is explained. Lastly, the innovative aspects of the mission are highlighted.

2.1 Rationale

- ***The chemical composition of the global atmosphere is changing as a result of human activities. These changes have a direct impact on the environment on a global scale.***

The abundance of many trace gases in the atmosphere is changing on local, regional, and global scales. There is evidence that many of these changes are caused by anthropogenic emissions, related to energy production, transportation, industrial activities, land use, and agricultural practices. The formation of the springtime ozone hole over Antarctica presents striking evidence that human activities can have a direct and substantial impact on the composition of the atmosphere.

Also disturbing is the fact that anthropogenic emissions increase atmospheric concentrations of both aerosols and greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and (H)CFC's. Moreover, via secondary reactions, emissions of nitrogen oxides (NO_x = NO + NO_2), carbon monoxide (CO), and hydrocarbons produce tropospheric ozone, another important greenhouse gas.

The consequences of a changing atmospheric composition are manifold and include impacts on climate, human health, crop yields, flora and fauna. It is unclear how atmospheric composition will evolve in the future. However, global economic development and population growth are likely to drive significant changes in the coming decades. A major challenge for the scientific community in the coming years will be to improve the understanding of the changing atmospheric composition and the feedback mechanisms that may occur in the climate system. This will enable the consequences of atmospheric change to be assessed, predictions to be made on future atmospheric evolution, and support to be provided to policy making.

- ***Atmospheric composition changes in the upper troposphere and lower stratosphere are strongly coupled with climate change.***

The upper troposphere and lower stratosphere (the 'UTLS region' for short) lies roughly between 7 and 26 km altitude[1] at mid-latitudes. The UTLS is a key region of the atmosphere for composition and climate interactions that are not well understood:

- The UTLS region is the layer in which stratospheric and tropospheric air is mixed. The exchange between these atmospheric domains controls the influx of tracers *into the stratosphere*, including water vapour and long-lived greenhouse gases.

- The ozone (and NO_x) flux from the stratosphere *down through the tropopause* is an important and highly variable parameter in the upper tropospheric ozone distribution and chemistry.

- Radiative forcing by greenhouse gases such as water vapour and ozone is especially sensitive to concentration changes in the upper troposphere and lower stratosphere, due to the large temperature contrast with the surface.

- Lower stratospheric chemistry is very sensitive to temperature changes and, at high latitudes, to the presence of Polar Stratospheric Clouds (PSCs). Stratospheric ozone concentration changes and temperature changes are directly coupled. Stratospheric water vapour changes also couple with stratospheric chemistry.

- Due to the influence of rapid convection within cloud structures and the large-scale vertical transport associated with convergence, the imprints of lower tropospheric events such as biomass burning, forest fires and several regional air pollution events are also imposed on the upper troposphere.

For reliable predictions of future climate, it will be necessary to improve our knowledge of the processes that control the composition of the upper troposphere and lower stratosphere and climate interactions on the global scale.

- ***There is a demand for accurate, global, height-resolved observations of a number of constituents in the UTLS region, with high vertical and horizontal resolution.***

A characteristic of the upper troposphere is that important constituents exhibit large variability on a variety of spatial scales. To examine adequately the relevant physical and chemical processes involved, vertical and horizontal structure must be captured at fine scales.

[1] The tropopause and corresponding lower boundary of the UTLS are ~4 km higher in the tropics and ~4 km lower at polar latitudes.

To meet this demand, satellite measurement techniques for trace gases and temperature need to be optimised for this specific region of the atmosphere. They need to be sufficient in terms of the chemical constituents and physical parameters to be observed, and to extend over the entire globe.

This region will be the focus for the **Atmospheric Composition Explorer for CHEMistry and climate interaction (ACECHEM)** mission. The high vertical and horizontal resolution, the superior penetration of its measurements down into the troposphere and the suite of target species make this mission unique and unprecedented in terms of its capabilities to sound the dynamical, radiative and chemical behaviour of this region of the atmosphere. ACECHEM will therefore provide a major contribution to our understanding of the processes whereby changes in atmospheric composition couple with climate change. It will contribute through its unique measurements to the global international observation programmes on the environment (WMO/CEOS, 2001; ESA, 1998).

Given the specific focus of the ACECHEM mission upon the UTLS region, the contemporaneous MetOp satellite, with nadir-viewing instruments IASI, GOME-2, MHS and AVHRR-3, will be used to provide co-located humidity and temperature profiles at lower altitudes and, in addition, column measurements of tropospheric ozone, nitrogen dioxide, aerosols and some other gaseous compounds. Thus, using MetOp, and with additional constraints provided by models, it will be possible to synergetically connect the UTLS measurements of ACECHEM with the composition of the lower troposphere. A network of surface- and airborne observations will further complement the satellite measurements, which is important for validation. Finally, significant value will be added to the ACECHEM suite of measurements using atmospheric chemistry modelling combined with chemical data assimilation.

2.2 What has been Observed?

The conditions conducive to life on Earth are regulated by the climate system, which is driven by the Sun and includes the Earth's atmosphere, land, ocean and cryosphere. Analyses of ice core data have shown that, since pre-industrial times, atmospheric composition has been significantly influenced by human activities. In the last three decades, dramatic changes in trace constituent concentrations and related parameters have been identified in the atmosphere:

- The concentrations of several long-lived greenhouse gases are increasing. Carbon dioxide levels are rising, and much of the rise can be attributed to energy production and fossil fuel burning (IPCC, 2001). The abundances of other potent greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and (hydro-)chlorofluorocarbons ((H)CFCs) have also been increasing as a result of anthropogenic activities, as is shown in Figure 2.1 (IPCC, 2001).

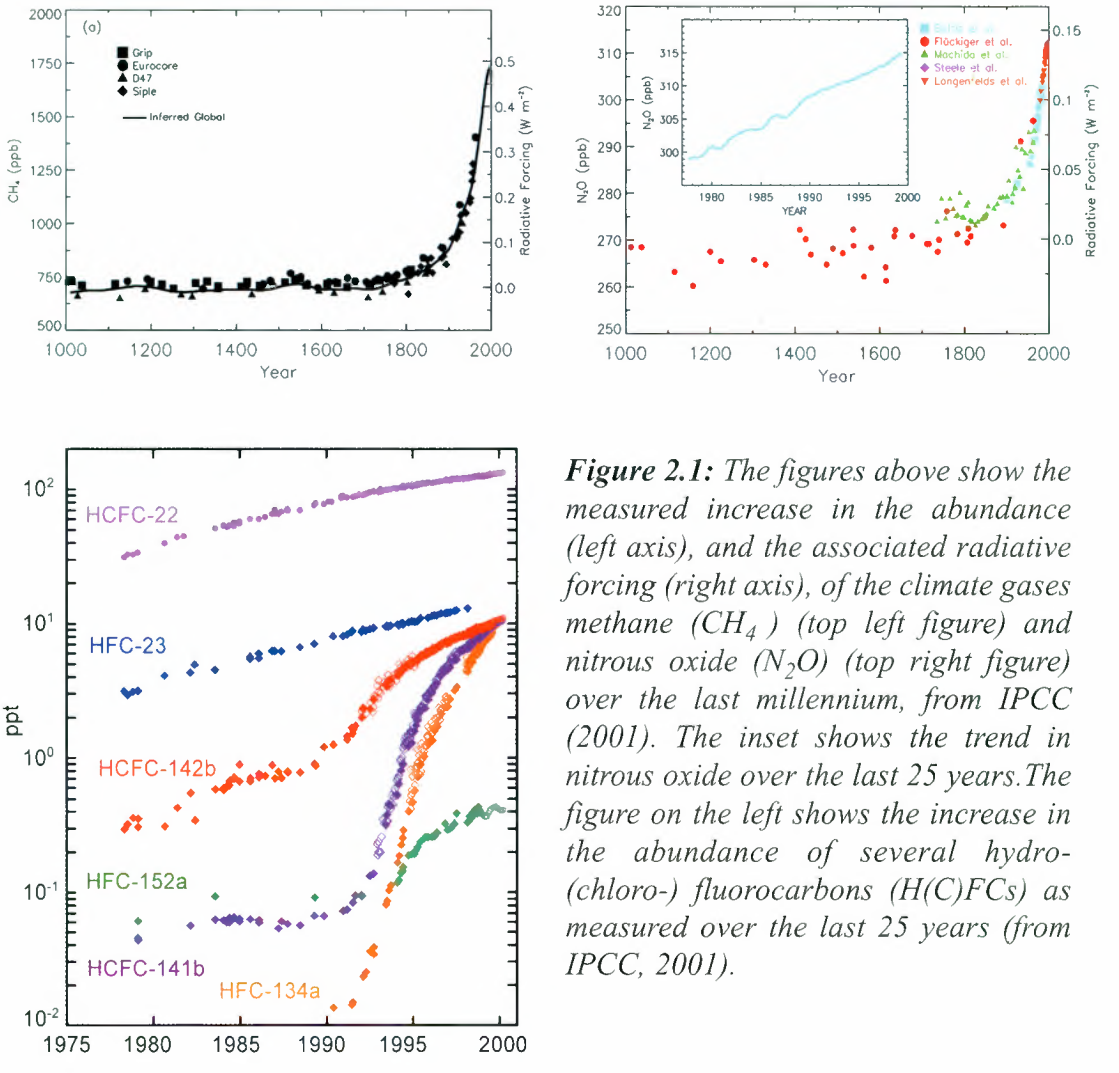

Figure 2.1: *The figures above show the measured increase in the abundance (left axis), and the associated radiative forcing (right axis), of the climate gases methane (CH_4) (top left figure) and nitrous oxide (N_2O) (top right figure) over the last millennium, from IPCC (2001). The inset shows the trend in nitrous oxide over the last 25 years. The figure on the left shows the increase in the abundance of several hydro-(chloro-) fluorocarbons (H(C)FCs) as measured over the last 25 years (from IPCC, 2001).*

- The springtime ozone hole above Antarctica and the substantial thinning of the ozone layer over Arctic regions have been well documented. The main cause is the increased chlorine and bromine content in the stratosphere as a result of anthropogenic activities (WMO, 1999). In response to the adherence to the Montreal Protocol and its amendments, emissions are reduced and most of the relevant chlorine compounds have started to level off around the year 2000, but many bromine compounds are still increasing rapidly in the atmosphere. Satellite measurements in combination with surface-based measurements have shown that since 1979 the total ozone column has had a negative trend of 3-4% per decade at mid-latitudes and of up to 10% per decade over Antarctica (WMO, 1999). A concomitant increase in the transmission of UV-B radiation has been observed at various locations worldwide (Figures 2.2 and 2.3).

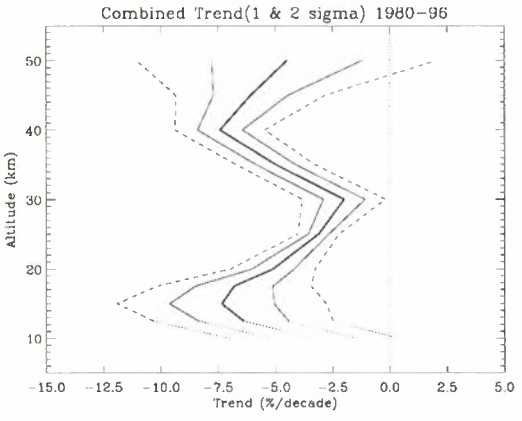

Figure 2.2: *The vertical ozone profile trend derived from available measurement systems at northern mid-latitudes. Combined uncertainties are shown as error lines for 1 sigma (solid line) and for 2 sigma (dashed line) (WMO, 1999).*

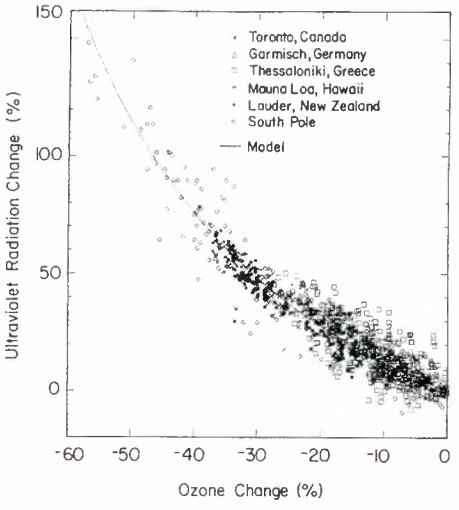

Figure 2.3: *The measured increase in erythemal (sunburning) ultraviolet radiation as a function of measured total ozone column change at different locations worldwide. The UV increases are in good agreement with those expected from calculations (represented with the model curve) (WMO, 1999).*

- Stratospheric ozone depletion has led to a cooling of the lower stratosphere since 1979, and additional cooling has occurred due to the increases in stratospheric water vapour (Figure 2.4) and carbon dioxide (Ramaswamy et al., 2001). A global negative trend of 0.8 K/decade (Figure 2.5) has been observed in the period 1979-1994 using radiosonde and satellite data (WMO, 1999). Substantially larger cooling rates are observed in the polar lower stratosphere during late winter/springtime. Determination of temperature and ozone trends in the UTLS region is complicated by possible changes in the tropopause height. Over the last three decades an increase in the tropopause height of about 300 to 500 m has been observed at several stations in the Northern Hemisphere (Forster and Tourpali, 2001).

- Decreasing stratospheric temperatures lead to an increased occurrence of PSCs. These provide the surfaces for heterogeneous reactions that enhance stratospheric ozone loss. SAGE II observations show a positive trend in PSC occurrence.

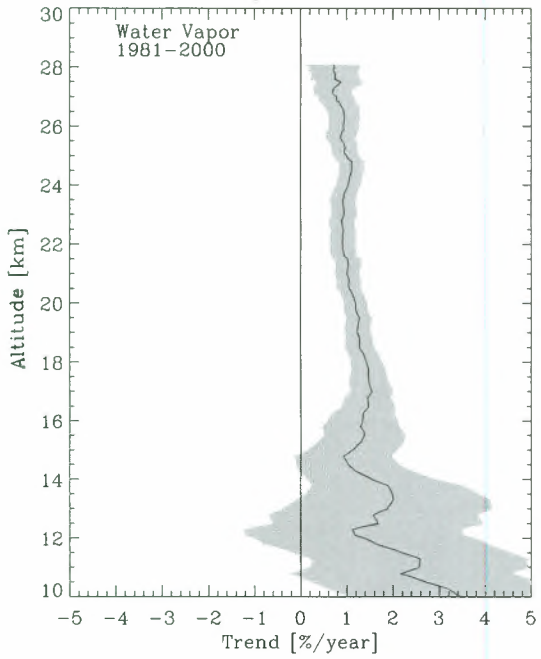

Figure 2.4: *The linear trend of UTLS water vapour mixing ratio (percent per year) and 95% confidence interval (shaded area) as a function of altitude over Boulder (SPARC, 2000).*

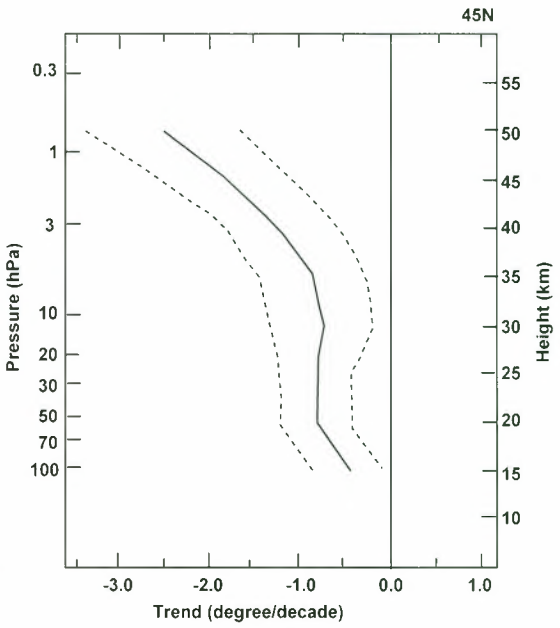

Figure 2.5: *Vertical profile of the trend in stratospheric temperature over the 1979-1994 time period, as compiled using radiosonde and satellite measurements. The dashed lines denote the uncertainty at the 2-sigma level (WMO, 1999).*

- Natural phenomena (e.g., solar variability, volcanic eruptions) affect the composition of the atmosphere. In particular the volcanic eruptions such as El Chichon (1982) and Pinatubo (1991) have caused large perturbations of the stratosphere (Figure 2.6).

- Tropospheric ozone trends are linked to anthropogenic emissions. The latter have led to an increase of photochemical smog formation in urban areas, which causes health problems. Tropospheric ozone also contributes significantly to the radiative forcing of climate. Its trends are highly variable. Observations have demonstrated that tropospheric ozone has decreased over Antarctica in the past two decades, and also over northern Canada (Oltmans et al., 1998). Non-polar locations reveal either increasing tropospheric ozone or no significant trend since the 1970s. Most European stations show a positive trend in tropospheric ozone, not only at sea level but also at mountain sites sampling free tropospheric air (Figure 2.7). The observed regional variability of ozone trends is closely related to emission patterns, chemical processes and to the coupling with the physical climate system.

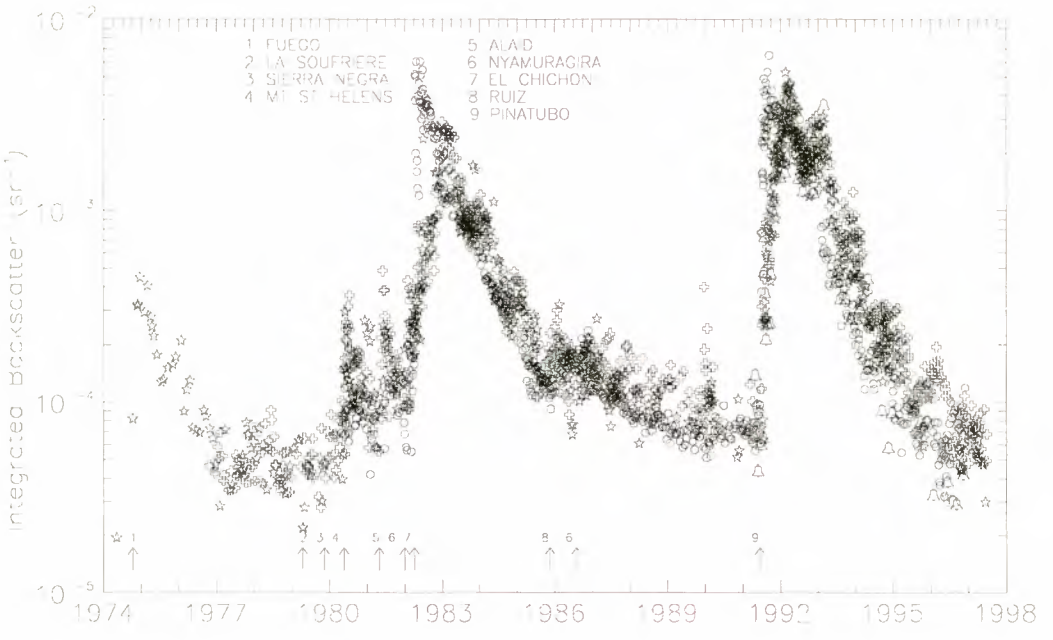

Figure 2.6: *Integrated aerosol backscatter at a wavelength of 0.6943 μm from lidar measurements at Garmisch-Partenkirchen (plus signs), NASA Langley (stars), Mauna Loa (circles) and Laramie (bells), for the period 1974-1998, showing the effect of volcanic eruptions on the stratospheric aerosol content (WMO, 1999).*

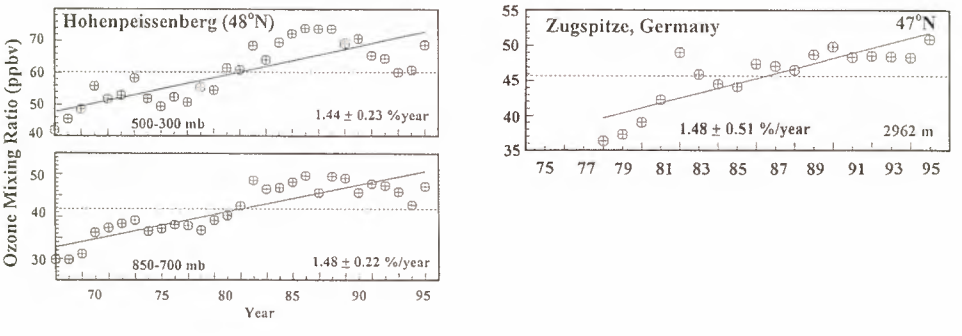

Figure 2.7: *Observations of the positive trends in the tropospheric ozone mixing ratio over Europe. The left panels show free tropospheric observations (500-300 hPa and 850-700 hPa) at Hohenpeissenberg (48° N) and the right panel shows surface data from Zugspitze (47° N) (Oltmans et al., 1998).*

- Apart from releasing carbon dioxide and water vapour, subsonic aircraft inject NO_x and particles directly into the UTLS region. NO_x emissions are likely to enhance local ozone production, and the aerosol particles can act as freezing nuclei that promote the formation of condensation trails ('contrails') and contribute to the formation of cirrus under favourable conditions. Emissions of various species have

stratosphere and so the response of surface temperature to a percent perturbation in ozone extends throughout the lower stratosphere. Current uncertainty in our knowledge and understanding of the global distribution of tropospheric and lower stratospheric ozone is the limiting factor on estimates of ozone radiative forcing.

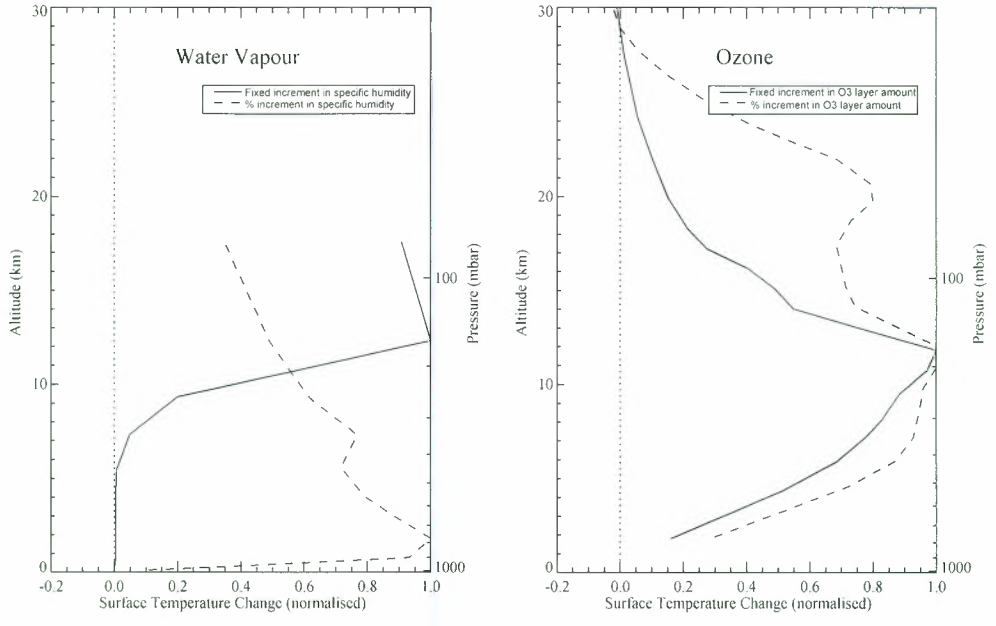

Figure 2.8: *Surface temperature responses to perturbations in water vapour and ozone as a function of height, as calculated by a radiative-convective climate model. The curves show normalised surface temperature responses to both a fixed increment in number density (solid) and a fixed percentage increment (dashed). Adapted from Shine and Sinha, 1991 (H_2O) and Forster and Shine, 1997 (O_3).*

The most important greenhouse gas that acts as a forcing agent is carbon dioxide (CO_2), which is relatively abundant and well-mixed in the atmosphere. A CO_2 increase acts to heat the troposphere and to cool the stratosphere due to its strong long-wave absorption. The total absorption by other greenhouse gases is smaller than for CO_2, but CH_4, N_2O and CFCs are also important absorbers because their bands lie within long-wave atmospheric windows and therefore these gases contribute to the heating of the troposphere. Other greenhouse gases, such as HCFCs, HFCs and PFCs, and SF_6 have a potential to heat the troposphere if their emissions continue to increase drastically. The radiative forcing by the well-mixed greenhouse gases decreases from equator to pole and its temporal and spatial variations further depend strongly on the water vapour and cloud distributions. The estimated radiative forcing due to the increase in well-mixed greenhouse gases since pre-industrial times is 2.42 Wm^{-2} (IPCC, 2001).

Aerosols play an important role in tropospheric climate via 'direct' and 'indirect' mechanisms. For the direct mechanism, sulphate aerosols are important as scatterers of

sunlight and cool the troposphere. However, combustion produces black carbon, which can get mixed within the aerosol mass. These mixed aerosols also absorb sunlight and warm the lower troposphere. The relatively short lifetime of aerosols due to rain, washout, and deposition, leads to a spatially heterogeneous distribution and therefore to a spatially-heterogeneous radiative forcing. For the 'indirect' mechanism, aerosols act as Cloud Condensation Nuclei (CCN) and Freezing Nuclei (FN). A change in atmospheric aerosols affects cloud droplet size distributions, and thus the lifetime of clouds, their reflectivity and precipitation. This may significantly change the radiation budget in both the (solar) shortwave and the (terrestrial) longwave regions of the spectrum. The magnitude of the indirect forcing due to aerosols is very uncertain.

2.3.2 Stratosphere-Troposphere Exchange (STE)

The general circulation of the atmosphere has a considerable influence on atmospheric composition and its variability. Large-scale circulation patterns and planetary waves determine inter-hemispheric exchange, and Stratosphere-Troposphere Exchange (STE). The mixing is actually accomplished by numerous processes operating at a variety of scales from the global down to the smallest (turbulence).

STE is part of the mean meridional circulation, also known as the Brewer-Dobson circulation (Figure 2.9), which involves upward cross-tropopause transport in the tropics, poleward advection in the stratosphere (most strongly towards the winter pole), and downward transport into the extra-tropical troposphere. Lateral mixing occurs between the mid-latitude lowermost stratosphere and the tropical troposphere. The transport across the tropopause is highly variable in space and time, as is the tropopause height itself.

The forces created by the breaking of gravity- and planetary waves in the upper stratosphere and mesosphere are a major cause of the Brewer-Dobson circulation. The waves are also damped at critical layers or levels below, mostly in the UTLS region. This filtering of upward propagating waves in the UTLS region is poorly understood, yet it is a major controller of the Brewer-Dobson circulation.

The UTLS region is also a key region in the atmosphere because it is the mixing layer for air that is exchanged between stratosphere and troposphere. In these layers pollution from the troposphere may impact on stratospheric processes and, for example, form stratospheric aerosol. The transport into the stratosphere of greenhouse gases that are well mixed in the troposphere is strongly influenced by the dynamical processes in the UTLS region. The exchange of ozone from the stratosphere to the troposphere is important for its radiative forcing.

In the tropics, STE is mainly from the troposphere to the stratosphere. Updrafts in tropical convection regions rapidly lift humid and ozone-poor boundary layer air up to the upper troposphere. Convection, followed by condensation and precipitation,

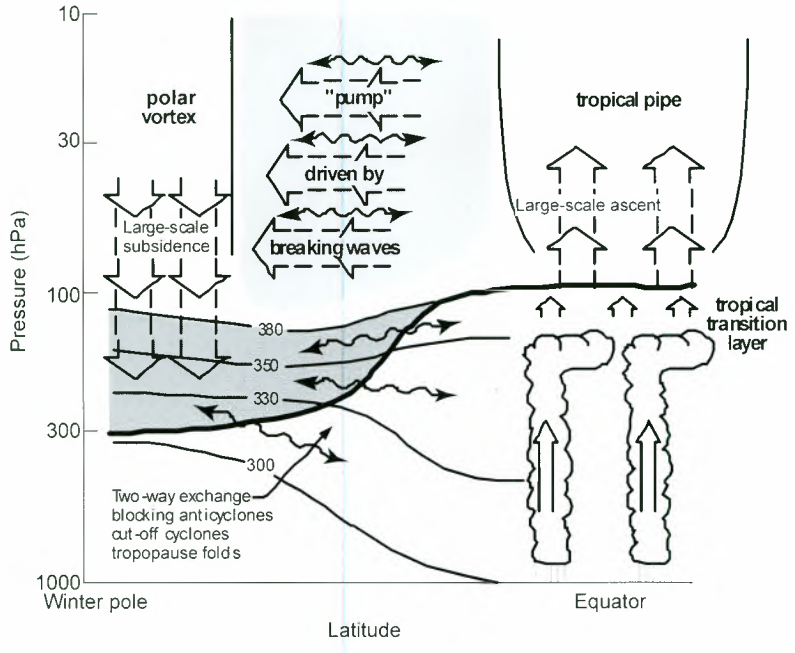

Figure 2.9: *Stratosphere-Troposphere Exchange (STE) is important at all latitudes. The figure gives a schematic representation of the wave-driven Brewer-Dobson circulation with large-scale upward motions at tropical latitudes, poleward transport in the stratosphere and large-scale subsidence at middle and high latitudes. The thick solid line represents the tropopause. The thin lines are isentropic surfaces. The vertical lines in the stratosphere indicate the polar vortex (on the left) and the tropical 'pipe' (two lines on the right). The tropical barriers isolate the lower tropical stratosphere from mid-latitudes. The figure has been created by making modifications – based on recent insights – to a figure that was originally published by Holton et al. (1995).*

efficiently dries the rising air, and the amount of water vapour entering the stratosphere is critically dependent on the minimum temperature encountered during upward transport. The processes that determine the transport of tropospheric water vapour into the stratosphere are a subject of scientific debate. The intrusion of water vapour into the tropical stratosphere is critical, because it is the largest source of stratospheric water vapour. The oxidation of CH_4 is another source of stratospheric water vapour. In general, understanding the strength of the upward transport in the region of the tropical pipe, i.e. the region that lies just above the tropical tropopause, is important in determining the time that air remains in the stratosphere before returning to the troposphere ('the age of air'). Measurement of humidity and tracers in the UTLS region therefore yields valuable information on dynamical processes.

In the extra-tropics, there is mainly downward transport of stratospheric, ozone-rich air into the troposphere. STE in the extra-tropics is accomplished by a variety of meso- and small-scale processes. One process is tropopause folding, which occurs along local

wind maxima (jet streaks) of the polar, mid-latitude and subtropical jet streams. The tropopause is folded downward and equatorward, and stratospheric, ozone-rich air within the fold can be irreversibly transported into the troposphere by turbulence or radiative effects. Shallow layers with elevated ozone concentrations in the troposphere due to folds are ubiquitous and can be quite persistent. Given the complicated processes involved, the contribution of stratospheric ozone to the tropospheric ozone budget is still poorly quantified and shows a large variability in time and space.

An important process at mid-latitudes is the exchange of ozone by deep convection, particularly in the cores of cut-off lows where the vertical stability is small. Typical horizontal scales of cut-off lows are several hundreds of kilometres and vertical mixing in their cores may persist over several days. Other mechanisms of extra-tropical STE include mixing by turbulence and waves, and by radiative heating and cooling, associated with inhomogeneous distributions of clouds, aerosols and greenhouse gases.

It will be important to investigate whether a changing atmospheric composition could affect the Brewer-Dobson circulation and related processes, e.g. by changing the upward propagation of the waves that drive the circulation. In any case, climate change is expected to influence the dynamics of the UTLS region by changing the distribution of radiative heating in the atmosphere and possibly by changing the tropopause temperature. These dynamical changes may in turn trigger changes in atmospheric composition in the troposphere and stratosphere. Feedbacks between changes in composition and changes in atmospheric dynamics are likely to be important, but are largely unexplored.

2.3.3 Stratospheric Chemistry

The dramatic loss of ozone in polar regions (Figure 2.10) is caused by the activation of chlorine compounds through heterogeneous reactions that occur on the surfaces of PSC particles. Stratospheric clouds form only under the extremely cold conditions during the polar night in the Arctic and Antarctic. PSCs consist of water and nitric acid (HNO_3); a substantial amount of the available gas-phase nitric acid is sequestered by the PSC particles. PSC formation is mainly determined by the available nitric acid and by the prevailing temperatures. During the recent SOLVE-THESEO 2000 field experiment, nitric-acid-containing PSC particles have been observed to grow to large sizes (about 20 mm in diameter) and to reach considerable fall speeds. These particles permanently remove nitric acid from the stratosphere, a process called 'denitrification'. Denitrification suppresses the formation of NO_x which is required for chlorine deactivation (to form the reservoir species $ClONO_2$), terminating the catalytic ozone loss cycles by chlorine in spring. Enhanced PSC formation therefore not only leads to stronger chlorine activation (ClO formation), but also extends the period of ozone loss considerably, well into spring.

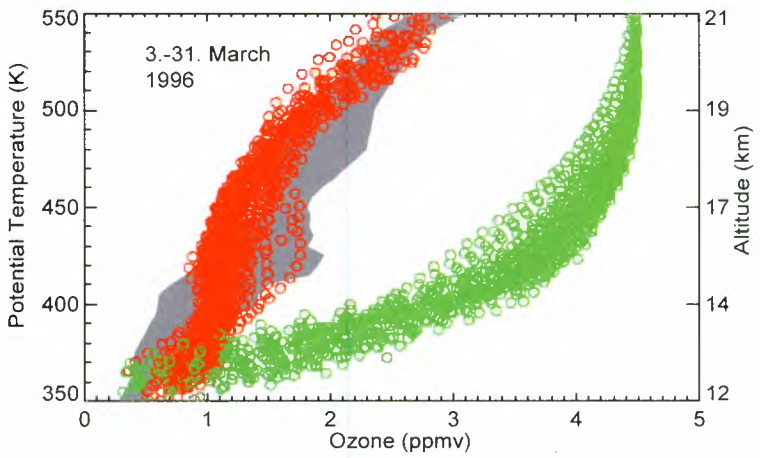

Figure 2.10: *Chemical ozone loss in the Arctic vortex. Ozone measurements are shown from HALOE in March 1996 (red). Ozone values expected in the absence of chemical loss (green) are calculated from HALOE measurements of O_3 and CH_4 (to correct for transport effects). The grey area indicates ozone measurements from Antarctica in austral spring 1985; from Müller et al., 1997 (Courtesy: R. Müller).*

In the future the stratosphere is expected to cool further, due to the continued increase in stratospheric CO_2 and H_2O. Such a cooling could extend both the temporal and spatial extent of PSCs. A small amount of cooling would lead to a strong increase in PSC activity and thus to a strong enhancement of chemical ozone loss.

Another element of coupling between stratospheric chemistry and climate change relates to the increase in stratospheric water vapour. Such an increase has been observed by a variety of instruments. Neither the cause of the increase nor its exact magnitude is known. Larger stratospheric water vapour concentrations not only lead to cooling of the stratosphere (Forster and Shine, 1999), but also to an increase in HO_x levels that enhance ozone loss in two ways: directly through enhanced catalytic loss due to HO_x chemistry, and indirectly because of enhanced ClO_x production via the reaction of OH with HCl.

It is predicted that stratospheric ozone will have started to recover by the end of this decade. To properly characterise the recovery or possible deviations from the current predictions, it will be critical to better understand all the chemical, physical, and dynamical factors (and their temporal development) influencing stratospheric chemistry.

Because of climate change, changes in the stratospheric circulation are likely to occur. Such circulation changes would affect the transport of stratospheric ozone from the tropics to mid-latitudes, and thereby change the profile and total column of ozone, with consequences for the radiative balance in the stratosphere. This change in radiation,

together with the change in ozone concentrations, implies a strong perturbation of stratospheric chemistry. Stratospheric ozone changes also impact directly on the penetration of UV radiation to the troposphere.

2.3.4 Tropospheric Chemistry

In the troposphere, ozone is photochemically produced by oxidation of carbon monoxide (CO), methane (CH_4), and non-methane-hydrocarbons (NMHCs), in the presence of nitrogen oxides (NO_x), water vapour, and ultraviolet solar radiation. Emissions of these so-called ozone precursor gases arise from a variety of sources including combustion processes (energy production, industry, transportation and biomass burning) and agricultural practices. As a consequence, large amounts of ozone are produced over polluted continental regions.

In photochemical smog areas near urban centres, ozone levels occasionally reach values as high as 500 ppbv (parts per billion by volume), compared to typical lower tropospheric mixing ratios of 10 to 60 ppbv. In the formation of the photochemical smog, the primary pollutants are nitrogen oxides (NO_x) and organic compounds, which are rapidly converted to secondary pollutants. The most important secondary pollutant is ozone; others include organic nitrates, e.g., Peroxy Acetyl Nitrate (PAN), oxidised hydrocarbons, e.g. formaldehyde (H_2CO), and the so-called photochemical aerosol.

Since the photochemical lifetime of ozone can be more than one month in the free troposphere, export from source to remote regions affects the background level of tropospheric ozone on the large scale. This can be clearly demonstrated when transport takes place over source-free regions, e.g. oceans. More particularly, transport of ozone and its precursors from North America and the chemistry over the Atlantic Ocean strongly influence background concentrations over Europe. Export of pollutants from Asia influences the distribution of species over the Pacific Ocean and North America. As shown in Figure 2.11, ozone is also produced over biomass burning regions in Africa and then transported aloft.

The observed regional variability of ozone concentrations is related to the transport of key precursors, particularly reactive nitrogen, CO and NMHCs (e.g. C_2H_6, C_2H_2) from their source regions and of ozone itself. However, the chemistry of ozone can be non-linear: increased emissions of, for example, NO_x do not necessarily lead to linear responses in ozone concentrations. The relationship of precursor emissions to ozone concentrations may vary strongly in space and time. Surface, aircraft and satellite observations have been used to show that, due to the short lifetime and uneven distribution of sources, NO_2 shows strong temporal and geographical variability (Figure 2.12). Tropospheric NO_x levels vary from a few tens of pptv (parts per trillion by volume) in remote regions to more than one ppbv in industrial regions. Therefore, depending on the prevailing conditions, different photochemical regimes can exist in

the troposphere. Away from source regions (e.g. in the UTLS) NO_x levels are strongly affected by chemistry and by recycling from reservoir species. In particular, nitric acid (HNO_3) and PAN represent a significant fraction of the total nitrogen content at these altitudes.

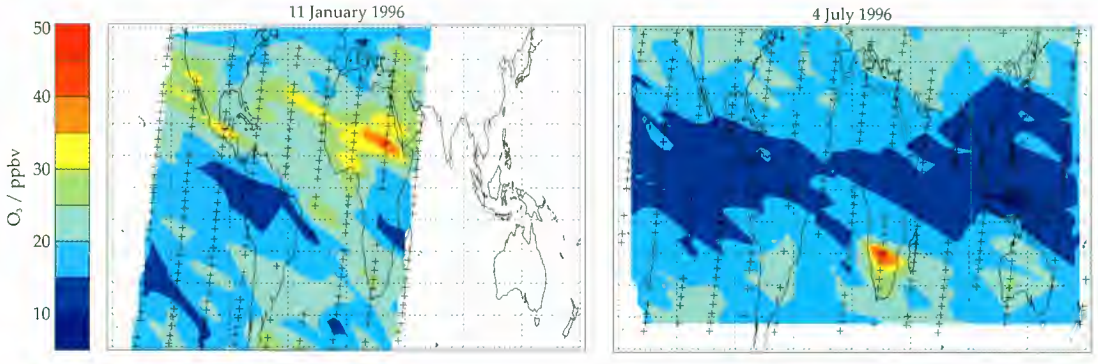

Figure 2.11: *Surface level ozone observations from GOME, showing elevated concentrations above the African continent for 11 January 1996 and 4 July 1996. The latter shows elevated concentrations over biomass burning regions in Southern Africa. Pluses indicate individual GOME profile measurements (Courtesy: R. Siddans).*

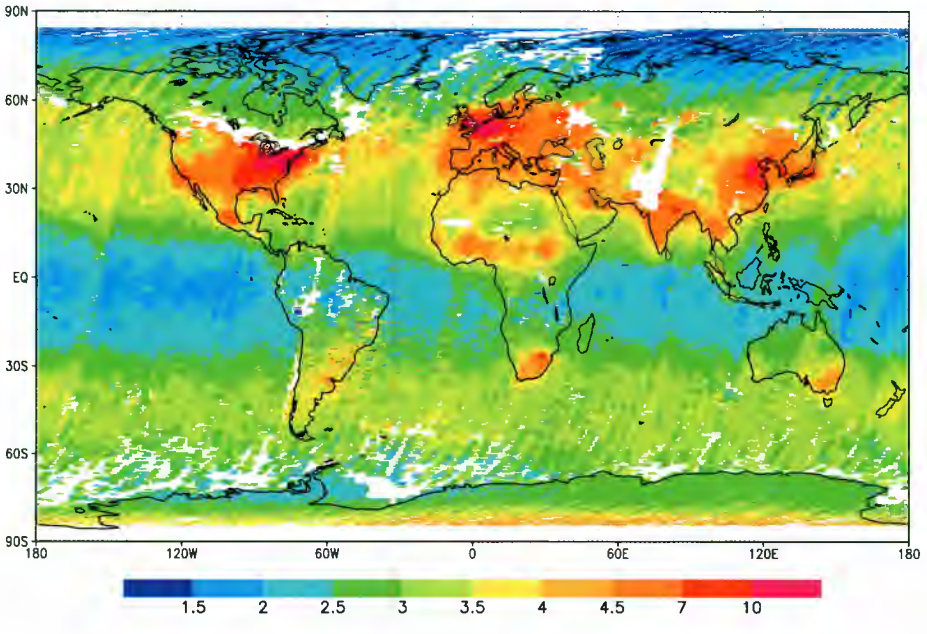

Figure 2.12: *Monthly-mean global distribution of the NO_2 column for March 1997 (in 10^{15} molecules cm^{-2}). The NO_2 column has stratospheric and lower-tropospheric contributions. Stratospheric NO_2 is mainly characterised by a zonal distribution, tropospheric NO_2 is largely confined to emission regions, which are visible as red spots in the figure (Courtesy: H. J. Eskes).*

The hydroxyl (OH) radical, owing to its strong reactivity, is the primary cleansing agent of the lower atmosphere and is largely responsible for the removal of almost all gases that are emitted into the atmosphere by biospheric and anthropogenic processes. The OH radical controls the lifetime of greenhouse gases such as methane, HCFCs and HFCs and is also involved in the oxidation of sulphur compounds leading to aerosol particles. By far the most important source of OH is the reaction of water vapour with electronically excited atomic oxygen that has been produced from ozone through absorption of solar ultraviolet radiation. Therefore tropospheric O_3 and H_2O play a critical role in controlling the oxidising capacity of the atmosphere. Enhanced ultraviolet radiation (UV-B) levels in the troposphere due to the stratospheric ozone depletion, and possible water vapour increases due to a global warming of the troposphere, will increase the primary OH-production, and thus feedback on the chemical lifetimes of O_3 and CH_4. In dry regions (in particular in the UTLS region) other species like formaldehyde (H_2CO), acetone (CH_3COCH_3), and peroxides (H_2O_2, CH_3OOH) are also important sources of HO_x radicals.

The chemistry of the troposphere is directly influenced by changes in temperature and humidity, as well as by interactions between tropospheric aerosol particles and trace gases. These couplings provide feedbacks between climate change induced by increasing greenhouse gases and the chemical processing of trace gases. Furthermore, the biosphere response to global change will also impact on the atmospheric composition. The changes in climate (e.g. temperature, humidity, precipitation) and in chemistry will alter ecosystems and consequently natural emissions of trace gases such as isoprene. This provides additional feedbacks that may add further indirect greenhouse forcing.

2.4 ACECHEM Observations: Science Perspective

This section introduces the mission objectives of ACECHEM, which will address the aspects of atmospheric science outlined in Section 2.3, focussing particularly on the UTLS region.

2.4.1 Role of the UTLS Region for Radiative Forcing and Feedback Mechanisms

The following main scientific questions related to the role played by the UTLS region in the radiative forcing and feedback of climate will be addressed by ACECHEM:

- What are the magnitudes of the radiative forcings and feedback mechanisms? What are the abundances and spatial/temporal variabilities of the greenhouse gases H_2O, O_3, CH_4, N_2O, and (H)CFCs in the UTLS region?

- What are the chemical and dynamical processes responsible for the variability of ozone and its precursors in the UTLS region?

- What are the climatic and chemical effects associated with aerosols and cirrus in the UTLS region?

Radiatively active gases and aerosols play a major role in the heating and cooling of the troposphere and lower stratosphere. CO_2 – although the most important radiative forcing agent – is not relevant in the context of ACECHEM observations, since it is very well mixed throughout the atmosphere and so its radiative forcing can be determined from ground-based measurements. For climate prediction, in addition to having knowledge of CO_2, it will be necessary to obtain information on water vapour which is the most important greenhouse gas in the troposphere, and on other greenhouse gases, such as O_3, N_2O, CH_4, and various (H)CFCs, in order to constrain the radiation budget and its changes. O_3 and H_2O are both highly variable throughout the troposphere and lower stratosphere. Greenhouse gases such as N_2O, CH_4, and (H)CFCs are uniformly mixed in the troposphere but have a stratospheric sink and therefore show spatial and temporal variability in the lower stratosphere and above. Therefore, in order to assess the impact of atmospheric composition changes on climate, the objectives of ACECHEM are mainly to provide a good representation of spatial and temporal variabilities of longer-lived climate gases (H_2O, CH_4, N_2O, halocarbons), of O_3 and its precursors, and of aerosols and cirrus in the vicinity of the tropopause and above.

The MetOp instrument IASI will be able to provide information on water vapour in the *lower and middle troposphere* with about 1 km vertical resolution and about 25 km x 25 km horizontal resolution. ACECHEM will provide high-resolution water vapour data in the *upper troposphere*, which is essential for a better understanding of convection processes and cirrus formation. Moreover, upper tropospheric humidity is a very important element in the Earth radiation budget. Change in its vertical distribution and variability is known to be one of the most important feedbacks modulating climate forcing. The Third Assessment Report of the IPCC (2001) concludes that: 'considerable uncertainty remains in observations and the ability of models to properly treat upper tropospheric humidity'.

Ozone is another important greenhouse gas that will be measured in the UTLS region. Limb measurements will define ozone at high vertical resolution in this critical height region where radiative forcing and ozone trends vary strongly with altitude. The detailed UT measurements will, as well, provide important constraints on retrieval of lower tropospheric ozone from both IASI and GOME-2 on MetOp. The budget of ozone in the UTLS region is difficult to establish due to various, not well understood, contributions from chemistry and transport. In particular, in this region, ozone is controlled by the input from the stratosphere, *in-situ* chemistry, and convective and long-range transport of ozone and its precursors from source regions. To study the causes of the variability of ozone in the UTLS region, ACECHEM and MetOp will provide observations of ozone and its precursors (e.g. CO, H_2CO, HNO_3, and acetone). Several of these precursors have been observed during aircraft campaigns. However,

climatological data in the UTLS region remain scarce. ACECHEM will provide these crucial measurements on a global scale.

These measurements will also allow the study of ozone-climate interactions which are of particular interest in the lower stratosphere and in the upper troposphere. In the lower stratosphere, there are two important issues regarding these interactions. Firstly, changes in ozone will directly affect the temperature distribution through the heating and cooling rates, secondly, changes in the stratospheric distribution of greenhouse gases cause a change in temperatures and consequently in the ozone loss. Additionally, the radiative forcing associated with tropospheric ozone change is particularly sensitive to ozone trends in the vicinity of the tropopause.

Aerosols are important constituents in the UTLS where they act as surfaces for catalysing heterogeneous chemical reactions and as scatterers of solar radiation. They also contribute to global cooling of the troposphere. In the lower stratosphere, they can play an important role in both the radiation budget and the chemical balance, as evidenced by the impact on the thermal structure and ozone loss after the Mount Pinatubo eruption. Freezing of H_2O and HNO_3 in the cold polar lower stratosphere leads to the formation of PSCs which catalyse polar ozone loss. In the upper troposphere, a fraction of the aerosols act as freezing nuclei for the formation of cirrus.

Stratospheric aerosols have *in-situ* sources such as injection of SO_2 from volcanic sources or STE in the tropical pipe. Oxidation of biogenic carbonyl sulphide (COS) in the stratosphere is also important. In the upper troposphere at mid-latitudes, the stratosphere can act as a source of aerosols. *In-situ* production from oxidation of heavy organics and SO_2 lifted from the lower troposphere may also act as secondary sources. Convection can efficiently transport lower tropospheric air to the upper troposphere. Soluble components and larger aerosols are likely to be removed while non-soluble components and aerosols with sizes between 0.1 and 1 micron (less efficiently removed) can be transported upwards. Thus, this smaller-sized component from lower tropospheric aerosol sources such as sea salt from the ocean, and sulphate from ocean emissions of dimethyl sulphide (DMS) and also from oxidation of fossil fuels, forest fires, biomass burning, blowing dust and volcanoes may end up in the upper troposphere. Thus it is essential to understand their role in climate and chemistry.

ACECHEM will contribute to this understanding by providing measurements in cloud-free views of aerosol extinction and scattering properties in the upper troposphere. As for gaseous species, ACECHEM will be able to utilise its aerosol measurements to provide added value to column information on aerosol optical depth from AVHRR-3 and GOME-2, allowing discrimination between aerosol optical thickness in the lower and upper troposphere.

As noted above, the ice crystals in cirrus act as efficient greenhouse agents since they are largely transparent to solar radiation but absorptive in the thermal IR, trapping

radiation from the lower atmosphere and re-emitting at a much lower temperature. Cirrus also provides surfaces for heterogeneous chemical reactions similar to those occurring in the lower polar stratosphere. These reactions may affect ozone and other chemical compounds in the UTLS region. The quasi-synoptic ACECHEM measurements of cirrus, H_2O, temperature and aerosols in the upper troposphere will provide a novel data set for investigations into cirrus formation and also for validation of weather forecast models, such as ECMWF, with prognostic cirrus capability, and for climate models.

2.4.2 The Importance of Stratosphere-Troposphere Exchange (STE) in Atmospheric Chemistry and Climate

ACECHEM will address the main scientific questions related to the role of STE in atmospheric chemistry and climate:

- How is the dynamical coupling between the stratosphere and the troposphere established and which processes are involved in this coupling in different latitude ranges?

- What is the role of STE for the budgets and distribution of O_3, H_2O and the so-called well-mixed greenhouse gases that are destroyed in the stratosphere?

- What is the spatial and temporal variability of the height and temperature of the tropopause and how does this variability impact on stratosphere-troposphere exchange?

Estimation of the transport of ozone from the stratosphere into the troposphere requires detailed knowledge of the 4-dimensional ozone concentrations and the atmospheric general circulation. The ozone flux from the stratosphere to the troposphere depends on different processes with a large range of horizontal scales, from the planetary scale down to the scales of turbulence. Studies investigating the contribution of tropopause folds and the outflow from large convective systems have shown that at least 1° x 1° resolution in the horizontal is required (Siegmund et al., 1996). With increasing height in the stratosphere, the horizontal resolution can be somewhat coarser as structures tend to become larger with increasing height. Data assimilation may be used to combine observations and modelling for improving the analysis.

ACECHEM observations of the ozone, water vapour and temperature spatial distributions will be essential to study climate-composition feedbacks via dynamics. Together with these measurements, the ACECHEM observations of longer-lived tracers such as N_2O, CH_4 and CFCs will be employed to quantify transport. Simultaneous observations of (at least) two tracers in the same air mass are especially useful to distinguish between different air mass origins and to identify mixing processes. Also measurements of water vapour and shorter-lived species such as CO

and HNO_3 can be used to study mixing of tropospheric air into the lowermost stratosphere. Other indicators for dynamical causes in ozone variability around the tropopause are temperature, potential temperature, potential vorticity, and cloudiness as a signature of convective events. Accurate descriptions of meteorological parameters, in particular wind and potential vorticity, are required for the interpretation of the ACECHEM observations and can be obtained from meteorological analyses by the weather centres.

Temperature and height variations of the tropopause are directly linked with synoptic weather patterns. Tropopause height typically follows low- and high-pressure systems closely. The tropospheric circulation of a high-pressure system leads to a high tropopause, and therefore to a geometrically thinner overlying stratospheric ozone column. The tropopause temperature determines the stability of the transition layer in the upper tropical troposphere (Figure 2.9), and therefore is a key parameter in estimating STE. Further, tropical tropopause temperature is the most critical parameter for the water vapour concentration at the tropical tropopause, and thus for the water vapour flux into the stratosphere. In combination with numerical weather prediction model analyses, the ACECHEM profile measurements of temperature, water vapour and ozone in the UTLS region will allow us to study the tropopause and its variations in detail.

2.4.3 Stratospheric Change and its Interactions with Stratospheric Chemistry and Climate

The future evolution of the stratospheric ozone layer will be a major environmental issue for the coming decades. One objective of the ACECHEM mission will be to address the following key questions in stratospheric chemistry:

- How will the ozone layer evolve in a future climate that is most probably characterised by a decrease of the concentrations of anthropogenic halogen compounds, by decreasing stratospheric temperatures, and by increases in H_2O?

- What are the precise chemical mechanisms underlying future ozone losses?

- How large is chemical ozone loss in the presence of substantial ozone variations due to transport?

The phase-out of CFCs has led to a reversal or decline in their atmospheric growth rates that is detectable in atmospheric observations. Owing to this fact, a recovery of the ozone layer is to be expected in the future. However, it is unclear when such a reversal in the ozone trend will be detectable and what the time scales of recovery are.

The ACECHEM observations will improve future predictions of the evolution of the stratospheric ozone layer. Precise measurements of ozone, the ozone destroying

halogen oxides BrO and ClO, and the major chlorine reservoir gas HCl, will contribute to a better and in particular more quantitative understanding of the chlorine chemistry that controls ozone depletion. This is especially important in the polar regions, where strongly enhanced concentrations of ClO are observed due to PSC activity. Furthermore, precise measurements from ACECHEM of lower stratospheric H_2O and HNO_3 will be of central importance. These species control the activity of PSCs during a period (post-2008) when enhanced PSC activity is anticipated owing to the expected further cooling of the stratosphere. Direct observations of the temperature profile, stratospheric aerosols, and stratospheric cloud occurrence by ACECHEM will contribute significantly to addressing these issues. In addition, the continuing expected decrease in the stratospheric burden of organic chlorine can be studied through observations of CFC-11, CFC-12, and HCFC-22.

Another important feature of ACECHEM measurements is that, together with the high spatial resolution ozone measurements, precise tracer (e.g. N_2O, CH_4, CFCs) observations will be available. This fact will allow the transport contribution to be estimated to a precision that will not be available prior to ACECHEM. In this way, chemical effects will also be more clearly identified.

2.4.4 Impact of Pollution on the Composition of the Upper Troposphere

The objectives of ACECHEM related to pollution issues and tropospheric chemistry impact on climate can be outlined as follows:

- What is the influence of pollutant export from industrial regions on the composition of the upper troposphere?

- How does the atmosphere cleanse itself of emissions of trace gases which directly or indirectly affect the radiative balance (e.g. greenhouse gases or aerosol precursors) and how will the oxidising capacity of the atmosphere evolve in the future under human activities?

- What is the contribution of widespread forest fires and other biomass burning emissions to the composition of the upper troposphere, with particular emphasis on tropical regions?

ACECHEM will measure the distribution and seasonal variation of ozone in the UTLS region where its contribution to the greenhouse effect is the largest. With the help of numerical models and *in-situ* measurements ACECHEM will address the fundamental question of the origin of tropospheric ozone: what is the relative importance of the transport from the stratosphere, of *in-situ* production, and of transport from polluted regions? Our understanding of the export of pollutants from industrial regions will greatly benefit from simultaneous spaceborne monitoring of chemical species emitted or produced from industrial activities, and of transport processes. Pollutants can be

transported to and from the stratosphere, exported by frontal systems, and uplifted by convection directly from the boundary layer to the upper troposphere. Emissions in developing countries like China and others in South-East Asia are expected to increase strongly over the next decades. Satellite observations are well-suited to determining the global extent of the impact of emissions.

An important tropospheric constituent is OH. Its measurement in the troposphere from space is practically impossible, mainly because of its very low concentrations. However, many of the more-abundant, longer-lived species that control its density in the UTLS region, such as CO, O_3, CH_4, H_2O, HNO_3, PAN, H_2CO, C_2H_6, C_2H_2, and acetone, will be measured by ACECHEM and these measurements will constrain OH. Global mapping of these species will advance our understanding of the oxidising capacity of the troposphere.

With the ACECHEM measurements that provide high resolution measurements of the UT region, special attention can be devoted to the tropical regions. The tropics is the region of the troposphere in which the largest net upward transport occurs and which therefore influences most directly the composition of the UTLS. The behaviour of trace gases in the tropics is extremely complex, involving micro-meteorological processes in the boundary layer, surface emissions (biogenic and from biomass burning), convective activity, lightning NO_x production, and active photochemistry. Our understanding of these regions is quite limited and advances will be made by simultaneous measurements of active fires (and burned area) and measurements of chemical species such as ozone and its precursors. In addition to the height-resolved measurements in the upper troposphere from ACECHEM, GOME-2 and IASI on MetOp will provide information on the column amounts of tropospheric ozone, H_2CO, and NO_2, not only in biomass burning regions, but also over polluted areas such as eastern North-America and Europe. AVHRR-3 on MetOp will monitor fire activity and provide information on the aerosol optical depth. Especially in the tropics, the height-resolved ozone measurements in the UTLS by ACECHEM, in conjunction with the column information from MetOp, will help to further distinguish between upper and lower tropospheric ozone.

2.5 ACECHEM Observations: Societal Benefits

European governments have accepted the precautionary principle and the need to restrict the impact of anthropogenic activities on the atmosphere. In addition to national and European legislation concerning air quality, two international treaties have been agreed on, which aim to control atmospheric emissions caused by man's activities: the Montreal Protocol and its amendments to protect the ozone layer, and the Kyoto Protocol to limit the emission of climate gases.

To accord with the precautionary principle, policy decisions are being guided by predictions founded on scientific knowledge, which is far from complete. Current

differentiated from upward transport of pollutants from the surface and downward transport of ozone and nitrogen oxides from the stratosphere.

Another interaction between composition, climate and human activities is mediated by lower stratospheric ozone, whose distribution is significant to radiative forcing and which controls the flux of solar UV radiation penetrating into the troposphere. In addition, lower stratospheric ozone is important to the thermal structure of the lower stratosphere. In turn, the temperature distribution feeds back on ozone via stratospheric chemistry and dynamics. ACECHEM observations will uniquely allow the evolving stratospheric ozone layer and the controlling chemistry and dynamics to be examined at the global scale during the period of predicted chlorine decrease and continued temperature decrease.

- O_3, H_2O, tracers, chemically-active chlorine, bromine and nitrogen species, sulphate aerosol, PSCs and temperature will all be observed simultaneously and with significantly better vertical and horizontal resolution than by earlier missions. This innovation will allow the dynamical and chemical influences on ozone to be better discriminated and will significantly improve understanding of this interaction between atmospheric composition, climate and human activities.

The limb-emission measurements of upper tropospheric and lower stratospheric composition by ACECHEM will be unique and innovative, for the reasons outlined above. A further innovation of the mission is the formation flying with MetOp, which couples the observations of the two missions synergetically. These aspects are further addressed in Chapter 4 and Section 5.3. Although other space missions planned for this period meet very few requirements of the mission, they could complement and further enhance the scientific return of ACECHEM, as outlined in Section 5.5.

3 Research Objectives

The main goal of the Atmospheric Composition Explorer for CHEMistry and climate interaction (ACECHEM) mission is to investigate:

- the composition of the upper troposphere and the lower stratosphere
- its interaction with climate, and
- the impact of anthropogenic activities.

More specifically, ACECHEM will improve our understanding of how atmospheric processes (chemistry, radiation and dynamics) determine atmospheric composition and its interactions with climate. This will provide new insight into how trace gas emissions resulting from human activities are translated into changes in atmospheric composition and climate on the global scale.

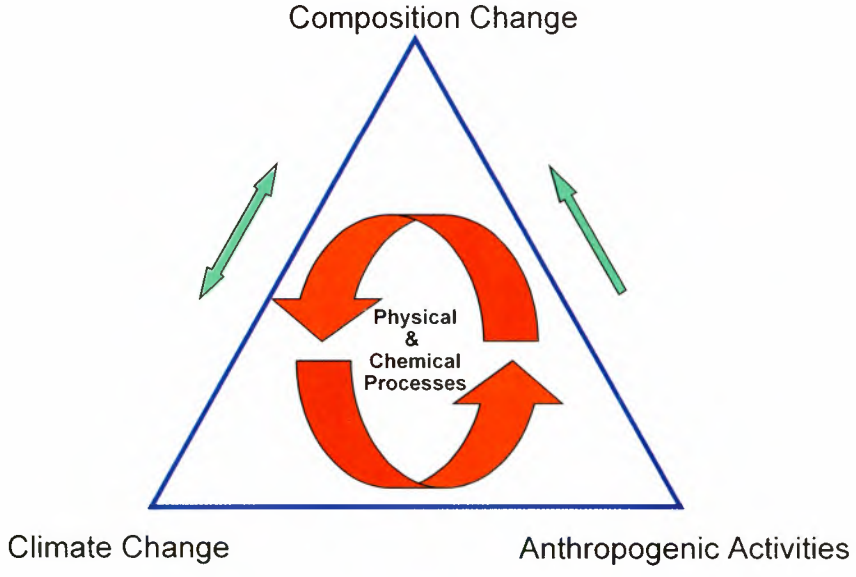

Figure 3.1: *ACECHEM will focus on how physical and chemical processes cause interactions between atmospheric composition in the UTLS region and climate (two-way arrow), and the mission will also provide a better insight into the processes by which anthropogenic activities change atmospheric composition (one-way arrow).*

For the reasons discussed in Chapter 2, the upper troposphere and lower stratosphere (UTLS) region is critical to investigation of composition-climate interactions. It is essential to gain a better understanding of the climate forcing and feedback mechanisms in relation to composition changes at these altitudes. The four ACECHEM

mission objectives derived in Section 2.4 and the most important scientific questions associated with each mission objective, are summarised below.

Objective 1: Role of the UTLS Region for Radiative Forcing and Feedback Mechanisms

The main scientific questions related to the role played by the UTLS region in the radiative forcing of climate and for the study of climate-chemistry feedbacks are:

- What are the magnitudes of the radiative forcings and feedback mechanisms? What are the abundances and spatial/temporal variabilities of the greenhouse gases H_2O, O_3, CH_4, N_2O, and (H)CFCs in the UTLS region?

- What are the chemical and dynamical processes responsible for the variability of ozone and its precursors in the UTLS region?

- What are the climatic and chemical effects associated with aerosols and cirrus in the UTLS region?

The most important trace gas observations for this objective are the profile measurements of H_2O, O_3, CH_4, N_2O, and (H)CFCs. The most relevant other observations in the UTLS region include the temperature profile and the height resolved measurements of aerosols and cirrus.

Objective 2: The Importance of Stratosphere-Troposphere Exchange in Atmospheric Chemistry and Climate

The importance of STE in atmospheric chemistry and climate, as will be addressed by ACECHEM can be summarised in terms of the following scientific questions:

- How is the dynamical coupling between the stratosphere and the troposphere established and which processes are involved in this coupling in different latitude ranges?

- What is the role of STE for the budgets and distributions of O_3, H_2O and the so-called well-mixed greenhouse gases that are destroyed in the stratosphere?

- What is the spatial and temporal variability of the height and temperature of the tropopause and how does this variability impact on stratosphere-troposphere exchange?

The measurement of the temperature profile in the UTLS region is of the highest relevance to this mission objective, in combination with the trace gas profile observations of H_2O, O_3, CH_4, N_2O, CFCs, CO, and HNO_3.

Objective 3: Stratospheric Change and its Interactions with Stratospheric Chemistry and Climate

The evolution of the stratospheric ozone layer will be a major environmental issue for the coming decade. ACECHEM will address the following key questions in stratospheric chemistry:

- How will the ozone layer evolve in a future climate that is most likely characterised by a decrease in the concentrations of anthropogenic halogen compounds, by decreasing stratospheric temperatures, and by increases in H_2O?
- What are the precise chemical mechanisms underlying future ozone losses?
- How large is the chemical ozone loss in the presence of substantial ozone variations due to transport?

To meet these objectives the trace gas profile observations of H_2O, O_3, ClO, HCl, BrO, CFCs, HCFCs, $ClONO_2$, HNO_3, NO_2, N_2O and CH_4 are most important, as well as temperature and PSC observations.

Objective 4: Impact of Pollution on the Composition of the Upper Troposphere

The scientific questions related to pollution issues in the upper troposphere and the impact of tropospheric chemistry on climate can be outlined as follows:

- What is the influence of pollutant export from industrial regions on the composition of the upper troposphere?
- How does the atmosphere cleanse itself of emissions of trace gases which directly or indirectly affect the radiative balance (e.g. greenhouse gases or aerosol precursors) and how will the oxidising capacity of the atmosphere evolve in the future under human activities?
- What is the contribution of widespread forest fires and other biomass burning emissions to the composition of the upper troposphere, with particular emphasis on tropical regions?

Research relative to this objective will make most use of the height-resolved observations of O_3, H_2O, CO, H_2CO, CH_4, C_2H_6, C_2H_2, CH_3COCH_3, NO_2, HNO_3 and PAN in the upper troposphere with co-located O_3, NO_2, CO, CH_2O and SO_2 columns from MetOp. Measurements of height-resolved aerosol in the upper troposphere by ACECHEM and of aerosol optical depth by MetOp are also of relevance to this objective.

4 Observational Requirements

4.1 Requirement to Observe Atmospheric Composition from Space

Observations from space will be essential to an integrated mission to address the four objectives identified in Chapter 3 because they will provide a unique global perspective and uniform sampling of constituents which vary both spatially and temporally. In particular, they will contribute height-resolved information encompassing the UTLS, the region of prime importance to the identified objectives, which can be accessed only sparsely from the ground and only infrequently from aircraft and balloons.

The research objectives identified in Section 3 impose stringent observational requirements (Section 4.2), which can be met only by observations from a dedicated platform and only with innovations in UT and LS observing capabilities from preceding space missions: observations of ozone, water vapour and other trace gases will need to be made with substantially improved vertical resolution and horizontal sampling and reduced susceptibility to cloud and aerosol. Characterisation of aerosol and cirrus in the UT and PSCs will need to be improved significantly.

During the time frame of the second cycle of the Earth Explorer core missions, no other major atmospheric composition sounding mission is planned. Neither Envisat (launch 2001) nor EOS-Aura (launch 2003) is expected to be functioning at that time. However, should any of the relevant Envisat or Aura instruments still be working, a temporal overlap with ACECHEM would present the opportunity for direct reference to these well-validated data sets of species measured in common within overlapping altitude ranges.

Availability of complementary observations by nadir-sounders on the MetOp series of satellites can be relied upon in the relevant time frame for synergetic use by ACECHEM, and observations by the OMPS instrument on the US NPOESS mission may also be available.

Ground-based and airborne observations will be needed to validate the space observations. They will also contribute information on finer temporal and spatial scales at particular locations and times, and on additional species, which will further enhance the scientific return from the mission.

4.2 Geophysical Variables and Observational Requirements

The relevance of atmospheric trace gases with respect to the research objectives identified for this mission has been outlined in Section 2.4 and Chapter 3. In the present Section, the rationale for geophysical variables (Figure 4.1) and their observational

requirements (Table 4.1) is briefly summarised[1] for each research objective, and spatial and temporal coverage requirements are outlined. The observational requirements are multivariate and multidimensional. For each geophysical variable, it is necessary to consider in parallel the requirements on height-range, precision, vertical resolution, horizontal and temporal sampling. Horizontal scales of atmospheric variability are typically smaller in the troposphere than in the stratosphere, and this is generally reflected in the requirements.

4.2.1 The Importance of the UTLS Region for Climate Forcing and Feedback Mechanisms

The trace gases that have most impact on the radiation budget and temperature of the Earth-atmosphere system are H_2O, CO_2, O_3, CH_4, N_2O and CFCs. Observations of these gases are needed in the UTLS region, with sufficient accuracy to prescribe their radiative properties. The only exception is CO_2 whose radiative properties can safely be derived from ground measurements because it is close to being uniformly-mixed throughout the troposphere and stratosphere. CH_4, N_2O, and CFCs are destroyed photochemically in the stratosphere and the resulting strong variations with height and latitude have an impact on radiative forcing. A vertical resolution of 2 km will be necessary to track these important variations. Among the most stringent observational requirements are those on H_2O and O_3, whose radiative impacts depend strongly on altitude (Figure 2.8), so that very accurate vertical profile measurements are needed to characterise them. Horizontal sampling requirements on H_2O and O_3 (target: 50 km x 50 km) reflect their high spatial variabilities in the UTLS. For analysis of the radiation budget in the UTLS region, important additional measurements will be the local temperature profile, the occurrence of cirrus clouds and the aerosol optical depth. Observation of elevated concentrations of SO_2 injected by volcanoes is also desirable, with respect to their indirect effect on climate via stratospheric aerosol formation.

4.2.2 The Role of Stratosphere-Troposphere Exchange in Atmospheric Chemistry and Climate

High spatial-resolution measurements in the UTLS of the tracers H_2O, O_3, CH_4, N_2O, CFCs, CO, and HNO_3, in combination with the temperature profile, are of the utmost importance to this objective. Temperature profile measurements with high accuracy (target 1 K) and vertical resolution (target 2 km) are needed to determine precisely the location of the tropopause and its geographical and temporal variations[2]. Simultaneous, co-located observations of tropopause altitude and tracer concentrations will allow the exchange of constituents between the troposphere and the stratosphere to be quantified

[1] Mission objectives, geophysical variables and observational requirements have been investigated extensively in a recent study (Kerridge et al., 2001).

[2] Combination of the measurements with high-resolution models will permit even more detailed information to be obtained on tropopause structure.

and relationships between different tracers to be examined. These can be used to determine the origin of the observed air masses and to distinguish between different STE processes. The target requirement on horizontal sampling is stringent (50 km x 50 km) because structures associated with a number of such processes are known to occur on spatial scales of ~100 km or smaller (tropopause folds, convective outflow). The time scales associated with these processes point to target sampling requirements of at least once, but preferably twice, a day for O_3 and H_2O [3].

4.2.3 Stratospheric Change and its Interactions with Stratospheric Chemistry and Climate

Compared with the present day, the stratosphere will be characterised after 2008 by evolving chlorine and bromine levels, lower ozone concentrations, higher concentrations of water vapour and other greenhouse gases, lower temperatures and more pervasive and persistent PSCs. Therefore, for this objective, the most important trace gases to be observed will be: O_3, H_2O, ClO, BrO, HCl, $ClONO_2$, halocarbons, HNO_3, N_2O, and CH_4. Observations of the temperature distribution and detection of PSCs will also be important. The accuracy and temporal resolution requirements on chlorine (ClO, $ClONO_2$) and bromine (BrO) species are defined for polar latitudes[4].

High accuracy (target 2%) ozone observations will be needed in the lower stratosphere to quantify its chemical loss directly. Observations of HNO_3 in the vapour phase will be needed to identify denitrified air masses. Accurate observations of temperature (target 1 K) along with the tracers N_2O and CH_4 (target 5%) will be needed with good vertical resolution (target 2 km). These are necessary to quantify ozone transport processes (and discriminate these from chemical transformation) and the role of dynamics in establishing conditions for PSC production. To capture the large scale structure of filaments and other dynamical features associated with the polar vortex and the distribution of PSCs, horizontal sampling is required to be ~ 100 km x 100 km.

4.2.4 Atmospheric Pollution and the Interactions between Tropospheric Chemistry and Climate

For this objective, observations of O_3, H_2O, CO, NO_2, HNO_3, H_2CO, CH_4 are required, observations of C_2H_2, C_2H_6, acetone and PAN are desirable, and observations of tropospheric aerosol are also of potential relevance. HNO_3 is the principal reservoir species for nitrogen oxides which, on account of its long lifetime in the UTLS, can release NO_x far from source regions, as can PAN. Measurement of upper tropospheric

[3] Again, in combination with models, it will be possible to 'zoom' in time to still finer scales.

[4] For ACECHEM to also contribute to detection of the Cl decrease *within the stratosphere* anticipated as a result of policy measures on emissions taken during last decade, concurrent measurements of major Cl source gases (CFC-11, CFC-12, HCFC-22), reservoirs (HCl, $ClONO_2$) and active radicals (ClO) will need to be made with high accuracy.

hydrocarbons (CH_4, C_2H_2, and C_2H_6) and the products of their oxidation (principally CO, also H_2CO and acetone) contain information on the origin of the air masses and their chemical processing. Acetone is also a significant source of radicals in the upper troposphere. The accuracy requirements for these chemically-active species are typically based on enhanced levels, i.e. cases in which the upper troposphere is polluted.

The (tropospheric) column requirements on NO_2, CO and H_2CO are 20-30%, such as to give detailed geographical information on their main emission sources. For CH_4, the column requirement is more stringent (threshold 5%) because its spatial variability is correspondingly lower. An accuracy of 5% for O_3, CO, and HNO_3 in the upper troposphere will be sufficient to capture their large concentration variations in this altitude domain. For C_2H_2 and C_2H_6, the required accuracy is 20-50%. For the lower troposphere, horizontal sampling of 25 km x 25 km is desirable in order to determine the locality of emissions[5]. In the UTLS region the sampling requirements are typically <100 km x 100 km.

4.2.5 Spatial and Temporal Coverage

The four research objectives span tropical, middle and high latitudes, requiring measurements with full global coverage. Required vertical domains are given in Table 4.1. Their altitude assignment varies with latitude. The altitude range spanned by the UTLS is typically 6 to 26 km at mid-latitudes, with an upward/downward shift reaching ± 4 km in the tropics/polar regions. In the context of this report, the lower troposphere 'LT' is defined to be the region below the UTLS. With lower priority, occasional measurements above the UTLS are also desirable to address additional scientific issues.

The processes to be studied by ACECHEM are modulated by atmospheric variability on various time scales. The requirement for the mission duration is determined by the need to understand their patterns in the data. These variabilities are known to vary themselves from one cycle to the next, making it necessary to cover several cycles. Most important are the seasonal cycle, the Semi-Annual Oscillation (SAO), the Quasi-Biannual Oscillation (QBO) and the irregular interannual variability in Arctic winter meteorology. The requirement is therefore five years, covering about two cycles of the QBO and providing a high probability of observing cold as well as warm Arctic winters.

[5] Trace gases can be observed in the lower troposphere only in cloud-free scenes, whose frequency depends inversely on pixel size, as shown in Figure 4.3. The target requirement on spatial sampling of the lower troposphere takes this factor into account.

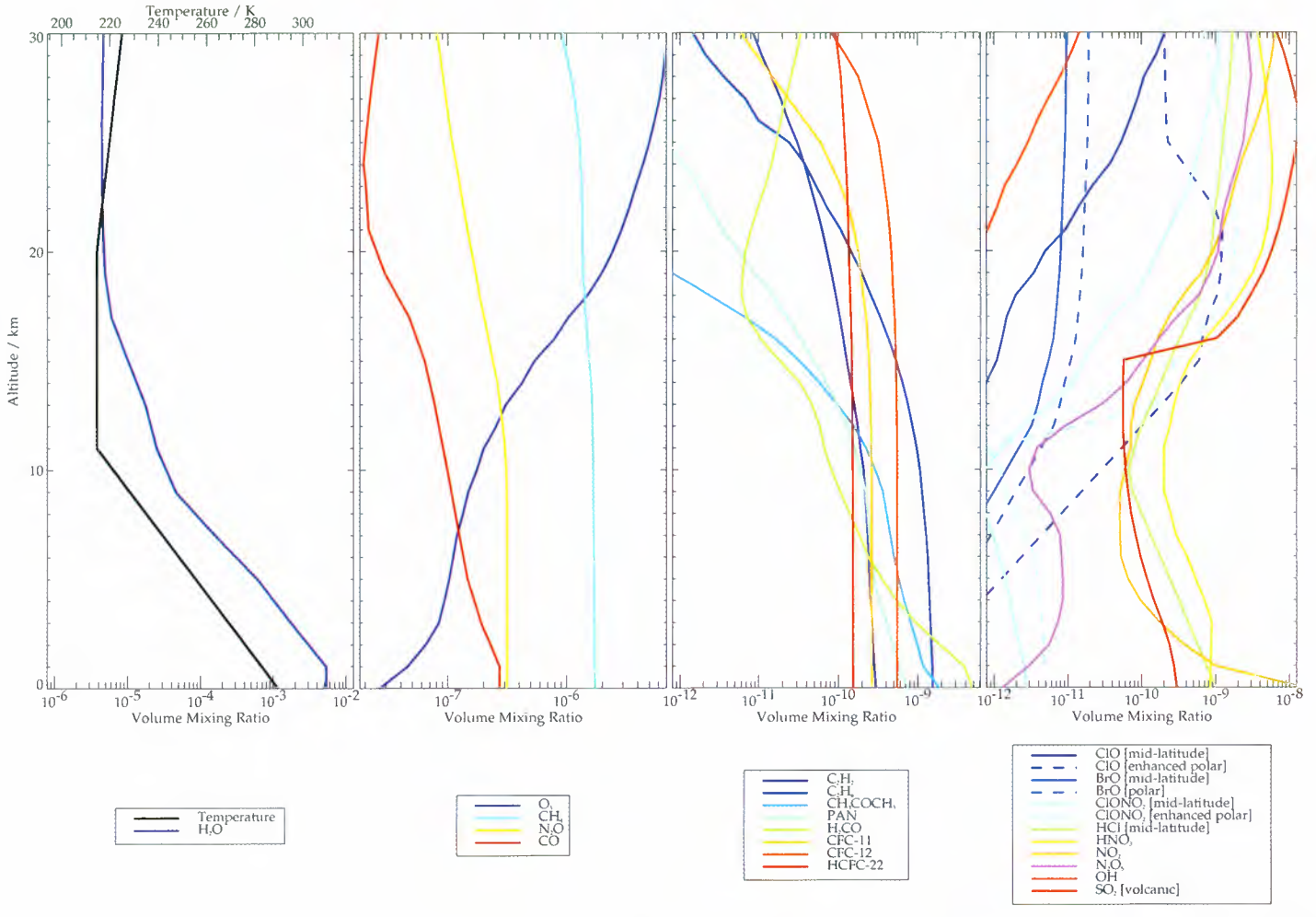

Figure 4.1: *Vertical profiles of trace gas volume mixing ratios and temperature, representative of mid-latitude conditions. For BrO, ClO and $ClONO_2$, profiles representative of polar conditions are also shown. For SO_2, the profile is representative of elevated concentrations in the lower stratosphere following a volcanic eruption.*

Variable	Priority	Domain	Objectives	Uncertainty	Horizontal sampl. [km]	Vertical res. [km]	Time sampl. [days]
O_3	A	LS	1, 2, 3, 4	2% / 10%	50 / 100	2 / 3	0.5 / 3
	A	UT	1, 2, 4	5% / 20%	50 / 100	2 / 3	0.5 / 3
	A	LT	1, 4	20% / 20%	25 / 100	2 / C_T	0.5 / 3
H_2O	A	LS	1, 2, 3	5% / 20%	50 / 100	2 / 3	0.5 / 3
	A	UT	1, 2, 4	5% / 20%	50 / 100	2 / 3	0.5 / 3
	A	LT	1, 4	10% / 20%	25 / 100	2 / 3	0.5 / 3
Temperature	A	all	1, 2, 3, 4	1K / 2K	50 / 100	1 / 3	0.5 / 3
CO	A	UT+LS	2, 4	5% / 20%	50 / 100	2 / 3	1 / 3
	A	LT	4	20% / 20%	25 / 100	2 / C_T	1 / 3
HNO_3	A	UT+LS	2, 3, 4	5% / 20%	50 / 100	2 / 3	0.5 / 3
NO_2	A	UT+LS	2, 3, 4	5% / 30%	50 / 100	2 / 3	0.5 / 3
	A	LT	4	20% / 30%	25 / 100	2 / C_T	0.5 / 3
CH_2O	A	UT+LS	4	20% / 30%	50 / 100	2 / 3	0.5 / 3
	A	LT	4	20% / 30%	25 / 100	C / C	0.5 / 3
N_2O	A	UT+LS	1, 2, 3	5% / 10%	50 / 100	2 / 3	1 / 3
CH_4	A	UT+LS	1, 2, 3, 4	5% / 10%	50 / 100	2 / 3	1 / 3
	A	LT	1, 4	2% / 5%	25 / 100	C / C	1 / 3
CFC-11	A	UT+LS	1, 2, 3	2% / 20%	50 / 100	2 / 3	1 / 3
CFC-12	A	UT+LS	1, 2, 3	2% / 20%	50 / 100	2 / 3	1 / 3
HCFC-22	A	UT+LS	1, 3	5% / 20%	50 / 100	2 / 3	1 / 3
ClO (polar)	A	LS	3	5% / 20%	50 / 100	2 / 4 0	5 / 3
BrO	A	LS	3	5% / 20%	50 / 100	2 / 4	0.5 / 3
HCl	A	LS	3	5% / 20%	50 / 100	2 / 4	1 / 3
$ClONO_2$	A	LS	3	5% / 20%	50 / 100	2 / 4	1 / 3
SO_2 (volcanic)	A	UT+LS	1, 3	20% / 50%	50 / 100	2 / 4	0.5 / 3
(polluted)	A	LT	1, 4	20% / 50%	25 / 100	C / C	0.5 / 3
Aerosol OD	A	UT+LS	1, 3, 4	20% / 100%	50 / 100	- / -	1 / 3
	A	LT	1, 4	10% / 50%	25 / 100	- / -	1 / 3
Cirrus OD / contrails	A	UT	1, 2	20% / 100%	25 / 100	- / -	0.5 / 3
PSC occurrence	A	LS	1, 3	- / -	25 / 100	- / -	1 / 3
Cloud occurrence	A	UT+LS	needed for	- / -	0.6 / 1.5	0.2 / 0.5	synchronous
	A	LT	retrievals	- / -	1 / 4	1 / 2	synchronous
Fire occurrence/ area	A	surface	4	- / -	25 / 100	- / -	0.5 / 3
C_2H_6	B	UT	4	20% / 50%	50 / 100	2 / 3	0.5 / 3
C_2H_2	B	UT	4	20% / 50%	50 / 100	2 / 3	0.5 / 3
CH_3COCH_3	B	UT	4	20% / 30%	50 / 100	2 / 3	0.5 / 3
PAN	B	UT	4	20% / 30%	50 / 100	2 / 3	0.5 / 3
N_2O_5	B	LS	3	20% / 50%	50 / 100	2 / 4	0.5 / 3

Key: Domains are: LT = lower troposphere, UT = upper troposphere, LS = lower stratosphere. Target value/threshold value are provided for each requirement. C = total column; C_T = tropospheric column; OD = optical depth; Horizontal sampling: '25' means 25 km x25 km.

Table 4.1: *Geophysical variables and observational requirements.*

4.3 Evaluation of Observational Techniques

Capabilities to meet requirements on trace gas observations have been evaluated for an extensive set of *passive* remote-sensing techniques in a recent study (Kerridge et al., 2001). A presumption of that study was that, in the context of remote-sensing of atmospheric trace gases from space, *active* techniques (i.e. lidar or radar) firstly would offer measurement of very few of the required gases, for which the resources required would be disproportionate, and secondly would have difficulty in fulfilling the requirement on mission duration, driven by QBO and other interannual variability.

Scientific criteria applied in the study for the evaluation of passive techniques included:

- Retrieval simulations performed on a common basis.
- Vulnerability to cloud and aerosol.
- Susceptibility to other uncertainties in radiative transfer modelling.

To sound tropospheric composition accurately from space presents a major scientific and technical challenge:

- Observations of tropospheric trace gases and aerosol are limited first and foremost by cloud, whose optical properties are highly inhomogeneous and difficult to characterise.
- The spatial and temporal scales of variability of designated target species (e.g. H_2O) are typically smaller than in the stratosphere.
- To 'see' the troposphere from space, a space instrument must look through the stratosphere and higher layers, where trace gas concentrations may be much larger (e.g. O_3).
- Radiative transfer is more difficult to model (even in the absence of cloud) than in the stratosphere. For example: spectral interference due to pressure-broadening and continua is greater; backscattered solar radiation is sensitive to (multiple-) Rayleigh scattering, aerosol scattering and surface reflectance; refraction becomes important.

To meet this challenge, ACECHEM will be better equipped than preceding or concurrent missions since it will:

1. Exploit synergetically the complementary attributes of limb- and nadir-viewing and of different wavelength regions.

2. Exploit technical advances in order to maximise vertical resolution and horizontal sampling, so as to capture the spatial variability of designated target species with high fidelity.
3. Deploy a limb-imager to characterise cloud and aerosol in the UT and LS.

The ability of space-borne remote-sensing techniques to penetrate into the lower stratosphere and troposphere is controlled by atmospheric opacity, and therefore by the availability of spectral 'windows' between the major atmospheric absorption features, which depends on viewing-geometry.

Windows in the millimetre (mm)[6], mid-infrared (mir) and near-infrared (nir) wavelength ranges allow limb-sounding down into the troposphere. To limb-sound above the tropopause, additional windows are available in the sub-millimetre (sub-mm), far-infrared (fir), visible (vis) and ultraviolet (uv). *Vertical resolution* and *sensitivity* to optically weak spectral features, attributes of particular value to the ACECHEM mission, are both highest for limb-geometry. Research objectives (1), (2) and (4) (Chapter 3) require observations in the upper troposphere with vertical resolution and sensitivity attainable only by limb-sounding, and research objectives (1), (2) and (3) require observations in the lower stratosphere with vertical resolution and sensitivity, again, attainable only by limb-sounding.

The occurrence frequency of cloud viewed in limb-geometry has been established as a function of height, latitude and time-of-year for clouds designated as 'opaque' and 'sub-visual' at 1 μm by SAGE-II solar occultation observations (Figure 4.2). Global mean frequency in the upper troposphere is seen to be:

for 'opaque' clouds <10% at middle and high latitudes and ~15% in the tropics,
for 'sub-visual' clouds ~20% at middle and high latitudes and ~40% in the tropics.

The SAGE-II vertical field-of-view (VFOV) is ~1 km, and cloud will be encountered more frequently by limb-sounders with larger VFOVs. Cirrus extinction at mir wavelengths is comparable to that at 1 μm, but cirrus extinction at mm wavelengths is typically several orders of magnitude smaller (Figure 4.3). Limb-observations at mm wavelengths will therefore not be affected at all by clouds in the *sub-visual* category and will be affected by only a fraction of clouds in the *opaque* category. Insensitivity to cirrus is a major advantage for sounding trace gases in the upper troposphere, and limb-mm observations are also unaffected by aerosol and polar stratospheric clouds.

[6] For the purpose of this report, wavelength ranges are defined as:
uv < 0.4μm < vis < 0.75 μm < nir < 4 μm < mir < 20 μm < fir < 150 μm < sub-mm < 900 μm < mm.

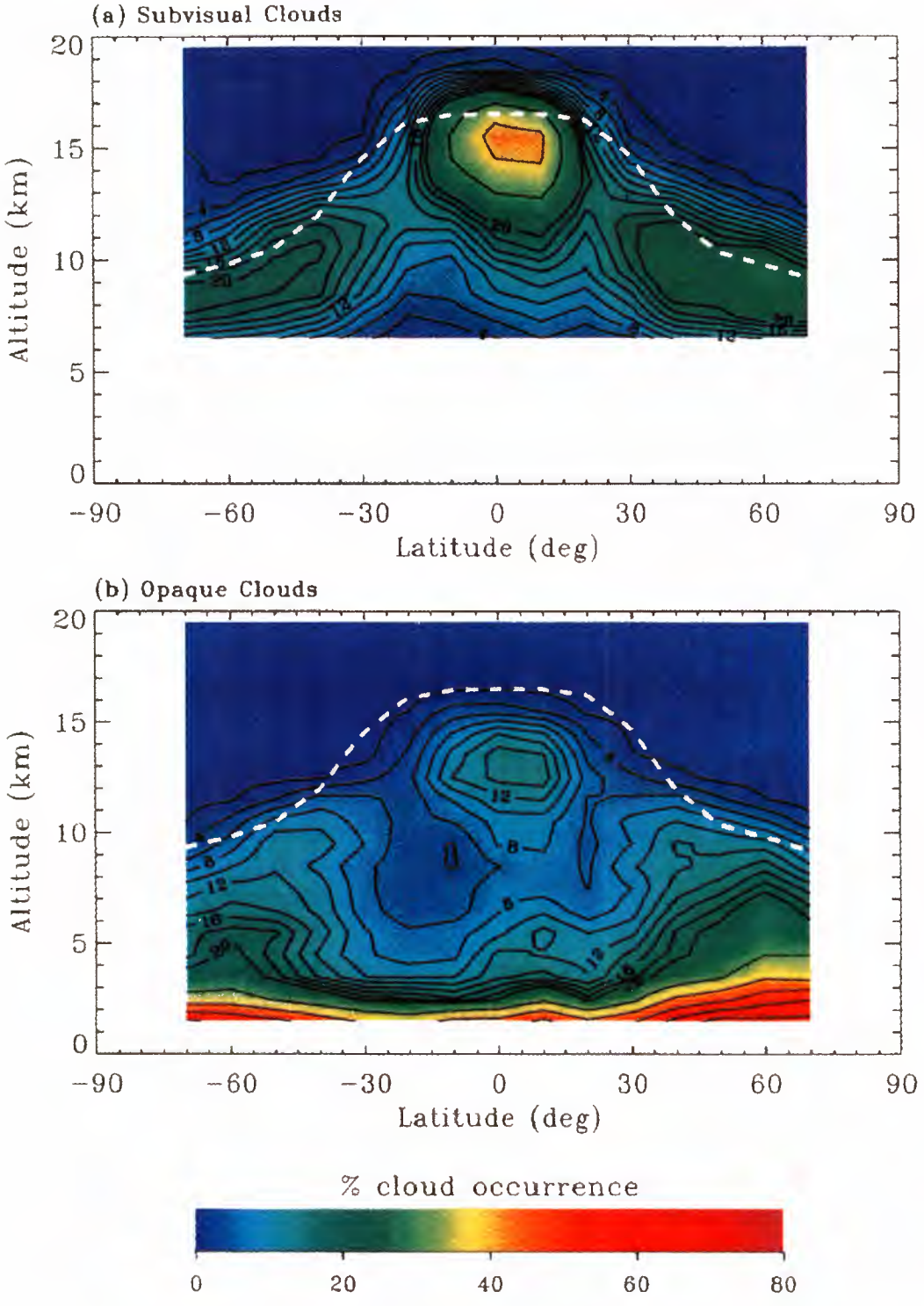

Figure 4.2: *SAGE II zonally averaged subvisual and opaque cirrus cloud occurrence frequency as a function of latitude and altitude. The data represent 6-year averages for the period 1985-90. The dashed line indicates the climatological tropopause. (Figure from Solomon et al., 1997, based on analysis of Wang et al., 1996).*

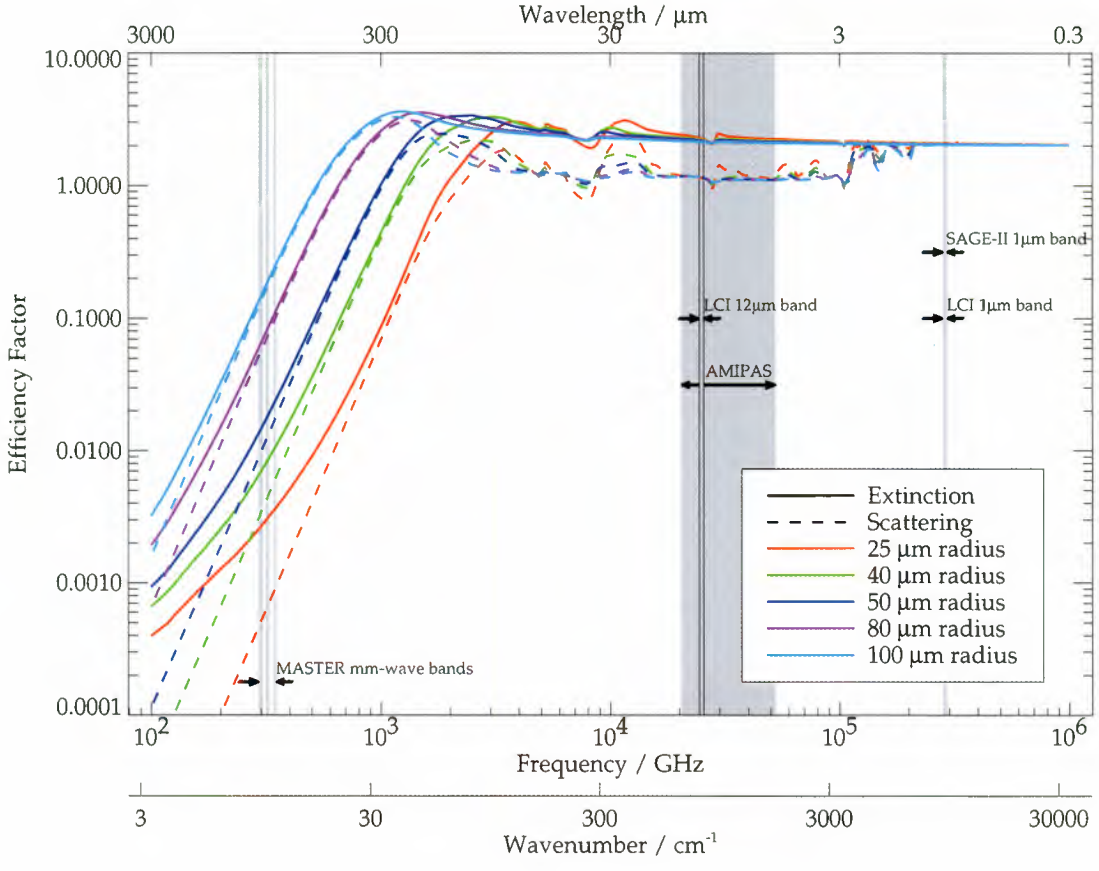

Figure 4.3: *Extinction and scattering efficiencies for a range of ice particle sizes calculated with Mie theory using ice refractive indices compiled by Warren (1984). Spectral band-passes of the ACECHEM instruments and the SAGE-II 1.02μm channel are indicated by grey shading.*

On the other hand, in cloud-free scenes, mir windows offer deeper penetration into the troposphere than mm windows for sounding H_2O, O_3 and HNO_3. Upper tropospheric observations of C_2H_6, C_2H_2, acetone and PAN in mir windows also complement those of CO in the mm window near 345 GHz.

Radiative transfer modelling is inherently simpler for thermal emission than for multiply-scattered solar radiation viewed in limb (e.g. Flittner et al., 2000; McPeters et al., 2000) and is susceptible to uncertainties in fewer geophysical and spectroscopic parameters.

- For example, in order to retrieve trace gas distributions accurately from backscatter measurements, the spatial distributions of atmospheric scattering agents must be known in 3-D (i.e. below and to either side of the limb-path, as well as along and above it), along with optical properties such as the phase function and scattering

coefficient. For limb-sounding of trace gases in the *upper troposphere*, mm and mir windows are therefore generally preferable to those in the nir.

- The altitude range over which constituent retrievals are sensitive to 'non-thermal' molecular emission typically extends to lower altitudes for the nir (stratosphere) than for the mir (mesosphere) or for the mm (thermosphere). For limb-sounding of trace gases in the *lower stratosphere*, windows at mir and longer wavelengths are therefore similarly preferable to those at shorter wavelengths.

To sound trace gases in the upper troposphere, it will be invaluable for limb-emission spectrometers to have knowledge of co-located cloud and aerosol distributions at substantially higher spatial resolution than their fields-of-view. Limb-imaging in a nir window (in addition to a mir window) will allow detection and characterisation of cirrus clouds in the upper troposphere, polar stratospheric clouds and aerosol from their scattering properties. This will provide essential information to complement that from MetOp for the analysis and scientific interpretation of trace gas observations by the limb-emission sounders.

The combination of limb-viewing, emission-sensing spectrometers to observe trace gases at mm and mir wavelengths with a limb-viewing sub-pixel cloud/aerosol imager with broad-band channels in the mir and nir is therefore considered optimum for observations of the upper troposphere in the ACECHEM mission. Addition of sub-mm channels allows stratospheric observations of ClO and HCl, along with other required constituents.

Because atmospheric path-lengths are longest for limb-viewing geometry, possibilities to 'see' down to the surface are very rare. The shortest path-lengths, and hence the greatest atmospheric *penetration depths*, occur for nadir-viewing geometry, and windows exist at mm, mir and nir/vis/nuv wavelengths in which to see to the surface and hence to probe the composition of the lower troposphere. It is only possible to sound aerosol and trace gases in the lower troposphere in 'cloud-free' scenes, whose frequency of occurrence is inversely proportional to horizontal area (Figure 4.4). For nadir-viewing geometry, horizontal areas of individual observations (pixel sizes) are smallest and dense horizontal sampling can be achieved across-track as well as along-track. The ability of nadir-viewing instruments to detect constituents in the lower troposphere is of particular value to research objective (4) and can be exploited to best effect by combining nadir-sounding observations synergetically with co-located, limb-sounding observations of the upper troposphere. This will permit the lower troposphere to be discriminated from higher altitudes, which is rarely possible by nadir-viewing alone.

An extensive suite of nadir-viewing instruments is due to be deployed on the MetOp series of platforms, commencing with MetOp-1 in 2005. Although the nadir-sounders

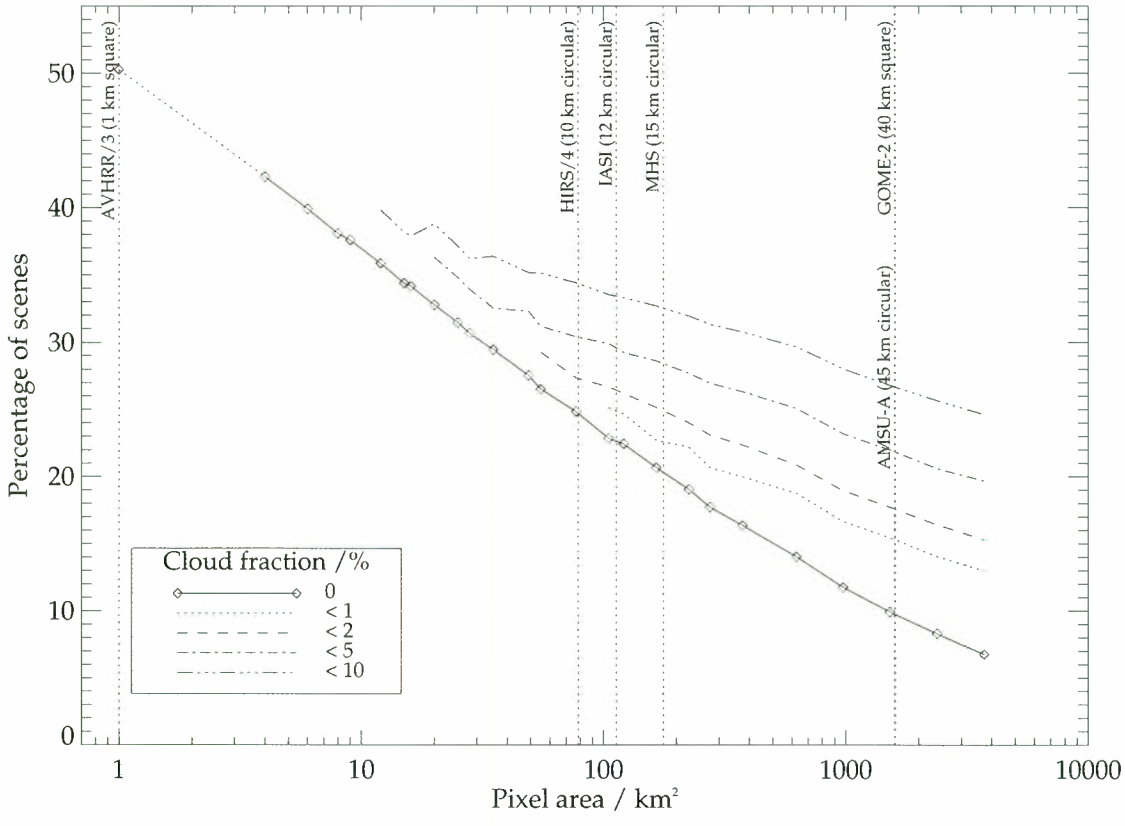

Figure 4.4: *Dependence of the percentage of observations with a given cloud cover on pixel size, derived from 1 x 1 km ATSR-2 images sampled appropriately. Data represent a global average for a single day (4 July 1996). Pixel areas for MetOp instruments are indicated.*

on MetOp have been designed primarily to meet observational requirements for NWP and climate monitoring, they can also address certain requirements for ACECHEM.

The proposed mission to address research objectives (1) to (4) will therefore comprise a dedicated ACECHEM platform carrying:

1. Limb-viewing emission-sensing spectrometer (MASTER) with three mm channels to target[7]:
    - H_2O, O_3 and CO in the upper troposphere
    - H_2O, O_3 and CO, together with HNO_3 and N_2O in the lower stratosphere and two sub-mm channels to target:
    - ClO, BrO and HCl in the stratosphere

[7] MASTER will observe several trace gases in addition to those specifically targeted. For example, CH_3Cl, HOCl and H_2CO will be detected, and SO_2 will be measured in the lower stratosphere if concentrations are elevated following a volcanic injection.

2. Limb-viewing mir emission-sensing spectrometer (AMIPAS) to target[8]:
    - T, H_2O, O_3, HNO_3, C_2H_2, C_2H_6, CH_3COCH_3, and PAN in the upper troposphere
    - T, H_2O, O_3, HNO_3, CH_4, N_2O, NO_2, N_2O_5, $ClONO_2$, CFC-11, CFC-12 and HCFC-22 in the lower stratosphere
3. Limb-viewing mir/nir cloud imager (LCI) for:
    - cloud and aerosol detection in the upper troposphere and lower stratosphere at higher spatial resolution than the spectrometers.

This platform will fly in formation with MetOp so as to co-locate rearward limb-viewing observations from the former with nadir-viewing observations from the latter:

1. GOME-2 measurements of height-resolved O_3 and of NO_2, H_2CO and SO_2 columns in polluted air,
2. IASI observations of tropospheric temperature and H_2O profiles and of CO and CH_4 columns[9], and
3. AVHRR-3 images of cloud, height-integrated aerosol and surface properties.

4.4 The Role of Data Assimilation

Data assimilation provides an intelligent means: to interpolate observations in time and space; to integrate the diverse elements of a large measurement and modelling programme and; to combine, intercompare and characterise the observations from different types of instruments, systematically and in detail.

Data assimilation will add value to the ACECHEM observations by integration of:

- The two dedicated limb-emission sounders whose scan-patterns will differ, so as to optimise horizontal resolution in the along-track and across-track directions.

- The two limb-emission sounders with the co-located observations by the nadir-sounders on MetOp, and with measurements from other satellite platforms such as GCOM-A1 and NPOESS (which, unlike ACECHEM and MetOp, is in an afternoon equator crossing orbit)

[8] AMIPAS will observe a number of trace gases in addition to those specifically targeted (e. g. CCl_4, CF_4, H_2CO, SF_6, OCS and HCN). The mir spectral signatures of aerosol and polar stratospheric clouds will also be detected, from which information on their composition will be derived, to complement that on their spatial distributions from the limb-imager measurements at two fixed wavelengths (1 and 12 μm).

[9] Height-resolved retrieval simulations presented in Section 4.6 indicate IASI to be most sensitive to CO and CH_4 at around the 4 km level. Columns retrieved from IASI in cloud-free scenes will therefore provide information on these species at lower altitudes than can be accessed by the ACECHEM limb-sounders.

- The two limb-emission sounders and MetOp observations with *in-situ* observations, both ground-based and airborne.

- The above observations with model information on the dynamical state of the atmosphere to represent constituent distributions at finer scales than those observed (Figure 4.5).

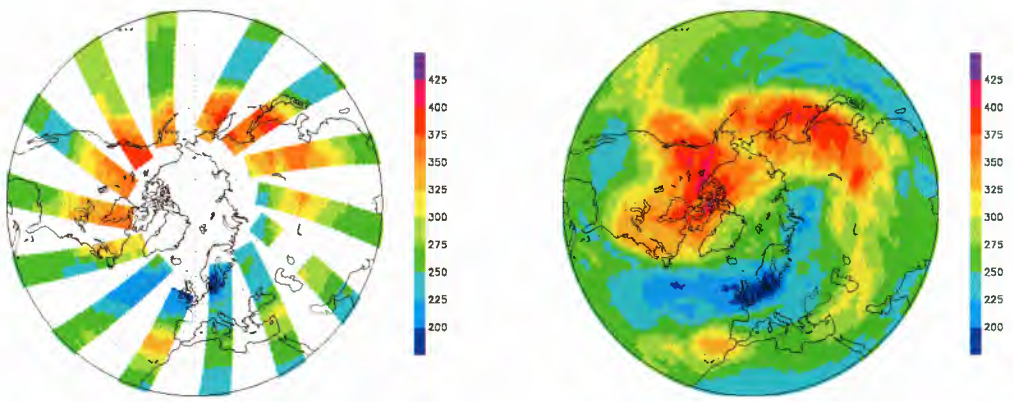

Figure 4.5: *An example of the value-adding of data assimilation. Dynamical information from a validated 3-D atmospheric model is combined with low resolution total ozone column observations from GOME. The figure on the left shows a collection of one day of GOME observations, for 30 November 1999. The figure on the right shows the total ozone distribution for 30 November 1999, 12 GMT, based on assimilation of the GOME observations into the chemistry-transport assimilation model TM3DAM (Courtesy: H.J. Eskes).*

In this way, data assimilation will also play a key role in the validation and scientific exploitation of the ACECHEM data.

Chemical data assimilation techniques are advancing rapidly and are expected to reach a high level of sophistication by the time of ACECHEM, following application in preceding missions. These techniques will also allow the distributions of species that are not observed directly by ACECHEM, but which interact chemically with observed species, to be inferred.

4.5 Key Mission and Instrument Parameters

4.5.1 General Sampling Requirements

The ACECHEM limb-viewing spectrometers will provide high-quality data products for UTLS constituents. However, emission from higher altitudes contributes to limb radiances detected at tangent-heights in the UTLS. To account for it in retrievals, in particular for the mir sensor, the tangent-height range is extended upwards by ~10 km,

leading to a required range of 3(10)...33(40) km at the poles (equator). To be able to occasionally address (lower priority) issues in the middle/upper stratosphere and mesosphere, a measurement capability up to 90 km is also desirable. The limb cloud imager needs only to cover the tangent-height range of cirrus and PSCs, i.e. 0...25 km.

All three instruments are synchronised to a measurement cycle satisfying the horizontal sampling requirement of 100 km along-track. Taking advantage of the specific capabilities of the different measurement techniques:

- the cloud insensitive mm/sub-mm limb-sounder performs one vertical scan per cycle contributing to two-dimensional tomographic sounding in the plane of the orbit;

- the radiometrically very sensitive mir limb-sounder performs five profile measurements at different azimuth angles within one cycle, providing good across-track sampling;

- the cloud imager makes co-located measurements with the mir spectrometer to support its data retrieval. Precise co-registration knowledge between both instruments is essential.

All ACECHEM measurements are within the swath width of the relevant MetOp instruments. To achieve full synergy, a time delay of less than a minute between co-located ACECHEM and MetOp observations and precise co-registration knowledge are required.

4.5.2 Instrument Parameters

Instrument requirements for limb-viewing spectrometers to measure thermal emission at mm/sub-mm and mir wavelengths have been investigated in depth and optimised for sounding the UTLS region in a series of studies (e.g. Buehler et al., 1998; Kerridge et al., 2001; Reburn et al., 1998, 2000; Verdes et al., 2000). In each case, sensitivities to instrument parameters and their uncertainties have been assessed for targeted trace gases and temperature through extensive retrieval simulations. Some key instrument requirements, derived from these studies for the mm/sub-mm and mir limb-sounders, are presented in this section, along with those for the mir/nir limb-imager, which have been derived through radiative transfer model simulations.

a) Millimetre/Sub-millimetre Wave Limb-Sounder (MASTER)

Requirements on spectral coverage and resolution, Noise-Equivalent Brightness Temperature (NEBT) and antenna Half-Power Beam Width (HPBW) (Table 4.2) in the three mm bands are determined by the observational requirements on H_2O, O_3 and CO in the upper troposphere. In particular, they are driven by the needs to resolve pressure-

broadened line shapes, to characterise 'continua' and the overlap between spectral lines adequately at the lowest observable altitudes and in the presence of steep vertical gradients in humidity. Requirements for the sub-mm bands have been similarly specified for observation of ClO, HCl, BrO, O_3, N_2O and other target gases in the lower stratosphere.

Primary Targets	Height Domain	Band	Spectral Coverage (GHz)	Spectral Resolution (MHz)	NEBT / Accuracy (K)	Vertical HPBW (km)
O_3, N_2O, O_2 (pointing)	UTLS	B	294.0-305.5	50	1.2/1.0	2.3
H_2O	UTLS	C	316.5-325.5	50	1.3/1.0	2.3
CO, HNO_3	UTLS	D	342.25-348.75	50	0.5/1.0	2.3
ClO, O_3, N_2O, BrO	LS	E	497.0-506.0	50	0.6/1.0	1.6
HCl	LS	F	624.0-626.5	50	2.0/1.0	1.6

Table 4.2: *Key MASTER instrument requirements.*

The tangent points shall be stacked vertically by selecting the vertical scan speed to compensate for horizontal movement of the tangent-point along-track caused by satellite motion. A vertical sampling interval of 1 km (oversampled with respect to HPBW) and exact knowledge of any pointing fluctuations during a scan will be needed to achieve the required vertical resolution in retrieved profiles.

b) Mid-Infrared Limb-Sounder (AMIPAS)

Requirements for the mid-infrared limb-sounder have been optimised specifically to address observational requirements on vertical and horizontal sampling for trace gases and temperature in the UTLS. The width of the field of view is 2 km (vertical) x 30 km (horizontal). A vertical sampling step of 2 km and high vertical pointing stability are needed. The unapodised spectral resolution[10] shall be 0.1 cm^{-1}. Spectral coverage, noise equivalent spectral radiance (NESR) and radiometric accuracy requirements are provided in Table 4.3.

c) Mid-Infrared and Near-Infrared Limb-Imager (LCI)

Requirements for the mid-infrared/near-infrared limb imager have been specified with respect to its sensitivity to upper tropospheric cirrus and aerosol and to providing co-located cloud and aerosol information of high-quality at sub-pixel resolution for the limb-emission spectrometers. The 12 μm channel permits detection of cirrus

[10] Precisely: the inverse of the two-fold maximum optical path difference of the Fourier transform spectrometer.

Primary Targets	Band	Spectral Coverage (cm^{-1})	NESR (nW / cm^2 cm^{-1} sr)/ Accuracy (%)
CO_2 (T, pointing), O_3, H_2O, HNO_3, $ClONO_2$, NO_2, C_2H_2, C_2H_6, PAN, CFC-11, CFC-12, HCFC-22	A	680 -1050	9.0 / 1
H_2O, CH_4, N_2O, N_2O_5, HNO_3, C_2H_2, PAN, CH_3COCH_3, CFC-11, CFC-12, HCFC-22	B	1050 -1550	5.5 / 1
NO_2	C	1550 - 1750	1.5 / 1

Table 4.3: *Key AMIPAS instrument requirements.*

throughout the day and night. The 1 μm channel provides complementary information on the scattering medium during daytime from which to distinguish between cloud and aerosol and to derive further information on these particulates. 2-D images of the atmospheric limb, aligned in azimuth with AMIPAS and covering its complete FOV, shall be acquired continuously with a vertical resolution of 300 m, a horizontal resolution of 1 km (both oversampled 2x) and a temporal resolution of 1 s. Exact co-registration knowledge between LCI and AMIPAS is needed. Key spectral and radiometric requirements are summarised in Table 4.4.

Primary Targets	Filter Centre λ (μm/cm^{-1})	Filter FWHM (μm/cm^{-1})	NESR & Accuracy (ph/s cm^2 nm sr)
Cloud, aerosol	1.04 / 9615	0.04 / 370	10^{12}
Cloud, aerosol	12.02 / 832	0.5 / 35	10^{12}

Table 4.4: *Key LCI instrument requirements.*

4.6 Ability to Fulfil Research Objectives

The ability of the proposed mission to deliver the data needed to fulfil the four primary research objectives can be gauged by comparing simulated retrieval capabilities against quantitative requirements. The observational requirements for each research objective are multivariate and multidimensional, and for each target species it is necessary to consider in parallel the requirements on height-range, precision, vertical-resolution, horizontal and temporal sampling (B. Kerridge et al., 2001). It is also necessary to take into consideration the likely impact of clouds on spatial/temporal sampling of the troposphere and the uncertainties inherent in the modelling of atmospheric radiative transfer (such as those due to cloud, aerosol, molecular non-thermal emission and spectroscopy).

Simulated retrieval capabilities for certain key species are presented in Figures 4.6, 4.7 and 4.10-4.15 for the representative mid-latitude profiles of Figure 4.1. The spatial and temporal variability of the species concerned is considerable (which is the rationale for

measuring them from space), so it should be borne in mind that retrieval capabilities depend *inter alia* on the distributions of trace gases and temperature. All simulations presented in these plots employ the *optimal estimation* approach with a relatively weak *a priori* constraint. All trace gas retrievals adopted 300% *a priori* uncertainty on retrieval levels spaced at 2 km, with no inter-level correlations.

Precision estimates for the limb-mm and limb-mir sensors account for radiometric noise (in accordance with instrument requirements in Section 4.5) and for random errors in atmospheric temperature (1 K RMS at 2 km spacing with no correlation between levels). For the limb-mm, random errors in *a posteriori* knowledge of limb-view spacing (50 m RMS) were simulated in addition.[11] Simulations for the limb-sounders assume rearward viewing with a horizontal spacing along-track of 100 km (or less) between successive profiles, in accordance with the instrument specifications outlined in Section 4.5. For the limb-mir, profiles will be acquired from five azimuth angles during each 15 s period, corresponding to an across-track sampling of ~570 km at the equator and ~285 km at 60°, in both ascending and descending orbit segments (i.e. during daytime and nighttime separately). Interleaving observations acquired from ascending and descending orbit segments over 24 hours would therefore result, on average, in across-track spacing of <300 km at the equator and <150 km at 60°. With a 3-day repeat cycle, orbits would be further interleaved, resulting in across-track sampling, on average, of <100 km at the equator and <50 km at 60° over this period. Threshold requirements (Table 4.1) on temporal sampling (3 days) and spatial sampling (100 km x 100 km) would therefore be met in combination.

Simulations for the relevant MetOp sensors are also presented. With the exception of the H_2O retrievals by IASI and MHS, which are presented at 2 km level spacing as for the limb-sounders, trace gas simulations for the MetOp sensors are presented on coarser vertical grids. The GOME-2 precision estimates account for radiometric noise and other major sources of random error. Those for IASI account for radiometric noise and for atmospheric temperature, by retrieving this jointly with target species. The horizontal sampling of GOME-2 is 40 km x 40 km and that implicit in IASI simulations is 100 km x 100 km[12], except for H_2O and temperature retrievals which are for individual samples.

Water vapour and ozone are of central importance to the four research objectives. In Figures 4.6 and 4.7 it can be seen that the limb-mm sensor meets observational requirements on precision and vertical resolution in the stratosphere and upper troposphere and that (in the absence of cloud) the limb-mir is capabable of extending this height range further downwards into the troposphere. The ability of IASI and

[11] For the limb-mir instrument, this error source does not exist, due to the use of detector arrays (see Chapter 6).

[12] Sampling of 100 km x 100 km assumes averaging of 64 individual samples (each is a 12 km diameter circle).

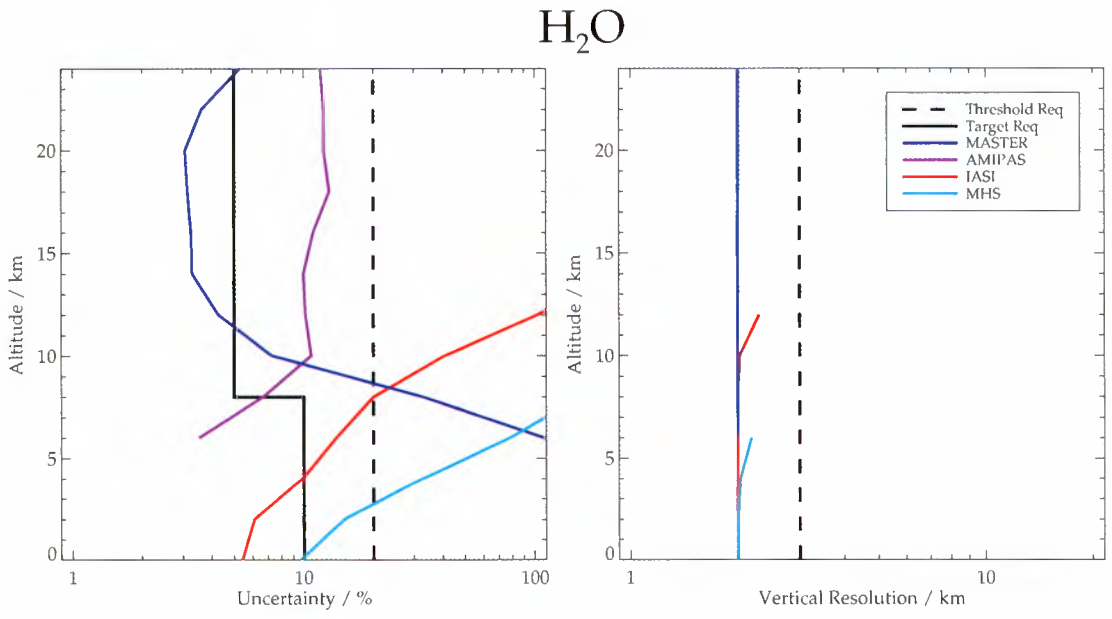

Figure 4.6: *H_2O retrieval uncertainty and vertical resolution for the ACECHEM limb-sounders and MetOp nadir-sounders, derived from simulations (described in the text) which account for major error sources. Threshold and target requirements are also shown.*

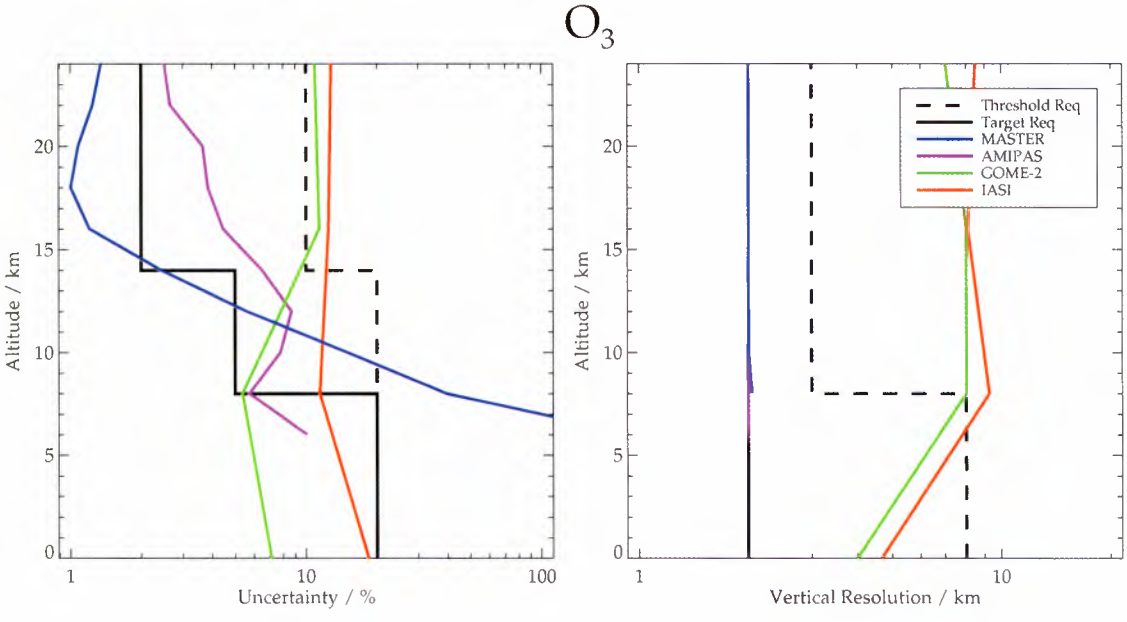

Figure 4.7: *As Figure 4.6 but for O_3.*

GOME-2 to complement height-resolved information on H_2O and O_3, respectively, in the (cloud-free) lower troposphere is also clearly evident in these plots. Information on tropospheric O_3 from IASI is also seen to be useful, and would be available during nighttime as well as daytime, although its precision is considerably lower than that of GOME-2 (daytime only), especially at the lowest level.

An important feature of the mission will be the ability of limb-mm and limb-mir sounders to retrieve the 2-D structure of UTLS fields within the orbit plane. This has been investigated in some depth through H_2O retrieval simulations for limb-mm, using a fully 2-D radiative transfer model and retrieval scheme. Figure 4.8 compares the output from such a simulation to the 'true' field for a tropopause fold event at mid-latitudes, demonstrating that horizontal as well as vertical structure in the field can be captured with high fidelity in the upper troposphere at horizontal scales down to <100 km. It can be seen in Figure 4.8 that MASTER's depth of penetration into the troposphere is controlled by the humidity field itself, since this is what controls limb-path opacity and hence the altitude at which 'blacking out' occurs[13]. Figure 4.8 illustrates that MASTER will retrieve 2-D structure in the humidity field with good fidelity up to a mixing ratio of ~300 ppmv and, in the mid-latitude examples shown, this contour ranges in geometric altitude from ~6 km to ~2 km. Figure 4.9 shows diagnostics from a 2-D simulation on a finer horizontal grid. In the upper troposphere, it can be seen that a precision of ~15% can be attained at a vertical (1.5 km) and horizontal (64 km) resolution limited by the corresponding retrieval grid spacings.

Carbon monoxide (CO) and nitric acid (HNO_3) are of central importance to objective (4) and also to objective (2). In Figure 4.10 it can be seen that the limb-mm sensor meets observational requirements for CO on precision and vertical resolution in the lower stratosphere and upper troposphere. The value of IASI to supplement this with CO information at lower altitudes in the (cloud-free) troposphere is also clearly evident. In Figure 4.11 it can be seen that the limb-mm sensor meets observational requirements for HNO_3 on precision and vertical resolution in the lower stratosphere and tropopause and that (in the absence of cloud) the limb-mir is capable of extending this height range further downwards into the troposphere.

Nitrous oxide (N_2O) and methane (CH_4) observations in the lower stratosphere are important to objectives (1), (2) and (3), and CH_4 observations in the troposphere would also be valuable for objective (4). In Figures 4.12 and 13 it can be seen that the limb-mm meets requirements for N_2O in the lower stratosphere and troposphere down to 10 km; and that the limb-mir meets requirements for N_2O and CH_4 in the lower stratosphere and in the troposphere for N_2O down to 8 km and for CH_4 down to 6 km.

[13] This is also true for the other MASTER bands, so penetration depth into the troposphere is primarily a function of the tropospheric humidity field also for other target species (e. g. O_3 and CO).

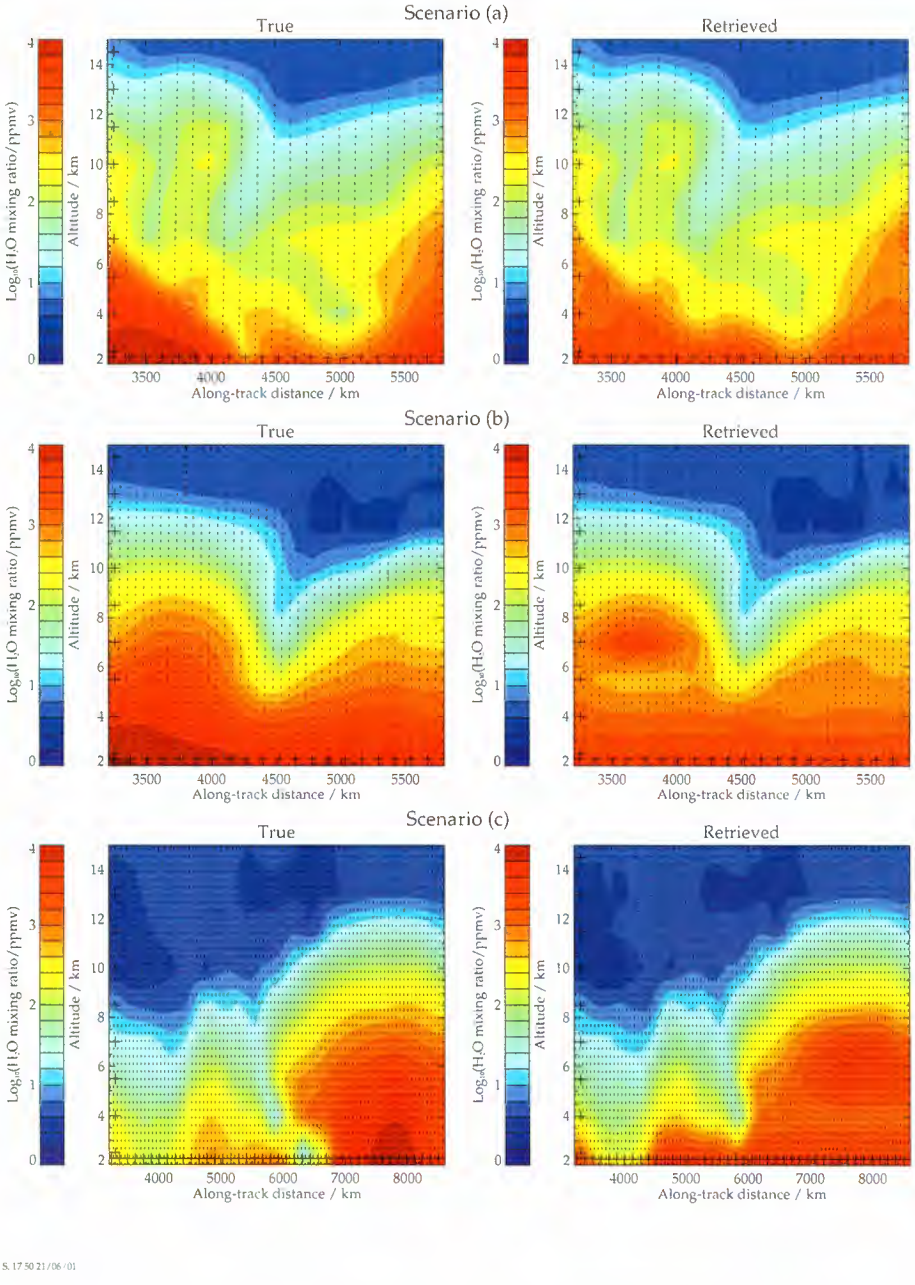

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Figure 4.8: *Simulation of MASTER's ability to retrieve 2-D structure in the upper troposphere humidity field. Three examples are presented, based on 'true' fields (left) selected from UGAMP 3-D model output for 20 March 1994. (Scenarios: (a) cross-section along longitude 23° W from 13 to 36° N; (b): cross-section along latitude 43° N from 25° W to 45° W; (c): cross-section along longitude 178° W from 81° N to 32° N.) Measurements were simulated based on these cases and retrievals conducted assuming no prior knowledge of the true horizontal structure (i.e. starting from a horizontally symmetric 'a priori' representation of the atmosphere). The resulting retrievals are shown in the right hand panels. Tangent point loci of the simulated measurements are indicated by dotted lines. '+' symbols indicate the horizontal/vertical retrieval grid.*

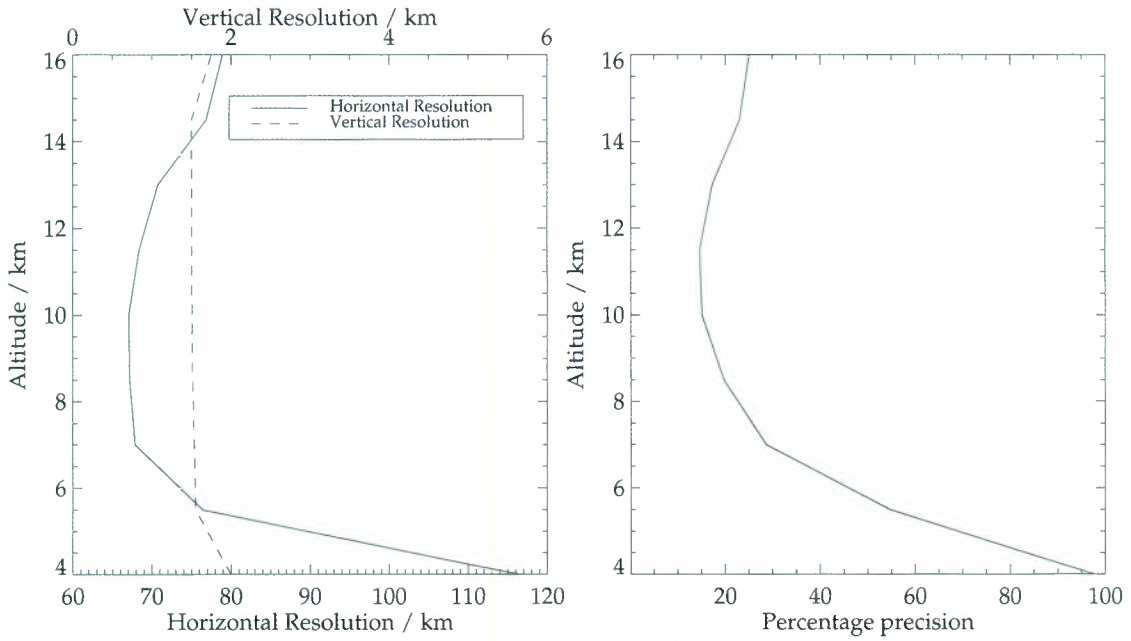

Figure 4.9: *Estimates of MASTER's resolution in 2-D and associated precision. The left hand panel shows horizontal and vertical resolution as estimated from full-width-half-maxima of the 'averaging kernel' matrix (Rodgers, 90) for a retrieval grid spaced at 1.5 km in the vertical and 64 km in the horizontal. Resolution <70 km in the horizontal and <2 km are seen to be attainable simultaneously in the upper troposphere. The right hand panel shows the associated precision estimate. (Precision depends in a non-linear way on retrieval grid spacing, and improves substantially for a grid of 1.5 km x 125 km, as used in Figure 4.8).*

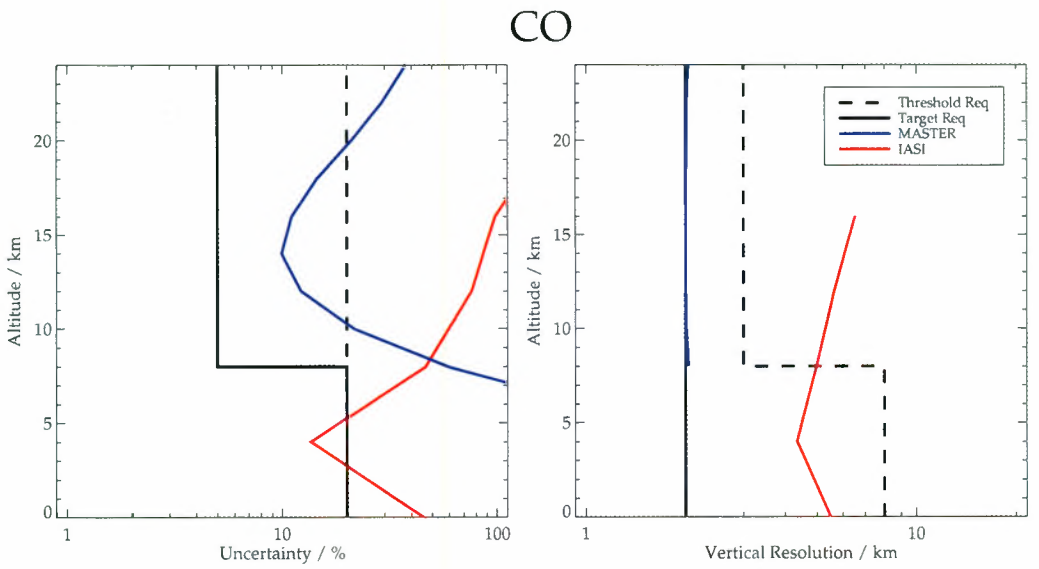

Figure 4.10: *As Figure 4.6 but for CO.*

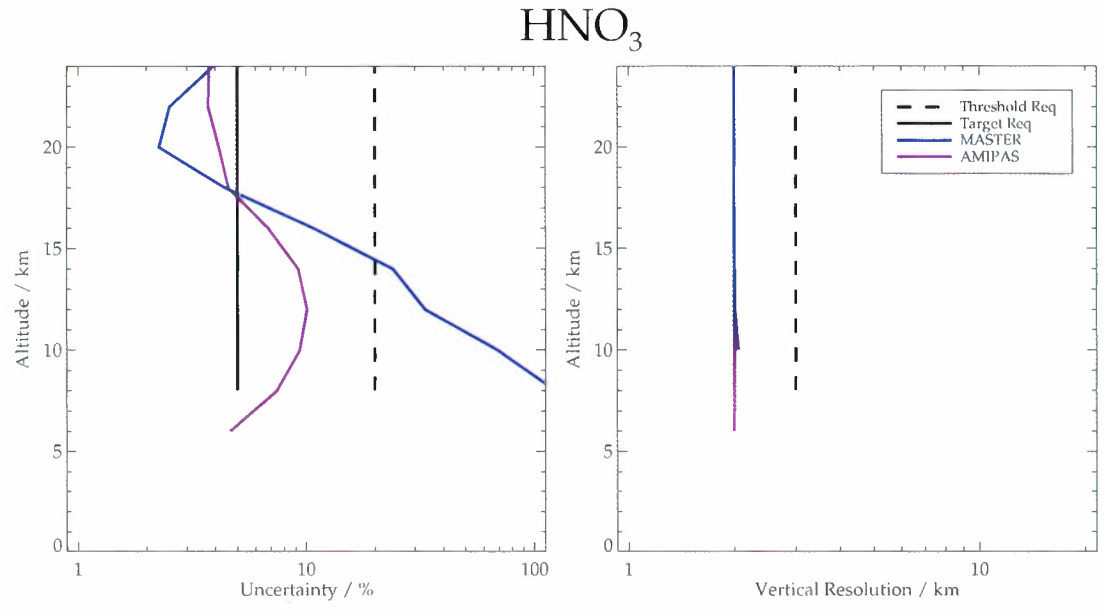

Figure 4.11: *As Figure 4.6 but for HNO_3.*

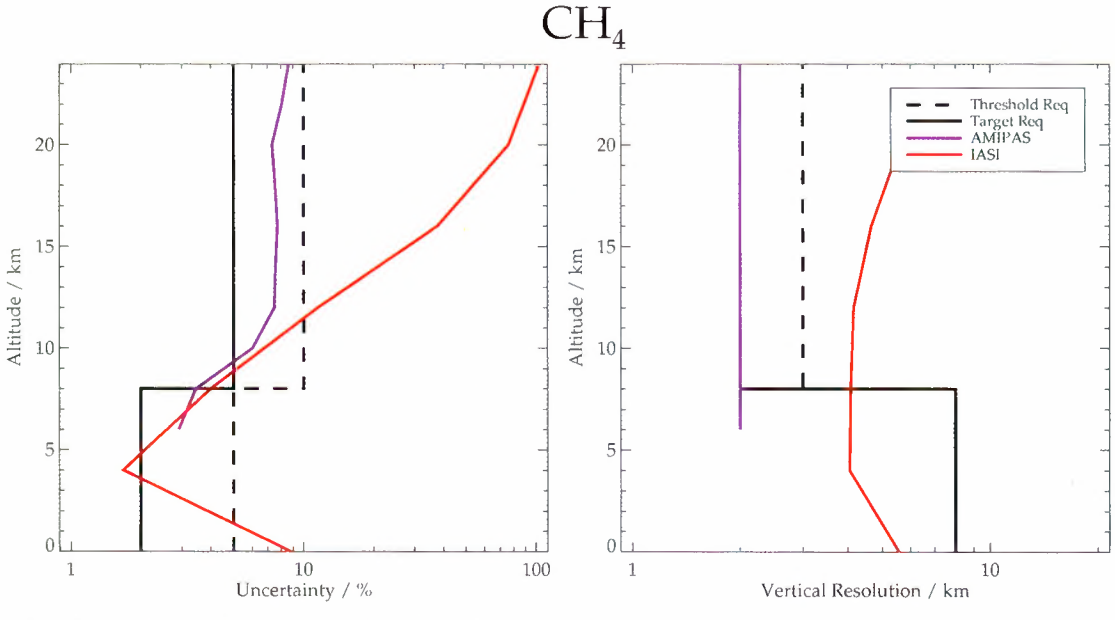

Figure 4.12: *As Figure 4.6 but for N_2O.*

The value of IASI to provide additional information on CH_4 at lower altitudes in the (cloud-free) troposphere is also evident.

Observations of elevated ClO concentrations in the polar lower stratosphere are crucial to objective 3. In Figure 4.14 it can be seen that the limb-sub mm observations by MASTER will be capable of meeting this requirement.

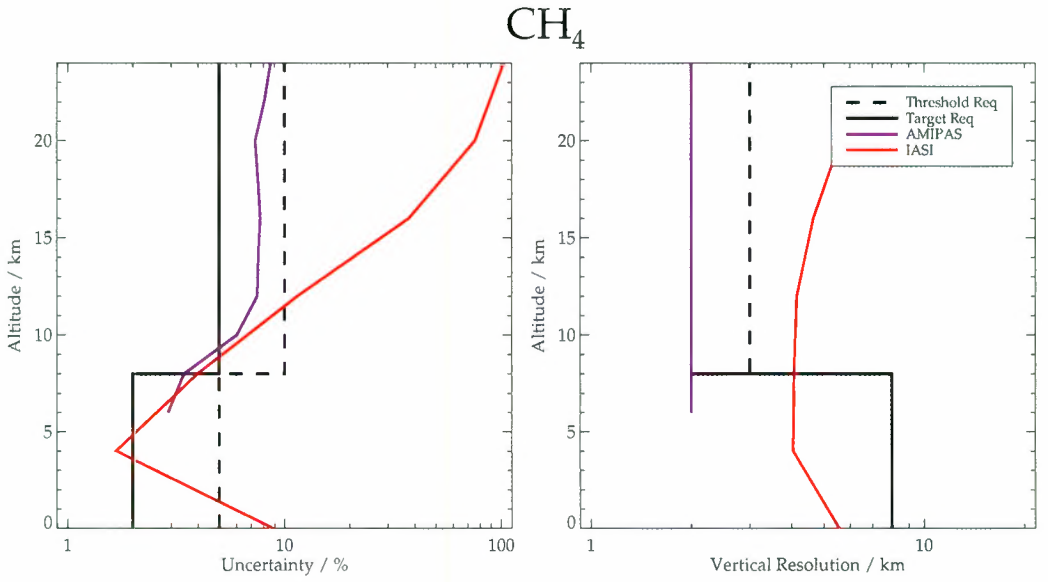

Figure 4.13: *As Figure 4.6 but for CH_4.*

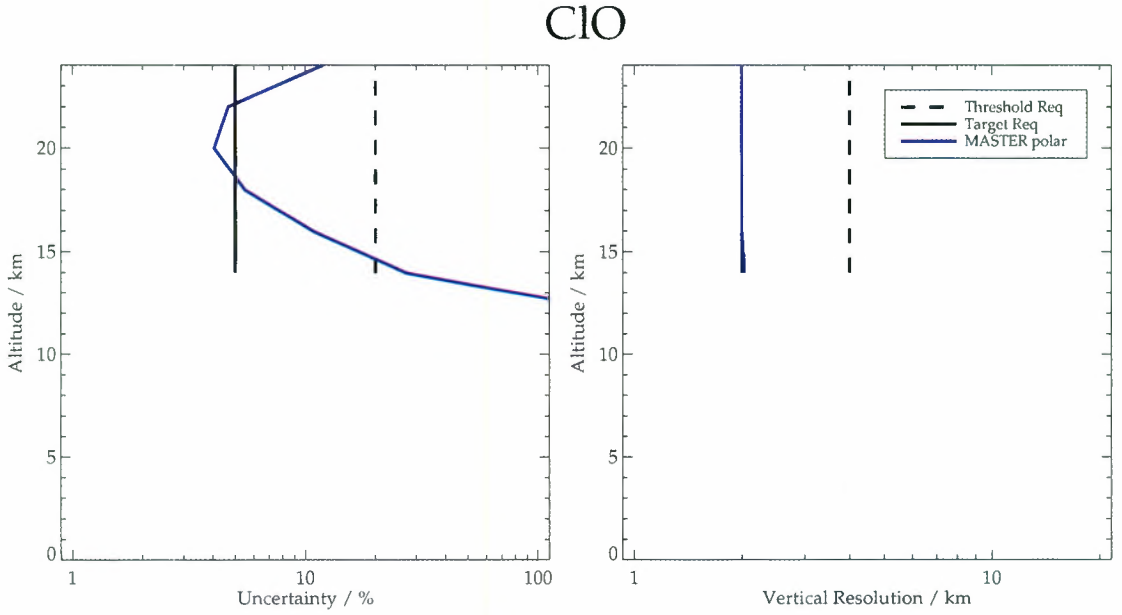

Figure 4.14: *As Figure 4.6 but for ClO.*

High quality temperature observations are explicitly needed to meet all research objectives, and are implicitly needed for retrieval of trace gas distributions from the limb-emission sounders. In Figure 4.15, the complementary nature of limb-mir observations and IASI's nadir-observations, in meeting requirements in the UTLS and lower troposphere, respectively, is clear[14].

[14] The IASI temperature simulation shown in this plot was performed on a different basis from all other simulations presented in this section. The vertical resolution commensurate with 1K retrieval error at every retrieval altitude has been determined in a simulation which adopts a relatively weak *a priori* constraint.

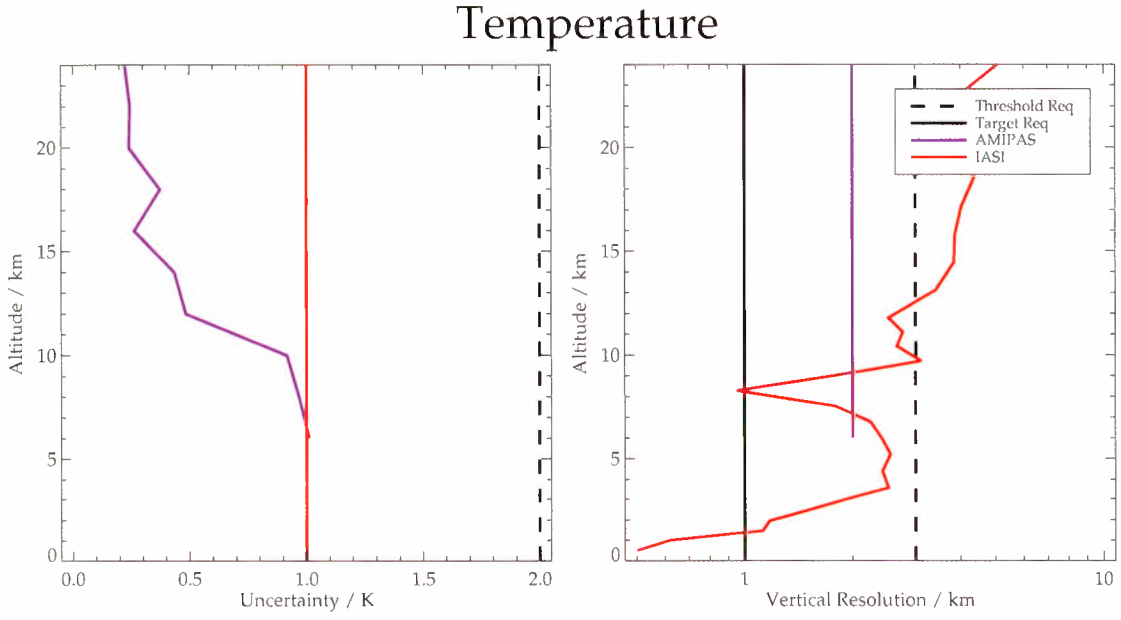

Figure 4.15: *As Figure 4.6 but for temperature. The IASI simulation is from a simulation by Prunet et al (2001) to show the vertical resolution attainable at NWP model levels for a prescribed retrieval precision of 1 K and an 'a priori' temperature covariance from climatology.*

The ACECHEM observational requirements have been specified to address the scientific research objectives of Chapter 3. However, the complementary perspective on upper tropospheric humidity and temperature offered by limb-sounding could also of be of interest to the Met Services (see Section 2.5.3). In Figure 4.16, a different type of retrieval simulation is shown which illustrates the value that could potentially be added by MASTER to the IASI nadir-sounder on MetOp in the frame of NWP. It clearly indicates that MASTER would reduce the background forecast error substantially and would add value to the retrieval of humidity in the upper troposphere above ~8 km[15].

[15] On the basis of Figures 4.6 and 4.15, it is anticipated that equivalent simulations for AMIPAS will show that significant value could similarly be added to IASI retrievals of both temperature and humidity in the upper troposphere.

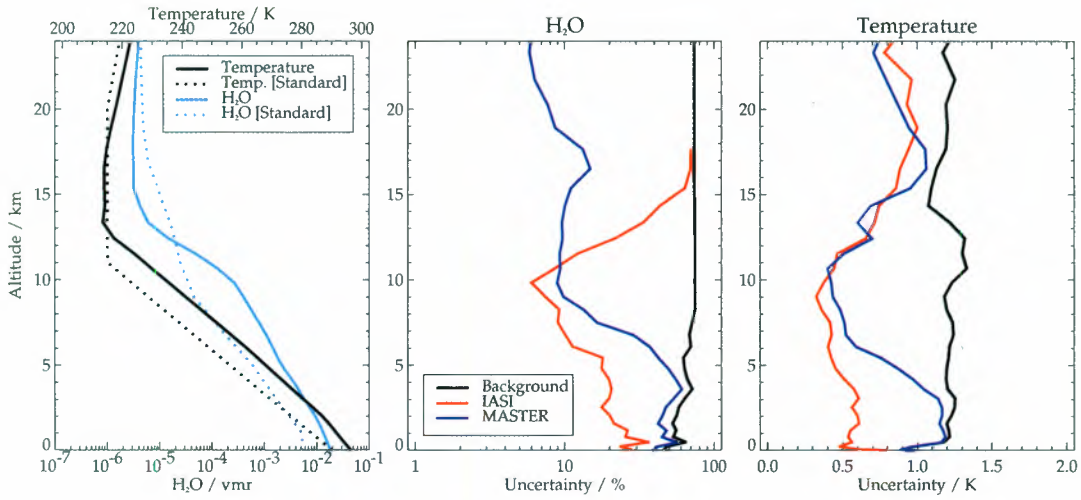

Figure: 4.16: *Estimated precision on humidity and temperature on NWP model vertical grid for IASI and MASTER retrieval simulations using ECMWF background covariance matrices as a priori. Mid-latitude summer temperature and humidity profiles used are shown in the left-hand panel (solid lines). Also shown, for comparison, are the 'standard' mid-latitude profiles used elsewhere in this report (dotted lines). The background standard deviation (square-root of the covariance matrix diagonal) is shown together with the precision estimates, in the centre and right-hand panels. Estimated precisions for IASI are taken from simulations performed at the UK Met Office (Collard, priv. comm.) and include IASI random noise and a simplified treatment of forward model error. Simulations for MASTER are for joint retrieval of temperature, humidity, continuum and all other significant absorbing constituents from the 300 and 325 GHz bands. Error sources for MASTER are system noise and correlated pointing errors (50 m standard deviation, 6.7 km correlation length).*

5 Mission Elements

5.1 Introduction

The ACECHEM Earth Explorer Core Mission will require measurements of the chemical composition of the upper troposphere/lower stratosphere. These measurements will be made globally and will be assimilated into atmospheric models to improve the understanding of the scientific issues identified in Chapter 2 and 3.

Taking into account the observation requirements described in Chapter 4, the following table maps these requirements to observation capabilities of spaceborne instrumentation:

Observing Technique	Instrument/Platform	Comment
mm/sub-mm wave limb sounding	MASTER / ACECHEM	Tomographic sounding of 2-D structure in orbit plane
mir limb sounding	AMIPAS / ACECHEM	Viewing in 5 azimuth directions for improved horizontal coverage
mir/nir limb imaging	LCI / ACECHEM	First application of sub-pixel cloud imager in limb viewing geometry to increase the retrieval accuracy
uv-vis nadir sounding	GOME-2 / MetOp	The MetOp nadir measurements have to be located *a posteriori* with the limb measurements
mir nadir sounding	IASI / MetOp	
microwave nadir sounding	MHS /MetOp	
vis/ir nadir imaging		

Table 5.1: *Observation sources.*

As shown in Table 5.1, the operational instruments on the MetOp satellites are utilised to fulfil the observation requirements for nadir looking instrumentation. To exploit the synergy between the limb sounders and nadir sounders, their respective measurements must be suitably co-located in space and time, which leads to a mission concept that contains the following elements:

- **Core Space Element** – A dedicated satellite to measure limb emission spectra in the mm/sub-mm and in the mir region, and limb images in the mir and nir to characterise clouds and aerosol. This satellite needs co-ordination with the MetOp satellite, in order to achieve the temporal and spatial co-location requirements.

- **Additional Space Element** – Measurements in the nadir geometry, made by MetOp, will be exploited synergetically with the measurements of the core space element.

- **Auxiliary Data** – Analysed fields from the meteorological services will be used as *a priori* information for retrievals of temperature, humidity and ozone. Observations by ground-based and airborne instruments will be used: (a) to validate those from the space sensors, and (b) to augment and aid scientific interpretation of those from the space sensors (e.g. in the lower troposphere).

5.2 Space Element and Instruments

5.2.1 The Mission

The core space element of the ACECHEM mission will be a satellite carrying the dedicated and innovative instruments to sound the atmosphere in limb geometry. This satellite will fly in formation with one of the MetOp satellites in such a way that the limb measurements of ACECHEM can be co-located with the nadir measurements of instruments flying on MetOp. This formation dictates the orbit characteristics of the ACECHEM mission.

The analysis of observational requirements for the upper troposphere (as described in Chapter 4) points to the need for two limb-sounding spectrometers operating in the mm and mir regions. A cloud imager making observations concurrently with the mir limb sounder complements these spectrometers. Details of these instruments are described in Chapter 6.

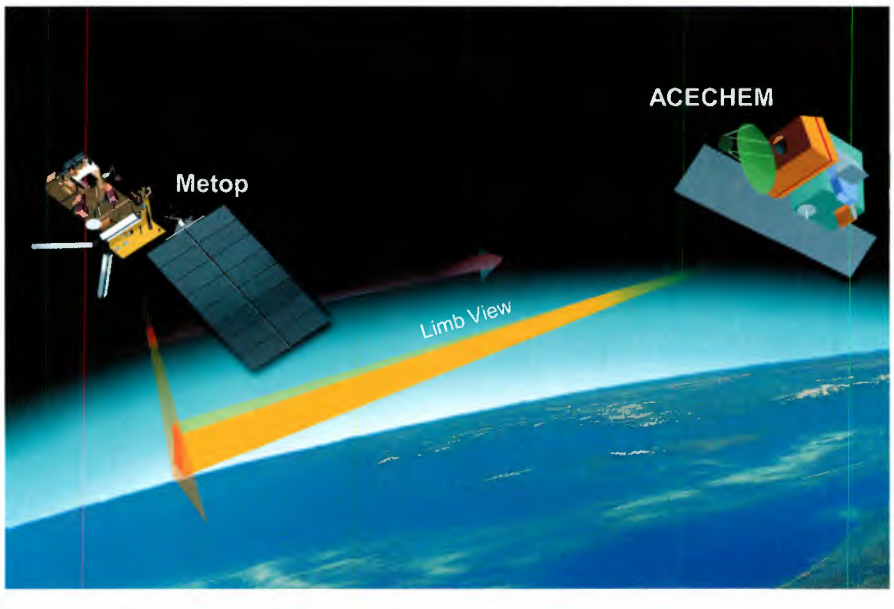

Figure 5.1: *Overall observation geometry of the ACECHEM mission.*

5.2.2 Millimetre/Sub-millimetre Wave Limb Sounder (MASTER)

Spectral measurements in the mm and sub-mm ranges will be made by means of a dedicated radiometer, scanning the horizon in limb geometry in the rearward direction. This instrument will perform tomographic sounding of the atmosphere along the track of the satellite with a tangent-point spacing of ~100 km along-track and an integration time corresponding to 1 km in the vertical. The scanning is from top to bottom, and the scan speed is adjusted in order to acquire a vertical profile in the sampled region.

5.2.3 Mid-Infrared Limb Sounder (AMIPAS)

The limb sounding spectrometer operating in the mir region will sample the same atmospheric volume as MASTER along-track, with a vertical spacing of 2 km, and will extend MASTER's horizontal coverage across-track by looking in four additional azimuth directions, with all five directions being sampled during one limb-scan of the MASTER instrument. It will also complement MASTER in two other ways. Firstly, the mir will allow complementary species to be measured and, secondly, in the absence of clouds, it will allow sounding to lower tropospheric altitudes.

5.2.4 Limb Cloud Imager (LCI)

In order to characterise cloud in the fields-of-view of the mir and mm spectrometers, it is necessary to acquire information at higher spatial resolution. This principle has been well-established for nadir-sounding of the atmosphere, e.g. by operational meteorological satellites. For this purpose, a limb-imager is accommodated on the satellite to look at the same scene as AMIPAS (including the azimuth viewing directions). It will therefore also view the same upper tropospheric air volume as MASTER.

5.3 Additional Data

ACECHEM will exploit opportunities for synergy with MetOp, specifically with observations to be made by the GOME-2, IASI and AVHRR3 instruments, directly and as fully as possible by flying in formation. The spatial/temporal *precision* with which nadir observations from MetOp will be co-located with limb observations from the dedicated ACECHEM platform and the fact that nadir-limb co-location will be achieved *continuously* are further innovations of the ACECHEM mission. (Synergistic use of nadir- and limb-sounding of trace gases will be pioneered by Envisat and Eos Aura. However, this will be undertaken by sensors on a single platform and therefore it will not be possible to view an airmass simultaneously from both geometries. SCIAMACHY on Envisat and TES on Aura will also alternate, i.e. time-share, between nadir and limb-viewing, and can therefore not achieve continuous coverage in both viewing modes.)

Flying in formation with MetOp will enable:

- MetOp's analysed fields of temperature, humidity, cloud and possibly other variables to provide *a priori* information for upper tropospheric retrievals from the ACECHEM sensors.

- Profiles of temperature and humidity retrieved from ACECHEM in the upper troposphere and lower stratosphere to be extended down to the ground using (cloud-free) co-located observations by MetOp. The constraint provided by ACECHEM's UTLS measurements will allow the lower tropospheric component of MetOp measurements to be discriminated.

- Information on other tropospheric trace gases contained in the spectra of IASI (e.g. CO, CH_4, other hydrocarbons, and O_3) and GOME-2 (e.g. O_3, H_2CO, NO_2 and SO_2) to be exploited in synergy with UTLS measurements of the same species made simultaneously by the limb sounding spectrometers. It will be required that these GOME-2 and IASI spectra be (re-)processed with schemes dedicated to this purpose. Therefore, not only the analysed fields, but also the relevant Level-1 data will be needed from MetOp.

- Surface properties, clouds and aerosol optical thicknesses observed by MetOp to complement and further extend the scope of the ACECHEM mission.

5.4 Ground Segment

The data from the instruments will be downlinked to a ground station in Kiruna, where Level-1 processing will be performed. It will then be transmitted to dedicated scientific centres, together with the required auxiliary data from other missions, for higher level processing and assimilation by atmospheric models.

5.5 Relation to Other Missions

Analysed wind fields in the troposphere and lowermost stratosphere will be further improved by **ADM-Aeolus**, ESA's Core Explorer mission for atmospheric dynamics (due for launch in 2006). Improved wind fields in the upper troposphere and lowermost stratosphere should complement and benefit the ACECHEM mission by allowing transport processes, particularly stratosphere-troposphere exchange, to be quantified more accurately and in greater detail.

Like MetOp, the next-generation US operational polar platform, **NPOESS** (first launch due in 2008), will focus on numerical weather prediction and climate. However, OMPS on NPOESS will observe height-resolved stratospheric distributions and total columns of several trace gases of relevance to ACECHEM, from an orbit with an *afternoon* equator crossing time rather than from the orbit of ACECHEM and MetOp with a

morning equator crossing time. The Japanese **GCOM-A1** (under consideration by NASDA for launch nominally in 2006) would also be complementary to ACECHEM. GCOM-A1 would have a precessing orbit and instruments (ODUS, SOFIS and SWIFT) which differ distinctly in their observational objectives and capabilities from ACECHEM. Observations from **MSG** (first launch due in 2002), **GIFTS** (2006) or other geostationary satellites could also complement and add value to ACECHEM, especially with respect to temporal sampling.

Overlap with relevant instruments on ESA's **Envisat** (launch in 2001) or EOS-Aura (launch in 2003), if still functioning in parallel to ACECHEM, would also be worthwhile since, in the case of species measured in common, this would present an opportunity for intercomparison and direct reference to the well-validated data sets from these earlier space missions.

5.6 The Users

The Level-1 data (geolocated, radiometrically calibrated radiances) will be distributed to dedicated scientific processing centres, which will produce the relevant Level-2 products (mixing ratios of the atmospheric constituents and other geophysical variables).

The atmospheric remote-sensing community will devise the retrieval and assimilation schemes to exploit Level-1 and -2 data. The atmospheric and climate research community will use higher-level data products in combination with observations from other sources (e.g. ground-based, airborne and other space missions) to address the scientific objectives of the mission (Chapter 2 & 3). Environmental agencies (such as the European Environmental Agency (EEA) and other international and national bodies) will draw on ACECHEM to provide guidance to policy makers at national and EU level.

6 System Concept

6.1 Introduction

The core space element of ACECHEM allows synergetic observations of the atmosphere in limb-viewing geometry in several spectral regions. For this purpose the space segment carries three limb-viewing instruments, namely a mm/sub-mm spectrometer (MASTER), a mir spectrometer (AMIPAS) and a limb-viewing cloud imager (LCI). ACECHEM observes the same atmospheric volume in limb as is observed in nadir by the operational MetOp satellite, as depicted in Figure 5.1.

6.2 Sampling Concept

Sampling of the same atmospheric volume as MetOp within 60 sec is achieved by flying the ACECHEM satellite in formation with MetOp. The satellite will fly ahead of MetOp and its instruments will look backwards. To meet the requirements related to the horizontal and vertical coverage, the following overall sampling concept is used:

- The proposed MASTER instrument has an instantaneous field of view (IFOV) of 2.3 km by 4.6 km in the mm bands and 1.6 km by 3.3 km in the sub-mm bands. A vertical profile is measured every 15 s by scanning the instrument's antenna over a tangent height range of 30 km; varying from 33 km down to 3 km at the poles, to 40 km down to 10 km in the tropics.

- The proposed AMIPAS instrument is based on a linear detector array, with a total field of view (FOV) of 30 km x 32 km at the limb. This array allows the simultaneous acquisition of a complete set of tangent-heights. Horizontal coverage is achieved by scanning the line of sight of AMIPAS in azimuth to five (programmable) directions, thus covering the required swath of ±1400 km across-track. This azimuth scan can be performed during one MASTER limb-scan, allowing one co-located AMIPAS 'scan' for each MASTER scan.

- The limb cloud imager follows the same scanning scheme as AMIPAS, aiming at an overlap of the IFOVs of both instruments.

The option to observe higher atmospheric layers with MASTER and AMIPAS, as well as the requirement for deep space viewing for calibration purposes for these two instruments, will be implemented by a pitch manoeuvre, pointing the entire satellite towards the regions of interest.

The timing of the scanning scheme is shown in Figure 6.1a, and the collocation of measurements in limb direction from ACECHEM in Figure 6.1b.

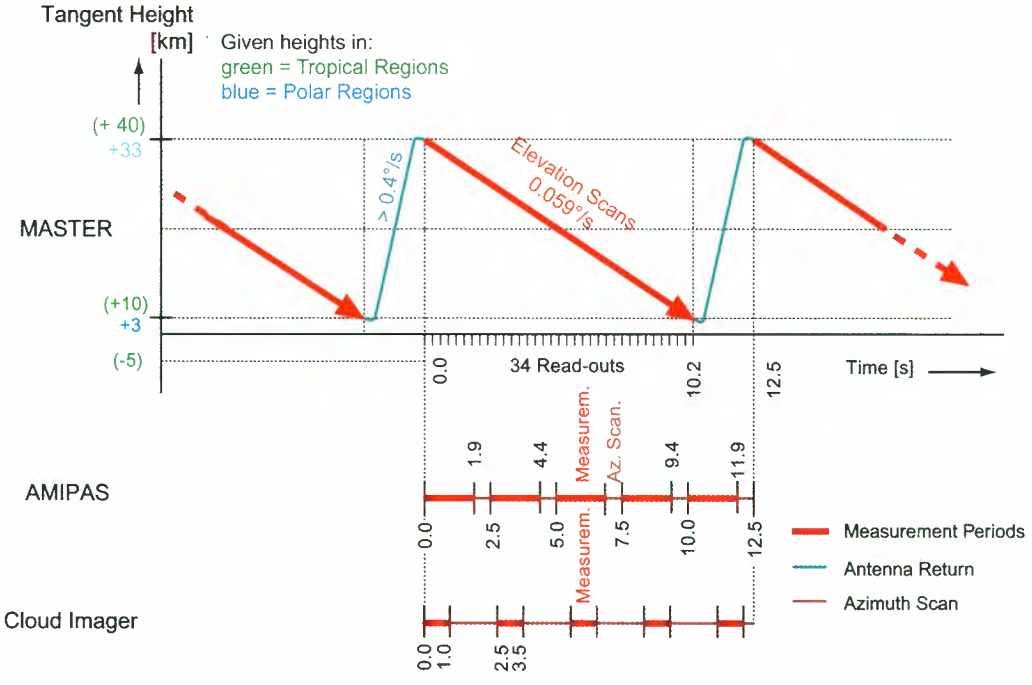

Figure 6.1a: *Scanning scheme for all ACECHEM instruments, showing the temporal interleaving of the scans of the different instruments.*

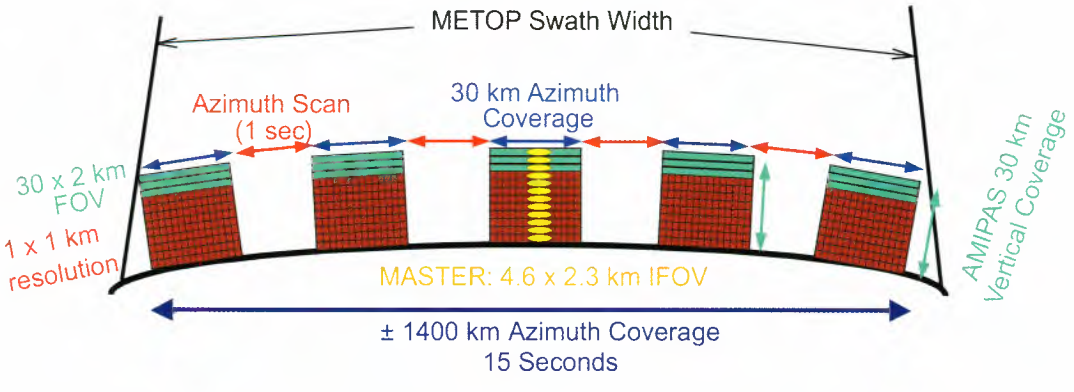

Figure 6.1b: *Limb view of ACECHEM satellite: The green grid (partially hidden) represents the AMIPAS acquisition. The red grid corresponds to the Cloud Imager, and the yellow ellipses indicates the collocation of the MASTER field of view for the along-track direction. The red lines indicate the MetOp swath (drawing not to scale).*

6.3 Payload

6.3.1 MASTER

Observation Concept

The MASTER instrument (*Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchange Research*) is a heterodyne spectrometer observing the Earth's atmosphere in a number of millimetre- and sub-millimetre-wave bands, with limb sounding geometry. A sketch of the instrument in orbit scanning the atmosphere is shown in Figure 6.2. Three different altitudes domains are shown: the normal scan ranges from 3-33 km in the polar regions, and from 10-40 km in the tropics; the optional scan reaches up to 90 km altitude; and an external calibration is foreseen at 150 km. A downward scan sequence has been designed to provide a quasi-vertical profile, accounting for the spacecraft movement. Global measurements of thermal emission induced by rotational transitions of atmospheric molecules will be conducted in the wavelength region between 0.5 and 1.0 millimetres. Pressure broadening of the emission lines enables the retrieval of altitude profiles for the target species and parameters listed in Table 4.1 of Chapter 4. MASTER will provide calibrated spectra of the atmosphere as a function of the tangent altitude on a global basis. The users will subsequently retrieve altitude profiles of the target species from the spectra provided.

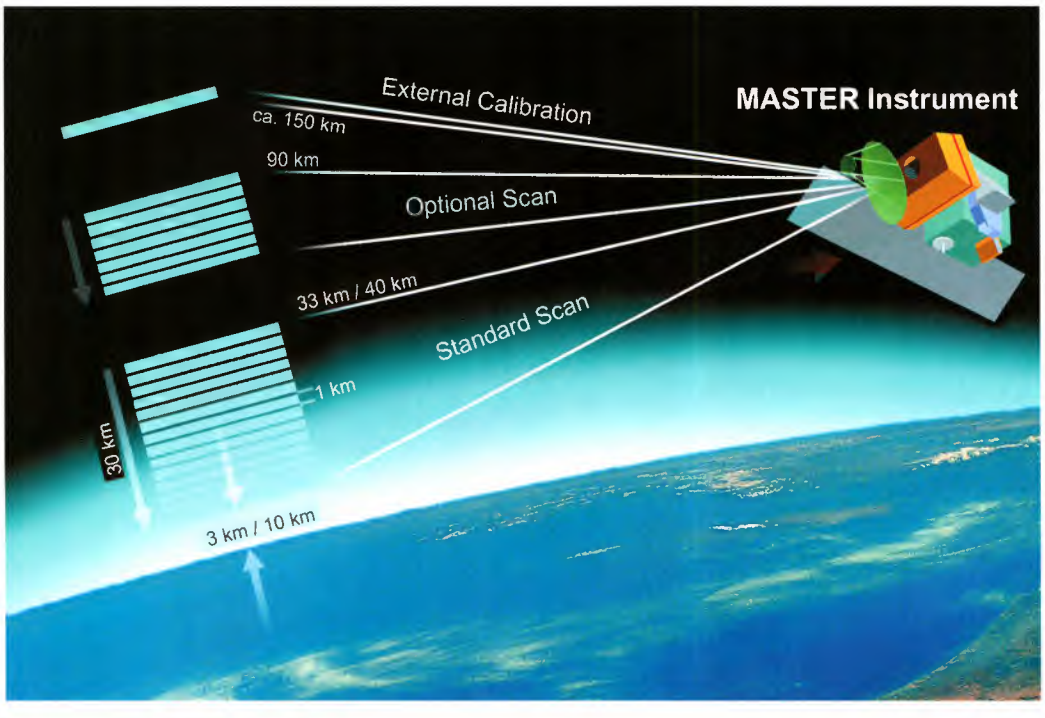

Figure 6.2: *MASTER observation geometry, showing the standard scan range and the extended scan ranges achieved by the platform.*

Instrument Concept

The frequency range selected for MASTER requires the application of the super-heterodyne principle to down-convert the received radiation for further spectral analysis. The proposed instrument concept is a single side-band design.

The frequency range is large, leading to the need for five separate receivers for the bands B to F, covering the frequency ranges listed in Table 4.2. The general functional layout of MASTER is shown in Figure 6.3. The instrument consists of the five subsystems indicated by blue boxes. The upper three subsystems belong directly to the mm/sub-mm instrument and the lower two to the spacecraft interface.

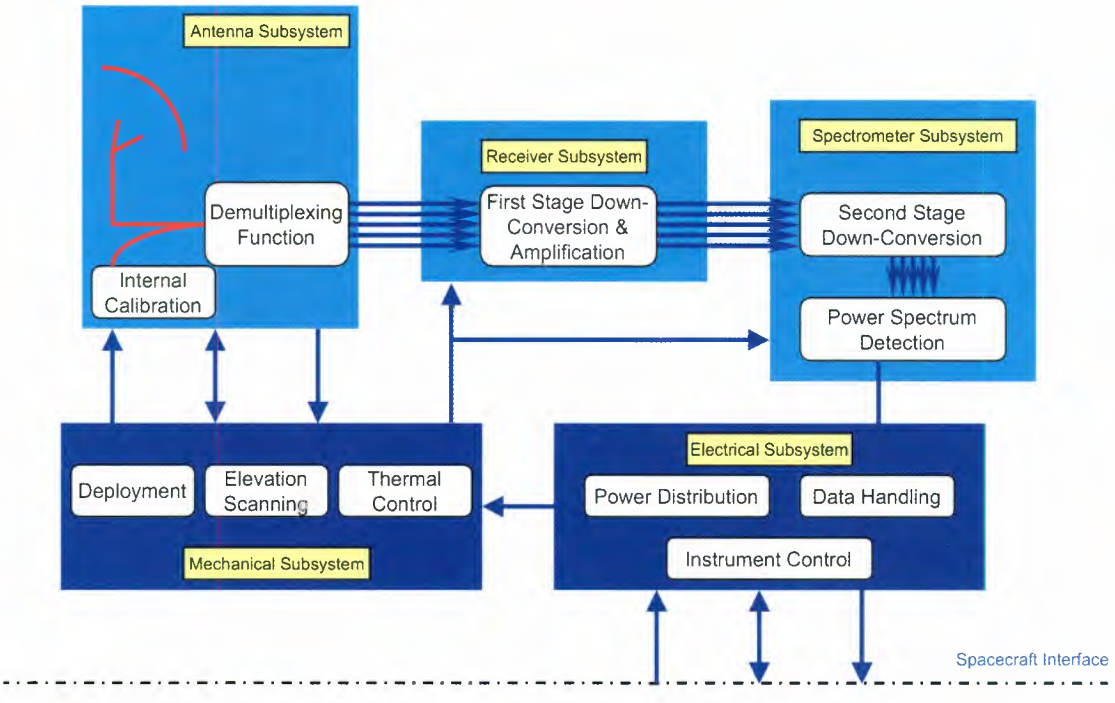

Figure 6.3: *MASTER functional block diagram.*

The emission of the atmospheric constituents at a given tangent height is collected for all five MASTER bands simultaneously by the same antenna. This subsystem includes the de-multiplexing unit in which the frequency bands are physically separated and relayed to the receiver subsystem. A dedicated mirror is used to point the demulti-plexing unit either to the calibration loads or to the Earth's atmosphere.

The received radiation is down-converted to the first intermediate frequency (IF). This subsystem includes the local oscillators, the mixers and low noise amplifiers for the five bands.

Frequency and power level at the first IF are matched to the spectrometer where the power spectrum is detected. The mechanical and electrical subsystems provide the structural integrity and the interface to the spacecraft and also control the scanning of the antenna. They ensure the thermal stability and data handling. A detailed description of the main components of the subsystems belonging to the mm/sub-mm instrument is given in the following paragraphs.

The MASTER **antenna** (offset Cassegrain type) is shared by all five receivers. It comprises a main and a sub-reflector. The vertical and horizontal directivity requirements lead to a system with a large elliptical main reflector of 1 x 2 m. Precise characterisation of the antenna pattern is indispensable for accurate retrievals and will be part of the pre-launch calibration activities.

Elevation scanning of the Earth's limb in the standard tangent-height range and in the optional range, and the acquisition of cold-space for radiometric calibration is achieved by a combination of manoeuvring the complete satellite to the three atmospheric domains indicated in Figure 6.2 and moving the main reflector at a constant speed to cover the vertical range of a given domain.

The required surface accuracy for the main reflector is in the 5 to 10 μm range. Considering thermal distortions and the zero gravity, this is challenging but feasible today. However, thermal distortions have to be minimised in orbit, potentially leading to the need for a sunshield. The main reflector will be made of Carbon Fibre Reinforced Plastic (CFRP). The total weight will be approximately 45 kg, comprising the antenna system, the support structure, and all mirrors leading to the de-multiplexing unit. The required scanning mechanism consumes approximately 25 W. The antenna system is depicted in Figure 6.4.

The radiation for the five MASTER bands is physically separated in the **demultiplexing unit** using quasi-optical techniques. Two different layouts following the same concept have been proposed. In both layouts the five MASTER bands are physically separated into two beams by a polarisation selective device. Afterwards the two beams are split by frequency selective surfaces and relayed to the different mixers by refocussing or planar mirrors.

The two layouts are shown in Figure 6.5. The first layout (left panel) is simple and optimised for cooling, but the overall design is larger than the second layout (shown right). The latter is relatively small and offers the advantage of fewer quasi-optical components in band D (with the most stringent NET requirement), and thus a low contribution to the system noise.

Free standing wire grids are one option for the **polarisation selective devices** and dichroic plates can be used to split up the different bands and as sideband filters at the same time. The sideband suppression requirement of 30 dB is stringent, but is considered feasible.

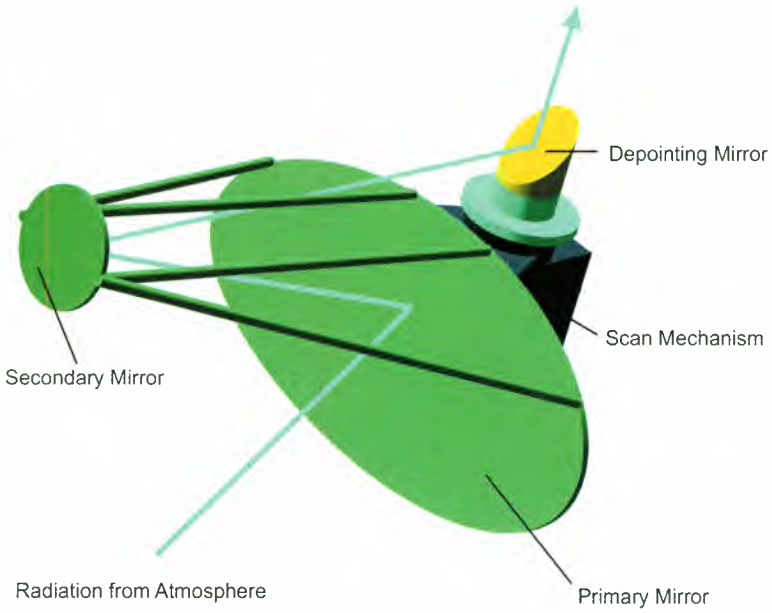

Figure 6.4: *The MASTER antenna system, illustrating the beam path.*

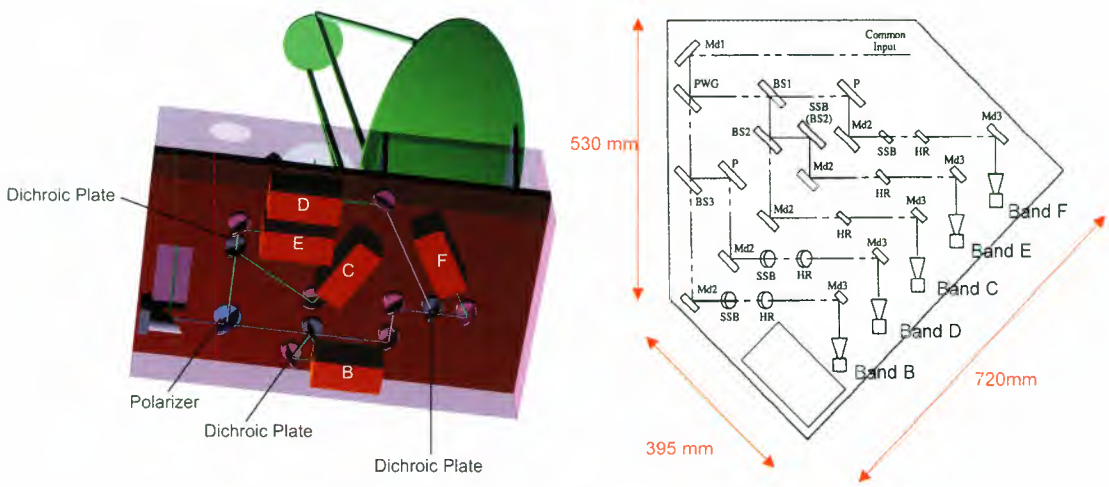

Figure 6.5: *Two possible MASTER quasi optical designs (left – layout I, right – layout II, for right panel: PWG = polarising wire grid, BS = beam splitter, SSB = single sideband filter, HR = harmonic rejection filter, P = planar mirror, Md1 and Md2 = ellipsoidal mirror and Md3 = redundancy switching mirror).*

Accurate **calibration** is indispensable for MASTER. A highly stabilised onboard hot calibration load and cold space will provide the references. For standard calibration a dedicated switching mirror in front of the de-multiplexing unit selects between the two calibration inputs and the main antenna feed after each altitude scan. At longer time intervals satellite manoeuvring will point the main antenna to cold space at a tangent altitude of 150 km.

The proposed concepts employ robust sub-harmonically pumped **waveguide mixers** using planar diodes as non-linear devices for the down-conversion process. To reduce system noise, passive cooling to 240 K for bands B, C and F is applied. To meet the more stringent NET requirements for bands D and E, active cooling by one or two cryo-coolers is foreseen. Layout I (Figure 6.5) of the de-multiplexing unit requires only one cooler whereas layout II needs two coolers. The local oscillator signals are provided by Gunn-diode oscillators that are phase-locked to a master reference crystal oscillator, followed by multipliers. Low-noise High Electron Mobility Transistor (HEMT) amplifiers follow the mixers, and band-limiting filters are used to reject unwanted IF frequencies. MASTER is required to make measurements over bandwidths from 2.5 to 11.5 GHz, which requires IF bands centred around 15 to 25 GHz where achieving low-noise amplifiers and low-loss filters is challenging. It is also necessary to sub-divide and further down-convert each receiver IF output to match the input frequency capabilities of the spectrometers.

The spectral measurements can be made using either Acousto-Optical **Spectrometers** (AOS), based on Bragg cell technology, or Digital Auto-Correlators (DAC). Spectral measurements are required at a resolution of 50 MHz over the complete frequency range. As an option, the addition of seven bands is foreseen with a resolution of 3 MHz over 600 MHz bandwidth for high altitude observations. Neither of the proposed spectrometer types could cover the complete frequency range of a given IF band as a single unit. A channel division network is required for both options to distribute the signal. For current, space-qualified designs of either type, approximately 35 individual spectrometers would be needed. The AOS option results in a relatively high mass design (70 kg). AOS is currently in use onboard the ODIN satellite. The DAC (also onboard ODIN) offers better mass efficiency (30 kg), but the development to combine low power electronics and low system noise has not yet been completed.

Development Status

The baseline concept employs well-proven and space-qualified technology for most of the components. Studies to develop low-noise wideband mixers and low-loss frequency-selective surfaces for this concept are under way, and indicate that the requirements can be met in time to be available for ACECHEM.

A more advanced concept using digital auto-correlators instead of acousto-optical spectrometers needs additional development effort, but promises to significantly reduce mass and power demands.

Overall Layout

A sketch of the complete MASTER instrument is shown in Figure 6.6. The left panel refers to layout I and the right panel to layout II. The outstanding feature of both designs is the large main reflector. In layout I the de-multiplexing unit is mounted on the rear side of the front-end base plate. In layout II the main reflector is on top and faces the de-multiplexing unit below the subreflector.

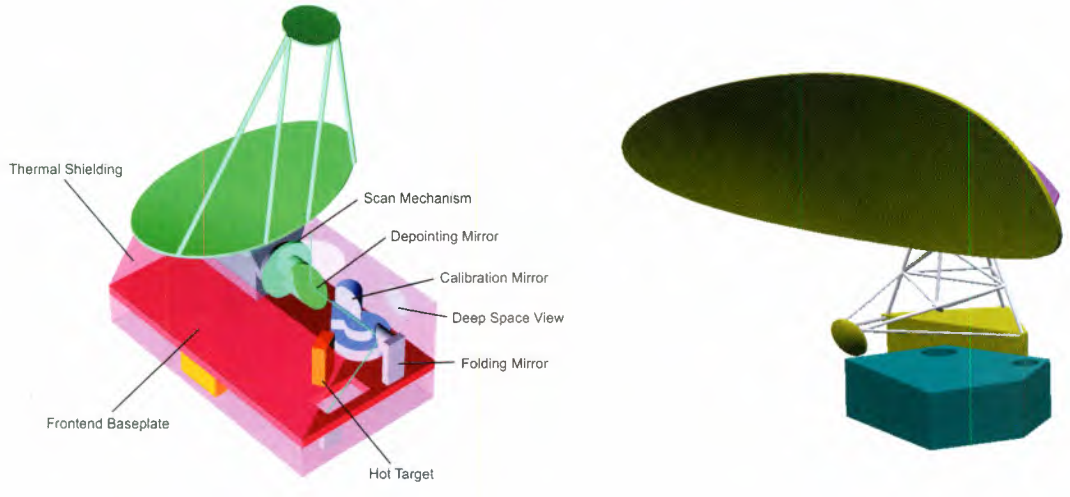

Figure 6.6: *The MASTER instrument in two envisaged configurations.*

Budgets

Table 6.1 shows the overall instrument budgets, differentiating between the DAC option and the AOS option.

	DAC	AOS
Mass [kg]	315	360
Power [W]	305	350
Data rate [kbit/s]	120	
Volume [m³]	2.6 x 2.2 x 1.9	

Table 6.1: *MASTER budgets.*

Performance

The performances predicted for the most important spectral and radiometric parameters for the derived mission concept are listed in Table 6.2.

	Band B	Band C	Band D	Band E	Band F
Operating temperature	240 K	240 K	80 K	80 K	240 K
Spectral performance					
Centre frequency [GHz]	299.75	321.0	345.6	501.5	625.25
Bandwidth [GHz]	11.5	9.0	6.5	9.0	2.5
Spectral resolution	50 MHz in 770 channels				
Radiometric performance					
Quasi optical loss	1.1 dB	1.2 dB	1.1 dB	1.2 dB	1.1 dB
System noise temperature	3580 K	3770 K	1610 K	1920 K	6380 K
Noise equivalent temperature (50 MHz, 0.3 s)	1.04 K	1.08 K	0.51 K	0.59 K	1.84 K

Table 6.2: *MASTER predicted performances and parameters.*

6.3.2 AMIPAS

Observation Concept

The '*Advanced Michelson Interferometer for Passive Atmospheric Sounding*' (AMIPAS) is a Fourier Transform Spectrometer (FTS), which will provide calibrated spectra of the atmosphere, as a function of the tangent altitude, in the wavelength range from 5.7 μm to 14.2 μm.

The FTS will provide measurements in the along-track direction, co-located with those of MASTER, and in the across-track direction, with a stepwise coverage of up to ±1400 km. The total field of view of the instrument is 30 km in elevation and in azimuth. The resolution elements are 30 km in azimuth by 2 km in elevation. The AMIPAS observation geometry is shown in Figure 6.1b.

A basic consideration for the AMIPAS instrument design concept is its ability to record the atmospheric emission spectra of an entire height profile within one interferogram acquisition cycle. Such a concept eases the requirements on the scan rate and eliminates those on the relative pointing stability in the case of a vertically scanning instrument.

Instrument Concepts

Two aspects of the implementation have been given particular attention in comparison to existing designs: dual or single port design, and the need for a telescope.

The trade-off single/dual port design is probably the most crucial for the instrument concept. For Enivsat-MIPAS a dual port design was selected, mainly based on redundancy considerations, as otherwise a single detector failure would lead to the loss of a complete band. For AMIPAS this argument is only partially valid: the present design is based on linear detector arrays with 16 elements in a column, each recording a spectrum at a specific tangent height. The loss of one detection element does not appear critical. A single port design will therefore bring major design simplifications. The single focal plane will have half of the thermal dissipation and require half of the signal processing power and therefore will lead to reduced data processing electronics and a more compact overall instrument.

For Envisat-MIPAS a telescope was needed to adapt to the strongly asymmetrical field of view (3 km x 30 km), providing a similar field of view in both directions. The field of AMIPAS is defined symmetrically, and thus a telescope is not needed for this purpose. On the other hand, a telescope allows one to potentially reduce the size of the interferometer, at the cost of wavefront errors, and a potential reduction in the optical performance and modulation efficiency of the instrument. Both concepts are outlined below.

Concept I

In this concept, the optical layout includes: an input scan mirror for azimuth pointing, a Michelson interferometer and a cold optics system to focus the signal on three linear detector arrays.

The scanning mirror points the instrument field of view within the required azimuth range. The azimuth scan mirror will also be used to point the instrument field of view towards the calibration black body.

The proposed spectrometer design is a single port Michelson interferometer, with the interferometer arms folded in the same way as in the Envisat-MIPAS instrument. A dual slide configuration, with a maximum Optical Path Difference (OPD) of ±5 cm, is proposed in order to achieve a momentum compensation. The beamsplitter/ compensator is a ZnSe plate.

Cats-eye retroreflectors are proposed for this design, instead of corner cubes. They have advantages for the large aperture and the related wavefront requirements. The slide mechanism for the cats-eye linear movement can be based on linear guidance systems with flexible suspensions, due to the short stroke length. This will ensure the required lifetime.

The interferogram sampling reference is provided by a laser reference system with a beam path parallel to the infrared beam, in the same manner as in the Envisat-MIPAS instrument.

Figure 6.7 shows the overall optical configuration. The entrance aperture is defined at the level of the cats-eye secondary mirror within the interferometer. The location of the entrance aperture matches with the input pupil of the relay optics, which finally images the scene on to the detector array after dichroic spectral band separation.

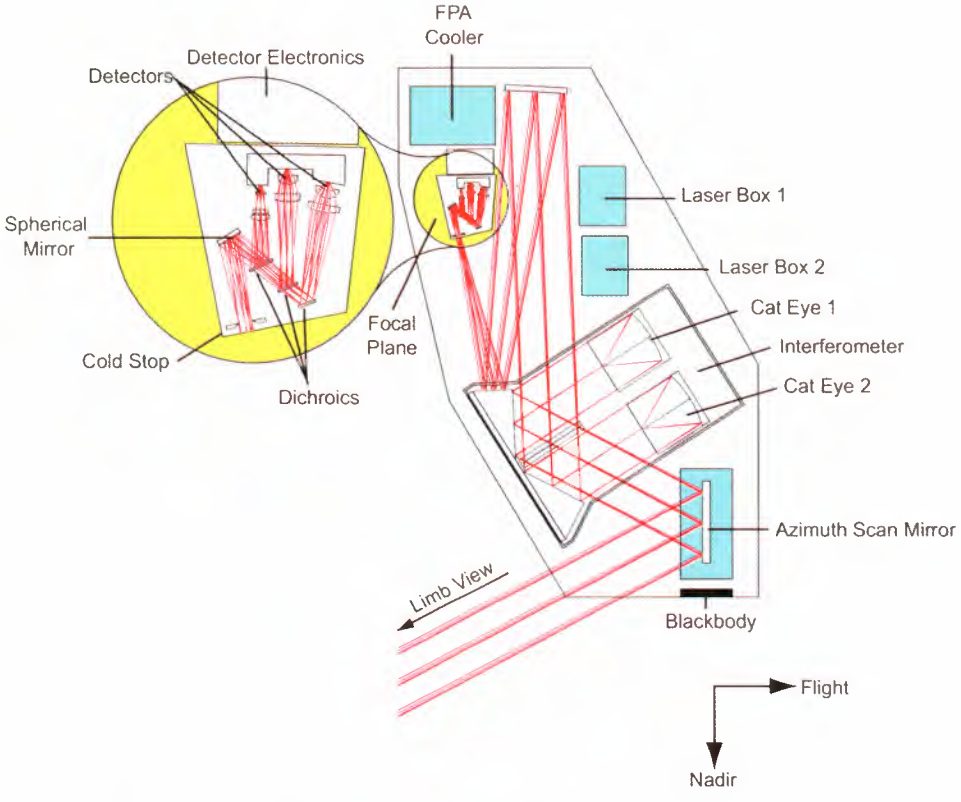

Figure 6.7: *AMIPAS overall optical configuration.*

The relay optics consists of one spherical mirror and one folding mirror. An additional spherical mirror and three dichroics are used to split the incoming light into three spectral bands, and three lens systems will image the scene on HgCdTe CMOS linear detector arrays. These elements form the Focal Plane Assembly (FPA), which is housed in a cryostat cooled to an operating temperature of about 60 K. The active cooling can either be performed by a pair of Stirling coolers or by pulse tube coolers, which are currently under development at ESA.

The Signal Processing Electronics (SPE) has to process the signals of the three linear detector arrays, with 16 pixels each. The basic functions are identical to the Envisat-MIPAS instrument. However the overall signal processing load is significantly increased due to the larger number of detector elements (48 instead of 8).

The Instrument Control Electronics (ICE) monitors and controls the instrument. It drives also the scanner, the interferometer and the reference laser system.

The AMIPAS operation is determined by the interferogram acquisition cycle, which consists of an interferogram recording time set to 1.9 seconds and an additional 0.6 seconds for turnaround of the cats-eye slides before the next acquisition can start. This leads to a cycle time of 2.5 seconds. The slide turnaround time is also the period in which the azimuth scanner positioning has to be performed, such that the required LOS stability is achieved at the beginning of the interferogram recording. The 2.5 seconds have been selected such that five interferogram acquisition cycles have a similar duration to one elevation scan of the MASTER instrument.

The AMIPAS instrument will require periodic gain and offset calibration. This is achieved by pointing the instrument to the calibration black body and to deep space. Gain calibration will be performed for about 20 minutes within time periods of more than two days by directing the instrument input to the black body. This can be performed anywhere in the orbit to minimise the loss of scientific data. For offset calibration, the instrument has to look to deep space at about 150 km tangent height. It is assumed that this will be performed by spacecraft pointing.

Mechanical

The instrument is composed of an Optics Module and the signal processing/ instrument control electronics, which are directly interfaced to the platform. The Optics Module consists of a stable optical bench on which all of the optical components are mounted, and has to be cooled passively to 160 K in order to limit the noise contribution due to self-emission. Therefore it has to be accommodated on the anti-Sun side of the satellite. Other elements included in the Optics Module are: a calibration black body, the reference laser boxes, the focal plane cooler with dedicated radiator and the Optics Module radiator. The arrangement of these elements is shown in Figure 6.8.

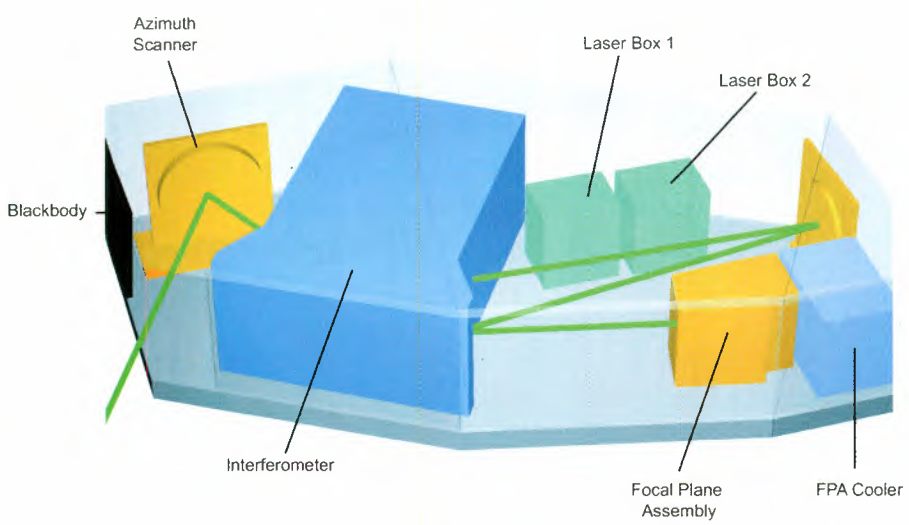

Figure 6.8: *Optics Module optomechanical configuration.*

Concept II

In this concept the optical layout includes an input scan mirror for azimuth pointing, an afocal telescope to reduce the size of the beam from 250 to 80 mm at spectrometer optics, a Michelson interferometer and a cold optics system to focus the signal on three linear detector arrays.

The input mirror will perform the required scanning movement to cover the whole azimuth across track coverage. A black body can be deployed in front of the input mirror in order to perform the internal calibration.

The input telescope is a classical three-mirror afocal telescope with a magnification of 2.5. The interferometer is placed on a dedicated optical bench to avoid vibration due to the scanning and calibration systems, using corner cubes as retroreflectors and ZnSe as beamsplitter. It is composed of two corner cubes, one moving with a linear motion of ±2.5 cm to achieve the required 0.1 cm^{-1} spectral resolution. The optical layout of the interferometer is presented in Figure 6.9.

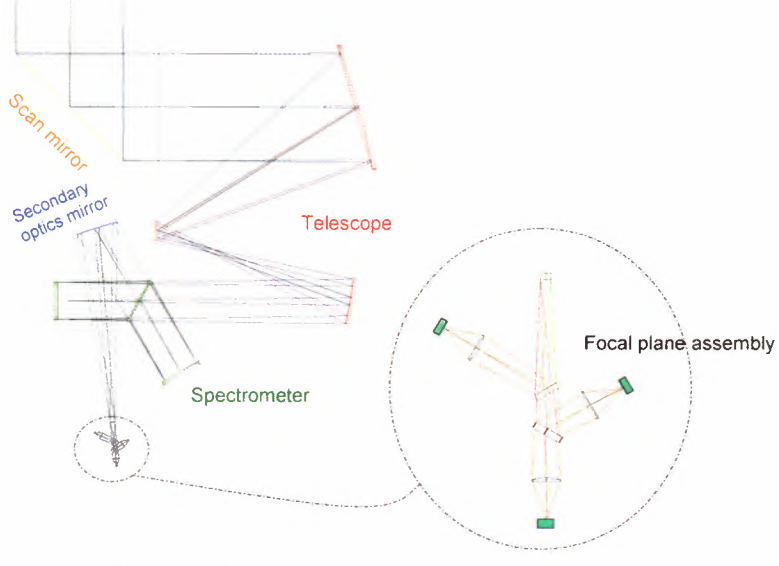

Figure 6.9: *Concept II optical layout.*

The secondary optics mirror focuses the beam at the output of the interferometer on the cold box, which encloses the detection unit and is equipped with a radiator for passively cooling the detectors to 100 K.

Inside the detection unit, different beam-splitters separate the three spectral bands and direct them to three focal planes. Focussing optics and Compound Parabolic Concentrators are used to concentrate the light on the detectors.

The linear array detectors are photovoltaic HgCdTe CMOS for the two first bands 5.7-6.45 μm and 6.45-9.5 μm, and photoconductor HgCdTe CMOS for the 9.5-14.7 μm band, both passively cooled to an operating temperature of about 100 K.

The electronics consists mainly of a Detector Unit with three separate and independent channels corresponding to each optical head and one Instrument Control Unit. The latter is responsible for the data handling, the control of the moving devices, and the control of the internal calibration sources (laser diode control and black body temperature).

The overall mechanical layout of the instrument is shown in Figure 6.10.

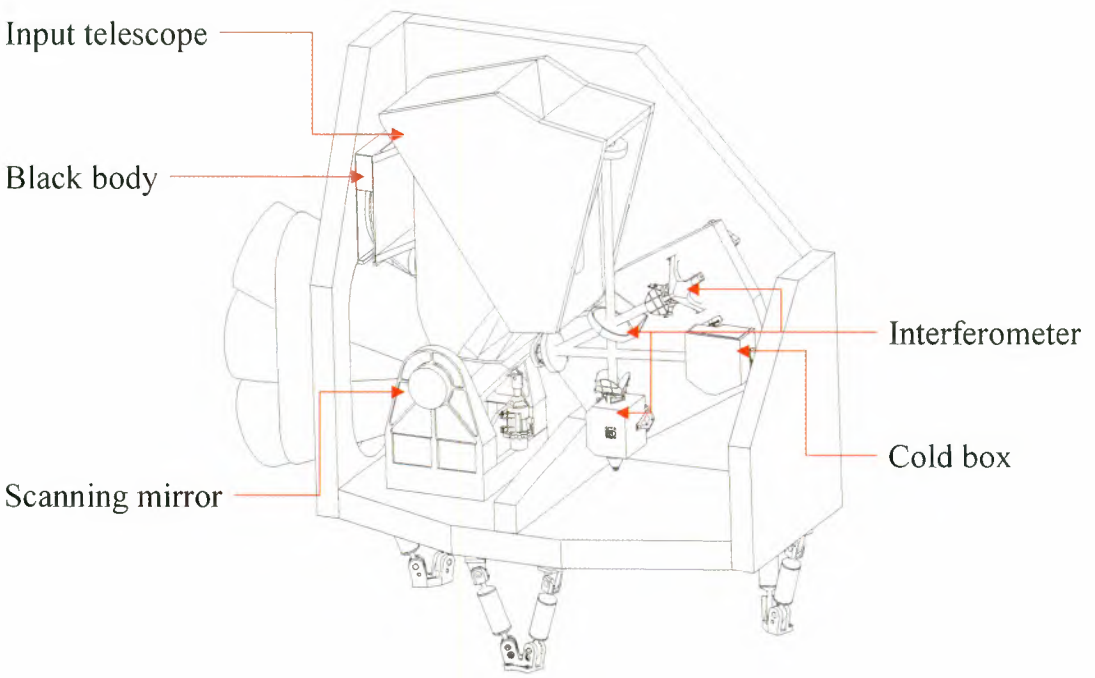

Figure 6.10: *Overall mechanical layout.*

Budgets

Table 6.3 summarises the instrument budgets for both concepts.

Performance

Both instrument concepts have comparable performances and are fully compliant with the requirements. The performance of Concept I is shown in Figure 6.11 below:

	Concept I	Concept II
Mass [kg]	230	200
Power [W]	260	270
Volume [mm³]	1200 x 850 x 400	1320 x 720 x 1270
Data rate [Mbit/s]	5 (after compression)	

Table 6.3: *AMIPAS budgets.*

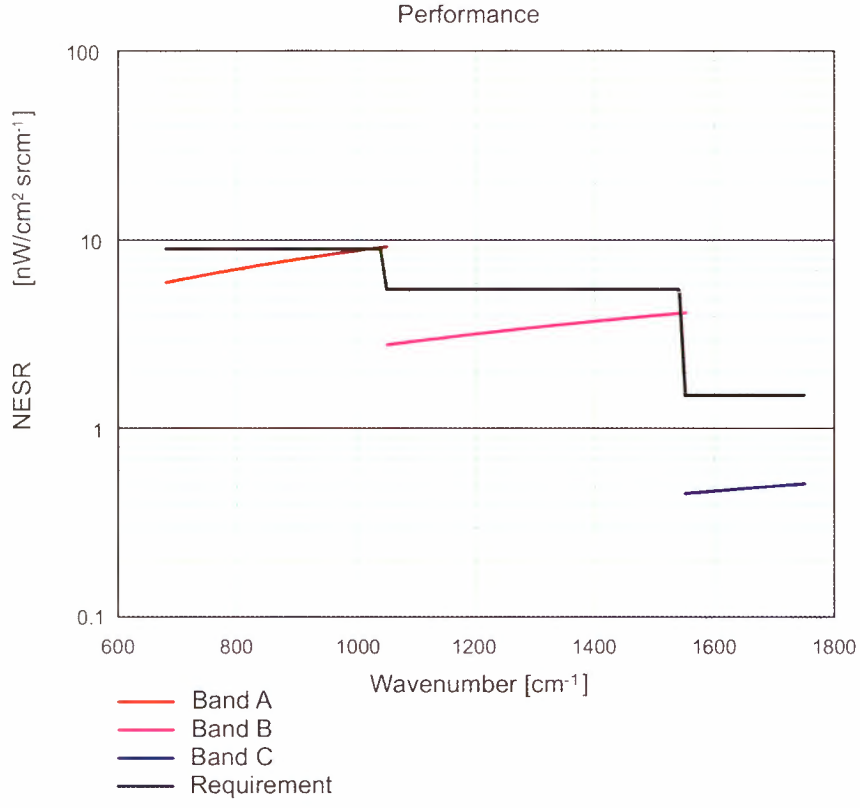

Figure 6.11: *Simulated NESR versus wavenumber for an instrument optics temperature of 160 K.*

6.3.3 Limb Cloud Imager (LCI)

Cloud imagers are reasonably simple instruments traditionally used in nadir viewing geometry. The design and performance of the LCI requires adaptation to the limb viewing geometry, and will significantly increase the size, weight and power consumption. Furthermore, the constraint to adapt the azimuth coverage of this instrument to that of AMIPAS (± 1400 km), implies the use of a complex system of pointing and calibration.

Although the vertical and azimuth coverages of LCI are basically the same as those of AMIPAS, the vertical coverage can be reduced to 25 km, due to the absence of clouds above this altitude. The observation geometry of LCI is shown in Figure 6.1b.

The LCI consists of two separate cameras operating in the nir and mir bands, since conventional detectors are unable to cover the two bands simultaneously and also because the constraints on the pupil are drastically different in the two bands.

The operating wavelength of the nir camera is 1.04 μm, with a bandwidth of 0.04 μm FWHM, requiring the use of CMT/CMOS detectors cooled to about 175 K. A dedicated radiator must be considered to passively cool the focal plane. The detector size is limited to 30 μm for physical reasons. This leads to an instrument with a focal length of 101 mm and a pupil size of 40.4 mm.

The operating wavelength of the mir camera is 12.02 μm, with a bandwidth of 0.5 μm FWHM, requiring the use of microbolometer detectors working at 300 K. The commercially available detector size is 45 μm, which leads to an instrument with a focal length of 152 mm and a pupil size of 152 mm. The overall instrument layout is shown in Figure 6.12.

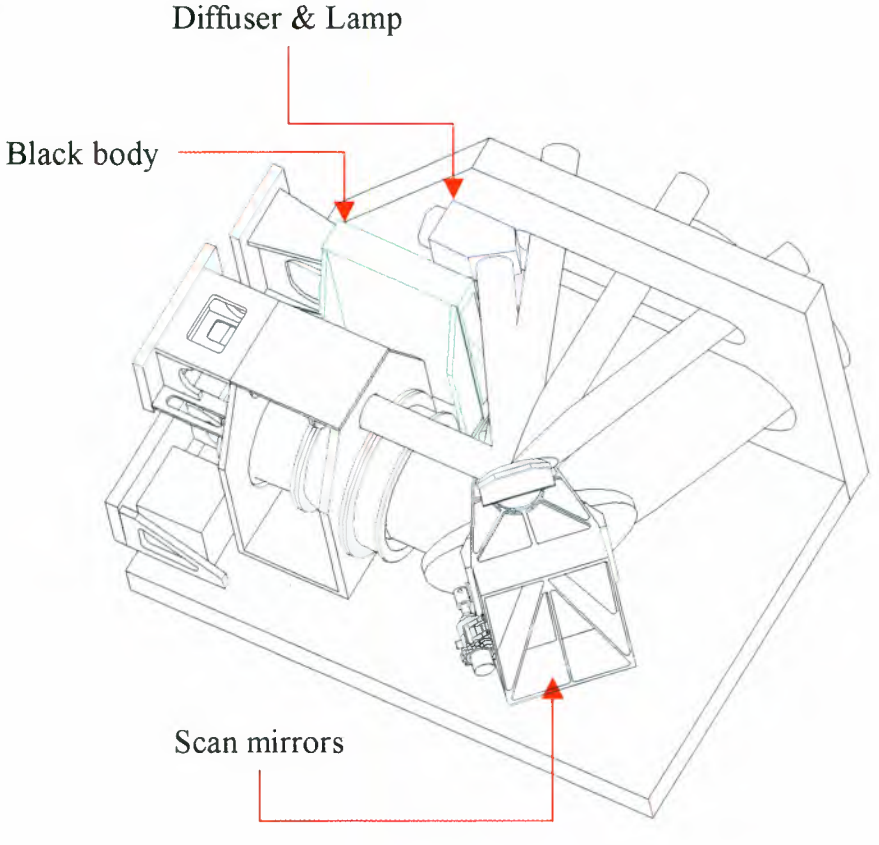

Figure 6.12: *LCI overall layout.*

The overall budgets of the LCI are listed in Table 6.4.

Mass [kg]	60
Power [W]	50
Volume [mm³]	520 x 665 x 860
Data rate [kbit/s]	90

Table 6.4: *Budgets for the LCI.*

6.4 Spacecraft

6.4.1 Satellite Configuration

Two different configurations have been proposed, linked to the partially different instrument concepts:

The first concept, shown in Figure 6.13, is designed around the MASTER Concept I and the AMIPAS Concept I. It consists of a box-shaped bus with an internal structural tube. The velocity face of the bus serves as an interface attachment to the launcher, and the dimensions of the bus are tailored to the shapes of the instruments and their required electronic units while minimising the cross section in the launcher.

The anti-Sun face is occupied by the AMIPAS instrument, and the additional area on this panel is required to accommodate the AMIPAS instrument electronics and allow an additional radiator surface on the anti-Sun side. The MASTER instrument will be mounted on the anti-velocity side, pointing towards MetOp. This arrangement will potentially require a sunshield for MASTER's main reflector to minimise its thermal distortions (not depicted in Figure 6.13). The cloud imager LCI will be mounted close to the AMIPAS instrument on the nadir face of the spacecraft structure.

The nadir side of the satellite bus will also serve as the surface for any radiators required for the bus electronics. This implies that the accommodation of any additional small payloads on the nadir face will be restricted in this configuration. The solar panel will be mounted on the Sun side of the bus. These panels will be articulated in order to be Sun-pointing. The area of the solar array required to provide the necessary power is 10 m^2.

The second proposed concept (designed for MASTER Concept II and AMIPAS Concept II) is shown in Figure 6.14. The main feature of this concept is that the payloads are all accommodated on the anti-Sun side of the spacecraft bus, which has certain advantages for the thermal control of the instruments. In this configuration the main reflector of MASTER is shadowed by the bus structure.

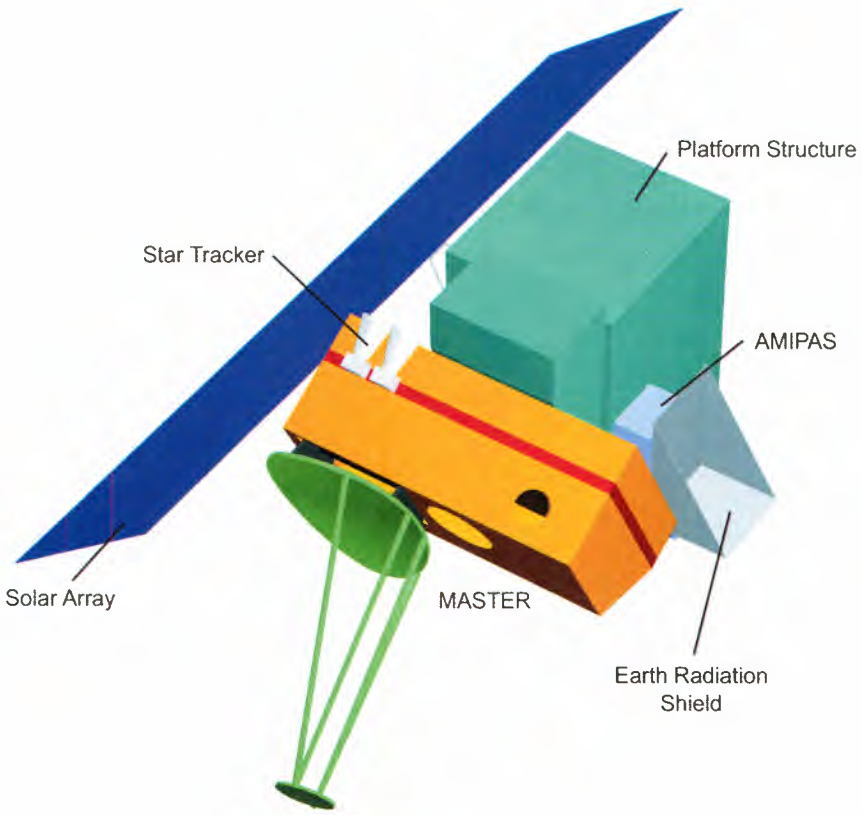

Figure 6.13: *ACECHEM satellite, Concept I.*

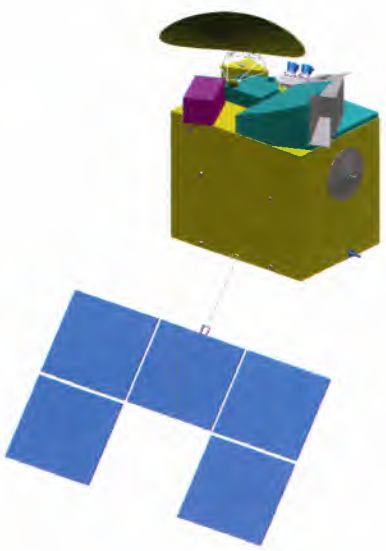

Figure 6.14: *ACECHEM satellite, Concept II.*

The structure features a central tube with shear walls, and the solar array is articulated as in the Configuration I. The panels and the central tube will be a carbon structure to fulfil the stringent pointing and alignment requirements by minimising the thermal distortions. All instruments will be accommodated on the same panel facing the anti-Sun side, together with star trackers to provide sufficiently accurate pointing knowledge.

6.4.2 Thermal Control

The thermal subsystem of the ACECHEM satellite must provide an overall heat dissipation of about 1100 Watt, about 750 W of which come from the instruments, and 350 W from the satellite.

In Configuration I the radiators will be accommodated mainly on the anti-Sun side for the instruments, and potentially on the nadir face for the spacecraft subsystems, due to the overall accommodation. In Configuration II the zenith and the anti-Sun face can be used to accommodate the required radiators.

All thermal control systems are based on passive components and on an actively controlled heater system.

The proposed concepts do not have large margins for accommodating additional heat dissipating instruments.

6.4.3 Electrical Architecture and Avionics

The main elements of the electrical architecture of the ACECHEM satellite are shown in Figure 6.15. A potential reference concept is based on a Power Conditioning and Distribution Unit (PCDU), and a Central Computing Unit (CCU) based on an ERC 32 processor.

The CCU includes command control and Attitude and Orbit Control System (AOCS) functions. Its architecture is based on an ERC 32 processor, which interfaces through an On-Board Data Handling (OBDH) bus with platform and payload input/output cards, and through a 1553 bus with AOCS sensors, and the payload. The need for two separate 1553 buses is driven by the real time constraints of the AOCS sensors required to improve stability performance.

The 200 Gbit mass memory is used for scientific and system data storage. The link between ACECHEM instruments and this mass memory is directly through a high speed serial link. Except for this mass memory and high speed link between the platform and the instruments, the concept relies on standard equipment and software.

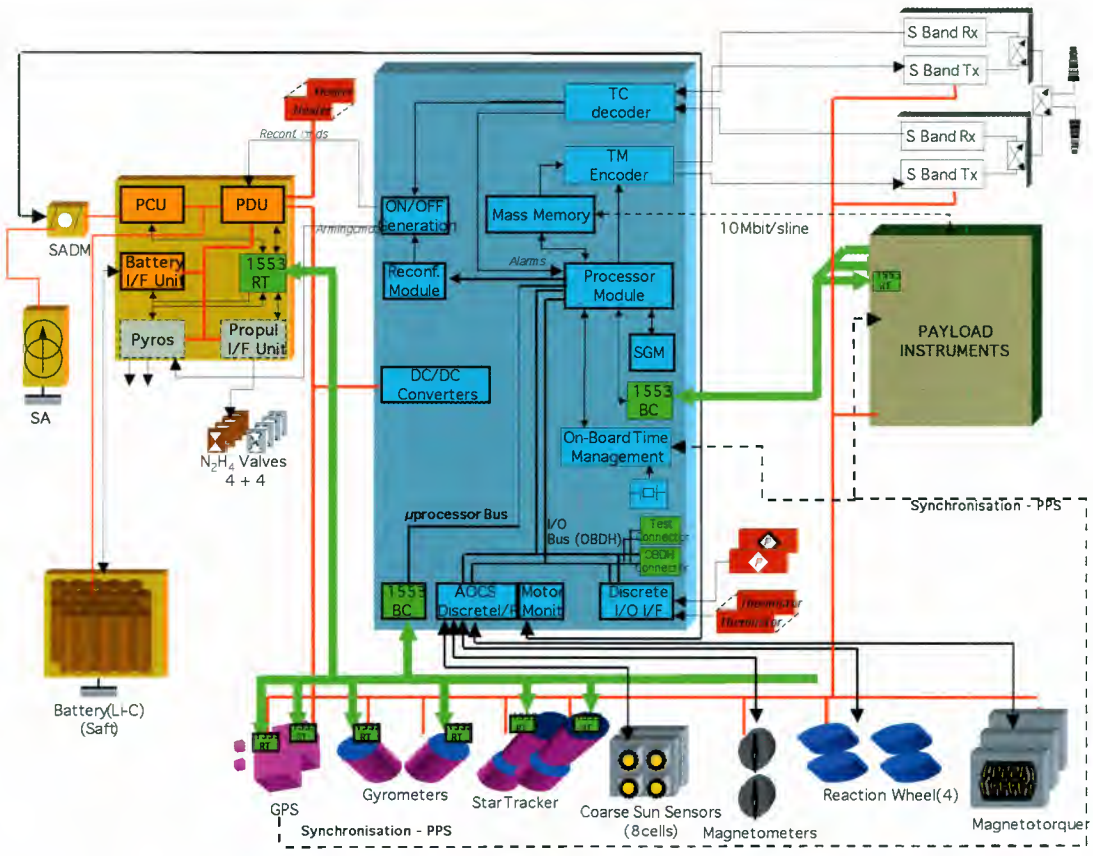

Figure 6.15: *Standard electrical architecture of ACECHEM.*

6.4.4 Attitude and Orbit Control

The main design driver for the AOCS design, and in particular for the selection of its equipment, is the challenging pointing accuracy, knowledge and stability requirement in the nominal Earth-pointing phase of the AMIPAS instrument. The instrument pointing performance requirements lead to the need for star trackers.

The nominal attitude pointing mode for ACECHEM is three-axis stabilised, such that the instruments can scan the Earth's limb in both elevation and azimuth.

Simulation results based on a reference design show that all azimuth related performance figures can be met. However, the required elevation performance figures are already at the technological limit of the standard AOCS design. In particular, the required pointing stability in elevation will have to be revisited in order to optimise the AOCS design.

Requirements and estimated performances are summarised in Table 6.5.

	Pointing Parameter	Required Satellite Performance	Simulated Satellite Performance
Azimuth	Pointing Accuracy	$\leq 0.7°$	$\leq 0.015°$
	Pointing Knowledge	$\leq 0.012°$	$\leq 0.003°$
	Pointing Stability	$\leq 0.019°/s$	$\leq 0.0005°/s$
Elevation	Pointing Accuracy	$\leq 0.012°$	$\leq 0.015°$
	Pointing Knowledge	$\leq 0.0025°$	$\leq 0.003°$
	Pointing Stability	$\leq 0.003°/s$	$\leq 0.0005°/s$

Table 6.5: *Satellite pointing requirements and estimated performance figures.*

A propulsion system is required to support the initial attitude acquisition after separation from the launcher and to keep the satellite in formation with the MetOp orbit. The total fuel required for both control tasks is of the order of 35 kg, assuming a hydrazine based mono-propellant pressurised system.

6.4.5 Payload Data Management

The design of the payload data management system is driven by the data rates of the instruments and the foreseen ground stations, such as the ESA station in Kiruna/Sweden or the commercial station on Svålbard/Norway. For the ACECHEM orbit, 10 and 15 ground contacts per day, with a mean contact duration per orbit of about 8 and 11 minutes, respectively.

The on-board memory has to be sized according to the expected number of blind orbits of the selected ground stations, including one additional orbit, in case of a ground station failure. This results in a memory size of 166 Gbit for the Kiruna and 56 Gbit for the Svålbard ground station. These memory sizes are compatible with current technology and the proposed design of the ACECHEM avionics.

6.5 Mission and Operation Profile

Formation Flight

ACECHEM is proposed to fly in tandem with MetOp, 466 s in advance of it (27.7° of Earth centre angle), at a mean altitude of 820 km.

In this concept, there is no specific constraint on MetOp orbit maintenance. The ACECHEM formation-flying is designed such that the synchronisation of ACECHEM limb measurements with MetOp Nadir is guaranteed along track with ±1 minute precision, and across track the ACECHEM limb measurements are guaranteed to be within the MetOp nadir instruments' field of view.

The formation geometry can therefore be maintained by ACECHEM alone. As control of the formation flying needs MetOp ephemeris information, autonomous control of

ACECHEM is not considered as a baseline. The station keeping strategy is to place ACECHEM ahead and above MetOp. The nominal decay would then steadily advance the position of ACECHEM relative to MetOp. A manoeuvre would place ACECHEM back in its initial position. The whole sequence lasts some months, and traces a typical 'D' shape, as shown in Figure 6.16.

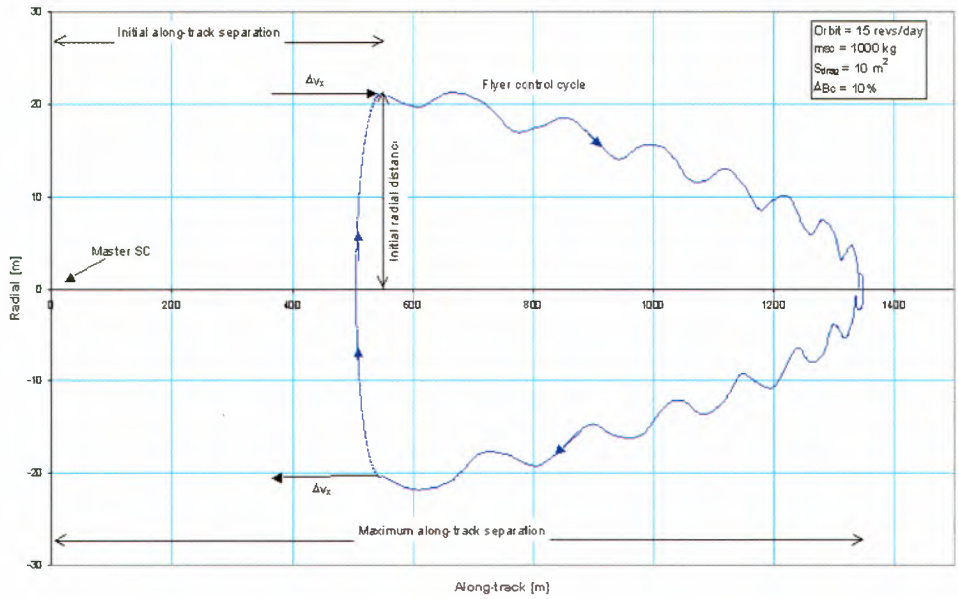

Figure 6.16: *Control cycle with differential ballistic coefficient.*

Coverage

The prescribed orbit and the azimuth scanning leads to the 24 h coverage for the ACECHEM instruments illustrated in Figure 6.17.

Operational Concept

The operational concept of the ACECHEM satellite is determined by the nominal and optional measurement modes, as well as by the calibration concept of the individual instruments.

After the commissioning phase, the satellite enters the nominal operational measurement mode, where MASTER performs the nominal elevation scans and AMIPAS performs the nominal azimuth scanning (five measurements in different azimuthal viewing directions).

For both instruments, so-called Optional Scan modes are required, where tangent heights up to 90 km have to be monitored. To make these measurements, the satellite

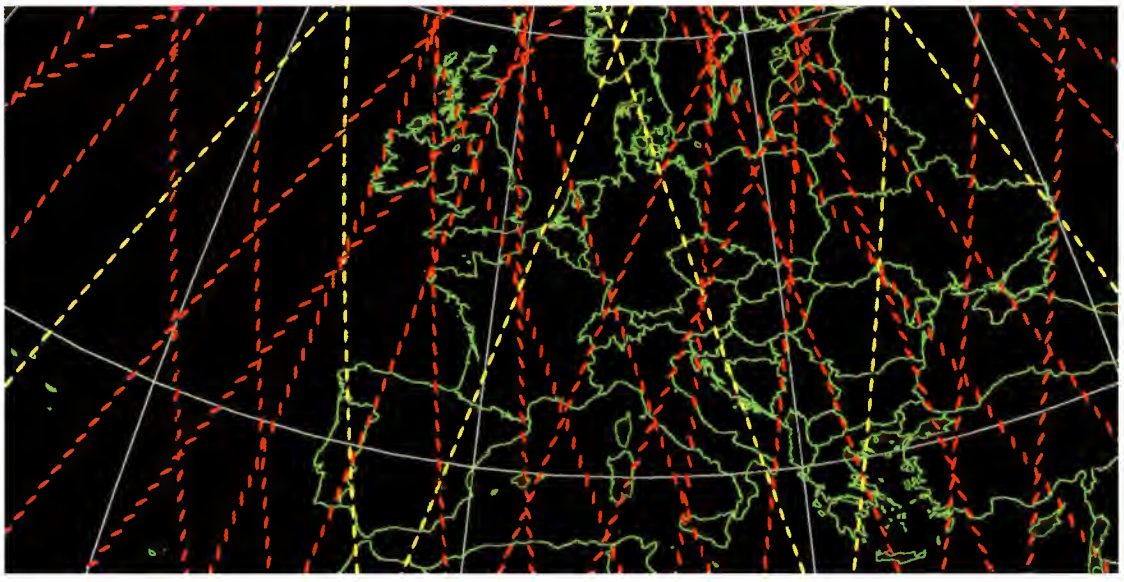

Figure 6.17: *European coverage of limb sounders in a 24 h period: the yellow marks represent the MASTER scans and the central AMIPAS measurement; the red marks indicate the azimuth views of AMIPAS.*

has to perform a pitch manoeuvre of about 1.0° to provide the required viewing direction. The satellite can stay in this mode as long as required by the instruments.

6.6 Budgets

The mass and power budgets for the two configurations are quite similar. Representative budgets are given in Tables 6.6 and 6.7 below. The ACECHEM power budget shows a mean orbital power demand of roughly 1 kW. The satellite has a solar generator based on GaAs cells with an area of 10 m^2, which is sufficient to comply with the end of life performance requirements.

AMIPAS	280
MASTER	360
LCI	60
Spacecraft	550
Subtotal	**1250**
+ System Margin (10%)	1375
Fuel	35
Total Launch Mass	**1410**

Table 6.6: *ACECHEM mass budget (in kg), including margin at instrument level.*

AMIPAS	270
MASTER	350
LCI	60
Spacecraft	300
Subtotal	**980**
+ System Margin (10%)	1078

Table 6.7: *ACECHEM power budget (in W).*

6.7 Ground Segment and Data Processing

An overview of the ACECHEM ground segment system context and reference architecture is provided in Figure 6.18. The main elements are the Command & Data Acquisition Element (CDAE), the Mission Operations & Satellite Control Centre (MSCC), the Processing & Archiving Element (PAE) and the Communications Network (not explicitly shown in the figure).

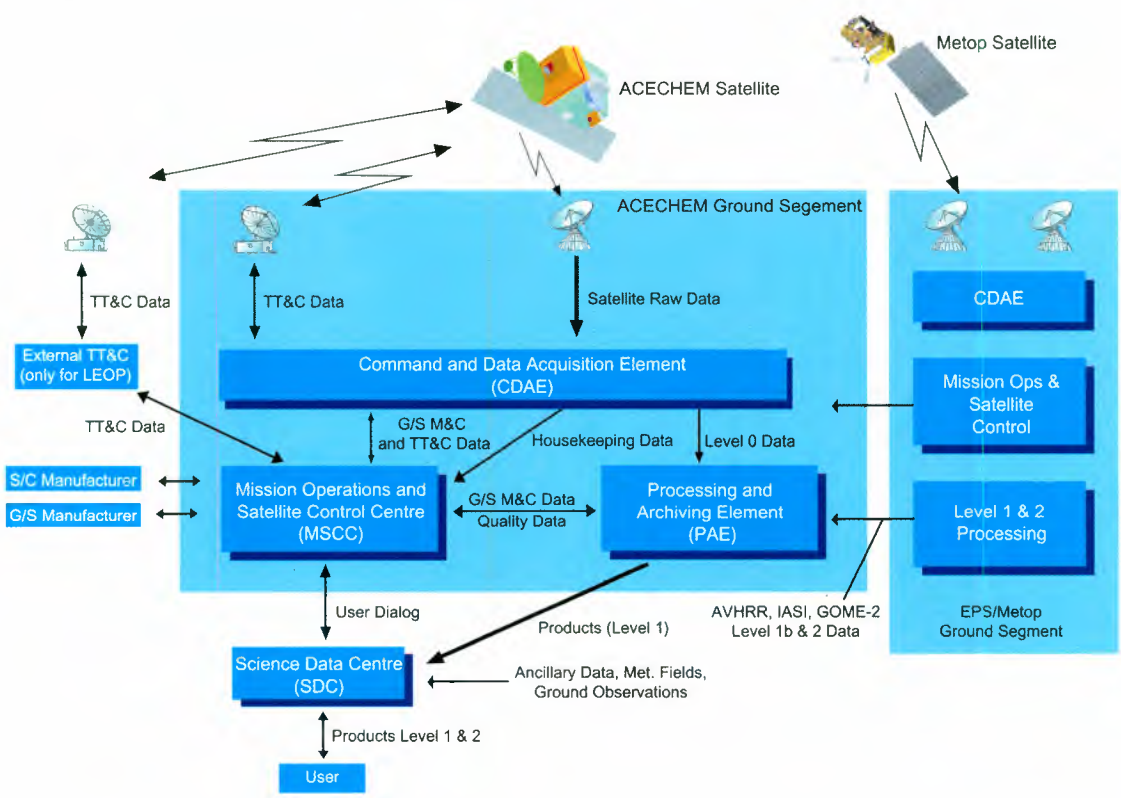

Figure 6.18: *ACECHEM Ground Segment reference architecture.*

The Science Data Centre (SDC) interfacing with the ACECHEM ground segment represents the users. Maximum use will be made of available ESA facilities and infrastructure.

Due to the characteristics of the mission and the data volume per orbit, X-band has been selected as the baseline transmission frequency range. Since there is no requirement on the timeliness of products, it is not necessary to down-link all data stored onboard the satellite during each orbit. In particular, for the Kiruna ground station the dimension of the down-link channel will be such that on average (e.g. over one day) all the acquired and stored data can be down-linked. The mission data volumes and resulting data rates are summarised in Table 6.8.

Parameter	Value
Data Volumes	
Data volume per orbit (typical orbit duration: 102 min)	24.5 Gbit
Total data volume per orbit (including 15% overhead)	27.8 Gbit
Total data volume per day (15 orbits in average)	417 Gbit
Downlink Data Rates	
G/S contact times (average)	8 Min. (Kiruna) 11 Min. (Svålbard)
Number of available orbits (average)	10 (Kiruna) 15 (Svålbard)
Downlink data rates (average over one day)	86.9 Mbit/s (Kiruna) 42.1 Mbit/s (Svålbard)

Table 6.8: *ACECHEM mission data and data rates.*

6.8 Launcher

The ACECHEM dimensions allow the satellite to be accommodated on a Soyuz IKAR launcher. The launcher provides a large performance margin for the 1400 kg satellite and the required orbit. The launch configurations for both concepts are shown in Figure 6.19.

6.9 Mission Performance

The major innovations to be achieved by the mm/sub-mm observations of the ACECHEM mission will be:

- Increased vertical resolution in the upper troposphere, by reducing the half-power beam widths of mm-wave bands to 2.3 km.

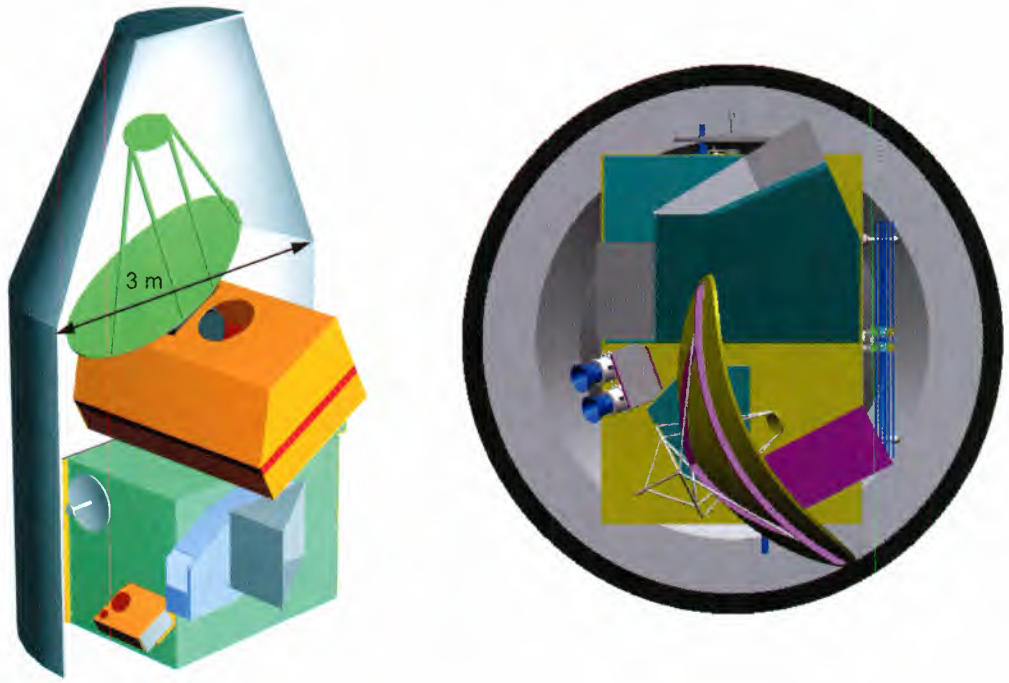

Figure 6.19: *ACECHEM Configuration I (left) and Configuration II (right) in stowed configuration in the Soyuz launcher.*

- Better separation between emission from target lines and that from interfering lines and *continua* by contiguous spectral coverage, in single side-band rather than double side-band.

- Improved sensitivity to upper tropospheric CO by an order of magnitude through use of a higher frequency line (345 GHz vs 231 GHz for EOS-MLS) and cooling the receiver to 80 K.

- Substantially improved sensitivity to ClO, BrO and other trace gases in the LS, in comparison to EOS-MLS, through use of a 500 GHz receiver cooled to 80 K.

The concepts chosen for ACECHEM overcome the limitations of contemporary satellite-based mir limb sounders by:

- Increasing the vertical resolution, by reducing the field-of-view vertical width and the spacing between limb-views from 3 km to 2 km.

- Eliminating the uncertainties in knowledge of spacings between tangent-heights which arise from limb-scanning, by use of a vertical detector array to view all tangent-heights simultaneously.

- Increasing the density of horizontal sampling by a factor five, both along- and across-track, by scanning the detector array in five azimuth directions and reducing the acquisition time to an equivalent of 100 km along-track.

Further innovations of the mission with respect to sounding tropospheric composition are:

(i) Deploying a limb imager with mir and nir channels to characterise cirrus and aerosol, in support of trace gas observations by the spectrometers.

(ii) Designing the mm/sub-mm and mir spectrometers, the limb imager and their measurement sequences specifically to exploit the synergy between them and with MetOp to the fullest extent.

As has been demonstrated above, all key technical requirements can be met to fulfil the mission objectives. The individual instrument performances, the sampling and the pointing budgets are compatible with the observation requirements. Based on the proposed design and the predicted performance parameters, the retrieval accuracy shown in Chapter 4 can be achieved.

7 Programmatics

7.1 Introduction

Section 7.2 of this chapter presents the technical maturity, the heritage and the risk areas for the concepts developed in the pre-Phase A studies. Section 7.3 presents the international context and the related missions, both approved and planned. The contribution of ACECHEM to the enhancement of the Earth observation capabilities and its application potential are outlined in Section 7.4.

7.2 Technical Maturity, Critical Areas and Risk

The technical maturity of the ACECHEM mission is compliant with a launch in the timeframe of the second cycle of the Earth Explorer Core missions. Several elements, mainly linked to the overall system complexity, indicate that a launch in 2008 will be challenging in terms of development schedule.

The AMIPAS mir limb-emission Fourier Transform Spectrometer proposed for ACECHEM has a heritage from Envisat-MIPAS and from IASI on MetOp, as well as from the ground-, aircraft- and balloon-based MIPAS instruments. The main innovation with respect to Envisat-MIPAS will be the linear array detector. The extended horizontal coverage through an azimuth scan has been proposed to increase the scientific return.

The MASTER heterodyne spectrometer instrument design will draw on the experience accumulated with the SMR instrument on Odin and the MAS instrument for ATLAS in Europe, and with MLS on UARS in the USA. The experience with MLS on EOS Aura, which is due for launch in 2003, will also be applicable. The development will benefit from the MASTER pre-development activities performed by the Agency since 1994.

Table 7.1 summarises the main aspects of the implementation and the heritages of key payload elements.

For the platform development, specific optimisation studies will support the attitude control subsystem specification. Assuming that instrument preparatory activities continue with increased pace and budget during Phase A, it should be possible to keep the number of instrument models to a minimum during the development phase. To ensure compatibility with the programmatic constraints of Earth Explorer Core missions, complexity and cost reductions are necessary before starting Phase A. This optimisation implies focussing of the mission requirements and this has already been initiated.

Element	Implementation	Risk/Heritage
AMIPAS		
Detector	HgCdTe CMOS Linear array	Performance remains to be demonstrated
MASTER		
Main reflector	CFRP	Breadboarding started in ADMIRALS technology project; similar technology to Herschel/Planck
Quasi-optical FSS		Prototypes need to be developed
Normal/high-resolution spectrometer	DAC	The DAC concept needs further development to combine low power, large bandwidth and low noise figure.
	AOS	Availability of Bragg cells needs to be addressed, breadboarding activities started.

Table 7.1: *Risk assessment for the most critical elements.*

7.3 International Cooperation and Related Missions

Because of its expected role in collecting key information for understanding chemical processes in the atmosphere and their relations to the climate, ACECHEM is of global interest. It is expected to play a major role in the international effort to further our understanding of climate evolution. Cooperation can be envisaged with other European international organisations. EUMETSAT has a special position through the need to access MetOp data.

The missions most closely related to ACECHEM have been discussed in Section 5.5. The strong complementarity of ACECHEM with MetOp, in particular with respect to the IASI, AVHRR-3 and GOME-2 instruments, has already been emphasised. Complementarity also exists with similar missions like JEM-SMILES, GCOM-A1 or the OMPS instrument on the NPOESS system. Finally, ACECHEM is expected to provide a large degree of continuity with respect to Envisat.

ACECHEM will play a key role in furthering the development of data assimilation models for the parametrisation of atmospheric chemical processes and in increasing the understanding of human impact on the composition and chemistry of the atmosphere, and of interactions between chemistry and climate.

7.4 Enhancement of Capabilities and Potential for Applications

The expected scientific advances have been discussed in previous chapters. This mission is also very relevant to the development of new applications and future operational systems.

The data from ACECHEM will contribute to monitoring of the long-term evolution of atmospheric composition and associated dynamical and radiative parameters.

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Acronyms

ACECHEM	Atmospheric Composition Explorer for Chemistry and Climate Interaction
ADM	Atmospheric Dynamics Mission
ADMIRALS	Antenna Development in Millimetre / Sub-millimetre-wave range for Astronomy and Limb Sounding
AMIPAS	Advanced Michelson Interferometer for Passive Atmospheric Sounding
AOCS	Attitude and Orbit Control System
AOS	Acousto-Optical Spectrometer
ATLAS	Atmospheric Laboratory for Applications and Science
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CDAE	Command & Data Acquisition Element
CFC	Chloro-Fluoro-Carbon
CFRP	Carbon Fibre Reinforced Plastic
CCU	Central Computing Unit
CMOS	Complementary Metal-Oxide Semiconductor
CCN	Condensation Nucleus
DAC	Digital Auto-Correlator
EarthCARE	Earth Clouds Aerosol and Radiation Explorer
EOEP	Earth Observation Envelope Programme
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environmental Agency
Envisat	Environmental Satellite
EOS	Earth Observing System
ESA	European Space Agency
FPA	Focal Plane Assembly
fir	far-infrared
FN	Freezing Nucleus
FOV	Field Of View
FTS	Fourier Transform Spectrometer
FSS	Frequency Selective Surface
FWHM	Full Width Half Maximum
GCOM	Global Change Observation Mission
GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GMES	Global Monitoring of Environment and Security
GOME	Global Ozone Monitoring Experiment
GOCE	Gravity field and steady-state Ocean Circulation Explorer
HALOE	Halogen Occultation Experiment
(H)CFC	(Hydrogenated) Chloro-Fluoro-Carbon

HEMT	High Electron Mobility Transistor
HFC	Hydro-Fluoro-Carbon
HPBW	Half-Power Beam Width
IASI	Infrared Atmospheric Sounding Instrument
ICE	Instrument Control Electronics
IF	Intermediate Frequency
IPCC	International Panel for Climate Change
JEM	Japanese Experiment Module
LCI	Limb Cloud Imager
LS	Lower Stratosphere
LT	Lower Troposphere
MAS	Millimetre-wave Atmospheric Sounder
MASTER	Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchange Research
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MHS	Microwave Humidity Sounder
mir	mid-infrared
MSCC	Mission operations and Satellite Control Centre
MSG	Meteosat Second Generation
mm	millimetre-wave
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency
nir	near-infrared
NESR	Noise Equivalent Spectral Radiance
NE(B)T	Noise Equivalent (Brightness) Temperature
NMHC	Non-Methane Hydrocarbon
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NWP	Numerical Weather Prediction
OBDH	On-Board Data Handling
ODUS	Ozone Dynamics Ultraviolet Spectrometer
OMPS	Ozone Monitoring and Profiling Suite
OPD	Optical Path Difference
PAE	Processing and Archiving Element
PCDU	Power Conditioning and Distribution Unit
PFC	Perfluorinated Carbon
PSC	Polar Stratospheric Cloud
ppbv	parts per billion by volume
ppmv	parts per million by volume
pptv	parts per trillion by volume
QBO	Quasi-Biannual Oscillation
SAGE	Stratospheric Aerosol and Gas Experiment
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography

SDC	Science Data Centre
SAO	Semi-Annual Oscillation
SMILES	Super-conducting subMIllimetre-wave Limb-Emission Sounder
SOFIS	Solar Occultation Fourier transform spectrometer for Inclined orbit Satellite
SOLVE	SAGE III Ozone Loss and Validation Experiment
SMOS	Soil Moisture and Ocean Salinity
SPE	Signal Processing Electronics
SPECTRA	Surface Processes and Ecosystems Changes Through Response Analysis
SPG	Scientific Preparatory Group
STE	Stratosphere-Troposphere Exchange
sub-mm	sub-millimetre wave
SWIFT	Stratospheric Wind Interferometer for Transport Studies
TES	Tropospheric Emission Spectrometer
THESEO	THird European Stratospheric Experiment on Ozone
UTLS	Upper Troposphere/Lower Stratosphere
UT	Upper Troposphere
uv	ultra-violet
VFOV	Vertical Field Of View
vis	visible
WALES	WAter vapour Lidar Experiment in Space
WATS	WAter vapour and temperature in the Troposphere and Stratosphere

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