→ TO OBSERVE ATMOSPHERIC COMPOSITION
FOR A BETTER UNDERSTANDING OF CHEMISTRY–CLIMATE INTERACTIONS

Six Candidate Earth Explorer Core Missions – Report for Assessment 5

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CANDIDATE EARTH EXPLORER CORE MISSION

premier – process exploration through measurements of infrared and millimetre-wave emitted radiation

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Chapter 1  Introduction

Earth Explorer missions focus on the science and research elements of ESA’s Living Planet Programme. Encompassing a new approach to observing the Earth from space, Earth Explorers are developed in direct response to scientific challenges identified by the scientific community. The fundamental principle of defining, developing and operating missions in close cooperation with the scientific community provides an efficient tool to address pressing Earth-science questions as effectively as possible.

Since the science and research elements of ESA’s Living Planet Programme were established in the mid-1990s, this on-going user-driven strategy has, so far, resulted in six Explorer missions selected for implementation. Together, they cover a broad range of issues to further our understanding of the Earth system and the impact of human activity. In addition, the scientific questions addressed also form the basis for the development of new applications for Earth observation data.

Earth Explorers missions are split into two categories – ‘Core’ and ‘Opportunity’. Core Earth Explorers are large missions addressing complex issues of scientific interest whilst Opportunity missions are smaller and supported scientifically by the proposing team. Through a process of selection, Core and Opportunity missions are implemented in separate cycles to ensure a steady flow of missions to address key Earth-science questions.

The first cycle for Core missions resulted in the Gravity field and steady-state Ocean Circulation Explorer (GOCE) launching in 2009, and the Atmospheric Dynamics Mission ADM-Aeolus (due for launch in 2010). The second cycle, initiated in 2000, resulted in the Earth Clouds Aerosols and Radiation Explorer (EarthCARE), due for launch in 2013. The first cycle for Opportunity missions resulted in the ice mission CryoSat, which is currently being rebuilt following a launch failure in 2005 and scheduled for launch in 2009, and the Soil Moisture and Ocean Salinity (SMOS) mission, also scheduled for launch in 2009. The second cycle resulted in the magnetic field mission Swarm, which is due for launch in 2010.

A third cycle of Earth Explorer Core missions was initiated by a Call for Ideas released in March 2005. In May 2006, six of the candidate missions were selected for Assessment Study (Phase 0) following a peer review of 24 proposed mission ideas. Prior to the next stage – the selection of missions for Feasibility Study (Phase A) – a Report for Assessment has been prepared for each of the six Candidate Earth Explorer Core Missions.

The following Reports for Assessment for each of the Candidate Earth Explorer Core Missions are provided to the Earth Observation research community prior to the User Consultation Meeting held in January 2009 in Lisbon, Portugal:

- A-SCOPE – to observe atmospheric carbon dioxide for a better understanding of the carbon cycle,
• BIOMASS – to observe global forest biomass for a better understanding of the carbon cycle,
• CoReH₂O – to observe snow and ice for a better understanding of the water cycle,
• FLEX – to observe photosynthesis for a better understanding of the carbon cycle,
• PREMIER – to observe atmospheric composition for a better understanding of chemistry-climate interactions,
• TRAQ – to observe tropospheric composition for a better understanding of air quality.

The six Reports for Assessment all follow a common structure comprising this introductory first chapter and six subsequent chapters as follows:

• Chapter 2 – identifies the issues of concern to be addressed by the mission, considers related past and present activities, justifies the mission set within the post 2015 time frame and includes a review of the current scientific understanding of the issue in question while identifying the potential ‘delta’ that the mission could provide,
• Chapter 3 – drawing on arguments presented in Chapter 2 this chapter summarises the specific research objectives of the mission,
• Chapter 4 – specifies the observational requirements within the context of the scientific objectives including geophysical parameters and associated data products, space/time sampling requirements, timing of the mission etc.,
• Chapter 5 – provides an overview of the mission elements, including the space segment, ground segments and products that are required to fulfil the observational requirements,
• Chapter 6 – details the complete system concept and reviews the technological challenges and levels of technical and scientific maturity,
• Chapter 7 – outlines a programme of implementation. Drawing on previous chapters, this chapter also addresses technical maturity, the development status of key technologies, risks, logistics and schedules.
This Report for Assessment covers the PRocess Exploration through Measurements of Infrared and Millimetre-wave Emitted Radiation (PREMIER) mission and is based on contributions from the following members of the Mission Assessment Group (MAG):

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1.1 Mission summary

Objectives

The aim of the PREMIER mission is to quantify processes controlling global atmospheric composition in the mid/upper troposphere and lower stratosphere (5–25 km height range), which is a region of particular importance for climate change. Furthermore, by exploiting synergies with instruments on the operational meteorological satellite, EUMETSAT Polar System (EPS) MetOp, PREMIER aims to quantify links with surface emissions and pollution.

PREMIER’s three objectives are:

a. to quantify relationships between atmospheric composition and climate,
b. to quantify atmospheric transport processes important to climate and air quality,
c. to quantify relationships between atmospheric dynamics and climate.
Science

Better qualitative and quantitative understanding of the atmospheric chemical and dynamic processes that control atmospheric composition is one of the challenges in climate-change research. Improved chemistry–climate models will be needed to simulate the feedbacks necessary to accurately predict future changes in climate on decadal to century time-scales. These models currently rely on parameterisations of the detailed physical and chemical processes that occur on spatial scales too small to be explicitly captured by global chemistry–climate models. Due to the lack of high spatial- and temporal-resolution measurements, many of these processes are poorly understood.

Mission

PREMIER will be the first mission to generate atmospheric trace-gas fields at a resolution high enough to study stratospheric–tropospheric exchange, tropical convection, the Indian monsoon, forest fires/pyro-convection, and signatures of mesoscale dynamics including gravity waves. Through the use of limb imaging spectrometry in the infrared, PREMIER will observe 3D fields of atmospheric composition in the upper troposphere and lower stratosphere. The millimetre-wave limb-sounder will provide data in the presence of cirrus cloud and complementary chemical species. Combined with data from instruments on the EPS MetOp platform, PREMIER data will be extended to the surface, to improve estimates of biogenic, pyrogenic and anthropogenic emissions.
Chapter 2 Background and Scientific Justification

2.1 Introduction

Quantitatively understanding and predicting climate change is one of the biggest challenges facing civilisation in this century. The ESA report ‘The Changing Earth’ (ESA, 2006) highlights several climate change challenges, including better qualitative and quantitative understanding of the role of the atmosphere in climate-change. In this context, state-of-the-art models that couple atmospheric composition and climate will be needed to simulate the feedbacks necessary to accurately predict future changes in climate on decadal to century-long time-scales. These models currently rely on parameterisations of the detailed physical and chemical processes that occur on spatial scales too small to be explicitly captured by the model, for example, rapid vertical transport by convective clouds, ice microphysics and heterogeneous ozone chemistry. Many of these processes are poorly understood due to the lack of appropriate observations and, consequently, our current understanding of the interactions between changes in climate and atmospheric chemistry is subject to large uncertainties. The Intergovernmental Panel on Climate Change (IPCC) (Denman et al., 2007) has identified the interaction between atmospheric chemistry and climate as an area of high priority for future research, an appraisal reflected in the establishment of a major joint project on atmospheric chemistry and climate involving the World Climate Research Programme and the International Geosphere Biosphere Programme (ACC, 2008).

Climate is particularly sensitive to changes in the Upper Troposphere and Lower Stratosphere (UTLS) region of the atmosphere, as shown Figure 2.1. This is the region where most of the mid-IR radiation escapes to space and cirrus clouds trap significant amounts of outgoing terrestrial radiation. In this region, ozone originating from a variety of sources is a very important GreenHouse Gas (GHG). In the UTLS, water vapour, the most significant GHG, has strong vertical gradients. This region is also subject to injection of surface pollution by large-scale convection and upward transport by frontal systems. It is the region where commercial aircraft fly, injecting CO$_2$, water vapour, nitrogen oxides and aerosols, forming contrails and impacting cirrus clouds.

The next generation of climate models are beginning to incorporate chemistry–climate interactions to simulate important biogeochemical feedbacks. To achieve this, complex chemistry–climate models (essentially atmospheric general-circulation models with comprehensive chemistry packages) are the subject of intense ongoing research and development. SPARC (Stratospheric Processes And their Role in Climate) (http://www.atmosp.physics.utoronto.ca/SPARC/) initiated a model comparison for both current and future conditions (Eyring et al., 2006; 2007). Their evaluation revealed significant disagreement among many of the models. Therefore, in order to reduce the uncertainties associated with predictions of future climate there needs to be considerable improvement in our scientific understanding. This, in turn, requires global observational data of higher quality than is currently available.
In this chapter we describe the UTLS in the context of the PREMIER mission and the new advances in the understanding of Earth’s climate that we anticipate will follow from this mission. Section 2.2 explains why the UTLS is so critical to understanding future climate change and outlines the outstanding science questions that PREMIER will address. Section 2.3 presents the unique measurement characteristics of PREMIER in context of past, current and planned satellites and describes the extensive synergy between PREMIER and nadir-viewing instruments that will be available on both the European and American operational meteorological satellites, MetOp and NPOESS respectively. The conclusions in Section 2.4 present the major scientific advances that PREMIER can deliver.

2.2 Why the UTLS is so important

The UTLS will play an important role in determining future climate change but our understanding of this region is hampered by lack of detailed and accurate measurements. Figure 2.1 illustrates the complexity of the processes in this region and suggests why detailed spatial and temporal resolution will be required to understand these processes and to represent them accurately in models. The physical and chemical properties of the UTLS are difficult to measure from space. Most nadir-viewing instruments do not have the vertical resolution to resolve
strong vertical gradients of interest, whereas limb-viewing instruments have
difficulties because the atmosphere becomes nearly opaque at low spectral
resolution and long path-lengths. Also, there are often clouds sufficiently thick that
many instruments cannot see through them. *In situ* measurements from platforms
such as aircraft do not provide sufficient spatial and temporal coverage to rigorously
test physical and chemical properties of the atmosphere.

As noted above, the UTLS is a region of particular sensitivity to climate as it is
a region where cooling to space occurs. The following section (2.2.1) describes
the connection between composition, climate and cooling in this region. The
composition of the UTLS is determined by upward transport of species from the
surface, stratosphere–troposphere exchange, horizontal transport, lightning and
*in situ* homogeneous and heterogeneous chemistry (Section 2.2.2). Convection
in cumulonimbus clouds can rapidly loft gaseous and aerosol pollution from the
surface to the upper troposphere and some of these deep convective systems
penetrate the tropopause and inject tropospheric air into the stratosphere. Also,
pyroconvection, resulting from the interaction of unstable air and large surface
fires, can inject material as high as the lower stratosphere (Section 2.2.2). The UTLS
is also where commercial planes fly. Their exhaust emissions affect the formation
of cirrus clouds (both directly and via aerosols), and the chemistry of ozone and
methane (via NOx). Stratosphere–troposphere exchange of trace gases is controlled
in a non-local fashion as waves generated in the troposphere, such as Rossby waves
and gravity waves, propagate into the stratosphere (Section 2.2.3) and drive the
Brewer-Dobson (BD) circulation linking tropical and extratropical air masses of the
stratosphere.

### 2.2.1 Composition and climate

Changes of atmospheric composition in the UTLS region are a major driver of
surface climate-change and have a profound effect on the chemical and dynamical
evolution of the stratosphere. Therefore, understanding these changes presents
a major challenge in climate prediction. PREMIER will provide global composition
measurements of the UTLS with unprecedented 3D spatial and temporal resolution,
thereby improving understanding of radiation processes and consequently, climate
change. The major drivers and feedbacks involve the interaction of the radiation
field with water vapour, ozone, cirrus clouds and aerosols.

The cold UTLS region is characterised by significant cooling to space. As a result, the
largest radiative forcing\(^1\) of greenhouse gases occurs in this region, as illustrated in
Figure 2.2. Additionally, even small changes in the abundance of thin cirrus clouds

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\(^1\) When the atmospheric composition of GHG changes, the distribution and rate of cooling to space
will change. To properly estimate the impacts of such changes requires long runs of climate models in
order to tease out statistically-significant small changes. Radiative forcing is a metric often introduced to
estimate the instantaneous changes due to a perturbation of GHGs or other types of forcing in lieu of more
detailed calculations. There are several ways of defining radiative forcing. The definition adopted here is the
instantaneous change in energy flux at the tropopause resulting from a perturbation of the atmospheric
system in which the stratosphere is allowed to adjust to a thermal steady-state.
Figure 2.2: Illustration of how the surface climate impact depends on the altitude and latitude where the ozone (top), water vapour (middle) or methane (bottom) change takes place. Shading shows relative surface impact, measured as a radiative forcing, from either a fixed mass increase applied at different altitudes (left-hand frames) or a fixed percentage increase applied at different altitudes (right-hand frames). Red shows where increases of the gas lead to maximum surface warming - this is typically in the upper troposphere / lower stratosphere region. Increases are applied to a one km thick layer centred on the y-axis pressure. Figure follows methodology outlined in Forster and Shine (1997). [Figure courtesy of P. Forster]
and greenhouse gases can have large effect on the Earth's radiation balance (Zhang et al., 2004).

2.2.1.1 Water vapour

Water vapour is the dominant greenhouse gas in the atmosphere. In the lower troposphere, its changes are largely driven by thermodynamic constraints. In the Upper Troposphere (UT) our understanding of the processes that control humidity is poor, especially in the tropics, reflecting the sparseness of high-quality measurements (Soden et al., 2004; Trenberth et al., 2007). In addition, the response of UT water vapour to changes in temperature is more complex than in the lower troposphere and not well captured by models (Randall et al., 2007). The temperature response in the UTLS exhibited by climate models is largely determined by uncertain parameterisations of deep-convection and cloud micro-physics. In reality, competing processes control the vertical transport of water vapour and understanding them relies on observations that can accurately capture their spatial and temporal heterogeneity. The vertical transport of water vapour in the UT can occur rapidly in convective updrafts and in large-scale frontal ascent but also more slowly, over large horizontal distances in the tropics (Fueglistaler and Haynes, 2006). It has been suggested that rapid ascent is likely to be the most important process (for example, Dessler and Minschwaner, 2007), but this is still a subject of debate.

The studies mentioned above emphasise that detailed observations of water-vapour transport mechanisms are needed over large areas, covering not only the updrafts within tropical convection, but also the wider areas of subsidence and the response within the tropical tropopause-layer. Due to our incomplete understanding, current uncertainties in the water-vapour radiative feedback term are of the order of 20% (for example, Randel et al., 2007). This uncertainty can lead to factors of two or more uncertainty in current estimates of Earth’s climate sensitivity. To measure these tropospheric water vapour processes in the upper troposphere and tropopause region, PREMIER will provide 3D observations at one km vertical resolution.

Observed long-term positive trends in stratospheric water vapour above 30 km (for example, Oltmans et al. 2000) are larger than those expected due to increases in methane alone and its subsequent oxidation products. There may also have been long-term increases at lower levels. There may be data-quality issues with these trends but, if real, they could have had a large effect on climate change – as large as that from water-vapour feedback in the troposphere (Forster and Shine, 2002). The processes driving these long-term trends are not well understood; in fact, in recent years, mixing ratios of stratospheric water vapour have actually decreased (Randel et al., 2006). Randel et al. (2006) suggest that recent lower-stratospheric water-vapour changes mainly follow the temperatures at the coldest part of tropopause. Water vapour may enter the stratosphere through monsoon-circulations and recent work by Lelieveld et al. (2007) has shown that this could be particularly important for the extra-tropics. These studies suggest a variety of mechanisms at different spatial and temporal scales are contributing to water-vapour transport, which demands that detailed, global measurements of processes are required over a
period of several years in order to understand their relative importance in different meteorological situations. Without this understanding, it is impossible to predict future levels of stratospheric water-vapour and hence future climate change both in the stratosphere and at the surface.

### 2.2.1.2 Ozone

In the troposphere, $\text{O}_3$ is formed by the ‘smog’ reactions involving CO and Volatile Organic Compounds (VOCs), nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) and UV sunlight. Biomass burning (Figure 2.1), anthropogenic and biogenic emissions are the major sources of VOCs in the troposphere while, methane also acts as an important background source of ozone. In the upper troposphere, ozone is lost by its oxidisation of $\text{NO}_x$ into soluble products which are washed out or sedimented, by the HO$_x$ catalytic cycle and by photolysis to produce O(\(^1\text{D})\) which can react with water vapour to form HO$_x$ radicals. In the lower stratosphere, ozone is destroyed by catalytic reaction cycles involving NO$_x$, HO$_x$, ClO$_x$ and BrO$_x$. Most of the radical species, particularly NO$_x$ and ClO$_x$, can form reservoir species such as HNO$_3$, HCl and ClONO$_2$. These are species that act to (temporarily) store reactive nitrogen and chlorine species in less reactive forms: the examples of reservoir species given above, (for example, HNO$_3$) do not react with ozone. Thus knowledge, direct or indirect, of these minor species is important in determining the ozone budget in the lower stratosphere.

Nitrogen oxides therefore play an important role in the net production of ozone in the UT. The UT NO$_x$ budget is determined by convection of boundary layer NO$_x$, local generation by lightning and direct input from commercial aircraft. In the stratosphere, an increase in NO$_x$ generally leads to a decrease in ozone while in the UT it leads to a production of ozone. In the past, the transition zone or critical level appeared to be about 20 km. However, there is now some concern that the issue is more complex, with halogen chemistry and aerosols (see below) playing a role (Søvde et al., 2007). PREMIER data will contribute significantly to the resolution of these issues by providing measurements of relevant species on the mesoscale.

In the upper troposphere, heterogeneous reactions can occur on aerosols acting to transform NO$_x$ to HNO$_3$. In addition, nitrogen oxides (NO$_y$) may be taken up on cirrus clouds and removed by sedimentation. Also, it is thought that soot particles, particularly those from aviation combustion, can act as efficient ice-nuclei for the formation of aviation-induced cirrus clouds (Karcher, 2007, also see Section 2.2.1.4). There is also growing evidence that halogen chemistry plays a role in the ozone budget of the upper troposphere, due to heterogeneous reactions such as BrNO$_3$ hydrolysis or Polar Stratospheric Cloud (PSC)-type reactions on the surface of cirrus clouds that activate halogens (Søvde et al., 2007).

As for water vapour, the spatial distribution of ozone is not uniform (see Figure 2.3) and neither is the associated radiative-forcing. PREMIER has the capability to resolve species on these spatial and temporal scales (see Chapter 4). In addition, ozone has important feedbacks as it is a source of the hydroxyl radical (OH), the
main tropospheric oxidant sink, with implications for the lifetime of reactive atmospheric pollutants and for the GHG methane. An increase in ozone can lead to increases in radiative forcing and also OH (see below). *In situ* chemical production and destruction of ozone also contributes to the magnitude and variability of UTLS ozone. Direct sources of UTLS NO$_x$ from aviation, and in general any perturbation to the local nitrogen oxide budget (for example, convection), affects ozone formation. It is therefore important to simultaneously understand the photochemical and transport processes that determine the generation and spatial distribution of ozone in the UTLS. Although the global net photochemical budget seems reasonably well constrained, important details of the ozone distribution are not generally well understood on a global scale (Denman et al., 2007). PREMIER, by virtue of its high spatial resolution measurements, will address both the chemical and radiative aspects of ozone.

2.2.1.3 Methane

Methane is the third most important greenhouse gas after water vapour and CO$_2$. Its recent trends are poorly understood and individual budget source/sink...
terms are not well quantified (Forster et al., 2007). In spite of its lifetime of about eight years, CH₄ concentration gradients are sufficiently large that they can be used effectively to quantify surface sources (see Section 2.2.2). It has important feedbacks associated with ozone (Section 2.2.1.5) and the radiative impact of its change depends on where the change occurs (Figure 2.2).

As noted above, methane plays a role in determining the ozone abundance in the UTLS. It has biogenic, pyrogenic and anthropogenic sources and its main sink is oxidation by tropospheric OH, leading to a lifetime of approximately eight years. The globally integrated methane trend is well characterised by surface in situ measurements, but the strengths, regional distributions and variability of different sources are uncertain. The methane budget has recently come under scrutiny because of unexpected, and largely unexplained, changes in the growth rate of its atmospheric burden measured by in situ data². Other potentially significant sources are related to climate change, in particular warming of the permafrost at high latitudes and the possible release of clathrates from the deep ocean. These factors challenge our current understanding of the methane budget. Satellite observations of methane offer important constraints to the budget, but uncertainty in the size of individual sources prevents definitive attribution; for example, quantifying the regional importance of wetlands and terrestrial vegetation.

Spatially-resolved (in both the horizontal and vertical) profile information at the resolution provided by PREMIER, in synergy with EPS-MetOp (Chapter 4), will help significantly reduce the uncertainty of estimated source-strengths derived from inversion methods and will improve estimates of the radiation-climate feedbacks and radiative-forcing of methane.

2.2.1.4 Clouds and aerosols

Cirrus clouds play a significant role in determining the Earth’s energy balance. However, observations of their effects on outgoing longwave radiation do not appear to agree with model predictions, especially in the tropics (for example, Clement and Soden, 2005). Their formation and microphysical properties are still poorly measured and understood. For example, recent studies and campaigns have found unexpectedly-high levels of supersaturation (with respect to ice) within clouds (Gao et al., 2004). Understanding the processes that govern anvil formation and microphysics are particularly important, and information is needed on a range of scales (Mace et al., 2006). The role of aerosols in cloud formation is particularly important. The indirect aerosol-effect quantified by the IPCC is very uncertain and explicitly excludes aerosol-induced cirrus cloud changes (Forster et al., 2007). In addition, soot aerosols lofted from anthropogenic and biomass-burning sources and locally-produced aviation sources may play a very important role in determining the properties of UT aerosols (Karcher et al., 2007). In addition, aviation contributes in an important manner to the generation of cirrus via the production and spreading of

² There has been discussion regarding a possible large aerobic source from terrestrial plants. While there is evidence of this source of CH₄, its relative importance appears to be diminishing. (for example, Dueck et al., 2007).
condensation trails, formed from homogeneous nucleation. Recent field campaigns have examined some of these issues (for example, NASA-TC4, http://www.espo.nasa.gov/tc4/). However, satellite observations are required to provide information on global scales. PREMIER will provide the necessary global coverage and high spatial-resolution needed to both quantify these radiative forcings and understand their feedback mechanisms. It will achieve this by making state-of-the-science measurements of many trace gases, clouds and aerosols.

2.2.1.5 Chemical processes and feedback issues

Atmospheric chemistry and climate are intimately related. The direct effects of composition changes have been described above, but there are potentially even more important indirect effects. As already discussed, methane and ozone are coupled via the OH radical, but even this simple coupling appears more complex once we consider additional elements of the whole Earth system, for example, the detrimental effects of ozone on agriculture and forestry, both of which produce emissions of VOCs and other gases. As climate changes, other effects are predicted to become more important. For example, we note that the tropospheric ozone budget is a roughly equal balance between net \textit{in situ} photochemistry, transport from the stratosphere, and deposition on the surface. Chemistry–climate models are predicting future increases in downward STE and associated ozone flux into the troposphere, with far reaching implications for chemistry in the troposphere. The most straightforward feedback, due to stratospheric ozone on the troposphere, is that a reduced (increased) stratospheric ozone layer allows through more (less) UV radiation. This, aside from any human health issues (for example, Solomon, 2008), is the source of the O('D) radical which creates OH radicals acting as ‘cleaning agents’ for many tropospheric Air Quality (AQ) gases. However, OH also reacts with atmospheric methane. Thus, to first-order, a decreased (increased) ozone column in the stratosphere leads to increased (decreased) tropospheric OH and a reduced (increased) burden of methane.

PREMIER will address this issue of feedbacks by providing high spatial- and temporal-resolution data that will lead to improved understanding of chemical and physical processes in the UTLS and beyond. It will be used to test chemistry–climate models and also be useful for operational meteorological satellites and for synergistic use with other long-term missions such as the Sentinel missions.

2.2.2 Atmospheric transport processes important for climate and air quality

Changes in the composition of the UTLS can be driven by atmospheric transport via advective redistribution and via the upward supply of surface emissions by the general circulation. Rapid upward transport of surface or boundary-layer air can occur with the passage of frontal systems or by means of large-scale convective events. In the lower stratosphere, the BD circulation transports air poleward from tropical regions. Composition changes are also driven by the exchange of air between the stratosphere and troposphere within the UTLS (see Figure 2.1). These transport changes are superposed on gas-phase and heterogeneous-chemistry
induced spatial and temporal variations. Measurements of the detailed spatial and temporal structures of atmospheric trace gases therefore reveal important knowledge about atmospheric chemistry and dynamics. With its focus on high spatial and temporal resolution for measuring species and temperature, PREMIER promises to provide important new knowledge on processes important to climate.

2.2.2.1 Transport to the UTLS

Surface emissions, whose signatures are not readily measured by PREMIER, will be lofted to the free and upper troposphere by weather systems, such as frontal systems, which rapidly transport air from the boundary layer into the upper troposphere. These air masses can descend to lower levels, resulting in efficient intercontinental transport of pollution.

Convective systems, either at mid-latitudes or in the tropics, can rapidly transport polluted air and moisture from the boundary layer to the upper troposphere or higher, at the same time removing soluble species, such as HNO$_3$ and H$_2$O$_2$. The less-soluble species, such as acetone and NO$_x$, can help drive photochemistry and generate ozone. Over land, severe convective storms often generate lightning, associated with the formation of large amounts NO, a precursor for the production of ozone. These storms can also occur on a very large scale, as during the monsoon season. For example, large-scale convective events associated with the East-Asian monsoon inject trace gases into the free and upper troposphere, resulting in a significant perturbation of the budget of O$_3$ and other greenhouse gases in that region. PREMIER will bring a unique insight to the interplay between atmospheric transport and chemical evolution of climate-relevant trace gases trapped within this circulation and its implications for surface air-quality downwind.

Nitrogen oxides are an exemplar for how measurements of trace gases can be used to understand atmospheric transport. They are transported and generated in the UT, where they are oxidised to more stable forms such as PeroxyAcetyl Nitrate (PAN), and pernitric and nitric acids. Knowledge of these more stable species provides additional information on convection and heterogeneous chemistry. For example, owing to the relatively high solubility of HNO$_3$ noted above, NO$_x$/HNO$_3$ ratios in the UT region can be used as a ‘clock’ to monitor recent convection (Bertram et al., 2007). Probability distribution functions of NO$_x$/HNO$_3$ ratios can be used as valuable diagnostics for assessing the frequency and intensity of convection in the troposphere. PREMIER will measure such species at higher resolution, providing a greater understanding of the role of convection for chemistry–climate feedbacks.

Combustion of aircraft fuel produces CO$_2$, H$_2$O, NO$_x$, SO$_x$, soot, aerosols and some hydrocarbons. While this source of CO$_2$ is small compared to the background amounts (~ 3% of total anthropogenic inputs), water vapour can be important in the generation of condensation trails. It is thought that soot, even if deactivated, can act as ice nuclei for cirrus cloud-formation, while aviation NO$_x$ can lead to the generation of ozone, so the possibility of aviation–climate effects is of concern.
(Penner et al., 1999; Wuebbles et al., 2006). By quantifying the magnitude and source of NOx in the UTLS, PREMIER will contribute to a better understanding of commercial-aircraft impacts on this region of the atmosphere.

As noted above, transport of species in the lower stratosphere is largely controlled by the BD circulation (Figure 2.1). In the tropical source region in the LS ozone has a chemical lifetime sufficiently long that it is transported from this source region polewards by the BD circulation to higher latitudes, following the downward-sloping isentropes. In the polar regions the downward motion associated with the BD circulation delivers stratospheric air (with mixing ratios characteristic of high ozone and low water-vapour) to the troposphere via various events of stratosphere-to-troposphere transport, for example, in ‘cut-off’ lows.

Overall, the global distribution of trace species in the UTLS (for example, water vapour, ozone, methane, N2O, and CFCs) is governed by the combination of the stratospheric BD circulation, uplift in the troposphere (for example, by convection), and stratospheric–tropospheric exchange processes such as cut-off low pressure systems which can lead to the deep penetration of stratospheric air into the troposphere (for example, see Figure 2.4). In the stratosphere fast quasi-horizontal transport/mixing occurs on isentropic surfaces. Isentropic transport/mixing plays an important role, for example, for the exchange of air between the tropical upper troposphere and the extra-tropical lower stratosphere (see Figure 2.1). This transport/mixing involves structures such as synoptic-scale or mesoscale filaments. PREMIER will provide high-resolution 3D-data sets of atmospheric tracers (for example, CFC-11, SF6) needed to study the role of transport structures (for example, filaments) in Stratosphere–Troposphere–Exchange (STE) (see, for example, Stiller et al., 2008).

2.2.2.2 Transport, surface emissions and air quality in the UTLS

Air pollution is now recognised as a global problem (for example, IPCC, 2007; Keating and Zuber, 2007). Surface emissions from one continent can exit the boundary layer and associated trace gases (for example, CO and VOCs), or photochemical produced pollutants (for example, ozone), with atmospheric lifetimes longer than a week or so, can be transported around the hemisphere and affect surface air-quality on other continents and generally raise ‘background’ values.

Air pollution is not restricted to industrial activity. Burning of biomass material (for example, trees, agricultural waste, vegetation, grasses) at tropical and boreal latitudes represents a large source of atmospheric pollutants such as CO, NOx and VOCs. Emission estimates from industrial sources are relatively well quantified, based on population density and fuel use. Biomass burning is strongly seasonal, related to agricultural practices, but its frequency and spatial and temporal coverage are intrinsically stochastic and, consequently, associated emissions are difficult to estimate reliably. The location of active fires can already be determined using imagers that use short-wave IR to measure surface temperature. This information, combined with models of lofting of fire material and long range transport, can
be used to guide the analysis of PREMIER data to identify regions over which we expect elevated concentrations of air pollution. The trace-gas mixture emitted by open biomass burning varies by orders of magnitude, depending on the fuel being burned and on the stage of the fire, (for example, flaming versus smouldering). PREMIER will measure diagnostic tracers of biomass burning such as HCN, that will be used to identify enhancements in other trace gases.

![Figure 2.4: A slice of a model simulation of the ozone field cut through the front shown in Figure 2.3. Intrusions of stratospheric air with high levels of ozone are clearly shown. The resolution of the features (15×15 km² model resolution) is comparable to that of PREMIER across track. [Figure courtesy of Alex Lupu, 2008)](image)

One of the difficulties of assessing the impacts of biomass burning is estimating the height to which the plume is lofted. This is difficult to address using nadir viewers alone. PREMIER will be able to identify the height to which material is lofted (cf. Figure 2.5) by sampling biomass burning markers such as HCN or CH₃CN. This capability, combined with the ability of the nadir viewers that will be flying concurrently (for example, GOME-2, IASI on MetOp), promises to provide a whole new view of biomass-burning processes.

The unique spatial sampling approach of PREMIER that provides accurate trace gases measurements in the free and upper troposphere (Chapter 4), in concert with meteorological analyses and inversion methods, will improve the attribution of pollution events to specific sources. Source attribution will also be improved by using complementary column species data from the nadir instruments aboard the operational meteorological platforms (for example, aboard MetOp and NPOESS) that are generally more representative of the lower and free troposphere. Synergistic analysis of atmospheric constituent data from the PREMIER and MetOp platforms, with commensurate spatial data in the horizontal domain, would provide additional constraints to the MetOp retrievals of trace gases and would generally
improve the height resolution over the whole troposphere of trace gases common
to both platforms. Modest improvement of vertical species resolution of pure nadir
sounders which are sensitive to different heights (Aura/TES and Aura/OMI) has
already been demonstrated theoretically (Worden et al., 2007): PREMIER will have
much better vertical resolution than previous missions.

Figure 2.5: The upper plot shows a latitude/height slice of HCN produced from fires in South America and
Africa for 16 July 2004 as calculated by the GEM-AQ model. The lower plot shows the GEM-AQ HCN 400-ppt
isosurface for the same day. [Figure courtesy of Alex Lupu, 2008]

2.2.2.3 Transport in a future climate

The importance of better characterising climate processes becomes clear when
it is realised that all the transport processes described above will likely change in
our future climate. Model studies suggest that the BD circulation will strengthen
in the future, in response to planetary and gravity-wave activity (see 2.2.3.1), and this could impact the delivery of stratospheric ozone to the troposphere and the budget of tropospheric ozone (Eyring et al., 2007). Convection is likely to be impacted, modifying transport directly and additionally modifying the rate of lightning generation.

Surface emissions will also change in the future, affecting climate. Scenarios of future anthropogenic emissions suggest substantial increases, all of which will impact the UTLS, either directly or indirectly. In particular, aircraft emissions are expected to increase by about a factor of 2–3 in the next 20–30 years. As surface temperatures, humidity and precipitation changes, biogenic emissions will change. Likewise, in a changing climate, burning of boreal forests is expected to increase. To better forecast these processes it is necessary to measure and quantify these feedbacks. Accurate measurements of trace–gas distributions in the free and upper troposphere are essential to improve quantitative understanding of the transport of pollutants, subsequent tropospheric chemistry, and the resulting radiative perturbations.

2.2.3 Dynamics and climate

Atmospheric dynamics refers to the thermal state and the motions of the atmosphere on a rotating planet in response to space and time dependent heating and cooling, friction, and the excitation and dissipation of waves, for example, of gravity waves resulting from the gravitational restoring force (for example, Shepherd, 2003). Atmospheric dynamics comprises atmospheric flows, from the global scale to scales of turbulence in the boundary layer or in clouds. Dynamics organises the forcing by molecular or microphysical processes in larger scales, for example, streamers or stratiform clouds, but is at the same time driven by these processes (for example, ozone photochemistry both heats and creates the stratosphere). The interaction of dynamics and forcing results in the complex observed circulation, consisting of large scale modes of variability such as the North Atlantic Oscillation (NAO), or the Quasi-Biennial Oscillation (QBO), or synoptic-scale circulation in fronts in mid-latitudes, or mesoscale convective circulations in the tropics.

Modelling atmospheric dynamics necessarily needs to separate resolved and unresolved dynamics, through closure assumptions and parameterisation of the effects of the unresolved dynamics, especially those associated with gravity waves. Also, processes acting as a forcing need to be parameterised since they are not resolved explicitly. Typical resolutions of current, global, numerical weather-forecast models and climate models are 20 km and 200 km respectively.

Detailed measurements of the spatial (3D) and temporal variations in the atmospheric dynamic variables and in tracers provides the basis for the quantification of the variability of these quantities and of the processes constituting the ‘forcing’ of the dynamics. Improved understanding of the forcing from different processes allows better parameterisation of the forcing functions in atmospheric circulation models.
2.2.3.1 Mesoscale dynamics

Mesoscale gravity waves play a crucial role in forcing the QBO of equatorial zonal winds in the stratosphere (Dunkerton, 1997), which strongly influences transport and mixing of radiatively-active chemical species between the tropics and mid-latitudes in the UTLS. Gravity waves also significantly contribute to the driving of the BD circulation. Moreover, a recent model study (McLandress and Shepherd, 2008) suggests that parameterised orographic gravity-waves and resolved waves are about equally important for trends in the BD circulation.

Our understanding of the impact of mesoscale gravity waves on large-scale dynamics is rather limited. This is mainly a result of a lack of global observations of gravity-wave momentum flux and our poor knowledge on the global distribution of gravity-wave sources. Current versions of weather forecast models, GCMs, and chemistry–climate models do not have resolutions adequate to resolve all gravity waves. As a result, the impact of gravity waves in these models has to be parameterised. The inadequate parameterisation of gravity-wave effects currently used in these models is one of the important sources of uncertainty. In their review, Fritts and Alexander (2003) note that gravity wave parameterisations in models have a number of tuneable parameters which are adjusted in a way that the simulations can match the observed large-scale wind and temperature fields for specific geophysical situations. This engineering type of approach is not satisfactory and certainly inadequate for the treatment of feedback processes that may occur with climate change. Key issues for improved gravity-wave representation in global models are the quantification of dominant wave sources and the associated direction-resolved momentum fluxes (Fritts and Alexander, 2003).

The great potential of gravity-wave observations from space has been demonstrated in several studies (for example, Eckermann and Preusse (1999); Preusse et al. (2002)). However, the spatial resolution of previous global observations was insufficient for the determination of direction-resolved momentum flux (Ern et al., 2004). The combination of high-resolution 3D temperature measurements and good altitude coverage offered by PREMIER will allow for simultaneous determination of gravity-wave temperature amplitudes and the associated horizontal and vertical wavelength (wave-vector), as illustrated in Figure 2.6. From these quantities, global distributions of direction-resolved momentum-flux can be derived for the first time (see also Sections 2.3.3 and 4.3.9). By this approach, the development of parameterisations of sources and gravity-wave effects in atmosphere models will be facilitated. In addition, high-resolution PREMIER data will be ideally suited to validating and improving the ability of global weather forecast models, such as the ECMWF model, which resolve at least part of the atmospheric gravity-wave spectrum (see Section 4.3.9).

2.2.3.2 Downward coupling on weather patterns

An important part of the large-scale variability of the extra-tropical tropospheric climate can be related to annular modes or the north-south redistribution of mass
in the atmosphere; their related indices are useful tools for climate analysis. For example, the weather in Europe is strongly impacted by low-pressure systems in the North Atlantic. One means of characterising this influence is via a metric or index called the North Atlantic Oscillation (NAO) (related to the Northern Annular Mode (NAM)), which measures the difference in air pressure between the low-pressure areas south of Iceland and Greenland and the high-pressure zones near the Azores. During the past few decades, the NAO index has indicated a stronger subtropical high and a deeper Icelandic low than in the past. The increased pressure difference corresponds to warm and wet winters in Europe as a result of stronger winter storms crossing the Atlantic Ocean on a more northerly track. Interestingly, the (positive) trend of the NAO index coincided with a tendency of the Arctic stratospheric polar-vortex in the 1990s to become stronger, i.e. less disturbed by planetary waves. In addition, fluctuations in the strength of the stratospheric polar vortices are observed to couple downward to surface climate (Baldwin and Dunkerton, 1999, Thompson et al., 2002) (see Figure 2.7). Baldwin and Dunkerton (2001) showed that, on average, anomalous vortex conditions tend to descend through the lower stratosphere and are followed by corresponding NAO anomalies at the surface for about two months. Such results point to the possibility of forecasting aspects of the weather several weeks into the future. As the climate changes, it is expected that the downward coupling would be modified by changes in both the tropospheric-wave forcing of the stratosphere and changes to the stratosphere itself. Although the described coupling process is robust in the observations, the mechanisms of coupling are not well understood. Global
observations with high vertical and horizontal resolution (and sufficient altitude coverage), as provided by the PREMIER mission, will enable the mechanism to be investigated, and their assimilation could potentially improve medium-range weather forecasts, for example for Europe.

2.2.3.3 Numerical Weather Prediction (NWP)

PREMIER will make important contributions to NWP in two important areas, directly by improving the initial meteorological conditions in the upper troposphere/stratosphere region, and indirectly by refining the parameterisations of atmospheric processes in forecast models.

PREMIER will improve NWP analyses of temperature, humidity, ozone, and potentially other species in the UTLS region. This is a region in which current NWP analyses show considerable systematic errors and in which observations of temperature, humidity, and ozone at the combined horizontal and vertical resolution provided by PREMIER are lacking. Previous assimilation studies with
MIPAS or MLS temperature, humidity, and ozone data have highlighted how limb data is able to correct for such errors in the analyses (for example, Bormann and Thépaut 2007). PREMIER data are expected to improve on these results by providing even better vertical and horizontal resolution. In the post-2015 timeframe, PREMIER will be the only mission to provide height-resolved O₃ and H₂O at tropopause level and above, which could be used by NWP to improve stratospheric analyses. By providing information on atmospheric tracers (for example, O₃ and CH₄), PREMIER is also giving information on stratospheric motions, with the potential to improve the analysis of stratospheric winds (for example, Riishøjgaard 1996; de Grandpre et al., 2007).

Improved analyses of the UTLS are beneficial for NWP in several respects. For example, improved analyses of the temperature structure in the tropopause region can be crucial for forecasting the intensification of mid-latitude weather systems. In addition, improved stratospheric analyses offer some potential for improved extended-range tropospheric weather forecasts (beyond 1–2 weeks, for example, Baldwin et al. 2003, Thompson et al. 2002, Charlton et al. 2004; see also Section 2.2.3.2). There are also benefits for the assimilation of tropospheric data. For instance, improved analyses for the lower stratosphere can be beneficial for the assimilation of radiance information for tropospheric channels from nadir sounders whose signal has a non-negligible contribution from the stratosphere. In these cases, uncorrected errors in the stratosphere can yield spurious information on the troposphere, with detrimental impact on forecasting skill. Currently, such channels often cannot be used in the analyses.

Apart from the lack of high-resolution observations, another reason for larger systematic errors in NWP analyses of the stratosphere are shortcomings in the model processes acting in this region, for instance radiation processes, chemistry or gravity-wave parameterisations. By design, PREMIER data will add to the characterisation of these systematic errors and simultaneously help their reduction by improving the representation of model processes or important input parameters. For instance, a better representation of the ozone field allows an improved modelling of radiation processes in this region.

2.3 PREMIER in relation to past, present and planned activities

2.3.1 Heritage from earlier limb-emission sounders in space

PREMIER, with its focus on the UTLS, has provenance from the series of infrared limb emission-sounders launched over the last three decades³ and millimetre-wave limb emission-sounders launched over the last two decades⁴. These instruments⁵ were

⁵ Instruments to measure limb-scattered solar radiation have provided additional information on the stratosphere, mesosphere and lower thermosphere: SME (1981), OSIRIS (Odin, 2001), SOLSE/LORE (Space shuttle, 1997,2003), SCIAMACHY (Envisat, 2002), MAESTRO (SCISAT, 2003); future OMPS (NPOESS). Limb opacity is too great at UV and visible wavelengths to see below the tropopause. At near-IR and shortwave-IR
all designed to focus on the stratosphere, mesosphere and/or lower thermosphere, and have led to major advances in our understanding of the dynamics and chemistry of those regions, particularly when combined in recent years with increasingly sophisticated atmospheric 3D general-circulation and chemistry–transport models. For example, they have led to better characterisation of various aspects of the global circulation (such as the BD circulation, the tropical pump, downward control and the role of gravity waves), polar ozone depletion, and the impacts of volcanoes and solar and geomagnetic disturbances.

Although these satellite limb-emission sounders have been designed for the stratosphere, Envisat MIPAS and Aura MLS, for example, have also offered glimpses into the upper troposphere, and their sampling has been sufficient to develop a global climatological perspective on the composition of the upper troposphere and lowest stratosphere, from which the PREMIER strategic goals have emerged. Advanced instrumentation will allow PREMIER to resolve, for the first time, processes of major importance in the UTLS height range, for which the limited spatial and temporal resolution of current instruments are insufficient.

2.3.2 3D fine resolution for processes controlling trace gas distributions

Limb-emission sounders traditionally have much better vertical resolution than nadir-sounders, but comparatively low horizontal resolution; generally of order 400–500 km along-track and inter-orbit spacing across track (approximately 1400 km at the equator). However, by exploiting array detectors at IR- and mm-wavelengths, PREMIER will increase sampling density by several orders of magnitude; thereby increasing vertical and horizontal resolution dramatically. Vertical resolution will be 1–2 km (an increase by a factor of two in some cases), along track resolution will be 50 km (an increase by a factor of about six). Across-track coverage within a 300 km swath will allow 3D-structure to be observed for the first time and significantly increase the probability of viewing between clouds. This density of sampling will reveal, for the first time from space, structures in the distributions of trace gases associated with a variety of transport processes, and will also enable a suite of trace gases to be detected in plumes from boreal forest-fires, tropical biomass-burning and industrial pollution sources which have so far been detected serendipitously by the IR solar occultation sensor ACE on SCISAT-1 (with 15 profiles per day at two latitudes, compared to more than 45 000 profiles per day distributed globally for PREMIER), and which are undetectable in nadir-geometry.

wavelengths, solar radiation scattered into the limb direction will first have propagated into the lower atmosphere and been (multiply) scattered by clouds, aerosol and Earth’s surface. These complexities in radiative transfer modelling, in practice, limit trace-gas retrieval from limb-scattered radiation to the stratosphere also at these longer wavelengths.

6 These include hydrogen cyanide (HCN) and methyl cyanide (CH₃CN), which are specific indicators of biomass burning, in addition to other organic compounds including carbon monoxide (CO), methanol, (CH₃OH), formaldehyde (H₂CO), ethane (C₂H₆), peroxyacetyl nitrate (PAN) and isoprene, which have sources in addition to biomass and forest burning.

7 This figure refers to the chemistry mode of the infrared limb-sounder. In the dynamics mode, 180 000 profiles per day would be acquired and the mm-wave limb-sounder would acquire ~11 200 profiles per day.
2.3.3 **3D fine resolution for gravity waves and other dynamical studies**

PREMIER will provide the flexibility to change from a high spectral-resolution (chemistry) mode to a lower spectral- but higher spatial-resolution (dynamics) mode, in order to investigate mesoscale structures in atmospheric temperature and a limited number of trace gases. By measuring temperature structures in 3D at much higher spatial resolution than preceding limb emission-sounders, PREMIER will specifically improve estimates of the (vertical) flux of (horizontal) momentum transported by gravity waves. PREMIER will observe on a regular 3D grid along the orbital track, thereby also providing the relevant across-track information. Using this approach, both horizontal and vertical wavelengths of gravity waves can be determined and thus the direction as well as the magnitude of momentum flux can be derived. This offers a major advance. In particular, the observations will access a major part of the momentum-flux spectrum needed to constrain gravity-wave parameterisation schemes in global circulation models. This is a distinct and different contribution to what is attainable from the increasing number of GPS receivers (including the impressive COSMIC constellation), which deliver accurate temperature observations with comparable vertical resolution but offer no horizontal wavelength, and therefore no directional momentum-flux information. This is a result of their highly-irregular geographical distribution of sampled profiles.

2.3.4 **PREMIER – in combination with EPS-MetOp nadir-sounders**

Nadir-viewing satellite instruments operating in the thermal infrared have been used for more than three decades for temperature and humidity sounding in support of NWP, and those operating in the ultraviolet have been used for a similar period to monitor stratospheric and total-column ozone. The first nadir-viewing infrared instrument to be used for trace-gas sounding was MAPS, which measured tropospheric CO from the space shuttle in 1994 and opened a new window on the measurement of air pollution from space. In the last 10–15 years, nadir-viewing instruments have yielded new insights into the geographical distributions and sources of tropospheric trace gases and aerosols. The ‘surface’ footprint of the nadir-viewing spectrometers on MetOp is 80 km × 40 km (GOME-2) and 12 km diameter (IASI). The horizontal sampling of PREMIER will therefore be commensurate, allowing full advantage to be taken of combining colocated limb and nadir observations within the PREMIER swath.

High quality observations from PREMIER of the mid/upper troposphere and lower stratosphere will mitigate the major deficiency of nadir-sounders, that is their...
absence of height-resolution, and will enable lower-tropospheric information to be retrieved from the nadir-sounders that would otherwise not be available. This will allow links to lower-tropospheric pollution and anthropogenic, biogenic and pyrogenic emissions to be quantified more accurately by PREMIER/MetOp than would otherwise be possible.

2.3.5 PREMIER – in the context of planned future operational monitoring activities

Concerted efforts are currently underway under the GEMS (Global Environmental Monitoring using Satellite and in situ data) integrated project to develop the first-ever system for operational monitoring and forecasting of atmospheric composition and dynamics on global and regional scales. The basis for the GEMS system will be advanced assimilation of satellite and in situ data into numerical models.

In the 2015 timeframe, the prototype GEMS system is expected to evolve through the Monitoring of Atmospheric Composition and Climate (MACC) project and be integrated within a GMES Atmosphere Service to coordinate environmental monitoring capabilities. Within the GMES Atmosphere Service, the GEMS system will provide pre-operational real-time global analyses of long-lived greenhouse gases (i.e., carbon dioxide and methane), water vapour, ozone, other reactive gases (for example, NOx, CO, SO2 and HCHO) and aerosols in the troposphere and stratosphere. Multi-model, air-quality forecasts will be produced over Europe. Forward and inverse modelling will be used to estimate sources and sinks for the greenhouse gases.

Despite being a prototype operational system, the GEMS system is designed to assimilate data from research satellites, such as Envisat, the EOS series, or PREMIER, as well as data from operational satellites, such as MetOp or NPP/NPOESS. In the 2013–2020 timeframe, space observations will be limited to partial or total column information from passive nadir-sounding instruments on-board MetOp and NPOESS/NPP. PREMIER, however, will provide observations of many key species in the GEMS system, giving coverage in the mid/upper troposphere and stratosphere with unprecedented vertical and horizontal resolution. PREMIER will facilitate the process studies in this region necessary for improved air quality and climate prediction that will not be facilitated by MetOp or NPOESS. The GEMS system will provide an integrated framework for the overall study and refinement of all processes captured by PREMIER, with direct benefits to operational applications. Through synergy with nadir instruments such as IASI and GOME-2 on MetOp or CrIS and OMPS on NPOESS, PREMIER is also expected to improve our capability to derive information on lower tropospheric distributions of trace gases measured by these nadir instruments. The GEMS system is very well suited to fully explore the PREMIER/MetOp/NPOESS synergy.

The GMES Atmosphere Service will evolve to incorporate future observations by the GMES Sentinel missions and by sensors on Eumetsat’s MTG and post-EPS satellites. The GMES Sentinel programme will include Sentinel-3, to deliver aerosol
information from a dual-view visible/IR imager (SLSTR) of quality comparable to that from ATSR-2 and AATSR. It will also include the Sentinel-5 precursor, an advanced UV/visible/NIR/SWIR (UVNS) spectrometer with a comparatively small ground pixel-size, scheduled for launch in 2013 into an afternoon polar orbit to augment GOME-2 on MetOp (9:30 am) and OMPS on NPOESS (1:30 pm), and fly concurrently with PREMIER. This will be followed by the Sentinel-5 UVNS itself on the post-EPS platform, alongside an advanced version of IASI (IRS) and a visible/IR imager (VII). An advanced visible/IR imager (FDHSI) is planned for launch on Eumetsat’s MTG-I geostationary platform in 2017, and the first FTIR in geostationary orbit will be launched on Eumetsat’s MTG-S platform, around 2019. A UV/visible/NIR (UVN) spectrometer is also currently baselined for MTG-S.

The future operational satellite observing system as currently planned therefore includes no limb-emission sounders. PREMIER would therefore also serve a further function as a pre-operational demonstrator of this potential future element of the GMES space component, as this evolves to more comprehensively meet the needs of the GMES Atmosphere Service.

2.4 Conclusions

The region between roughly 5 km and 25 km, or the mid/upper troposphere and lower stratosphere, is very important for climate science because it is the region where the atmosphere cools to space and is most sensitive to changes in the distributions of radiative gases and clouds. Thus, there are important interactions between composition and climate, via water vapour, ozone, methane, clouds and aerosols, which relate to transport processes in this region and into/out of this region. Transport processes from mesoscale (for example, weather systems) to planetary scales (for example, BD circulation) control the distributions of these constituents. Surface pollutants are lofted into the height domain directly measurable by PREMIER. Trace gas and temperature measurements with global coverage on much finer spatial scales than have been possible before will be exploited to better study the dynamics of this region. In addition, PREMIER will be able to exploit the synergy between limb and nadir measurements to better resolve lower-troposphere distributions of trace gases and to better quantify emissions from anthropogenic, biogenic and pyrogenic sources.

The contributions to our understanding of atmospheric science from satellite, aircraft and ground-based observations, as well as from theory and modelling, have been considerable. In particular, it has become clear that in order to understand processes that control atmospheric composition, the atmosphere has to be observed at finer vertical and horizontal scales and in a variety of dynamic situations. As an example, Figure 2.6 shows the (spatio-temporal) sampling of

10 OMPS will measure solar radiation scattered into the limb direction as well as the nadir direction, from which aerosol, ozone, and possibly also nitrogen dioxide will be profiled in the stratosphere. Stratospheric aerosol from OMPS would complement PREMIER. However, the (daytime only) information on stratospheric ozone and NO from OMPS will not extend below the tropopause and neither will OMPS measure water vapour or any other trace gases to be observed by PREMIER.
temperature structures in the atmosphere generated by a hurricane, as sensed by the MIPAS instrument, compared with the superb detail obtainable with PREMIER instruments. This increased detail is expected to lead to increased knowledge.

The aim of the PREMIER mission is to quantify processes controlling global atmospheric composition in the mid/upper troposphere and lower stratosphere (5–25 km height range). To achieve this, PREMIER will use new and innovative instruments with proven scientific heritage to make global 3D measurements of composition and temperature in the UTLS with unprecedented resolution. By doing so, PREMIER will provide new perspectives on stratosphere–troposphere exchange, water vapour feedback, cirrus clouds, pollutant uplift by the Indian monsoon circulation and plumes from industrial pollution, biomass burning, and boreal forest fires. This will help quantify important climate impacts. In addition to the primary aim, PREMIER will exploit synergy with nadir-viewing instruments on EPS-MetOp and NPOESS to provide a closed budget for pollutants within the lower troposphere. This synergy explores the role of the UTLS on surface air-quality and conversely, the role of surface-pollutant emissions on the chemical composition of the UTLS.

With regard to the challenges that arise out of the IPCC 2007 report and those articulated in ESA's 'The Changing Earth' report, PREMIER focuses on addressing the climate-change issue via a detailed study of climate-related processes in the UTLS region. A secondary goal will be to combine the capabilities of MetOp with the detailed 3D capability of PREMIER in the upper troposphere to address the long range/hemispheric transport of air pollution.
Chapter 3 Research Objectives

The aim of the PREMIER mission is to quantify the processes controlling global atmospheric composition in the mid/upper troposphere and lower stratosphere (5–25 km height range), a region of particular importance for climate change. Furthermore, by exploiting synergies with instruments on the operational meteorological satellite EPS-MetOp, PREMIER aims to quantify links with surface emissions and pollution.

The Intergovernmental Panel on Climate Change report (IPCC, 2007) stated that detailed observations of climate and biogeochemical quantities were essential to understand and model the climate system. Observations in the 5–25 km region, i.e., the mid/upper troposphere and lower stratosphere are particularly important for climate change because this region of the atmosphere governs emission of infrared radiation to space (Figure 2.2). Climate is therefore sensitive to changes in greenhouse gas abundances and cirrus clouds principally in this height range.

PREMIER will achieve its aim by resolving 3D structures of chemical species, thin clouds and temperature in this atmospheric region on finer scales than has previously been possible from space, allowing the following specific objectives to be addressed:

a. To quantify relationships between atmospheric composition and climate. Processes controlling the detailed distributions of climate gases, water vapour, ozone, methane and cirrus (notably including ultra-thin tropical tropopause cirrus) will be quantified in the height range of particular importance to climate.

b. To quantify atmospheric transport processes important to climate and air quality. Processes linking the tropical troposphere and lower stratosphere will be characterised, including convective transport of trace gases in the tropical tropopause-layer. Plumes of biogenic, pyrogenic and anthropogenic origin will be observed in 3D and characterised globally.

c. To quantify relationships between atmospheric dynamics and climate. Mesoscale dynamics in this height-range will be examined by resolving (3D) temperature structure down to fine scales, including propagating gravity waves and their influence on stratospheric circulation. In combination with weather forecast and climate models, the downward influence of the stratosphere on the lower atmospheric circulation and weather will be better quantified.

Case study examples of how PREMIER will meet its objectives are given below.

Tropical convection

Water vapour is the strongest greenhouse gas. Changes in its distribution in the mid-upper troposphere are a particularly important climate feedback. Further, changes in stratospheric water vapour were highlighted by the IPCC as an
important uncertainty in predicting climate change. Tropical deep convection, especially in the west pacific (for example, Hector) transports water vapour up to and even across the tropopause. Methane coming from the troposphere also generates water vapour in the stratosphere. By making measurements of water vapour, tropical tropopause cirrus, methane and other trace gases, PREMIER will quantify the processes controlling stratospheric water vapour.

**Stratospheric/tropospheric exchange**

The global distribution of trace species in the UTLS such as water vapour, CFCs, and ozone is determined by the stratospheric BD circulation, uplift in the troposphere (for example, by convection), and rapid quasi-horizontal transport/mixing processes on isentropic surfaces in the UTLS. For example, stratospheric–tropospheric exchange delivers as much ozone to the troposphere as net photochemical production. Isentropic transport/mixing also plays an important role for the exchange of air between the tropical upper troposphere and the extra-tropical lower stratosphere (see Figure 2.1). This transport/mixing involves structures such as synoptic-scale or mesoscale filaments. PREMIER will provide high-resolution 3D-data sets of atmospheric tracers such as CFC-11 and SF$_6$ needed to study the role of transport structures in stratosphere–troposphere exchange.

**Indian monsoon**

Large-scale convective processes, such as the Indian monsoon, inject trace gases into the free and upper troposphere, resulting in significant perturbations of the global distributions of water vapour, ozone and methane in the upper troposphere and lower stratosphere. Thus, accurate measurements of trace gas distributions in the free and upper troposphere are essential to improve quantitative understanding of the transport of pollutants, subsequent tropospheric chemistry, and the resulting radiative perturbations.

**Forest fires/pyroconvection**

Forest fires inject gaseous and particulate material such as organic and black carbon into the troposphere: in exceptional circumstances, when the background air is already unstable, the emissions can be injected into the lower stratosphere (pyroconvection). Trace-gas plumes from biomass burning events and forest fires will be detected, and their impacts on the composition and chemistry of the upper troposphere and lower stratosphere observed directly. PREMIER observations combined with weather forecast dynamical data, will also provide constraints on vertical emission profiles and emission factors. A species of particular interest is HCN, as it is almost exclusively emitted by forest fires, making it a very good diagnostic.
**Gravity waves/mesoscale dynamics**

PREMIER will take a 2D image roughly every 50 km along the satellite track and thus will provide unprecedented global detail of atmospheric temperature and some species. With this 3D sampling of the atmospheric temperature field, it will be possible to study the interaction between large-scale dynamics (circulation, planetary-scale waves) and mesoscale dynamics (gravity waves). In particular, the novel information on gravity waves will help to characterise much of the gravity wave spectrum that is important to understanding dynamics in the stratosphere and UTLS, and possibly locate associated wave sources.

**Links to lower tropospheric pollution and surface emissions**

Industrial pollution is transported on intercontinental scales in the mid/upper troposphere. These plumes will be observed directly by PREMIER, including trace gases such as ethane and PAN which are detectable only with limb-geometry. The coupling of surface emissions, air pollution and climate through atmospheric global composition will also be addressed by combining with spatially and temporally colocated EPS-MetOp measurements which extend to the surface. This combination will allow lower-tropospheric distributions to be resolved and improved estimates of surface sources of methane and carbon monoxide from anthropogenic and natural sources to be made.

**Summary**

As stated by the IPCC, the ability to model future climate represents a challenge for this century. To achieve this, it will be important to understand chemical and physical processes so they can be adequately represented in models. The PREMIER mission will address this objective by making measurements of unprecedented spatial resolution (in three dimensions, globally) for trace gases and temperature. PREMIER will therefore bring into sharp focus processes in the mid/upper troposphere and lower stratosphere, a region of complexity and particular importance for climate. The mission will also address coupling between atmospheric composition, climate and pollution through combination with EPS-MetOp.
Chapter 4 Observational Requirements

4.1 Requirements for satellite data products

4.1.1 Geophysical data requirements

PREMIER aims to quantify processes controlling atmospheric composition in the height range of particular importance to climate. The specific science objectives (see Chapter 3) are interconnected geographically and global in reach, so coverage from equatorial to polar latitudes is mandatory. Global distributions are required to be observed at least once per day for a sufficient duration (~4 years) to sample the El Niño Southern Oscillation as well as the Quasi-Biennial Oscillation. To achieve its aim, PREMIER has to resolve structure in temperature and constituent fields in the highly-variable region of the mid/upper troposphere and lower stratosphere with unprecedented resolution. In addition, the observations must provide sufficient altitude coverage to account for coupling to the mid/upper stratosphere and to the lower troposphere.

Specific innovative sampling requirements for PREMIER include:

- Sampling of temperature and trace gases:
  - Temperature, H$_2$O, O$_3$, CH$_4$ & tracers: 0.5 km (vertical) × 25 km (across-track) × 50 km (along-track),
  - CO, C$_2$H$_6$, PAN, HNO$_3$ & additional nitrogen and organic compounds: 2 km (vertical) × 80 km (across track) × 100 km (along track).

- Sampling of cirrus:
  - Particle size, volume density & ice water-content, in addition to extinction, sampling at 0.5 km (vertical) × 4 km (across-track) × 25 km (along-track).

A summary of the geophysical product requirements is given in Table 4.1.

For atmospheric dynamics, it is relevant to specify precision rather than accuracy, because it is the variation within a field which has to be observed. The parameters listed in Table 4.1 have highest priority. Observations of additional constituents are required at particular locations and times:

- CH$_3$CN, HCN, CH$_3$OH & H$_2$CO in plumes from biomass-burning;
- HDO, CFC-12, HCFC-22 & N$_2$O as additional tracers in the upper troposphere and lower stratosphere;
- SF$_6$ throughout the stratosphere as indicator of age-of-air;
- active nitrogen and halogen gases including NH$_3$ and, in the lower stratosphere, NO$_2$, N$_2$O$_5$, HO$_2$NO$_2$, NH$_3$, ClONO$_2$, CH$_3$Cl, CIO, CH$_3$Br, BrO and BrONO$_2$ and
- ice water-content, aerosol and PSC extinction, PSC radius and PSC composition. As for cirrus, sampling of aerosol and PSCs is required to be 0.5 km (vertical) × 4 km (across track) × 25 km along track.
The PREMIER mission objectives require in addition that links to the lower troposphere be observed. This requirement will be fulfilled by flying PREMIER in tandem with EPS-MetOp such that limb observations from PREMIER will be co-located with nadir observations from MetOp (Section 6.3). This configuration will allow synergies between the two data sets to be optimally exploited (Section 4.3 and 5.5.1). The FTIR instrument IASI onboard MetOp profiles H₂O at high vertical resolution in the lower/mid-troposphere and will also discriminate one or more coarse tropospheric layers for O₃, CH₄, CO and HNO₃, whose absorption is relatively strong (Section 4.3). The GOME-2 UV/visible spectrometer profiles O₃ at modest vertical resolution through the stratosphere and troposphere and will also add total-column information on several other trace gases such as NO₂ and H₂CO, from which lower tropospheric distributions can be derived. To achieve this additional mission objective, the corresponding Level 1b and Level 2 data is therefore required from EPS-MetOp.

### 4.1.3 Timeliness of data

The timeliness requirement for PREMIER Level 1b and Level 2 data stems primarily from the assimilation of data into operational systems. The data for high-priority products needs to meet the cut-off times typical for these systems. Based on typical cut-off times expected to be used in 2016 by operational centres, the target for timeliness of PREMIER data is three hours, with a threshold of five hours. Even faster data delivery would increase the data available for some operational systems with even shorter cut-off times, but is not considered important enough to drive costs.

![Table](#)
Research users will also benefit from near-real-time data delivery, for instance for use of the data during field campaigns or to respond quickly in case of significant events such as volcanic eruptions or substantial forest fires. The timeliness requirements for such applications are equivalent to those for operational applications.

4.2 Timing of the mission

PREMIER will be launched more than one decade after Odin (2001), Envisat (2002) and Aura (2004). Overlap with these earlier missions is therefore unlikely, and their data will by then have been extensively exploited. Meanwhile, the increased resolution and sophistication of atmospheric global models and insights from airborne campaigns planned in the intervening period will further stimulate and consolidate the case for global data with the resolution of PREMIER. A mission commencing in 2016 would also exploit developments to assimilate chemically-active species into general-circulation models.

With the successful launch of the first EPS-MetOp satellite in 2006, MetOp data analysis will have reached a mature stage by 2016. Combining with data from PREMIER will therefore offer a new dimension and timely advance in exploitation of MetOp data for trace-gas emissions, pollution and air-quality applications worldwide.

Launch in 2016 will allow pre-operational demonstration ahead of a possible limb-sounding component in the post-EPS system (2020–30 and beyond), and bridge the gap in height-resolved monitoring from Odin/Envisat/Aura limb-sounders.

4.3 Performance assessment: capabilities to fulfil mission objectives

4.3.1 Introduction and approach

PREMIER’s primary aim, to observe processes which control atmospheric composition in the region of particular importance to climate, and its secondary aim, to observe processes linking this region with the lower troposphere, will be realised by fulfilling the specific objectives identified in Chapter 3, for which observational requirements have been specified in Sections 4.1 and 4.2 and Table 4.1. To meet these rather stringent requirements in the mid/upper troposphere and lower stratosphere will demand substantial advances (Sect 4.3.2) over the observing capabilities of current limb-emission sounders and also those of EPS-MetOp and future nadir sounders planned to fly concurrently with PREMIER. The capability to fulfil specific objectives has been assessed through simulations (Sect 4.3.3-4.3.9), based on state-of-the-art global atmospheric models, radiative transfer and retrieval schemes, for PREMIER’s Infra-Red Limb-Sounder (IRLS) and Millimetre-Wave Limb-Sounder (MWLS) specifications and instrument concepts outlined in Sections 5.2/5.3 and 6.4.2/6.4.3, respectively. Furthermore, the value which PREMIER could add to EPS-MetOp in assimilation systems such as that under development for the GMES Atmosphere Service has been quantified (Section 4.3.10).
4.3.2 Advances on current limb-sounders and nadir-sounders

In order to achieve a major scientific advance, PREMIER will sample the atmosphere much more densely than the limb-emission sounders which are currently flying in space. The daily number of limb-views of the atmosphere between 6 km (400 hPa) and 24 km (30 hPa) is of order 20 000 for Envisat MIPAS\(^1\) in its new operating mode. For PREMIER this number will be of order 5 000 000 for IRLS (dynamics mode), 200 000 for IRLS (chemistry mode) and 64 000 000 for the Infra-Red Cloud Imaging (IRCI). These increases by several orders of magnitude in sampling density for IRLS/IRCI will enable: (i) the across-track dimension to be added; (ii) finer spacing along-track and (iii) finer vertical spacing of limb-views. In combination with narrower fields of view, this finer vertical spacing is designed to increase vertical resolution substantially with respect to MIPAS. While the total number of limb-views per day between 6 and 24 km for MWLS will be comparable to Aura MLS (~160 000), along-track spacing will be reduced from ~180 km to 50 km and vertical resolution increased substantially, through a more efficient observing sequence to be facilitated by a narrower antenna beam-width and advances in mm-wave technology (Section 6.4.2).

Vertical resolution is also a function of atmospheric radiative-transfer, spectral resolution and radiometric sensitivity. The extent to which improvements to vertical resolution will be realised in practice is evident from Figure 4.1 which displays precision and vertical resolution as functions of height, as estimated through (1D) retrieval simulations on a consistent basis for PREMIER IRLS (dynamics mode) and MWLS, Envisat MIPAS, Aura MLS and MetOp IASI and GOME-2. The IRLS and MWLS simulations adopt Noise-Equivalent Spectral Radiance (NESR) and other requirements specified in Sections 5.2 and 5.3. For IRLS and Envisat MIPAS, microwindows totalling 15 cm\(^{-1}\) of the available spectral coverage are used in joint retrievals of all trace gases with temperature, whereas for MWLS, MLS and IASI, contiguous coverage over their full spectral ranges is used in joint retrievals of all trace gases. The NESR values adopted for MIPAS, MLS and IASI are as reported, respectively, by Fischer et al., (2008), Waters et al., (2006) and Turquety et al., (2004), with due account taken for the respective limb-scan sequences of MIPAS and MLS and for the shorter integration time applicable for the 50 km along-track spacing required by PREMIER.

Figure 4.1 shows that H\(_2\)O, O\(_3\), CH\(_4\) and CO profiles retrieved from PREMIER will have two key attributes:

- Precision requirements (Table 4.1) will be met in the required height range at the required vertical resolution (2 km or 1 km), which is substantially higher than can be achieved by the current limb-emission sounders\(^2\).

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1 In its nominal mode of operation, the figure is 16 000, and in a UTLS special mode it reaches 23 000. In the nominal mode used by MIPAS during the first two years after launch, it was 7000.

2 It should be noted that trace-gas data products from Envisat MIPAS and Aura MLS are routinely generated on vertical grids matched to their own vertical resolution, ie 3 km, rather than 2 km as adopted in these simulations. Because the relationship between retrieval precision and vertical resolution is non-linear,
Vertical resolution in the limb-sounding height-range will exceed that of the MetOp nadir-sounders. For O₃, CO and CH₄ this applies over the full limb range and for H₂O above ~10 km, where IASI’s resolution degrades rapidly with height.

The NESR requirements specified in Section 5.2/5.3 and instrument concepts in Sections 6.4.2/6.4.3 are therefore consistent with the retrieval precision and vertical resolution requirements specified in Table 4.1. It should be noted that simulations for all sensors presented in Figure 4.1 consider NESR only and not other random or systematic errors. Three principal sources of additional random error for trace-gas retrieval precision at 3 km spacing is considerably higher than at 2 km spacing, and meets the requirements of the current missions.
retrievals from current limb-emission sounders will be substantially reduced for PREMIER IRLS and MWLS:

- Errors in knowledge of limb-view vertical spacing will be eliminated through use of fixed arrays rather than vertical scanning (Sections 5.2/5.3 and 6.4.2/6.4.3),
- Errors in knowledge of cloud will be reduced through characterisation by an IR cloud imager (IRCI) integral to IRLS (Sections 5.2 & 6.4.3),
- Atmospheric temperature will be retrieved to high accuracy by IRLS (Section 4.3.9).

Accuracy of trace-gas retrievals would not be expected to exceed 1%, however, due to possible forward-modelling errors from residual cloud, spectroscopy or instrument characterisation.

4.3.3. Detailed simulation of atmospheric scenarios

4.3.3.1 Scenarios and atmospheric models

PREMIER’s capabilities to address the specific objectives defined in Chapter 3 by exploiting advances outlined in 4.3.2 are illustrated here through simulations for six scenarios. Distributions of meteorological variables and trace gases for each scenario are taken from global atmospheric models or observational data as follows:

1. Transport between the tropical tropopause layer and neighbouring regions – ClaMS (McKenna et al., 2002; Konopka et al., 2004),

2. Tropical convection and thin cirrus layers – ER-2 lidar data for TOGA-COARE campaign (R. Hogan, private comm; J. Spinhirne, private comm.),

3. Methane uplift through the Indian monsoon circulation – ECMWF/GEMS analysis (R. Engelen, private. comm.),

4. Plumes from biomass burning in Brazil – GEM-AQ (Kaminski et al., 2008),

5. Links to industrial pollution – GEM-AQ (Struzewska and Kaminski, 2008),


4.3.3.2 Atmospheric retrieval schemes

A suite of state-of-the-art radiative transfer and retrieval schemes has been employed in simulations of the above scenarios. All these schemes have heritage from data analysis for earlier satellite limb-emission sounding projects, notably including Envisat MIPAS, CRISTA and Odin SMR, and also earlier ESA studies (for example, Kerridge et al., 2004a). For the IRLS dynamics mode and MWLS retrievals
of \( \text{H}_2\text{O} \) and \( \text{O}_3 \), 2D (tomographic) schemes have been applied\(^3\). For the IRLS chemistry mode and for MWLS retrievals of CO and the biomass-burning indicator HCN, 1D (conventional) schemes have been applied. For MetOp GOME-2 and IASI, the schemes are based closely on those applied in GOME-1 \( \text{O}_3 \) profiling (Munro et al., 1998) and extensive simulation studies for Eumetsat and ESA (for example, Kerridge et al., 2004b, Siddans et al., 2007). A common vertical (2 km) and horizontal (100 km) grid has been used in general, so as to facilitate combined retrievals. However, a 1 km \( \times \) 50 km grid has been used for the IRLS dynamics mode, so as to simulate structure from, for example, gravity waves at the highest achievable resolution. All schemes employ optimal estimation with weak or negligible \textit{a priori} constraints.

**4.3.3.3 Cloud**

To assess PREMIER’s capabilities for trace-gas sounding, it is necessary to consider distributions of ice and liquid cloud as realistically as possible. For each scenario for which retrieval simulations have been performed, cloud parameters have been extracted from the same global model as the trace-gas and temperature distributions. However, global model grids are coarse by comparison to cloud properties, so a finer-scale representation is required for more adequate representation in both limb- and nadir-viewing geometries. A power-law has been applied to extrapolate cloud properties down to finer scales in a manner which conserved ice water and liquid water content within each grid box of the global model (Kerridge et al., 2004a). Each along-track/height cross-section of temperature and trace gases is accompanied by a set of thirteen different cross-sections of cloud fraction, ice or liquid water content and effective radius, representing the thirteen independent viewing directions across-track by the IRLS in its dynamics mode. In cross-sections (height – latitude) presented below, tropospheric penetration depth is indicated for each sensor by the contour of 0.03 transmittance in the absence and presence of typical cloud estimated on this basis\(^4\).

**4.3.4 Transport between the tropical tropopause layer and neighbouring regions**

The distributions of water vapour, ozone, methane and shorter-lived gases in the Tropical Tropopause Layer (TTL) and neighbouring regions are continuously changing. They are controlled by complex chemical, micro-physical, and transport processes, which are only poorly understood. For example, detailed knowledge of transport and dehydration processes in the vicinity of the TTL, where the main entry of air into the stratosphere occurs, will be crucial to understand the unexplained long-term variations of stratospheric water vapour (Section 2.1). To achieve its

\(^3\) In 1D (conventional) schemes, the atmosphere is represented as a series of concentric, homogeneous layers from which a single vertical profile is retrieved. In 2D (tomographic) schemes, horizontal variations within the along-track (limb-viewing) plane are explicitly included in the radiative-transfer model and trace-gas distributions are retrieved on a height vs along-track grid from all limb-views within the domain.

\(^4\) Because transmittance is controlled either by water vapour or cloud, which both have very strong height-dependences, this indication of tropospheric penetration depth is quite insensitive to the precise choice of transmittance value; the 0.05 and 0.10 contours, for example, lie very close to the 0.03 contour, though not shown for clarity.
primary mission aim, PREMIER must therefore significantly improve knowledge of such processes and their representation in models.

Transport mechanisms that influence trace gas budgets in the TTL region are: (a) the large-scale Brewer-Dobson circulation; (b) tropospheric convection and (c) fast quasi-horizontal transport/mixing events on isentropic surfaces. An example of fast isentropic transport/mixing between the extra-tropical stratosphere and the TTL is associated with the Asian monsoon. This process is illustrated in Figure 4.2a for water vapour on the 420 K surface (~18 km) from a three-year integration of the CLaMS model. Figure 4.2a indicates that air in the TTL in the region of the Asian monsoon (for example, over India) consists of a mixture of: (a) ‘young’ tropospheric air (high water-vapour values) from fast convective upward-transport in the centre of the Asian monsoon (30° N, 90° E) and (b) quasi-horizontal in-mixing of ‘older’ extra-tropical stratospheric air (low water-vapour values) at the edge of an anticyclone associated with the Asian monsoon (Konopka et al., in prep.).

Unlike Eulerian (ie grid-point) Chemistry-Transport Models, where the numerical diffusion often outweighs the physical diffusivity, CLaMS is a Lagrangian (ie trajectory) model, which computes transport of air parcels using a physical parameterisation of mixing and, consequently, shows some ability to reproduce
observed small-scale structures such as filaments on isentropic surfaces. The irreversible part of transport, i.e. mixing, is controlled by the local horizontal strain and vertical shear rates. A recent analysis of Konopka et al. (2007) suggests that mixing (as represented in CLaMS) also plays an important role for the upward transport of air masses (water vapour, ozone etc.) from the outflow region of convection into the TTL. In this context, it is notable that the variance of CLaMS water vapour and ozone daily fields is considerably larger than for corresponding ECMWF fields (not shown). This is mainly a result of different transport and mixing schemes. PREMIER will have the precision needed to verify model transport-schemes and associated trace-gas structures that give rise to differences in daily variances of trace-gas fields.

Figure 4.2b: Distributions near 30°N, 144°E of water vapour at 420K (~ 17.5 km) and ozone at 460K (~ 19 km) from the CLaMS model (upper panels) compared to simulated retrievals for the PREMIER IRLS dynamics mode (lower panels). The retrieval vertical resolution is ~ 1 km for water and ~ 1.5 km for ozone. These simulations demonstrate that PREMIER will be capable of resolving horizontal structures on considerably finer scales than earlier limb-emission sounders, thereby filling the gap in scales between observations by satellites and aircraft. [Figure courtesy of L. Hoffmann and P. Preusse]
Overall, mixing in this altitude region can be understood as a scale cascade from synoptic scale streamers over elongated filaments down to small-scale three-dimensional turbulence. Currently, there is an observational gap between the synoptic-scale streamers resolved by current satellite instruments and small-scale features resolved by *in situ* instruments (for example, Sparling and Bacmeister, 2001). PREMIER will fill this gap by providing high-resolution fields of water vapour, ozone, and transport tracers (for example, CFC-11) (see Table 4.1), as illustrated in Figure 4.2b & c.

**4.3.5 Tropical convection and thin cirrus layers**

Convection in the tropics and extra-tropics plays a major role in transporting water vapour and other trace gases upwards from the boundary layer and in controlling their distributions at these latitudes throughout the troposphere (Chapter 2). In intensive convective events, such as Hector off the northern coast of Australia, air rising from the boundary layer can be injected directly into the tropical tropopause layer, or even the lowest stratosphere, where it can then be transported laterally over a large geographical range (Section 4.3.4).
Thin cirrus layers have been detected by airborne lidar to be pervasive in the tropical tropopause layer (T. Peter et al., 2003), yet the physics of their formation is not understood and therefore not represented in either global or mesoscale models. The sensitivity required to detect such layers has to be much greater for a nadir-viewing satellite lidar than for an airborne lidar, due to the much greater observing altitude and much shorter integration time. By imaging the atmospheric limb on finer vertical and horizontal scales than the dynamics and chemistry modes but over the same azimuth range, the PREMIER IRCI will observe the geographical distribution of multiple layers of thin cirrus in the tropical tropopause layer.

Cirrus layers separated by ~1 km are resolved in the simulated 12 μm image because they have significant opacity in limb geometry, while remaining semi-transparent, and the IRCI has a vertical field of view of <1 km. Furthermore, this layered cirrus would be invisible to the MWLS, because particle sizes are small (<10 μm), so would therefore have no influence on its retrieval of water vapour or other trace gases (Section 5.4). Observations of water vapour by MWLS, co-located with thin cirrus observations by IRLS, will therefore allow the geographical distribution and formation of these layers to be investigated from space for the first time. The simulated image in Figure 4.3 also demonstrates that the IRCI will map precisely the distribution of convective cloud tops below the thin cirrus layers, to interpret trace-gas observations by PREMIER and to complement information on lower cloud from MetOp.

![Figure 4.3: Thin cirrus layers observed above tropical convective cloud in the TOAGA-COARE campaign by the ER-2 1 μm lidar (left panel) and limb image simulated for the PREMIER IRCI at 12 μm (right panel). The IRCI image has been simulated with the SHDOM 3D multiple-scattering model, using the lidar 1μm backscatter coefficient data and particle size and ice water content information from T. Peter et al. (2003), assuming a horizontal extent of ~100 km in the line-of-sight direction. [Figure courtesy of R. Siddans]](image)

**4.3.6 Methane uplift by the Indian monsoon circulation**

The efficiency of methane as a greenhouse gas is much greater than carbon dioxide, and biogenic emissions of methane constitute one of the critical but poorly-quantified climate-feedback mechanisms to be mediated via atmospheric

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5 A simulation of the TOGA-COARE scenario by the UK’s Large Eddy Model, for example, does not produce these thin cirrus layers which overlie the convective cloud.
Biogenic emissions of methane in the wetlands of Bangladesh can be uplifted by large-scale convection associated with the Indian monsoon circulation into the atmospheric region of particular importance to climate, which is targeted by PREMIER. In connection with this circulation, elevated concentrations of water vapour and carbon monoxide have been detected over widespread regions of the lower stratosphere by Envisat MIPAS and Aura MLS, and elevated levels of methane have also been detected in the upper troposphere by AIRS (Xiong et al., 2008). Radiative forcing by methane is particularly sensitive to perturbations in the upper troposphere (Figure 2.2). It can be estimated that zonal asymmetry in the methane vertical distribution associated with the monsoon (Figure 4.4) could potentially increase methane radiative-forcing by up to ~20% in comparison with a zonally-symmetric distribution.

Figure 4.4 indicates that PREMIER will observe methane’s distribution in the height-region of particular importance to climate in finer detail than has previously been possible from space, allowing better quantification of the transport processes which control its distribution in this region. Furthermore, through combination with IASI, height-resolved information will extend downwards into the lower troposphere, enabling links to sources to be identified more precisely and emissions to be estimated more accurately than would otherwise be the case.

Increased emissions from wetlands and release of methane hitherto trapped in Arctic tundra/permafrost, lakes and the deep ocean could potentially generate a large positive feedback as warming takes place.
4.3.7 Plumes from tropical biomass burning and boreal forest fires

Biomass burning at tropical and mid-latitudes and large-scale fires in the boreal forests of Alaska, Canada and Siberia emit organic compounds in significant quantities. These intense fires create pyroconvective uplift by which plumes are lofted through the mid troposphere, reaching the upper troposphere and sometimes the lower stratosphere where they can be transported over very long distances. Hydrocarbons and other organic compounds emitted by these fires, and secondary compounds produced by their oxidation, influence production of ozone in this height region of particular importance to climate. The frequency and occurrence of such fires constitute one of the feedbacks on climate mediated by atmospheric composition which are poorly quantified at present.

The cross-sections in Figure 4.5 of methanol (CH$_3$OH) retrieved from IRLS and carbon monoxide (CO) and hydrogen cyanide (HCN) retrieved from MWLS illustrate PREMIER’s capabilities to detect and resolve plumes from pyrogenic sources. Hydrogen cyanide and methyl cyanide (for which MWLS retrieval has also been
simulated but not shown) are indicators unique to biomass burning. The simulated HCN retrievals from MWLS therefore illustrate PREMIER’s capability to assign these plumes to pyrogenic sources, and to differentiate from anthropogenic or biogenic sources. Although these and other biomass burning products are detectable by the IR solar occultation sensor ACE on SCISAT-1, as only one northern latitude and one southern latitude are sampled per day, the probability of observing a given plume is low.

4.3.8 Links to industrial pollution

Once above the planetary boundary-layer, long-lived primary pollutants emitted by industrial sources (for example, carbon monoxide (CO) and hydrocarbons such as ethane (C₂H₆)) and secondary products (for example, peroxyacetyl nitrate (PAN) and nitric acid (HNO₃)) can be lofted into the mid/upper troposphere by fronts and other weather systems, where they can be transported on intercontinental and hemispheric scales and influence ozone chemical production in the height-range of particular importance to climate. The geographical region in which surface chemical production and loss of ozone depend strongly on height, through UV spectral intensity, temperature and pressure as well as reactant concentrations which vary with height.
pollution, and hence air quality, is also affected by such plumes depends upon their trajectories, which in turn depend on their altitudes. The future GMES Atmosphere Service could therefore determine this impact more reliably with global information from space on the heights and composition of such plumes.

Seasonal composite distributions of these organic compounds have been generated in the mid/upper troposphere by Envisat MIPAS (Glatthor et al., 2007; von Clarmann et al., 2007), however, its comparatively sparse sampling density is not sufficient to generate daily distributions nor to resolve individual pollutant plumes.

Figure 4.6b illustrates that the PREMIER limb-emission sounders will be able to resolve vertical and horizontal structure in individual cross-sections of organic and nitrogen compounds important to ozone production, including pollutant plumes crossing the Atlantic from north America to Europe. Observations by PREMIER of height-resolved distributions of ozone pre-cursors and of ozone itself will enable these production processes to be quantified more comprehensively. The capability to observe constituents of pollutant plumes will also allow PREMIER to demonstrate the value which limb-emission sounding could add to nadir-sounding for air-quality forecasting applications of the GMES Atmosphere Service.

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Figure 4.6a. CO distribution at 371 hPa for 18th November 2001 from the GEM-AQ model (A. Lupu, private comm.). Elevated CO in plumes from North America are seen crossing the Atlantic. South of 20°N, plumes from biomass burning in South America and Africa are also seen. The white line indicates the N-S transect at 9°W for which cross-sections of CO, C2H6, PAN & HNO3 and their simulated retrieval are shown below (Figure 4.6b). [Figure courtesy of G. Miles]

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8 A larger suite of organic compounds has been detected by SCISAT-1 ACE through IR solar occultation spectrometry. However, its coverage of only one northern and one southern latitude per day is wholly insufficient to sample the distribution of pollutant plumes and to quantify their impact on tropospheric ozone production.
Satellite data can potentially contribute to the attribution and quantification (through inverse modelling) of surface pollutant emission sources. The value of this satellite contribution to the future GMES Atmosphere Service will depend upon which trace gases can be detected and the accuracy and resolution with which their distributions can be retrieved. The tropospheric ozone residual distributions derived from Aura MLS and OMI (Schoeberl et al., 2007) provide an initial indication of the potential of combining limb-emission with nadir-UV observations. However, height resolution within the troposphere will be key to application of trajectories and to discriminate between near-surface and higher layers to pin-point and quantify sources. An example of how PREMIER measurements can add value to Metop’s IASI data, even in the lower troposphere, is given in Figure 4.7.

In the case of NO₂, for which approximately half of the total column resides in the stratosphere but only one piece of information is available from MetOp GOME-2, estimation of the lower-tropospheric or boundary-layer column depends on the accuracy with which the stratospheric column can be characterised by other
Figure 4.7a: $O_3$ distribution at 811 hPa on 31st August 2005 (14:30 UT) from the GEM-AQ model (A. Lupu, private comm.). Concentrations in the lower troposphere are seen to be highest over North America and Europe, near to pollution sources. The plume centred near 45°N, 83°W is located directly beneath an intrusion of high-ozone stratospheric air, as shown in Figure 4.7b in the N-S transect (white line) at 83°W, where local time is ~ 9.30am, when MetOp and PREMIER observe. GEM-AQ cross-sections of both CO and $O_3$ and their simulated retrieval are shown in Figure 4.7b. [Figure courtesy of B. Latter]

Figure 4.7b: Cross-sections (N-S) of CO (upper panels) and $O_3$ (lower panels) at 83°W (~ 9:30 local time) on 31st August 2005 over America as modelled by GEM-AQ, in comparison to simulated retrievals from MetOp and from the PREMIER-MetOp combination. The addition of MWLS and IRLS is seen to sharpen up vertical structure in CO and $O_3$ within the limb-sounding range above elevated concentrations in the model lower troposphere retrieved by MetOp. PREMIER allows pollutant plumes to be differentiated from intrusions of stratospheric air. For $O_3$, vertical structure is seen to be better-resolved also in the lower troposphere; notably including the plumes at ~ 2 km near 45°N below the intrusion and at 65°N. The dashed white line shown in all panels is an indicative lower limit to tropospheric penetration for IASI, as inferred for this particular transect from cloud information from GEM. Corresponding lower limits for MWLS & IRLS are also shown as dashed white lines in the two right-hand panels. [Figure courtesy of A. Waterfall and M. Höpfner]
means. Limb-emission observations co-located with MetOp would be optimal for this purpose.

It is therefore evident from these simulations that PREMIER will have the capabilities to examine the impact of pollution on ozone production in the height range of particular importance to climate and also to demonstrate the potential value of limb-emission sounding to the pollution monitoring and air quality forecasting applications of the GMES Atmosphere Service.

4.3.9 Gravity waves

In preceding sections (4.3.4–4.3.8) it has been shown that PREMIER will directly observe key processes by which constituents are transported into, within and out of the height-range of importance to climate. In addition, PREMIER will provide information on dynamic structures such as gravity-waves, which play an important role in driving atmospheric circulation patterns (see Fritts and Alexander, 2003) and associated transport of radiatively-active species. Changes in the atmospheric circulation caused by changes in wave dynamics are an integral part of climate change.

Gravity waves transport momentum from the troposphere to higher atmospheric levels. Their sources are mainly in the troposphere, and they propagate upwards, and accelerate or decelerate the global-scale wind-field as they break, by depositing momentum. Global distributions of the vertical flux of horizontal momentum $u^*w^*$ (horizontal and vertical wind fluctuations) are not directly observable from space as a result of the comparably small vertical velocities ($< 1 \text{ m s}^{-1}$). However, in linear theory, gravity-wave momentum flux can be expressed as a function of temperature amplitude, horizontal, and vertical wavelength on the basis of fundamental polarisation and dispersion relations. Also, all current gravity-wave parameterisation schemes used in dynamic models calculate wave propagation (conservative or at the saturation limit) and the onset of wave breaking according to linear perturbation theory. Therefore, global observations of 3D temperature structures with sufficient spatial resolution, which are currently not available, would provide data necessary for progress in this critical field.

The capabilities of the dynamics mode of PREMIER IRLS (see Table 4.1) to resolve 3D temperature structures are illustrated in Figure 4.8 based on ECMWF fields which have a grid resolution of 1/4 degree, allowing part of the mesoscale gravity-wave spectrum to be resolved. The tomographic 2D retrieval simulation shown in Figure 4.8 is clearly able to resolve all of the temperature structures contained in the original ECMWF data set. The 2D tomographic retrieval that can be applied due to the regular PREMIER measurement grid even provides the correct amplitudes of the small-scale structures and avoids the cumbersome amplitude-damping effects.

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9 An established procedure in the absence of stratospheric profile observations is to rely upon a chemical transport model to predict the stratospheric NO$_2$ distribution for subtraction from the total column measured by nadir-sounding. This prediction is sensitive to the model NO$_x$ distribution, which is sensitive to stratospheric wind-fields prescribed by analyses from ECMWF, and also to NO$_x$ partitioning.
inherent in 1D retrieval techniques (Ern et al., 2004). Therefore the PREMIER data set will be ideally suited for validation of the small scale structures contained in ECMWF and other high resolution GCMs, as well as high resolution gravity wave model simulations.

The fine scale temperature fluctuations seen in Figure 4.8 are due in large part to atmospheric gravity-waves. Wavefronts of single wave events and superpositions of different waves from a broad spectrum are visible in both ECMWF temperatures and PREMIER retrieval results. Consequently, PREMIER, with its regular three-dimensional measurement grid, will provide all the information needed (temperature amplitudes, the true horizontal and vertical wavelengths of the gravity-waves, as well as the direction of the wave fronts, i.e. the direction of the horizontal wave vectors) to derive momentum flux-vectors of the single wave events and their superpositions. PREMIER therefore offers the best perspective from which to assess net momentum-fluxes from space, i.e., the vector sum of the momentum fluxes of the various gravity-wave events that form the spectrum of gravity waves in a certain region. This is the quantity most relevant for comparison with gravity-wave parameterisations in GCMs.

PREMIER will be capable to resolve gravity waves with horizontal wavelength longer than 50 to 100 km and vertical wavelength longer than 2 to 3 km. This is a result of the combined effect of the observational filter (Preusse et al., 2008) and the sampling pattern of the dynamics mode (see Table 4.1). This implies that PREMIER will cover the whole unsaturated part of the vertical-wavelength spectrum at long vertical wavelengths, which provides information on the gravity-wave source processes. Even part of the saturated wave spectrum at vertical wavelengths shorter than about 3 km in the lower stratosphere will be measured. At higher altitudes, the saturated part of the spectrum starts at longer vertical wavelengths and can be measured even more easily. Another reason why it is important that PREMIER covers a comprehensive vertical wavelength-range is that Doppler shifting due to changes in the atmospheric background winds can move waves into or out of the visibility range of an instrument. This Doppler shifting effect is strongly alleviated by the large vertical wavelength-range covered by PREMIER.

In contrast to preceding limb sounders such as HiRDLs and SABER and the COSMIC constellation of radio occultation sensors, the PREMIER infrared limb imager (see Section 5.2) will observe the 3D wave-structure on a comparatively dense and uniform grid along the flight track, thereby providing novel information on global gravity-wave momentum flux. The direction as well as the magnitude of the vertical flux of horizontal momentum associated with the gravity-wave spectrum can be derived for the part of the gravity-wave spectrum visible to the PREMIER infrared limb-sounder (see Preusse et al., 2008).

The benefit achieved by the regular PREMIER sampling pattern, providing high resolution information along and across the satellite track at the same time, is further illustrated in Figure 4.8 (lower panel). The wave fronts of several wave events as well as their superposition can be clearly identified in the PREMIER
measuring track, while the sampling pattern of the COSMIC GPS radio occultation observations is too sparse and too irregular. In Figure 4.8 (lower panel), PREMIER observation obtained in about 15 minutes (coloured track) are compared with locations of GPS profile observations obtained during a day (black dots). The white arrows in Figure 4.8 indicate the direction of the wave vector for the dominant wave component at 290° longitude and 35 km altitude. It can be shown by back-tracing studies (Preusse, private communication) that the highlighted structure is associated with a mountain wave generated over the southern tip of South America. Other prominent sources of gravity waves include equatorial convective systems and geostrophic adjustment (for example, in the vicinity of...
the edge of the polar vortex). The PREMIER data set will be ideally suited for the validation of gravity-wave source models by back-tracing methods, since it provides direction-resolved wave vectors.

### 4.3.10 Estimate of error reduction in data assimilation

In the following, we estimate how PREMIER data can add value in an operational assimilation system such as the one under development for the future GMES Atmosphere Service. To do so, 1D background-error covariance matrices from the ECMWF/GEMS system are used, characterising the random error in short-term forecasts from this system. We estimate how the assimilation of PREMIER data reduces these expected errors through a linear, 1D error analysis. While the actual performance of PREMIER data within a full 3 or 4D data assimilation system will be more complex (for instance, due to cycling effects, interaction with other assimilated data, and effects of cloud or systematic biases), these estimates give a useful first characterisation of the expected impact, also in comparison to the impact of other instruments. The background errors used are taken from ECMWF’s operational assimilation system for temperature, H2O and O3; for CH4 and CO they are preliminary, first estimates from the GEMS system. The GEMS system assimilates data from a variety of operational and research satellites, and the size of the background errors reflects the quality of the analyses achieved with these observations. Due to the limited amount of observations, background-error estimates for humidity above the tropopause and for other trace gases are likely to be underestimates of the true background errors. Note that only instrument noise is taken into account in this analysis; effects of other random errors, systematic errors or biases in PREMIER, MetOp or model data are not considered here. Note also that, whereas the IRLS simulation used a set of microwindows totalling 15cm⁻¹, the full spectral bandwidth available to IASI was used in each case.

Figure 4.9 shows that individual profiles observed by the PREMIER limb-emission sounders will add significant value, irrespective of whether data from sensors on EPS-MetOp (and other nadir-sounders) have been assimilated first. Significant improvements are evident in terms of the standard deviations. Also, the combined use of PREMIER data and nadir sounders has a clear benefit for ozone and methane in the lower troposphere below the region directly sounded by PREMIER. The height-resolved limb-emission observations overcome vertical correlation (i.e. off-diagonals) in the background error covariances to an extent that cannot by achieved with nadir-sounders alone. This demonstrates the synergy of the limb and nadir sounding data. Assimilation of PREMIER data will therefore improve the analysis fields of these trace gases, and hence also forecasts of these gases and those related chemically to them, through the multivariate system. Improved analyses of ozone, water vapour and other tracers in the lower stratosphere are also expected to improve wind analyses in that region, not highlighted here.

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10 Accuracy would not be expected to exceed 1% in practice, however, due to possible forward modelling errors, for example from residual cloud, spectroscopy or instrument characterisation.
In the above sections, it has been demonstrated through sophisticated simulations based on global atmospheric models, radiative transfer and retrieval schemes that, through deployment of advanced IR and mm-wave limb-emission sounders, PREMIER will fulfil its specific objectives and thereby achieve its primary aim. In particular, it has been demonstrated that PREMIER will have the capability to observe distributions of the key radiative gases, water vapour, ozone and methane, and tropical cirrus layers, on significantly finer scales in the height region most important to climate than has previously been possible from space, and thereby critically test and discriminate between models of the atmospheric dynamical and transport processes which control them. This will allow significantly improved representation in climate models of the processes which control their global distributions in this critical height region and climate feedbacks mediated by atmospheric composition and circulation.

It has also been demonstrated that PREMIER will have the capability to observe distributions of other trace gases produced from biomass burning, boreal
forest-fires, industrial pollution and biogenic emissions which are transported into this height region, where the additional ozone that they produce has greatest impact on climate radiative-forcing. Observations will be made of organic and nitrogen compounds which are not detectable in nadir-geometry, and plumes from biogenic, pyrogenic and anthropogenic sources will be resolved in 3D for the first time.

In addition, it has been demonstrated that, in combination with EPS-MetOp, PREMIER will have the capability to resolve lower tropospheric concentrations of trace gases measured in common, and thereby fulfil its secondary mission aim to quantify links to lower tropospheric pollution and surface emissions.

*It can therefore be concluded that PREMIER will improve quantitative understanding of processes which control atmospheric composition in the height-range of particular importance to climate and links to pollution and surface emissions.*

Furthermore, it has been shown quantitatively that, by resolving vertical structure in the mid/upper troposphere and stratosphere, PREMIER will add substantial value to EPS-MetOp and other operational satellites through assimilation of data into the ECMWF system used currently for numerical weather prediction and under development for the future GMES Atmosphere Service. It can therefore be concluded that PREMIER will also demonstrate the potential of a future limb-emission sounding component of an integrated observing system for numerical weather prediction, global pollution monitoring and air quality forecasting.
Chapter 5  Mission Elements

5.1  Introduction

The primary aim of PREMIER is to explore processes controlling the composition of the mid/upper troposphere and lower stratosphere, the region of highest sensitivity for climate radiative-forcing and feedback. This objective demands the structure of this region to be resolved in 3D more fully than by any previous, current or planned satellite mission. The PREMIER observations will allow quantification of the relationships between atmospheric composition, transport, dynamics and climate (see science objectives, Chapter 3). In addition, PREMIER will exploit the synergies between these 3D high-resolution observations and spatially and temporally commensurate observations by EPS-MetOp nadir-sounders (Figure 5.1) to explore links with lower tropospheric pollution and surface emissions.

The primary aim of PREMIER requires 3D observations of a suite of atmospheric trace constituents with unprecedented spatial resolution. This calls for the utilisation of two distinct limb-emission sounding techniques

- InfraRed Limb Sounding (IRLS)
- Millimetre-Wave Limb Sounding (MWLS)

The limb-emission sounding technique exploits the radiation thermally emitted in the atmosphere along the line of sight (LOS) of the instrument, which is directed towards the limb of the Earth’s atmosphere (Figure 5.1). The point of LOS closest to the surface is called the tangent point. Under optically-thin conditions, the tangent point is representative for the measurement location. The limb-viewing geometry yields good vertical resolution, since the LOS segment for the layer immediately above the tangent point is relatively large compared to other segments and the total density of the atmosphere strongly decreases with altitude. The horizontal

![Figure 5.1: Scheme showing the complementary attributes of limb- and nadir-sounding geometries to be exploited fully for the first time by PREMIER in combination with EPS-MetOp. (Figure courtesy of R. Siddans)](image-url)
resolution of a single profile trace-gas observation is somewhat coarse along the line of sight for single profile observations as a result of radiative-transfer weighting functions (300 km). However, it can be strongly improved by dense horizontal sampling along the line of sight and application of 2D retrieval schemes (50 km, see Section 5.4). In the case of cloud observations, considerably higher horizontal resolution can be achieved, down to a few kilometres. The limb-geometry permits measurement of key trace-gases which are too tenuous to be detectable in the shorter path lengths of nadir-geometry. Observation in emission against the background of cold space, rather than in absorption against the warm background of Earth’s surface, whose temperature and emissivity are inhomogeneous and variable, is also an advantage for accuracy. Limb-emission sounding yields good geographical coverage, since observations are possible at all locations during daytime and nighttime.

PREMIER is a mission specifically designed to exploit the complementary attributes of IR- and MW-limb sounding for multiple trace-gas constituent measurements. Three-dimensional observations with unprecedented spatial resolution are achieved by two major innovations:

- the first satellite Fourier Transform InfraRed (FTIR) limb-imager, with integral cloud/aerosol imaging at finer resolution,
- the first satellite Millimetre-Wave Limb-Sounder optimised for upper-troposphere sounding

All limb views are made simultaneously at each measurement location. Fixed tangent-point spacing (i.e. fixed layer thickness) prevents noise of vertical registration and therefore facilitates high vertical resolution. Dense sampling of the atmosphere along LOS is achieved by high measurement speed (seconds). In addition, the Infrared Limb-Imager provides a large number of simultaneous limb views across the LOS that means dense across-track sampling (see Figure 5.2).

### 5.2 InfraRed Limb Sounder (IRLS)

#### 5.2.1 Measurement technique

A number of satellite instruments have used the infrared limb-emission sounding technique (Section 2.3). Global observation of atmospheric infrared limb-emissions represents a reliable technique for obtaining vertically-resolved profile data of temperature, a variety of trace gases, aerosols, and clouds simultaneously, at daytime and at nighttime. First global infrared limb-emission observations of an extensive number of atmospheric trace species were made by LIMS (Limb Infrared Monitor of the Stratosphere) and SAMS (Stratospheric and Mesospheric Sounder) aboard the NIMBUS 7 satellite. Trace-gas fields obtained from these sensors (and follow-on IR-limb instruments aboard UARS and EOS-Aura) greatly contributed to our understanding of the three-dimensional composition, structure and large-scale dynamics of the middle atmosphere. Early in 2002, ESA launched Envisat, a polar-orbiting Earth-observation satellite, which included the MIPAS (Michelson
Interferometer for Passive Atmospheric Sounding (IRLS) instrument for broad-band limb-emission observations with high spectral resolution. MIPAS significantly expanded the number of detectable species and the corresponding height range compared to previous space missions (Fischer et al., 2008).

5.2.2 Concept of IRLS

All previous instruments have used telescopes with scanning mirrors or 1-dimensional detector arrays to obtain profile information of atmospheric trace species. While these instruments were rather restricted in terms of spatial resolution (and in particular horizontal sampling), recent developments in infrared detector array technology can provide the basis for an instrument capable of meeting the observational requirements summarised in Table 4.1 (see also Friedl-Vallon, F. et al. 2006 and Riese, M. et al., 2005).

To achieve the combination of high spatial resolution and multiple gas observations specified in Table 4.1, it is anticipated that the IRLS will combine two-dimensional detector arrays with a Fourier Transform InfraRed Spectrometer (FTIR) for the spectral separation of the emissions of atmospheric trace constituents. If, for the sake of illustration, each two-dimensional detector array is assumed to consist of about 100 × 100 pixels, about 10 000 limb views will be provided in the altitude range from 5 km to 55 km (within a 320 km across-track view) simultaneously. This ‘intrinsic’ sampling is much denser than the required atmospheric sampling specified in Table 4.1. To increase the signal-to-noise ratio, individual array pixels...
may therefore be co-added to obtain a suitable set of ‘super-pixels’ fulfilling the coarser sampling requirements of specific measurement modes.

For the spectral identification of the targeted atmospheric trace constituents (see Table 4.1), a Michelson interferometer with a maximum optical path difference of at least 2.5 cm (corresponding to a spectral sampling of 0.2 cm\(^{-1}\)) is used. The required spectral coverage is provided by two spectral bands extending from 770–980 cm\(^{-1}\) (band A) and from 1070–1650 cm\(^{-1}\) (band B), respectively. Typical mid-latitude spectra are shown in Figure 5.3 for both bands and tangent altitudes of 8 km and 12 km, respectively.

The main advantage of the measurement concept is its great flexibility: the balance between spatial and spectral resolution can be adapted to the scientific needs. Two basic measurement modes have to be implemented to address the requirements given in Table 4.1 in terms of altitude range, spatial sampling, detectable trace constituents, accuracy, and precision:

- **Atmospheric chemistry mode**: high spectral resolution mode, optimised for observation of minor trace gases.
- **Atmospheric dynamics mode**: high spatial resolution mode, optimised to resolve atmospheric structure.

The atmospheric chemistry mode provides the necessary spectral sampling (0.2 cm\(^{-1}\)) to resolve atmospheric trace constituents specified in Table 4.1 (2nd column; see also Figure 5.3). In this mode, the instrument operates with full spectral resolution.

The atmospheric dynamics mode is designed for a subset of atmospheric parameters with higher spatial sampling requirements (see Table 4.1, 3rd column). Due to relaxed spectral sampling requirements (1.25 cm\(^{-1}\)), a shorter stroke of the interferometer can be selected.
The typical operation time of one mode is between one orbit and one week or even more. The baseline is for observing times to be comparable in the two modes.

A *cloud-imaging capability* is provided by the IRLS as a result of the very high intrinsic spatial resolution of the IRLS (two-dimensional detector arrays). The centre burst of each interferogram can be used for each detector pixel in order to characterise cloud distribution in the corresponding limb view. For the corresponding spectra, a spectral resolution of 10–20 cm$^{-1}$ is sufficient. This procedure results in a data cube with very high spatial resolution, even if some co-adding of pixels is applied to reduce the data rate. The recording of the cloud information is done in parallel to the actual operation mode and without any interruption of it. Spatial as well as time attribution of limb cloud-images to spectra obtained in the two measurement modes is intrinsically perfect. The cloud spectra are available for all detector pixels that make up the sampling grid of the chemistry and dynamics modes, respectively.

### 5.2.3 Summary of Level 1 requirements

**Geometrical instrument requirements:** The vertical coverage of the observations must be at least 48 km for the chemistry mode as well as for the dynamics mode with a lower boundary that increases from the Arctic (3 km) to the equator (7 km) to account for part of the latitudinal variation of the tropopause height. For limb cloud-imaging it is sufficient to cover the altitude range with likely cloud occurrence, for example 3–18 km for polar regions (up to 30 km, in PSC season) and 7–22 km for tropical regions. Horizontal coverage, horizontal sampling, and vertical sampling are specified in Table 4.1 for the chemistry mode (2nd column) as well as for the dynamics mode (3rd column). The field of view (FOV) requirements are 2.2 km (FWHM) for the chemistry mode and 800 m (FWHM) for the dynamics mode and cloud imaging.

**Spectral instrument defining requirements:** The required spectral coverage can be provided by two spectral bands extending from 770–980 cm$^{-1}$ (band A) and from 1070–1650 cm$^{-1}$ (band B), respectively. In the atmospheric chemistry mode, a spectral sampling of 0.2 cm$^{-1}$ is required in order to resolve the relatively large number of chemical species needed to address the science objectives. For the reduced number of chemical species in the dynamics mode, a spectral sampling of 1.25 cm$^{-1}$ is sufficient. Limb-imaging of clouds is less demanding in terms of spectral sampling. In this case a value between 10 cm$^{-1}$ and 20 cm$^{-1}$ is sufficient.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>atmospheric chemistry mode</th>
<th>atmospheric dynamics mode</th>
<th>limb cloud imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band A:</td>
<td>threshold for full band</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>target for 790–900 cm$^{-1}$</td>
<td>3.2 nW/(cm$^2$ sr cm$^{-1}$)</td>
<td>2.2 nW/(cm$^2$ sr cm$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3 nW/(cm$^2$ sr cm$^{-1}$)</td>
<td>0.9 nW/(cm$^2$ sr cm$^{-1}$)</td>
</tr>
<tr>
<td>Band B:</td>
<td>threshold for full band</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>target for 1080–1250 cm$^{-1}$</td>
<td>1.9 nW/(cm$^2$ sr cm$^{-1}$)</td>
<td>1.4 nW/(cm$^2$ sr cm$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 nW/(cm$^2$ sr cm$^{-1}$)</td>
<td>1.0 nW/(cm$^2$ sr cm$^{-1}$)</td>
</tr>
</tbody>
</table>

Table 5.1: Radiometric requirements of IRLS.
Radiometric instrument defining requirements: Table 5.1 specifies radiometric sensitivities that must be achieved in order to fulfil the accuracy/precision requirements summarised in Table 4.1 (in the dynamic range from deep space to brightness temperatures up to 240 K).

5.2.4 Technical Demonstration

An airborne precursor for such a satellite instrument is currently under development by the research centres in Karlsruhe and Jülich. The first deployment of the instrument will be on the new German research aircraft HALO. First scientific missions are planned for the second half of the year 2009. While use of this sensor is directed at its own scientific program, it also provides a test bed with which to investigate the capabilities of this new instrument class and with which to develop tools for exploiting and interpreting the wealth of information provided by an imaging Fourier-transform spectrometer.

The airborne instrument uses a 256 × 256 HgCdTe detector array (FPA) operating at 50 K with a pitch of 40 μm. Its spectral coverage extends from 770 cm⁻¹ to 1400 cm⁻¹. The horizon is imaged onto the Focal Plane Assembly with an infrared lens system with a focal length of 72 mm. The Michelson interferometer (Figure 5.4 right) allows a maximum optical path difference of 10 cm. It is a single-slide design; priority for the mechanical layout was compactness, robustness, high stiffness and vibration insensitivity. The instrument setup does not comprise a telescope or any input optics. The spectrometer is mounted in a gimballed frame below the aircraft belly.

The instrument can provide a much higher spectral and spatial resolution than requested for the space instrument, reflecting the different scientific needs of an airborne carrier. The gimbal mount allows the spectrometer to scan the horizon from 45° to 128° with respect to flight direction (Figure 5.4 left). In this way, a tomographic analysis of the atmosphere is possible. In addition, the instrument

Figure 5.4: Demonstration of Infra-Red Limb Sounding (IRLS) and Infra-Red Cloud Imaging (IRCI) from the new research aircraft HALO: The GLORIA-AB instrument in the belly-pod of the HALO aircraft (left) and laboratory set-up of its interferometer (right). [Figure courtesy of H. Schneider, T. Kulessa and F. Friedl-Vallon]
can look in the nadir direction. The line of sight in all modes is precisely controlled with the help of an inertial navigation system.

A prototype version of the flight interferometer is already operating at the Research Centre Karlsruhe. Performance testing and optimisation is ongoing, and the production of the final flight model is planned for the second half of 2008. The gimbal is currently being manufactured at the Research Centre Jülich and the test phase will begin at the end of 2008. Mating of the flight spectrometer and gimbal is foreseen for early 2009 which will be followed by test flights in mid-2009.

5.3 Millimetre-wave Limb Sounder (MWLS)

5.3.1 Measurement technique

Microwave limb sounding is also a limb-emission technique but the technology is often very different from that used in the infrared since the wavelengths lie in a region between the traditional optical and radio regions of the electromagnetic spectrum. The first microwave limb sounder in space was MLS on the Upper Atmosphere Research Satellite (UARS) launched in 1991 (Barath et al., 1993). This instrument provided the first space measurements of chlorine monoxide (ClO). A similar instrument called MAS (Millimetre wave Atmospheric Sounder) (Hartmann et al., 1996) flew three times on the Space Shuttle in 1992, 1993 and 1994. These instruments used frequencies below 220 GHz (i.e. mm waves). The first sub-mm radiometer in space was flown in 2002 on the Odin satellite (Murtagh et al., 2002, Frisk et al., 2003) and employed frequencies up to 580 GHz. This instrument was used both for atmospheric measurements as well as for studies of the interstellar medium. The higher frequencies, however, limited the depth of penetration into the troposphere because of the strong absorption by water vapour and oxygen at these wavelengths. The most recent microwave limb sounder is the MLS instrument on board the Aura satellite (Waters et al., 2006).

The mm-wave spectral region contains a number of spectral lines from species that are difficult to measure at other frequencies, as well as many others of interest. The heterodyne measurement technique provides high spectral resolution, which enables information from the pressure-broadened lines, as well as pointing data to provide altitude registration (see Figure 5.5).

5.3.2 Technical concept of MWLS

All of the previous microwave limb sounders have employed scanning mechanisms to move the single field of view of the telescope across the limb in order to achieve the required altitude coverage. This reduces the possible along-track coverage since a certain integration time is required to obtain sufficient accuracy in the retrieved products. For PREMIER this limitation will be circumvented by employing, for the first time, a focal plane array of broad band receivers. Such focal plane arrays have started to be deployed for astronomical observations. Recent advances in spectrometer technology allow relatively large bandwidths to be analysed.
simultaneously with low power consumption. The PREMIER MWLS will take advantage of these technologies to utilise multiple sky-beams and to detect the broad band necessary to observe and separate species in the UTLS.

5.3.3 Summary of Level 1 requirements

**Geometrical instrument requirements:** The vertical coverage should begin at the lowest altitude observable, which is mostly determined by the water vapour concentration (see Section 5.4) and varies from about 3 km in the polar regions to ~ 7 km in the tropics. The vertical range of 22 km will be covered by 14 beams with 1.5 km spacing for the first 12 km and 2 km spacing in the upper part (see below). The vertical resolution of the instrument should be as high as possible in order to resolve fine-scale structures such as plumes and layering. The resolution is determined both by the antenna size and by the spacing of the beams. Technical limitations restrict the antenna to about 1.6 m in diameter resulting in about a 2.5 km FWHM beam on the limb. This limitation can be overcome by oversampling and using the intrinsic information on pressure in the line profiles. The most stringent requirement on good vertical resolution is in the ULTS region and we require a maximum spacing of 1.5 km in this region (see Table 4.1). Above 18 km this can be relaxed to 2 km.

**Spectral defining requirements:** The frequency coverage was chosen so as to include all the required species utilising both sidebands of the heterodyne-receiver technique. The 330 GHz region gives the advantage of higher vertical resolution compared to AURA-MLS, while penetrating much further into the troposphere than in case of the higher frequencies used on Odin SMR. The final band selection was based upon simulations of retrieval performance constrained by known technical considerations. At the lower altitudes the spectral lines are significantly pressure...
broadened so that high spectral resolution is not required in the spectrometers, on the other hand wide bandwidth is required, both to give coverage of the species to be measured and to enable the deconvolution of the broad lines from each other. Therefore we require a spectral resolution of $< 25 \text{ MHz}$.

**Radiometric instrument defining requirements**: Table 5.2 specifies the radiometric requirements needed in order to fulfil the accuracy/precision requirements summarised in Table 4.1.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometric sensitivity</td>
<td>0.5K (DSB) at 2.5 s integration time and 10MHz bandwidth</td>
</tr>
<tr>
<td>Absolute radiometric accuracy</td>
<td>1K</td>
</tr>
<tr>
<td>Radiometric linearity (deep space to 240 K)</td>
<td>$&lt; 0.5 %$</td>
</tr>
<tr>
<td>Spectrally varying radiometric errors</td>
<td>$&lt; 1K$ (knowledge $&lt; 0.1K$)</td>
</tr>
</tbody>
</table>

Table 5.2: Radiometric requirements of MWLS.

### 5.3.4 Technical demonstration: MARSCHALS

The MARSCHALS instrument has been designed as an airborne simulator of an advanced future satellite limb-sounder, and is the first millimetre-wave limb-sounder to be explicitly designed and built to target the upper troposphere. The instrument observes the MWLS frequency range in single side-band. Flying at typically $\sim 20$ km, it is also able to simulate other characteristics of MWLS for limb-sounding of the upper troposphere and lower stratosphere height-range.

To achieve comparatively high vertical resolution and pointing stability, MARSCHALS scans the atmospheric limb in 1 km vertical steps using a 235 mm diameter antenna controlled by a dedicated inertial measurement unit. A quasi-optical network directs radiation from the antenna or an ambient ($\sim 300K$) or cold ($\sim 90K$) calibration target into three front-end receivers, and suppresses each unwanted side-band by $> 30\text{dB}$ using multi-layer frequency-selective surfaces. Each receiver comprises a waveguide mixer pumped subharmonically by a phase-locked Local Oscillator (LO) and a wideband Intermediate Frequency (IF) preamplifier. The IF outputs are directed to channeliser spectrometers of 200 MHz resolution, which instantaneously and contiguously cover 12 GHz wide (RF) frequency bands centred near 300 GHz ($\text{O}_3$), 325 GHz ($\text{H}_2\text{O}$) and 345 GHz ($\text{CO}$). To identify clouds, images of near-IR sunlight scattered into the limb direction are recorded concurrently by an 850 nm wavelength camera.

MARSCHALS (Figure 5.6) has been built under ESA contract by a consortium led by Rutherford Appleton Laboratory in the UK, and had its first scientific flights on the Russian Geophysica (M55) aircraft in December 2005, during the SCOUT-$$\text{O}_3$$ campaign in Darwin, Australia. Trace gases were observed in the presence of ubiquitous, upper tropospheric ice cloud which was opaque to IR limb observations by MIPAS-STR & CRISTA-NF; thereby demonstrating one of the synergies to be exploited by PREMIER (see Figure 5.7, and Dinelli et al., 2008).
MARSCHALS will be upgraded in 2009 to improve the sensitivity of the millimetre-wave receivers, to enhance the inertial-guided scanning and pointing system and to perform extensive on-ground characterisation prior to further campaigns on Geophysica planned in 2010. Adaptation of MARSCHALS to operate alongside GLORIA-AB on HALO in subsequent campaigns is also under investigation.

Spectral intervals to sound the upper troposphere in limb geometry have been selected to exploit optimally the complementary and synergistic attributes of the IR and millimetre-wave regions. Most fundamentally, the suite of trace gases which have to be observed to meet PREMIER’s requirements (Table 4.1) can be covered only by combining observations in these two wavelength regions. Carbon monoxide (CO), a product of industrial pollution and biomass burning, will be targeted by
the MWLS, together with hydrogen cyanide (HCN) and methyl cyanide (CH₃CN), which are both indicators of biomass burning. The IRLS will target methane (CH₄) from biogenic sources, and also a suite of organic compounds from industrial and pyrogenic sources, including ethane (C₂H₆), formaldehyde (HCHO), and peroxyacetyl nitrate (PAN).

Of comparable importance, however, is that trace-gas emissions at millimetre-wavelengths are not attenuated significantly by aerosols (or PSCs) and are attenuated much less by cirrus clouds than emissions at infrared wavelengths. Only cirrus clouds containing relatively large particles (> 100 μm) can significantly attenuate/scatter limb-emission at millimetre-wavelengths, which means that trace gases can still be retrieved in the presence of most cirrus clouds. By contrast, cirrus clouds with predominantly smaller size components (and aerosol and PSCs) can be observed by infrared limb-sounding, as also required to meet PREMIER mission objectives.

Limb path transparency at IR and mm-wave wavelengths to be exploited by PREMIER is illustrated in Figure 5.8, which shows annual mean probabilities of transmittance > 3% at the two wavelengths as a function of latitude and height, as calculated from ECMWF analyses of temperature, humidity and cloud.

Figure 5.8: Comparison of limb path transparencies at IR (12 μm) and millimetre (300 GHz, ~ 1 mm) wavelengths. Annual mean percentage probabilities of transmittance > 0.03 calculated from ECMWF analyses of temperature, humidity and cloud are shown as functions of latitude and tangent-height. [Figure courtesy of R. Siddans]

1 The MWLS will also observe methyl chloride (CH₃Cl) in the upper troposphere and lower stratosphere, and the additional halogen compounds chlorine monoxide (ClO), bromine monoxide (BrO) and methyl bromide (CH₃Br), although large-scale averaging will be required if their concentrations are not enhanced.
2 The IRLS will also observe SF₆, CFCs and HCFCs, as additional tracers of atmospheric motion on a range of different timescales in the stratosphere.
3 Cloud liquid and ice properties have been down-scaled from the ECMWF model grid by adopting a power-law distribution and re-sampled on a finer vertical and horizontal grid to simulate more realistically distributions along limb-paths, while conserving ice and liquid-water content within ECMWF model grid boxes.
At millimetre-wavelengths, penetration is controlled by water vapour attenuation. Retrievals (of adequate precision and accuracy for all gases) are generally confined to water vapour mixing ratios < 1000 ppmv, and effectively therefore to the upper half of the troposphere.

In infrared windows, tropospheric penetration is limited principally by clouds. In the absence of cloud, IR limb-sounding extends down to about 3 km at mid-latitudes and about 10 km in the tropics. The azimuth range of the IRLS covers 300 km across-track. Within this swath 4 (chemistry mode) or 13 (dynamics mode) independent view directions are observed continuously, which significantly increases the probability of viewing between clouds.

For water vapour (H₂O), ozone (O₃), nitric acid (HNO₃), nitrous oxide (N₂O) and formaldehyde (HCHO) to be observed globally at both IR and mm-wave, the combination of the two data sets is therefore optimal. This is also the case for observations of HCN in plumes from tropical biomass-burning and boreal forest-fires.

5.4.2 Combination of IRLS and MWLS observations in practice

For PREMIEER’s scientific objectives, the value of the combination of IRLS and MWLS is greater than the sum of its parts, and increases substantially for observations of a common airmass. Optics and detector arrays for IR are sufficiently compact to image atmospheric limb emission continuously (in the vertical × across-track plane) by staring forwards or rearwards along-track. The mission requirements for vertical-resolution drive antenna size at millimetre-wavelengths, and the sizes of diffraction-limited quasi-optical elements and receivers inherent to millimetre-wave detection are large by comparison to IR. The MWLS configuration is a novel, compact vertical array to view fourteen tangent-heights simultaneously in the orbit plane (sets of seven elevation angles in each of two orthogonal polarisations). Although additional azimuth angles could be viewed, sharing of observation time would imply loss in radiometric sensitivity, and beam shape and width would degrade with off-axis angle. Therefore the increases in complexity, size, mass and power needed to achieve 3D millimetre-wave limb imaging would not be justified.

The IRCI will provide 3D cloud information on spatial scales finer than the vertical and horizontal beam widths of the MWLS receiver array and their along-track sampling (Sections 5.2.2 & 5.3.2) for screening and representation of partially-cloudy views in radiative transfer.

The MWLS offers the capability to see through aerosol and most ice clouds, therefore providing information on constituent distributions in the upper troposphere and lower stratosphere in most atmospheric conditions. For cloud-free limb-views, the IRLS will enhance this information and extend it to lower altitudes and across-track.

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4 Water vapour continuum and line absorption limits penetration into the lowest troposphere, with exception of arid polar latitudes.
The optimal configuration for PREMIER is therefore: mm-wave limb-sounding in the orbit plane combined with IR limb-sounding at multiple azimuth angles, including the orbit plane, from a common platform and in the same direction along-track (ie forwards or rearwards). The two sensors will then observe the same air mass simultaneously. To exploit the synergies outlined above, requirements placed on \textit{a posteriori} knowledge of their colocation (0.5–1.0 km vertical, 12.5 km horizontal) are comparable to those for the two IRLS wavelength bands, though it is not necessary to place stringent requirements on pointing control of the two sensors because their data will be processed sequentially.

5.5 Synergies between PREMIER and nadir observations of MetOp and other operational missions

5.5.1 EPS-MetOp and post-EPS

Nadir observations have comparatively low vertical resolution but, in absence of cloud, can see down to Earth’s surface, and therefore complement PREMIER’s limb-profiling of the mid/upper troposphere and lower stratosphere (Figure 5.1).

EPS-MetOp offers the most powerful suite of nadir-sounders for atmospheric composition to fly in the PREMIER time-frame. As MetOp is an operational system, it can be relied upon\textsuperscript{5}. To exploit this synergy to the fullest extent, it is therefore planned to fly PREMIER in (loose) formation with MetOp, with clocated limb tangent-points and nadir views. MetOp therefore constitutes a second \textit{mission element}.

Colocated observations from the nadir-sounders on EPS-MetOp in a sun-synchronous orbit with 9:30 am equator crossing times will be used to significantly enhance the scientific return from PREMIER:

- Trace gas profiles retrieved in the mid troposphere and above from PREMIER data will be extended into the lower troposphere through combination with EPS-MetOp data.
- Vertical profiles from PREMIER will, in return, improve substantially on the height-resolution and accuracy of the MetOp nadir-sounders (Sections 2.2.2.2 & 4.4), which will enhance the value of that mission.

An integrated processor will utilise the following data from MetOp in radiative-transfer modelling for PREMIER:

- Cloud, aerosol and surface properties from AVHRR/3,
- Temperature and humidity profiles from IASI and AMSU-A/MHS,
- IASI data for O\textsubscript{3}, CO, CH\textsubscript{4} and HNO\textsubscript{3},
- GOME-2 data for O\textsubscript{3}, NO\textsubscript{2}, H\textsubscript{2}CO and aerosol.

\textsuperscript{5} The post-EPS mission to follow EPS-MetOp is planned to fly in the same sun synchronous orbit and incorporate advanced sensors equivalent to IASI, GOME-2 and AVHRR/3 (IRS, Sentinel-5 UVNS and VII).
MetOp data on other trace gases would also be used in scientific exploitation of PREMIER through assimilation and other means.

EPS-MetOp will be superceded by EUMETSAT’s post-EPS mission. It is currently expected that the first post-EPS satellite will be launched around 2019 into the same polar orbit as MetOp and will embark IRS, UVNS (GMES Sentinel-5) and VII, advanced versions of IASI, GOME-2 and AVHRR/3, respectively, together with other sensors.

5.5.2 Operational missions additional to EPS-MetOp

The scientific return from PREMIER will be enhanced further by utilising higher-level data available from nadir-sounders flying on operational satellites in addition to EPS-MetOp. Information from these missions will be used opportunistically and is not required to achieve the mission objectives identified in Chapters 2 and 3. So, unlike EPS-MetOp, these are not mission elements. They potentially include: the GMES Sentinel-5 precursor mission flying in an afternoon polar orbit; the Sentinel-3 mission (height-integrated aerosol) in a 10:00 am polar orbit; MSG or MTG-I/MTG-S in geostationary orbit; US NPOESS satellites flying in 1:30 pm and 5:30 pm (aerosol only) polar orbits and potential geostationary satellites of US and other international agencies.

5.6 Data utilisation and user community

5.6.1 Introduction

The PREMIER mission will observe atmospheric composition in the height range of prime importance to climate by virtue of cooling to space and on spatial and temporal scales commensurate with the chemical and physical processes that determine variations in this region. Data products from PREMIER, summarised in Table 4.1 (and footnote), will be used to address the science objectives outlined in Chapter 2 and summarised in Chapter 3. The importance of these data is recognised by the atmospheric and climate modelling communities, reflected by the widespread support of the original PREMIER proposal. The synergy between PREMIER and MetOp instruments will permit the integrated data set to be used by the Air Quality (AQ) community to improve AQ forecasts and estimates of emission sources and by the numerical weather prediction community for process studies and improvement of wind estimates.

PREMIER activities will be fully integrated with European GMES activities in support of the international Global Earth Observation System of Systems (GEOSS). Data utilisation will also be emphasised within national activities of individual European member states. For example, the UK Natural Environment Research Council (NERC)

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6 On the NPOESS Preparatory Platform (NPP), OMPS will measure solar shortwave radiation scattered from the limb as well as from the nadir direction. If this capability is realised also on NPOESS, this would complement the PREMIER limb-emission sounders by profiling stratospheric aerosol under background conditions as well as in volcanically enhanced levels in which it would be observed by IRLS.
has recently established the National Centre for Earth Observation (NCEO) that brings together researchers across the UK in order to develop a coherent research strategy for the development and utilisation of current and future EO data. By virtue of PREMIER science activities the data and discoveries will automatically contribute to international activities such as IPCC\textsuperscript{7}, WCRP\textsuperscript{8}, IGAC\textsuperscript{9} and SPARC\textsuperscript{10}.

5.6.2 Scientific exploitation

In general, data usage by the science community will be enhanced through efficient data archival facilities. Currently, such facilities provide tools to visualise data products with global and/or regional domains, which both improve ease of use and encourage communities with less experience in satellite data to use data products. In the future we anticipate more sophisticated tools will be available.

Stratospheric meteorological and chemical data from satellites has long been used for dynamical and chemical process studies (Chapter 2) as well as for data-assimilation studies (Section 5.6.3). Utilisation of IRLS and MWLS data also has an extensive heritage from exploitation of data from Envisat MIPAS, Odin SMR, Aura MLS and earlier limb-emission sounders (see Section 2.3). In addition, recent work on retrieval algorithms has been pushing retrieval systems to probe the upper troposphere (Section 2.3.2). The across-track observations of PREMIER will literally bring a new dimension to these studies of the UTLS. In addition, it will also bring a new perspective and synergies with future possible in situ airborne campaigns using balloons or high-flying research aircraft.

SPARC recently established an initiative to improve the gravity-wave momentum-budget for general circulation studies. By providing new global measurements of gravity-wave momentum flux on the meso-scale, PREMIER will support these activities that aim to improve the predictive capabilities of global general-circulation models.

Currently, the UTLS user community has only a few satellite limb viewing instruments that have the capability of sensing this region (Section 2.3) and then only with relatively coarse spatial and temporal resolution. There are a number of outstanding science questions associated with understanding variability of water vapour, CH\textsubscript{4} and O\textsubscript{3} in the UTLS (Chapter 2) that cannot be addressed with current space-based sensors. Extensive EU investment in large integrative projects such as the FP6 Stratospheric-Climate Links with Emphasis on the UTLS (SCOUT-O\textsubscript{3}) reflect the widespread recognition by the UTLS community of the need for high-quality measurements that will be provided by PREMIER. The tomographic measurement approach of PREMIER will enable unprecedentedly detailed statistical analyses of chemical and dynamical/transport processes, which will provide a solid basis for testing next-generation Chemistry-Climate Models. This will lead to

\textsuperscript{7} Intergovernmental Panel on Climate Change (IPCC).
\textsuperscript{8} World Climate Research Programme (WCRP).
\textsuperscript{9} International Global Atmospheric Chemistry (IGAC).
\textsuperscript{10} Stratospheric Processes and their Role In Climate Change (SPARC).
improvements in parameterisations of physical, chemical and dynamical processes, with far-reaching implications for reproducing past trends and forecasting future impacts. PREMIER measurements will contribute to model evaluation activities similar to the current SPARC Chemistry-Climate Model Validation (CCMVal) activities and the joint IGAC/SPARC activity Atmospheric Chemistry and Climate initiative (http://www.igac.noaa.gov/ACandC.php).

As discussed in Section 2.2, PREMIER will contribute to many areas of tropospheric and lower stratospheric science such as long-range transport of air pollution, transport by the Asian Monsoon, and biomass burning (including pyroconvection), an important but poorly-quantified part of emissions from the terrestrial system. For example, PREMIER will measure several tracers of biomass burning (Table 4.1) that will be used to identify enhancements in other trace gases. Burning events that take place between the overpass times of PREMIER, 09:30 and 21:30, will be captured by additional elements of the operations system, for example, Sentinel-3 (10:00, 22:00) Sentinel-5 (afternoon), NPOESS (01:30 and 13:30), and geostationary platforms such as MSG and MTG/Sentinel-4. Synergy with MetOp sensors, in particular GOME-2 and IASI, will effectively provide concurrent information about the lower and upper troposphere, which can be used to determine vertical mass redistribution from rapid convective processes due to surface fires.

The stratospheric and tropospheric communities have tended to evolve independently, but recently a more integrated view has begun to emerge as new measurements span the vertical regions and coupled stratosphere-tropospheric models become common with increasing computer power. The next IPCC report will begin to evaluate results from coupled models that include a comprehensive treatment of stratospheric and tropospheric chemistry. Similarly, the spatial resolutions of global CTMs are increasing to the point where cloud-resolving models can be included over the next decade. Data from PREMIER will play an invaluable role in constraining these future models.

5.6.3 Data assimilation

Data assimilation is increasingly used in the atmospheric community to generate consistent analyses based on a combination of observations from different sources to generate the most complete representation of the atmosphere. The method also allows a stringent evaluation of the performance of numerical models compared to observations. The process of data assimilation was originally developed for Numerical Weather Prediction (NWP), to provide a best estimate or ‘analysis’ of the atmospheric state with which to initialise a numerical weather forecast model by optimally blending observations, short-term forecasts, and information on the atmospheric behaviour (for example, Daley 1993). During the assimilation, all observations are compared to a short-term forecast, and knowledge of the typical errors in the observations as well as the short-term forecast is used to calculate the final analysis.
Today, assimilation systems are used for increasingly complex models of the Earth System, including for models of the Earth’s chemical composition. A number of NWP centres and other research groups in Europe and elsewhere have demonstrated capabilities to assimilate temperature, humidity, ozone, and other chemical species information in the UTLS region (for example, Feng et al., 2008, Lahoz et al., 2007, Bormann and Thépaut 2007, Vigouroux et al., 2007, Geer et al., 2006, Wargan et al., 2005, Khattatov et al., 2000). These groups have demonstrated significant advances in their analyses from the assimilation of MLS and MIPAS data. Building on the positive experience with MIPAS or MLS data, these groups will use PREMIER data to further improve their analyses and their understanding of the UTLS region.

The power of data assimilation is threefold: Firstly, data assimilation allows a statistically optimal combination of various observations with different quality, coverage or other observational aspects. This means the resulting analyses are able to benefit from the high vertical resolution of limb-sounders, the high horizontal resolution and coverage of nadir-sounders, and the high accuracy of the conventional observing network. Data assimilation systems are arguably best-suited to fully explore the synergy between PREMIER observations and METOP or other satellite data, in order to push the boundaries of horizontal and vertical resolution currently observed. Data assimilation systems are also used to generate consistent reanalyses of past records, particularly useful for process studies (for example, Uppala et al., 2006).

Secondly, data assimilation continuously and quantitatively evaluates the consistency between numerical models, observations, and our knowledge about the errors in both on the time-scales considered in the assimilation. Improvements in the model or the assimilated observations tend to be associated with smaller differences between the short-term forecast and the observations. Data-assimilation systems are therefore expected to demonstrate in an integrated way the benefits from PREMIER either through enhancements to model processes or through the provision of observations of previously unavailable detail in the UTLS region.

Thirdly, and related to the above, data-assimilation systems provide a powerful tool to evaluate new observations, for instance during the calibration/validation phase. New observations are usually first monitored passively against the short-term forecast or the analysis, therefore effectively enabling comparisons to other observations which are not necessarily coincident with the new data. For example, data assimilation has recently provided key information to identify and correct anomalies in SSMI/S data arising from instrument anomalies (Bell et al., 2007). Similarly, data-assimilation techniques will be used for PREMIER to soundly establish the realism of observations or derived products, a crucial first step before advanced capabilities of the observations can be used.
5.6.4 Demonstration of operational applications

By taking advantage of the PREMIER data provision and timeliness for operational applications, PREMIER also serves as a demonstrator for the limb-sounding component of a much-needed operational atmospheric-chemistry observatory. Currently, no operational mission exists or is planned that provides the vertical resolution, global coverage, and comprehensive list of target species necessary for operational monitoring or forecasting of the key species of the atmosphere’s composition. Given the changing composition of the Earth’s atmosphere and its effect on climate, such operational monitoring will be essential in the future. This has also been recognised in international initiatives (WMO, CEOS, IGOS/IGACO), and in the definition of the EU/ESA GMES Sentinel and Eumetsat post-EPS (2019 onwards) programmes in Europe. In line with this, integrated operational applications of atmospheric-chemistry data are likely to expand in the next decade, and demonstrators of key European components of future operational systems to monitor atmospheric composition will be crucial in the 2010–20 period.

In the post-2015 timeframe, two operational applications will particularly benefit from PREMIER data: operational systems designed to monitor and forecast the atmospheric composition, such as air-quality forecasting, and NWP. As an example for the former, the GEMS/MACC system (Section 2.3.5) is expected to provide operational real-time global analyses of long-lived greenhouse gases (for example, CO₂, CH₄, in addition to H₂O and O₃), other reactive gases (for example, NOₓ, CO, SO₂ and HCHO), and aerosols in the troposphere and stratosphere. For NWP, PREMIER data is expected to be used to refine model processes (for example, gravity-wave or radiation parameterisations) and to improve initial meteorological conditions in the UTLS. For example, improved analyses of the temperature-tropopause location can be crucial for forecasting the intensification of mid-latitude weather systems. In addition, improved stratospheric analyses offer some potential for improved extended-range time-mean tropospheric weather forecasts (beyond 1–2 weeks, for example, Baldwin et al., 2003, Thompson et al., 2002, Charlton et al., 2004). Apart from providing a demonstration for the operational use of PREMIER data, the integration of PREMIER data products with such operational applications will maximise the benefits from the PREMIER mission.

5.6.5 Data validation

Validation of the innovative PREMIER instruments providing unprecedented spatial resolution will be both crucial and challenging. It needs to be based on correlative data from airborne instruments that are equivalent or even superior in terms of spatial resolution and precision/accuracy. Correlative data sets that meet these requirements may become available from in situ instruments operated on high-flying aircraft based on dedicated flight patterns. Such campaigns will need to be planned for geophysical situations where high spatial variability can be expected (as in connection with tropopause folds, etc.). Those experiments might be able to provide data that are measured with completely independent techniques at comparable spatial resolution and coverage.
Another important component of the validation will be the use of PREMIER-like instruments (for example, GLORIA-AB, MIPAS-B) operated from aircraft and balloons. Such measurements can be used even for the validation of Level 1 data. In addition, balloon measurements, the backbone of the Envisat-MIPAS validation, should be extensively used for correlative measurements. To validate vertical temperature structure associated with gravity-waves, lidar and rocket-sonde data will be used. Hemispheric distributions of momentum flux in the lower stratosphere will be compared to values derived from super-pressure balloons.

From a statistical view, satellite-satellite intercomparisons have also proven to be useful for identifying biases. However, the spatial resolution of PREMIER has to be downgraded for such comparisons with other satellite sensors. As in the Envisat-MIPAS case, PREMIER validation activities have to be planned well before launch addressing all important issues such as prelaunch activities, self-consistency tests, identification of suitable validation techniques, selection, planning and execution of suitable validation campaigns, database, and management.

As described in Section 5.6.3, data-assimilation systems will provide another way to validate PREMIER data.
Chapter 6  System Concept

6.1 Introduction

This Chapter provides the technical description of the PREMIER mission as derived from the preparatory activities at Phase 0 level, for implementation as an Earth Explorer in the frame of ESA's Living Planet Programme. It shows how candidate implementation concepts can respond to the scientific mission requirements defined in the previous Chapters. To this end, the expected system performance at Level 1b will also be described.

The system description is mainly based on the results of the work performed during parallel Phase 0 system studies by two industrial consortia (EADS Astrium GmbH, 2008; Thales Alenia Space Italy, 2008). When necessary, two concepts are described in order to present significantly different approaches capable of meeting the mission requirements. This applies to all elements of the mission architecture with the exception of the Millimetre-Wave Limb Sounder (MWLS) instrument, which is based on the STEAMR concept being developed by the Swedish Space Corporation in the frame of a Swedish nationally-funded programme. In accordance with the PREMIER proposal, the programmatic scenario assumes that the STEAMR instrument will be provided as a Swedish national contribution to the PREMIER mission.

After an overview of the mission architecture and the proposed orbit (in Sections 6.2 and 6.3) the space segment is described in detail (Section 6.4), followed by the ground segment and operations concept (Sections 6.5 and 6.6). The overall mission performance is described in Section 6.7.

6.2 Mission architecture overview

The main elements of the PREMIER mission architecture are depicted in Figure 6.1.

The space segment consists of a single satellite carrying the Infra-Red Limb Sounder/Infra-Red Cloud Imager (IRLS/IRCI) and the Millimetre-Wave Limb Sounder (MWLS). The satellite flies in the MetOp orbit ahead of the MetOp satellite in a rearward limb-viewing configuration, so to achieve the required co-registration between the PREMIER limb soundings and MetOp nadir observations.

The baseline Vega launcher will inject the spacecraft into its target orbit. The PREMIER satellite is also compatible with a launch by Rockot, Dnepr and PSLV, considered as back-up launchers.

The structure of the PREMIER Ground Segment follows the generic Earth Explorers Ground Segment Infrastructure and is composed of:

- The Flight Operation Segment (FOS), which includes the TT&C Ground Station and the Flight Operations Control Centre;
The Payload Data Ground Segment (PDGS), which includes the Science Data Acquisition Station, the Processing and Archiving Element and the Mission Planning and Monitoring Element.

6.3 Orbit

The selection of the orbit for the PREMIER mission is driven by the need to provide temporally and spatially co-registered observations between the PREMIER limb-observing instruments and the MetOp nadir-viewing ones.

PREMIER will therefore fly in the MetOp sun-synchronous orbit at a reference altitude of 817 km, with Local Time of Descending Node (LTDN) at 09:30. To fulfill the co-registration geometric constraints, PREMIER flies in a loose formation with MetOp, with a true anomaly shift corresponding to a temporal separation of about eight minutes, Figure 6.2.

The PREMIER satellite is subject to the same orbit-control strategy as MetOp, following the same sequence of orbit control manoeuvres. The MetOp orbit-control manoeuvres sequence consists of in-plane manoeuvres every 1.5 months for combined altitude and ground track control and of out-of-plane manoeuvres for orbit inclination control at a frequency of one manoeuvre every 16–18 months.

Depending on the differences in ballistic coefficient between the PREMIER and the MetOp satellites, PREMIER might require additional in-plane manoeuvres of
small magnitude, beside those driven by the MetOp sequence, in order to maintain
the two satellites within a control box dictated by the relevant co-registration
requirements. The size of the control box (longitudinal displacement around the
nominal position) is about ± 450 km for the goal temporal co-registration of 1 min.
and about ± 2200 km for the threshold temporal co-registration of 5 min.

The maximum eclipse duration for the selected orbit is about 32 min.

6.4 Space Segment

The PREMIER space segment consists of a single satellite carrying the Infra-Red
Limb Sounder/Cloud Imager (IRLS/IRCI) and the Millimetre-Wave Limb Sounder
(MWLS). The satellite configuration is driven by the accommodation of the sensor
suite, which requires free rearward looking FOV for limb observation as well as a
free-space view for calibration purposes. Additional constraints arise from the need
to protect the front side of the MWLS reflector from direct exposure to the sun and
from the need to accommodate sufficient radiating surfaces facing deep space.
The proposed satellite concepts present different solutions to the configuration
constraints mentioned above. The most significant differences are outlined in the
following sections of this document.

Following the payload concepts description in Subsection 6.4.1, the satellite
platform is described in Subsection 6.4.2 and is complemented by the description
of the overall satellite configuration and budgets in Subsection 6.4.3.
6.4.1 Payload

Overview

The payload complement of PREMIER consists of two instruments observing the limb of the Earth:

- The Millimetre-Wave Limb Sounder (MWLS)
- The Infra-Red Limb Sounder/Cloud Imager (IRLS/IRCI)

Figure 6.3 summarises the spatial requirements, illustrating the various geometries of the nested observation patterns of the two instruments.

The instrument observations are co-registered to high accuracy, with the most stringent requirement being the 10 m vertical registration of the pixels of the IRLS and IRCI, which gives a compelling reason to merge the IRLS and IRCI functionalities in a single instrument. The required vertical co-registration knowledge of 500 m (goal) between the MWLS and the IRLS/IRCI imposes an optimised design involving the mounting of the instruments and the attitude sensors on a common structure.
6.4.1.1 Millimetre-Wave Limb Sounder (MWLS)

The MWLS concept description is based on the STEAMR instrument concept being developed by the Swedish Space Corporation in the frame of a dedicated Swedish National Programme.

Observation principle

The STEAMR instrument is designed to provide spatially well-resolved (1–2 km vertically and 50 km horizontally) information on the distribution of Upper Troposphere/Lower Stratosphere (UTLS) key constituents such as water vapour, ozone and carbon monoxide on a global scale using bands in the 310–360 GHz spectral region. The STEAMR measurement concept is based on tomographic multi-beam limb sounding in the orbital plane using Schottky-diode heterodyne detectors. The instrument observes the limb at 14 tangent altitudes simultaneously, with a staring-view concept.

The altitude spacing between the imaging elements varies from 1.5 km at the lower end to 2 km at the higher altitudes, as shown in Figure 6.4. Appropriate satellite
attitude guidance follows the variation of the tropopause altitude with latitude and across the seasons.

Simulations have shown that Double SideBand (DSB) operation could be used for all altitudes, but separated Single SideBands (SSB) are the baseline for the lowest part of the atmosphere (below 18 km) since this is expected to deliver more robust retrievals in this altitude range. The double sideband operation for all altitudes remains a fallback option.

**Instrument overview**

A layout of STEAMR is presented in Figure 6.5. An offset antenna system receives thermal radiation from the atmospheric limb. Additional optical elements fold the path and refocus the beams on the focal plane. Calibration devices can be viewed by rotating a switch mirror close to the secondary aperture stop.

![Figure 6.5: STEAMR (MWLS) conceptual layout.](image)

A second rotating mirror selects the calibration source: one out of two cold-sky views, a temperature-controlled warm load or a sideband filter to calibrate the sideband ratios.

Polarisation splitting is used to slightly overlap the beams, see Figure 6.4. Individual mirror-horn combinations couple the signals into the waveguides of the 14 sub-harmonically pumped Schottky mixers integrated with the low noise amplifiers. The down-converted signals in the 9 to 21 GHz spectral region are distributed, after amplification, to a set of autocorrelation spectrometers, divided into six separate units to simplify the thermal control.
Quasi-optics

The high-frequency part of the instrument makes use of a set of mirrors to collect the radiation and to couple it into the mixer waveguides. The telescope structure and its reflectors are made of highly stable Carbon Fibre Reinforced Plastic (CFRP) whereas diamond-turned aluminium is used inside the instrument. A Ritchey-Chrétien design has been selected as a baseline for the antenna as it features superior side-lobe suppression performance for off-axis beams and is therefore highly suitable for array feeds.

The baseline primary reflector measures 800 × 1600 mm with a surface accuracy of 10 µm RMS. This accuracy could be relaxed at the expenses of higher side-lobe levels but it is preferred to keep the side-lobe level below the knowledge requirement to improve the in-orbit calibration accuracy.

The overall structure and accommodation of STEAMR is shown in Figure 6.6. The telescope support structure must minimise the deformations caused by temperature variations and gradients. As a baseline a CFRP tubular frame support structure has been selected.

![Figure 6.6: STEAMR (MWLS) back/top view structure and accommodation.](image)

Calibration devices

A rotating chopper interrupts the path from the mixers to the beam-adjusting mirrors. A lightweight, flat Mylar mirror is mounted directly on the axis of a redundant-drive stepper motor, which places the reflecting mirror into the beam path. A slower device, the switching mirror, provides two cold-sky directions (to avoid viewing the Moon) and a warm calibration-load. The self-emission of optical
components before the switching mirror can be estimated by observing deep space via the telescope.

It is planned to include a source for the in-orbit measurement of the relative sideband ratio. A tuneable four-port non-polarising Michelson interferometer or a tuneable line source with a high-frequency power detector are being considered. The latter provides only a relative calibration but this is sufficient for determining the sideband ratio.

Mixers and amplifiers

STEAMR uses the concept of the KOSMA 340 GHz array (Lüthi et al., 2005), although not with the same physical design. The KOSMA design achieved a combination of well-controlled beam shape and close packaging: the array was spaced by 3.6 beam waists translating, in our case, to 5.2 km at the limb. The fact that the mirrors and horn holders are machined from the same block gives very-high alignment stability. This approach allows the making of the required mirror-shape corrections on an individual beam basis.

The baseline mixers are passively-cooled sub-harmonically pumped Schottky mixers, all using air-bridged planar diodes and integrated Low Noise Amplifiers (LNA). The Local Oscillator (LO) is also mounted as close as possible to the mixers, but is thermally decoupled to simplify the thermal control of the mixers and amplifiers at lower temperature. Should the sideband rejection mixer design not reach adequate performance, the backup solution is to use only DSB mixers. The power consumption of each LNA and mixer unit is approximately 100 mW.

For the LO unit, a combination of frequency multipliers and power amplifiers is used, offering good reliability. The LO unit could consist of a frequency-multiplied Yttrium Iron Garnet source with power amplifiers and is expected to deliver around 250 mW at about 40 GHz.

Back-end spectrometers

The back-ends are required to select and process the frequency regions surrounding the molecular lines of interest, synchronised to instrument pointing and reference switching. The 340 GHz region requires a bandwidth of 12 GHz. Given the large bandwidth, special consideration must be given to the power consumption and dissipation in the design of both the IF chain and the spectrometers.

For STEAMR, four spectrometers are dedicated to $2 \times 12$ GHz Lower-SideBand (LSB) and $2 \times 12$ GHz Upper-SideBand (USB) channels, whereas two spectrometers are dedicated to $3 \times 12$ GHz DSB channels, see Figure 6.7. The spectrometer Application-Specific Integrated Circuits (ASIC) used for DSB and SSB are identical, apart from the number of processed inputs.
Chapter 6: Six Candidate Earth Explorer Core Missions

6.4.1.2 Infra-Red Limb Sounder and Cloud Imager (IRLS/IRCI)

Observation principles

The IRLS/IRCI instrument is a Fourier-transform spectrometer combining the functions of spectrometry and imagery. The IRLS provides two mutually-exclusive measurement modes, the Atmospheric-Chemistry Mode, featuring the highest spectral resolution to observe minor trace gases, and the Atmospheric-Dynamics Mode. The IRLS/IRCI observations are performed using views of cold space and of an on-board warm load to determine the signal scale. The calibration against the warm load, or reference loads, is carried out about once per minute. The pointing calibration takes place when the Moon passes through the orbital plane, thus about twice per month. The cold-space signal offsets and sideband ratios are measured during initial check out and later, when required, to maintain the in-orbit performance. The special calibration measurements generate a database for monitoring changes in instrument characteristics for use in the Level 1 and 2 processing.

Calibration

In-orbit radiometric calibrations are performed using views of cold space and of an on-board warm load to determine the signal scale. The calibration against the warm load, or reference loads, is carried out about once per minute. The pointing calibration takes place when the Moon passes through the orbital plane, thus about twice per month. The cold-space signal offsets and sideband ratios are measured during initial check out and later, when required, to maintain the in-orbit performance. The special calibration measurements generate a database for monitoring changes in instrument characteristics for use in the Level 1 and 2 processing.
Mode, providing a higher spatial resolution in order to resolve the finer atmospheric structures. The IRCI must work continuously, acquiring images at high spatial resolution in the same spectral ranges as the IRLS but at reduced spectral resolution (10–20 cm$^{-1}$).

The spectral range of the IRLS covers two bands: band A (770–980 cm$^{-1}$ or 10.2–13 µm) and band B (1070–1650 cm$^{-1}$, 6.0–9.4 µm). The spectral resolution is 0.2 cm$^{-1}$ and 1.25 cm$^{-1}$ in the chemistry and dynamic modes, respectively.

The IRLS measures limb radiance at vertical spatial-sampling intervals of 2 km and 0.5 km, in the chemistry and dynamics modes, respectively. The goals for the across-track and along-track sampling distances are 80 km × 100 km and 25 km × 50 km, respectively. The radiometric requirements are expressed as Noise-Equivalent Spectral Radiance (NESR) at the input of the instrument, in absence of external signal. A dynamic range equivalent to a blackbody with a temperature up to 240 K has to be covered.

The required spectrometric functions of IRLS and IRCI and the compatible spatial-sampling and coverage requirements justify the selection of a common Fourier-transform spectrometer, providing the highest spectral and spatial resolution required by the different measurement modes of the IRLS and the IRCI. Spectral and spatial processing of samples will produce the Level 1 products at the various required sampling intervals and resolutions.

*Instrument overview*

A functional overview of the instrument is presented in Figure 6.8.

Radiance from the limb enters the instrument via a pointing mirror, which is also used to view cold space and a flat or cavity blackbody for calibration. After beam size adaptation in the afocal telescope, a Michelson interferometer produces interferograms, which are acquired by two detector arrays after band splitting by a dichroic filter. A laser metrology system, using a diode laser or a Nd:YAG laser, monitors the path difference between the two arms. The detectors are cooled to 55 K with Stirling-cycle or pulsed-tube coolers, with the possibility of operating the band B detectors at a slightly higher temperature.

Various options have been investigated to find an optimised architecture for the instrument. The requirements for flexible acquisition of spatial samples at various resolutions, over a large spectral range, suggest an imaging Fourier transform spectrometer where the limb is imaged on a 2D detector array. Configurations with and without telescope have been traded. A beam-reducing afocal telescope has been finally selected as it simplifies the instrument without penalising the radiometric performance, and it reduces the size of the interferometer. A single-port interferometer was selected because the radiometric advantage of a two-port interferometer is not worth the complexity of two large co-aligned Focal-Plane Assemblies. The stroke of the interferometer needed to reach the resolution
required by the chemistry mode (1.25 cm per arm for bilateral interferograms) is small enough to allow considering a simple mechanism. Both concepts use a double-pendulum interferometer, realising the variation of optical path by rotation of two corner cubes located on a ‘V-shaped’ scan arm, actuated by a frictionless motor (for example, voice coil) using flexural pivots. This type of interferometer, with similar requirements, has already been built for flight in space (for example, ACE/SCISAT, TANSO/GOSAT), as illustrated in Figure 6.9.
The detectors are long, rectangular 2D arrays of HgCdTe diodes hybridised on a Complementary Metal-Oxide Semiconductor (CMOS) read-out circuit, using technologies similar to those being developed for the Meteosat Third Generation (MTG) programme. The format is identical in both focal planes, with each detector array featuring an aspect ratio of about 6:1 and about 100 vertical pixels covering the vertical range of 50 km at a vertical sampling distance of 0.5 km. Across-track pixels are binned on-chip to limit the frequency of the output amplifier and to minimise the read-out noise.

Figure 6.10 depicts two concepts of the instruments, showing in particular the entrance telescope, the interferometer, the detector cryostat and the mechanical coolers.

In each of the two modes of the IRLS, the interferometer is operating with a path difference corresponding to the required spectral resolution. On-board interferogram processing consists of offset and non-linearity corrections, re-sampling taking into account the data from the laser path-difference monitoring system, correction for off-axis frequency offset and truncation to the spectral resolution required by the IRCI.

Off-chip co-addition of interferograms to achieve the required across-track and along-track resolutions are performed after these corrections. In the atmospheric-dynamics mode and for the IRCI, no vertical co-addition is performed, to retain the full vertical resolution. Data-rate reduction is also achieved by filtering the interferogram to the useful bandwidth and subsequent decimation.

The Fourier transform of the interferograms is computed on ground. Additional on-ground processing includes calibration, using the spectra acquired by observations of deep space and of the on-board blackbody. Further spectral calibration can be achieved using strong lines of scene spectra and field-of-view calibration can be performed with observations of stars or planets. It is expected that the latter mode will rarely be required.
The performance analyses have shown that an instrument utilising the on-going technological developments, particularly for hybrid HgCdTe (MCT) detectors, can meet the radiometric requirements with an entrance aperture of about 7 cm, although with little margin. The use of more conservative assumptions more than doubles the aperture and increases the overall instrument mass from 160–230 kg.

The data rate of the instrument depends on the extent of on-board decimation/filtering processing, the use of compression schemes and the extent of co-addition. With an optimised data-reduction strategy, the data rate can be limited to about 15 Mb/s.

6.4.2 Platform

The satellite platform concepts have significant heritage from satellite systems under development in the frame of already approved Earth Explorer missions (ADM Aeolus, EarthCARE), of GMES Sentinels and other national missions (TerraSAR X, PRISMA, Odin). From the initial assessment of the requirements applicable to the platform subsystems, a significant reuse of equipment already existing or under development is foreseen.

Structure

The platform structural concept is based on a central cylinder providing the main load path to the launcher and supporting the propellant tanks.

The central cylinder is connected to four lateral panels, which support the accommodation of the platform equipment and the thermal radiators, via four shear panels. The main differences between the two concepts defined in the course of the studies are the accommodation of the payload on the spacecraft bus and the solutions identified to protect the MWLS antenna from direct sun exposure, Figure 6.11.

Figure 6.11: PREMIER structural concepts A (left) and B (right).
In Concept A, three of the lateral panels are extended to provide a common support structure to the instruments on the sun-shaded side of the platform. To protect the MWLS reflector from the sun, deployable sun-shields are used (see Section 6.4.3). Concept B is based on a more traditional box-shaped concept with the instruments accommodated on the upper panel and the sun shading achieved by means of dedicated panels visible on the top right corner of the platform. In Concept A, the low thermo-elastic stability performance of the payload support structure requires the accommodation of dedicated attitude sensors close to each instrument in order to achieve the instrument Line-of-Sight (LOS) knowledge performance required to meet the inter-instrument co-registration knowledge requirements (500 m as a goal).

**Thermal control**

The requirements for the platform thermal control are not critical and are fulfilled by a ‘standard’ passive thermal-control design based on Multi-Layer Insulation (MLI) and radiators. Heaters are used to maintain the required thermal environment in the cold cases. Sufficient resources in terms of required radiating surfaces are available in the proposed spacecraft configurations.

The IRLS/IRCI and the MWLS have their own dedicated thermal control. The IRLS/IRCI focal plane requires active cooling based on next-generation Stirling coolers or on pulsed-tube coolers, currently under development in the frame of other programmes. The MWLS thermal control requires sufficient radiating surface to dissipate about 240 W. Figure 6.12 provides a view of the possible accommodation of radiating surface on the shaded side of the spacecraft, in addition to the radiators accommodated on the instrument panels.

![Figure 6.12: Radiator (yellow patches) accommodation for instrument thermal control.](image-url)
The thermal control of the MWLS instrument requires further analysis in later phases to confirm the feasibility of a thermal-control system based on passive means, as opposed to an active system which would provide improved thermal stability.

**Power and energy storage**

Electrical power generation is provided by a single-wing deployable solar panel, which rotates around the satellite pitch axis to provide optimum sun illumination. The required power at the solar array is in excess of 2 kW. Triple-junction gallium-arsenide cells are considered as the baseline, leading to a total surface of 9–11 m². The Direct Energy Transfer (DET) power conditioning and distribution approach is suitable for the PREMIER satellite power needs in the selected orbit. Both regulated and unregulated power-bus solutions at 28 V are feasible.

**Data Handling and Transmission**

The command and data handling architecture is based on a single (redundant) onboard computer. The architecture is based on either the CAN or MIL standard buses for communication between the onboard computer and the remote terminal units providing the interfaces with the platform equipment. The SpaceWire bus is assumed for interfacing the instruments with the Payload Data Handling and Transmission (PDHT) subsystem, which consists of the mass memory and the payload data-transmission section.

The payload data transmission is in X-band. The required mass memory and downlink rate are driven by the data volume generated by the IRLS/IRCI instrument. Different options are available depending on the level of on-board processing of the raw instrument data, the implementation of on-board data compression and the selection of the end-to-end communication architecture with regard to the number and location of the ground stations for the payload data acquisition.
A reference solution enabling the transmission of IRLS/IRCI data at the goal sampling resolution to a single ground station requires a 512 Gb mass memory (including redundancy) and a downlink capacity of about 260 Mb/s, assuming on-board lossless compression. Other assumptions about the on-board processing lead to a downlink rate up to 520 Mb/s, which is still compatible with PDHT solutions under development in the frame of the GMES programme.

Figure 6.13 shows a possible PDHT architecture with dual (redundant) downlink channels at 260 Mb/s for a total downlink capacity up to 520 Mb/s.

Telemetry, tracking and command

Telemetry, Tracking and Command (TT&C) functions are implemented via a traditional architecture using S-band communications, consisting of a fully redundant transponder and two isoflux antennas accommodated on the nadir and anti-nadir sides of the platform. The TT&C subsystem will support telecommand uplink at 4 kb/s and telemetry downlink at up to 256 kb/s.

Attitude and orbit control

The PREMIER spacecraft is 3-axis stabilised. The pointing performance requires high-performance attitude sensors and assumes a gyro-stellar attitude estimator to achieve the required pointing-knowledge performance. To meet the inter-instrument co-registration performance the attitude sensors are accommodated close to the instruments in order to reduce the effect of thermo-elastic deformation between the instruments and the sensors.

The main modes of the Attitude and Orbit Control Subsystem (AOCS) are Normal mode, Acquisition and safe mode, and Orbit control mode. In normal mode, reaction wheels are used as actuators together with magneto-torquers for momentum damping. In safe mode, coarse Sun-sensors are used to ensure proper orientation of the spacecraft toward the Sun. In the orbit control mode, reaction control thrusters are used as actuators to provide the required delta-V. Depending on the selected thruster configuration, the out-of-plane manoeuvres might require a rotation of the satellite around the yaw axis to ensure a proper orientation of the thrust vector. The tracking of the seasonal and geographical variation of the tropopause height (see sub-section 6.4.1.1) is implemented by appropriate attitude (pitch) guidance.

The short-term relative pointing performance requires controlling the micro-vibration generated by solar array rotation, the reaction wheels and the active coolers. Specific activities to minimise the micro-vibrations will have to be performed during Phase A. Position, velocity and time data are provided by a GNSS receiver.
Propulsion

The propulsion subsystem provides the satellite with the delta-V required to correct launcher insertion errors and to perform in-plane and out-of-plane manoeuvres. It is also required at the end of life to move the satellite to a lower orbit in order to ensure its re-entry within 25 years.

A mono-propellant system using either hydrazine or high-performance green propellant in a pressurised system operated in blow-down mode is assumed, with two branches (nominal and redundant) of 4 × 1 N thrusters.

6.4.3 Satellite

Configuration

The following pictures show the spacecraft configurations relevant to the two concepts studied. The satellite observes the limb in the anti-velocity direction, minimising possible contamination of the instruments, and is therefore ahead of the MetOp satellite.

![Figure 6.14: PREMIER spacecraft configuration – Concept A.](image)

Concept A, shown in Figure 6.14, is based on a more traditional box-shaped configuration with one lateral panel providing a stiff and stable support for the accommodation of the payload. The attitude sensors are mounted close to the IRLS/IRCI instrument to minimise the effect of thermo-elastic deformation. The satellite maintains an Earth-pointing attitude, with the instruments’ Field-Of-View (FOV) aimed at the limb. The additional panels on the spacecraft lower left corner protect the front part of the MWLS from direct exposure to Sun illumination under all orbital conditions.
Figure 6.15 presents a different configuration for the PREMIER spacecraft. In this case the payload is accommodated on a supporting structure realised by extending three of the side panels that close the box-shaped spacecraft platform. The configuration features deployable sun-shields (heritage from the Swedish Odin mission) to keep the MWLS reflector in shadow.

This configuration is more susceptible to thermo-elastic deformations, therefore each instrument features dedicated attitude sensors mounted on the same supporting structure in order to improve the instrument LOS pointing-knowledge performance. The satellite maintains an off-nadir attitude by about 28° around the pitch axis to point the instrument FOV towards the limb.

**Budgets**

The following tables summarise the main satellite budgets. The range corresponds to the budgets relevant to the two concepts studied during the Phase 0. The payload data-rate of the IRLS/IRCI and the mass-memory sizing correspond to a solution compatible with the downlink of the IRLS/IRCI data at the goal spatial sampling, using on-board compression in addition to interferogram filtering and decimation in order to allow the science data downlink to a single ground station at a rate of about 260 Mb/s.
6.4.4 Launcher

The PREMIER satellite configuration, as shown in Figure 6.16, and its launch mass are compatible with the Vega launcher, with comfortable mass margins. As a back-up, Rockot (marginal), Dnepr and PSLV could be considered.

Figure 6.16: Under fairing (Vega) accommodation of the two PREMIER satellite concepts.
6.5 Ground segment and data processing

6.5.1 General

The PREMIER Ground Segment is based on the infrastructure developed to support the Earth Explorers as well as other ESA missions. It consists of two main components, the Flight Operation Segment (FOS) and the Payload Data Ground Segment (PDGS).

6.5.2 Ground segment elements

The overall PREMIER Ground Segment Architecture is presented in Figure 6.17.

The Flight Operation Segment (FOS) includes the TT&C Ground Station and the Flight Operations Control Centre.

The TT&C Ground Station provides the following main functions:

- House-keeping telemetry acquisition,
- Telecommand uplink,
- Satellite tracking, and
- Data connection to the Flight Operations Control Centre.

For TT&C, an S-band ground station contact once a day is proposed.
During the Launch and Early Operations Phase (LEOP), operations are supported by a dedicated LEOP ground station network. This uses ESTRACK core and enhanced stations where possible (depending on the chosen launch site).

The Flight Operations Control Centre is based at ESOC and will provide the following main functions:

- Satellite monitoring and control,
- Flight dynamics and manoeuvre planning,
- TT&C ground station network control,
- Overall satellite operations planning,
- On-board software maintenance,
- Mission simulation,
- FOS supervision,
- Spacecraft system data distribution, and
- Interface with the launch site for LEOP.

The Payload Data Ground Segment (PDGS) consists of the Science Data Acquisition Station, the Processing and Archiving Element and the Mission Planning and Monitoring element.

The Science Data Acquisition Station is in charge of acquiring the raw payload data and transmitting them to the Processing and Archiving Element. The timeliness goal of three hours (rather than the amount of data produced) drives the concept. No blind orbits are allowed. Use of a station in Svalbard, or some combination of Kiruna with another station, is assumed. The X-band ground stations assumed for PREMIER require a downlink capability in the range 260–520 Mb/s, depending on the on-board processing options selected.

The Processing and Archiving Element and the Mission Planning and Monitoring Element are implemented through maximal re-use of existing ESA Multi-mission Facility Infrastructure elements, and their final location will be selected in later phases.

They provide the following main functions:

- Acquisition of payload data from the Science Data Acquisition Ground Station(s),
- Acquisition of required ancillary data from appropriate providers,
- Generation and quality control of calibration, Level 1 and higher level products,
- Long-term archiving of mission products and related auxiliary files and reports,
- Implementing the payload planning strategy (routine and calibration) and forwarding it to the FOS,
• Instrument/mission performance monitoring,
• Systematic and on-request distribution of mission products to the user community, and
• Provision of user services.

The specific processing needs of the PREMIER mission are described in the following section.

6.5.3 Data Processing

**MWLS**

The Level 0 data consist of raw instrument data in the form of autocorrelation functions together with the associated housekeeping data, which includes pointing and spacecraft position data associated with each measurement. Before calibrating the data, the autocorrelations are corrected for the sampling method. The 3-level correlation scheme described in (Kulkarni et al., 1980) is used.

Once the true correlation coefficients are calculated, the data is converted from the temporal to the spectral domains by a Fourier transform. The spectral data are then calibrated using the cold-sky data together with warm-load measurements and by applying other known corrections (Level 1). The production of Level 2 data is based on standard retrieval methods and requires auxiliary data from the ECMWF.
**IRLS/IRCI**

Figure 6.18 depicts a possible ground functional-processing chain for the IRLS/IRCI data:

The processing steps in the ground segment are:

- Validation of received data (check sum, spike detection, etc.),
- Detection and correction of fringe-count errors,
- Fourier transform of interferograms into raw complex spectra,
- Correction of instrumental line shape,
- Radiometric calibration in the complex domain, using spectra acquired by observation of deep space and of an on-board blackbody,
- Spectral calibration and re-sampling on a common spectral grid, and
- Final pixel co-addition to achieve the desired spatial resolution.

**6.6 Operation and utilisation concept**

The PREMIER spacecraft is designed for an operational life of 4 years.

PREMIER must fly about 8 minutes ahead of MetOp within a ±1 minute control box (goal). The analysis has shown that the main constraint will be MetOp orbit-maintenance planning. As a consequence, PREMIER must follow the MetOp operational timeline. The same manoeuvres can be used to reset the absolute orbit and the formation. These should not be very frequent (every 2–3 months), but will require close co-ordination between the respective control centres.

The mission planning is expected to be relatively simple for this mission. It will be possible to pre-programme all commanding activities and load them onto an on-board mission scheduler.

**MWLS**

The set of receivers makes continuous total-power measurements by staring at the limb, interrupted only by calibration-reference measurements. The total power data is the sum of the internal receiver noise and the limb signal. Since the receiver noise is many times larger than the signal from the limb, frequent reference measurements of cold space are performed to reduce the sensitivity to amplifier gain-drifts. The difference between the true zero level and the cold sky is caused by the different optical paths and it is determined separately. Ground measurements of the mirror optical properties (emissivity) together with a set of temperature sensors enable an accurate knowledge of the difference signal, even when long periods occur between direct cold-sky calibrations (performed pointing the telescope towards cold space by spacecraft re-pointing). The timing of the switching is optimised in orbit to achieve optimum performance.
By making measurements of two known sources at different signal levels, the sensitivity scale or system noise can be determined. These sources are a warm load, implemented via a cone-shaped blackbody featuring very low reflections and stable temperature, and the cold sky. The timing of the switching is optimised in-orbit to achieve optimum performance. Typically the blackbody measurement is interleaved with the cold-sky measurements so that it is seen about once per minute. In-orbit determination of the relative alignment of the instruments and of the alignment error with the attitude sensors can be determined by observing the Moon rising above the Earth limb. This will be possible about twice per month and a good accuracy can be achieved using a dedicated attitude scan sequence.

IRLS/IRCI

For the IRLS, the two main operational modes are the nominal operation (limb view) and calibration modes. The two nominal operation modes are the atmospheric-chemistry and the atmospheric-dynamics modes. The modes use the same instrument hardware with different instrument configuration parameters. A switch between these modes will be triggered by a ground command.

The two calibration modes are:

- Regular Radiometric Calibration (cold space and blackbody). In normal operation it is expected that cold-space calibration will be performed a few times per orbit, for example, every 10 minutes, while blackbody calibration is only needed on longer timescales, for example, once every day.
- Line-of-Sight Calibration (on-ground and in-orbit by IR star or planet observation is conceivable). It can improve pointing accuracy and knowledge without requiring any additional hardware.

Spectral calibration is not expected to require a dedicated mode because it can be performed with the spectra acquired in the nominal operation modes.

The IRCI is required to have a single mode of operation. However, its combination with the IRLS implies that it shares its operational and calibration modes.

6.7 Performance aspects

The most demanding performance requirements at system level relate to the pointing aspects, as derived from the observation requirements of the two instruments, and to the associated co-registration requirements. These aspects have been discussed briefly in the satellite section and, though requiring detailed analyses in later phases, their feasibility is not considered critical. This section focuses on the performance assessment of the two observing missions implemented by the IRLS/IRCI and the MWLS instruments.
The most important performance parameters are summarised in Table 6.2.

The 14 antenna beams are characterised using an antenna test range before and after environmental testing. This data is used to verify performance and is also used in the Level 2 data processing. The in-orbit knowledge is limited by thermal deformations, gravity release and moisture release. These effects have been included in the performance estimate quoted in Table 6.2. It is planned to use an extensive set of calibration and verification devices in orbit. They will provide the data required for Level 1 processing, give a direct link to ground tests and save time during the in-orbit check-out phase, helping to resolve any anomaly. The system linearity can be verified both on ground and in orbit, using different temperature settings for the calibration load. The mixer sideband ratios are measured on ground and will be verified in orbit using a dedicated device. The instrument line profile can be characterised on ground by stepping a narrow frequency source (CW signal) across the complete input frequency band and by recording the data at the spectrometers output. This will also show leakage in filters and other possible artefacts. In addition to performing the characterisation on ground, it would also be possible to implement this source in the flight model to repeat the calibration in flight.

<table>
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<th>Parameter</th>
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<td>GHz</td>
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<td>Upper sideband</td>
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<td><strong>Sideband separation</strong></td>
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<td>Arctic</td>
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<td>@ 324 GHz</td>
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</table>

Table 6.2: MWLS performance summary.

*MWLS*

The most important performance parameters are summarised in Table 6.2.
The performance of the IRLS/IRCI instrument is summarised in Table 6.3 and Table 6.4.

Results of radiometric simulations to estimate the instrument noise referred to the input (NESR) are illustrated in Figure 6.19. They show compliance with the requirements for both IRLS modes at goal level.

The absolute-accuracy budget takes into account the error contribution of the calibration process, in particular errors in the knowledge of the temperature and the
emissivity of the calibration targets, drifts between calibrations and measurement noise. It shows that the requirement, defined as the quadratic sum of NESR, offset error and 1.5% of input radiance can be met, provided regular calibration a few times per orbit is performed.

Figure 6.19: IRLS (top) and IRCI (bottom) noise equivalent spectral radiance (in nW/cm² sr cm⁻¹). The required performance in the top figure is shown by the light-coloured continuous and dotted segments.
Chapter 7. Programmatic

7.1 Introduction

This chapter presents the technical maturity, the heritage and the risks associated to the implementation concepts developed in the frame of the Phase 0 studies. The overall development approach and schedule are briefly introduced and discussed with respect to the compatibility with a target launch date for the seventh Earth Explorer Core Mission during 2016.

7.2 Technical maturity, critical areas and risks

No critical elements have been identified for the PREMIER platform development since there is a strong heritage from the on-going Earth Explorers and other Low Earth Orbit (LEO) missions. The technical maturity of the instrument concepts is addressed in the following sub-sections. For the MWLS the technical maturity and the development approach relevant to STEAMR are presented.

7.2.1 MWLS (STEAMR)

The STEAMR instrument concept has a strong heritage from the Sub-mm Radiometer flown on the Swedish Odin mission. The elements with stronger heritage are:

- The mechanism designs based on existing, in-orbit, Odin devices,
- The telescope manufacturing processes, based on the Odin primary reflector with its 8 µm RMS surface accuracy,
- The Michelson interferometer, for measurement of the relative sideband ratio, based on a sideband filter device extensively used on Odin, and
- The correlator chip, developed under an ESA contract, is based on the Odin design but with a broader band, up to 8 GHz.

Other sources of technology, developed or under development are also used:

- The same concept of receiver block is used as for the KOSMA 340 GHz receiver array, though not with the same physical design.
- A first iteration of a sideband-separation mixer, designed by Rutherford Appleton Laboratory (RAL), has been carried out (sideband suppression up to −25 dB). Chalmers/Omnisys are carrying out an independent SSB design
- Suitable mixer Schottky planar diodes have been manufactured by RAL.

For the remaining components, mature technologies are already available.

Some of the foreseen STEAMR instrument equipment has already been either prototyped or developed. Further prototyping activities continue until the end of 2008 or are planned for 2009, the main elements being:
• Development of a receiver system breadboard, and
• Development of a test telescope reflector, to be manufactured in 2009.

The breadboard receiver system will include both a single-sideband mixer and a double-sideband mixer, with integrated low-noise amplifiers, a local-oscillator system, an intermediate-frequency stage and a back-end correlator chain with low-voltage power supply. It will be possible to use the breadboard to test a multi-receiver system. The required correlator chip will be available by the end of 2008.

7.2.2 IRLS/IRCI

The instrument concepts defined in the Phase 0 study use a Fourier-transform spectrometer based on a double-pendulum interferometer, for which a strong heritage exists in ground, airborne (MIPAS-B, MIPAS-STR) and space instruments, particularly the ACE/SCISAT and TANSO/GOSAT instruments. The latter instruments, as well as MIPAS on ENVISAT and IASI on EPS/MetOp, are relevant examples of complex space-borne Fourier-transform spectrometers.

Specific demanding aspects of the instrument require consolidation of the design and technical demonstration by predevelopment in later phases. Demanding design requirements include the dimensional-stability performance in relation to pointing and co-registration requirements and the spatial cross-talk requirement associated with a large across-track field-of-view. Subsystems whose performance requires validation by predevelopments are the detector arrays, particularly for band A, and the on-board processing.

**Very-Long Wave Infra-Red (VLWIR) detector arrays**

The 2D detector arrays feature specific functionality and architecture that require a custom development. The size of the read-out circuits and their overall functionality is well within reach of current technologies, although the performance of the on-chip binning has not been demonstrated in a representative chip. Meeting the NESR requirements in the most compact instrument option requires low-noise performance for the detector arrays; in particular, a large dynamic range for the read-out circuit and very-low dark-current. This low-noise performance is similar to that required in the current pre-development for the IRS instrument of the sounding satellite of MTG. Depending on the outcome of the MTG related activities, an additional development may be needed for IRLS/IRCI. Should improved VLWIR MCT diodes not reliably demonstrate the expected very-low dark-current performance, more standard manufacturing technologies can be used. These still allow meeting the instrument requirements, although at the cost of a larger collection aperture.

The objective of the envisaged pre-development is to develop a breadboard of the detectors and associated Read-Out Integrated Circuit (ROIC). This activity should be initiated during Phase A.

IRLS/IRCI will also benefit from the cooler development performed for MTG.
Verification of IRLS/IRCI on-board processing options and on-board processor prototyping

Different options have been analysed in the course of the Phase 0, trading the complexity of on-board processing of the IRLS/IRCI data for the data volume to be down-linked to ground and the associated complexity of the ground segment infrastructure (number of data downlink stations and complexity of the ground processor). After consolidation of the on-board processing options during Phase A, the requirements for verification of the performance achievable by the proposed on-board processing (re-sampling, spectral-shift correction, filtering/decimation and spatial co-addition) will be established. If these options are confirmed, a pre-development activity to validate the breadboard architecture in a representative data environment will be initiated accordingly, towards the end of Phase A.

7.3 Development approach and schedule

At instrument level the development approach is based on the early breadboarding of critical elements followed by a model set including at least a Structural (Thermal) Model and a Proto-Flight Model (PFM). For the MWLS (STEAMR) Engineering and Qualification models are also assumed, whereas for the IRLS/IRCI the need for an Engineering/Qualification model must be consolidated in later phases, taking into account that qualification models will be required at subsystem/equipment level.

The satellite development relies on a PFM approach. Model-based development and a verification environment with hardware in-the-loop will be used for software development. The critical path is the delivery of the instruments PFMs. The development schedule appears compatible with a launch during 2016.
References


Six Candidate Earth Explorer Core Missions


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Keating, T, and A. Zuber, Coordinating Co-Chairs, 2007: Hemispheric Transport of Air Pollution, UNECE, ISSN 1014–4625.


Kerridge, B. J., et al., 2004a: Consideration of Mission Studying Chemistry of the UTLS, Final Report, ESA Contract 15457/01/NL/MM.

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Six Candidate Earth Explorer Core Missions

References


## Acronyms

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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AATSR</td>
<td>Advanced Along Track Scanning Radiometer</td>
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<td>ACAP</td>
<td>Azimuthally Collapsed Antenna Pattern</td>
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<td>ACE</td>
<td>Atmospheric Chemistry Experiment</td>
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<td>ADM</td>
<td>Atmospheric Dynamics Mission</td>
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<td>APS</td>
<td>Aerosol Polarimeter Sensor</td>
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<td>AOCS</td>
<td>Attitude and Orbit Control System</td>
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<td>AQ</td>
<td>Air Quality</td>
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<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
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<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
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<td>ATSR</td>
<td>Along Track Scanning Radiometer</td>
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<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
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<td>A-SCOPE</td>
<td>Advanced Space Carbon and climate Observation of Planet Earth</td>
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<td>CALIPSO</td>
<td>Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation</td>
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<td>CCMVal</td>
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<td>Committee on Earth Observation Satellites</td>
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<td>CFC</td>
<td>Chloro-Fluoro-Carbon</td>
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<td>CFRP</td>
<td>Carbon Fibre Reinforced Plastic</td>
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<td>CLAES</td>
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<td>Chemical Lagrangian Model of the Stratosphere</td>
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<td>CMOS</td>
<td>Complementary Metal-Oxide Semiconductor</td>
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<td>COREH₂O</td>
<td>Cold Regions Hydrology High-resolution Observatory</td>
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<td>COSMIC</td>
<td>Constellation Observing System for Meteorology, Ionosphere and Climate</td>
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<td>Cross-track Infrared Sounder</td>
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<td>Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (-New Frontiers)</td>
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<td>Double Side-Band</td>
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<td>Envisat</td>
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<td>Earth Observing System</td>
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<td>ESRIN</td>
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<td>FDHSI</td>
<td>Full Disk High Spectral resolution Imagery</td>
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<td>FOCC</td>
<td>Flight Operations Control Centre</td>
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<td>Flight Operation Segment</td>
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<td>FOV</td>
<td>Field Of View</td>
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<td>FTIR</td>
<td>Fourier-Transform Infra-Red</td>
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<td>Global Environmental Monitoring using Satellite and <em>in situ</em> data</td>
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<td>GOCE</td>
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<td>IASI</td>
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<td>IGAC</td>
<td>International Global Atmospheric Chemistry</td>
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<td>Integrated Global Atmospheric Chemistry Observations</td>
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<td>IGOS</td>
<td>Integrated Global Observing Strategy</td>
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<td>Interferometric Monitor for Greenhouse gases</td>
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<td>IR</td>
<td>InfraRed</td>
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<td>Launch and Early Operations Phase</td>
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<td>LIMS</td>
<td>Limb Infrared Monitor of the Stratosphere</td>
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<td>LITE</td>
<td>Lidar In-space Technology Experiment</td>
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### Acronyms

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<th>Description</th>
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<td>LNA</td>
<td>Low Noise Amplifier</td>
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<tr>
<td>LS</td>
<td>lower stratosphere</td>
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<td>Local Oscillator</td>
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<td>LOS</td>
<td>Line Of Sight</td>
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<td>LTDN</td>
<td>Local Time of the Descending Node</td>
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<td>MARSCHALS</td>
<td>Millimetre-Wave Airborne Receivers for Spectroscopic CHaracterisation in Atmospheric Limb Sounding</td>
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<td>MAS</td>
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<td>MetOp</td>
<td>Meteorological Operational Satellite</td>
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<td>Michelson Interferometer for Passive Atmospheric Sounding (-Stratospheric aircraft)</td>
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<td>MISR</td>
<td>Multi-angle Imaging Spectroradiometer</td>
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<td>MOPITT</td>
<td>Measurement Of Pollution In The Troposphere</td>
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<td>MTG (S/I)</td>
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<td>NAM</td>
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<td>NERC</td>
<td>Natural Environment Research Council</td>
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<td>NESR</td>
<td>Noise Equivalent Spectral Radiance</td>
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<td>NPOESS</td>
<td>National Polar Orbiting Operational Environmental Satellite System</td>
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<td>OMI</td>
<td>Ozone Monitoring Instrument</td>
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<td>OMPS</td>
<td>Ozone Monitoring and Profiling Suite</td>
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<td>PAN</td>
<td>Peroxy Acetylene Nitrate</td>
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<td>Spherical Harmonic Discrete Ordinate Method</td>
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<td>Thermal And Near infrared Sensor for carbon Observation</td>
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<td>TES</td>
<td>Tropospheric Emission Spectrometer</td>
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<td>TOMS</td>
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<td>TRAQ</td>
<td>Tropospheric Composition and Air Quality</td>
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<td>Telemetry, Tracking &amp; Command</td>
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<td>TTL</td>
<td>Tropical Tropopause Layer</td>
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<td>Upper Side Band</td>
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<td>Upper Troposphere</td>
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<td>Upper Troposphere – Lower Stratosphere</td>
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<td>Very Long Wave Infra Red</td>
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<td>Volatile Organic Compound</td>
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<td>WCRP</td>
<td>World Climate Research Programme</td>
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<td>WMO</td>
<td>World Meteorological Organisation</td>
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TO OBSERVE ATMOSPHERIC COMPOSITION
FOR A BETTER UNDERSTANDING OF CHEMISTRY–CLIMATE INTERACTIONS

Six Candidate Earth Explorer Core Missions – Report for Assessment 5

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