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SP-1257 (2)

EarthCARE - Earth Clouds, Aerosols and Radiation Explorer

WALES - Water Vapour Lidar Experiment in Space

WATS - Water Vapour and Temperature in the Troposphere and Stratosphere

ACECHEM - Atmospheric Composition Explorer for Chemistry and Climate Interaction

SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis

European Space Agency
Agence spatiale européenne

REPORTS FOR ASSESSMENT

THE FIVE CANDIDATE EARTH EXPLORER CORE MISSIONS

ESA SP-1257(2) – The Five Candidate Earth Explorer Core Missions –
WALES – WAter vapour Lidar Experiment in Space

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1 Introduction

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

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

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

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

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

This particular 'Report for Assessment' is concerned with the WALES mission. It was prepared by a Core mission drafting team consisting of four members of the WALES Scientific Preparatory Group (SPG): Paolo Di Girolamo (Università della Basilicata, Potenza, Italy), Louis Garand (Meteorological Service of Canada, Dorval, Canada), Elisabeth Gérard (Météo France, Toulouse, France) and Volker Wulfmeyer (University of Hohenheim, Stuttgart, Germany). They were supported by the other members of the WALES-SPG, namely Gerhard Ehret (DLR - Institute for Atmospheric Physics, Oberpfaffenhofen, Germany) and David Tan (Hadley Centre, UK Met Office, Bracknell, United Kingdom).

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

The WALES mission will provide accurate profiles of water vapour contents, globally and at high vertical resolution, with the horizontal resolution expected for global atmospheric models in the 2008-2010 timeframe. It will consist of a single satellite in Sun-synchronous dawn-dusk orbit carrying a DIfferential Absorption Lidar (DIAL).

At present, no capability exists or is planned to measure water vapour in the atmosphere with sufficient vertical resolution and accuracy globally, particularly in the presence of clouds.

The primary objective of WALES is to overcome the shortcomings of radiosondes and passive satellite sensors. While the former do not cover the globe uniformly and do not provide reliable water vapour observations in the upper troposphere and lower stratosphere, nor at low humidity levels, the latter do not provide observations with sufficient vertical resolution and high accuracy. The target of the proposed WALES mission is to provide global water vapour observations suitable for a reliable assessment of its detailed temporal and spatial evolution. These analyses would lead to an improved description of climate processes in General Circulation Models (GCMs) and to benefits in Numerical Weather Prediction (NWP).

More specifically, it is proposed to employ DIAL techniques as the new and innovative component of the meteorological Global Observing System (GOS) and of the Global Climate Observing System (GCOS):

- to directly sample the four-dimensional (spatial and temporal) variability of atmospheric water vapour over the entire globe with unprecedented accuracy, not only above clouds but also through broken clouds,

- to improve the ability to quantitatively measure water vapour with high vertical resolution,

- to use for the first time advanced active DIAL technologies from a space platform and

- to establish a totally independent set of global water vapour profiles that will help answer questions about the relationships between changes in atmospheric forcing, radiation budgets and water-vapour/cloud interactions, and to validate other measurement techniques such as passive infrared and microwave.

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

- Chapter 2 addresses the background and provides the scientific justification for the mission set in the context of issues of concern and the associated need to advance current scientific understanding. It provides a clear identification of the potential 'delta' this mission would provide.

- Drawing on these arguments, Chapter 3 discusses the importance of the scientific objectives. It identifies the need for the proposed observations by comparing the data that will be provided by this mission with that available from existing and planned data sources, highlighting the unique contribution of the mission.

- Chapter 4 focuses on observational requirements. Starting from the generic rolling requirements of the World Meteorological Organization (WMO) and taking into account the mission's objectives, specific observational requirements are derived.

- Chapter 5 provides an overview of the mission elements such as space and ground segments and identifies required external data sources. It also identifies other missions benefiting from and complementing the WALES mission.

- Chapter 6 provides a summary description of the proposed technical concept (space and ground segments), identifies the main mission products, establishes basic system feasibility and provides a preliminary assessment of the expected performances.

- Chapter 7 outlines programme implementation, including technical maturity and risks. It also discusses WALES in the context of other related missions and outlines the potential of the mission for operational applications.

2 Background and Scientific Justification

"A major feedback accounting for the large warming predicted by climate models in response to an increase in CO_2 is the increase in atmospheric water vapour. An increase in the temperature of the atmosphere increases its water-holding capacity; however, since most of the atmosphere is undersaturated, this does not mean that water vapour, itself, must increase. ... Water vapour feedback, as derived from current models, approximately doubles the warming from what it would be for fixed water vapour. ... detrainment of moisture from clouds remains quite uncertain and discrepancies exist between model water vapour distributions and those observed."

from IPCC (2001)

2.1 Introduction

Earth Explorer Missions are designed to fulfil observation needs to better understand our planet. The WALES mission addresses the pressing need for water vapour measurements with high vertical resolution and high accuracy on a global scale from the surface to the stratosphere. For both the climate and NWP communities, the specific need for improved coverage and quality of water vapour (humidity) observations is particularly evident. The scientific assessment quoted above from the Intergovernmental Panel on Climate Change (IPCC) is a timely reminder of the importance of, and the uncertainties surrounding, atmospheric water vapour. Not only is water vapour feedback the most consistently important feedback accounting for the large warming predicted by general circulation models in response to a doubling of CO_2, but it also acts to amplify other feedbacks in models, such as cloud feedback and ice albedo feedback (Stocker et al., 2001). Water vapour in the upper troposphere, where the feedbacks are most important, remains largely unknown and almost everywhere the vertical resolution is poor.

In view of the importance of water vapour in the atmosphere, it is far from satisfactory that discrepancies exist between model water vapour distributions and those observed. In setting priorities for reducing such discrepancies, it should be remembered that existing observational datasets are not perfect. A comprehensive summary and evaluation of the current water vapour observational system has been conducted recently by the World Climate Research Programme (WCRP) special project on Stratospheric Processes and their Role in Climate (SPARC, see WCRP, 2000). A recurring theme in that evaluation is that the limitations of current data quality restrict the confidence that can be placed in scientific conclusions about the nature and role of water vapour in climate. The limitations also impact adversely on NWP and include (a) the sparse horizontal coverage of the radiosonde network and the poor response of radiosondes at low temperature and low specific humidity, (b) the difficulties in calibrating passive remote sensing systems (notably, the problems in identifying and quantifying biases that are potentially time-dependent and regionally varying), and (c) the lack of water vapour data in the presence of clouds.

Thus, better observations of the global water cycle are essential for advancing our understanding of the role of water vapour in climate and NWP. It can be argued that the only realistic opportunity for achieving the required global coverage, spatial and temporal resolution, and improvements in bias, is through a significant enhancement of the water vapour observing system, such as is offered by active remote sensing from space. This report explains the impact the WALES mission can have in realising this enhancement to benefit the closely related fields of climate and NWP.

Water vapour is the most important atmospheric gas in terms of the impact on climate and weather. Its direct links to radiation, clouds and precipitation, chemical processes and dynamics are sketched in Figure 2.1. Its high variability in space and time and its large dynamic range represent a major challenge for its observation. Various sources of humidity measurements available now or in the near future are of key importance for climate and NWP applications: land and ship synoptic reports, buoy data, radiosonde soundings and estimates derived from passive infrared and microwave sensors. Although the benefit from these sources of information has been proved, it is nevertheless acknowledged that each of them suffers from an incomplete description of

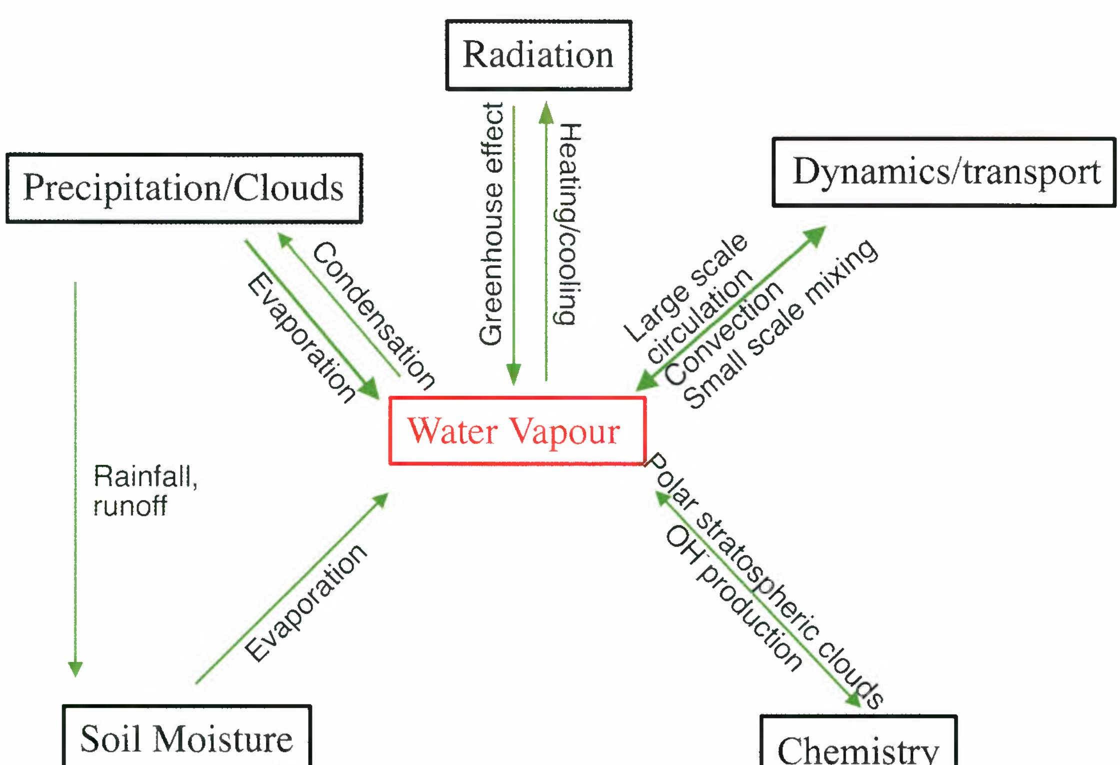


Figure 2.1: *The importance of water vapour in the Earth's atmosphere.*

the atmosphere in its spatial and temporal dimensions. Furthermore, the combination of all these sources also leaves enormous gaps, notably in the upper troposphere and lowermost stratosphere. In addition, everywhere, and especially over oceans, humidity and cloud analyses suffer from poor vertical resolution. Due to the size of our planet and the fact that two thirds of it is covered by oceans, remote sensing is the only way to achieve global coverage with the requisite horizontal, vertical and temporal resolution. WALES represents an important first step in routinely measuring water vapour profiles from space using an active remote sensing technique.

Sections 2.2 and 2.3 explain in more detail why improved water vapour observations are so important in order to progress in our understanding of, and consequently in our capability to predict, climate change and weather phenomena. The current status of humidity measurements as well as that of near-future systems is presented in Section 2.4. Section 2.5 emphasises the uniqueness of WALES among the various planned related remote sensing missions. Section 2.6 summarises the scientific arguments presented.

The terms accuracy and precision are very often used in this report. Accuracy refers to the systematic error or bias (which cannot be removed by averaging), while precision refers to the random error or standard deviation due to uncorrelated noise.

There is an intimate link between advances in climate-related studies and those in NWP. Indeed, climate studies are increasingly using analyses of atmospheric (and other) fields from data assimilation systems designed originally to provide initial conditions for operational weather forecasting models. Understanding of the atmosphere and its evolution is based to a large extent on the analysed fields from continuous data assimilation carried out at numerical weather prediction centres, so that progress in climate analysis is closely linked to corresponding progress in NWP. In line with this, extended atmospheric re-analysis projects (ECMWF, European Centre for Medium range Weather Forecasts, Re-Analysis, i.e. ERA15 and ERA40, NCEP, National Center for Environmental Prediction) are extremely valuable to the climate research community for the consistent data sets they provide. While climate and weather analysis applications are addressed separately in the following sections, it should be understood that these close links lead to the single set of observational requirements, serving both applications, given in Chapter 4.

2.2 Water Vapour and Climate

2.2.1 Role of Water Vapour in Climate

Water vapour plays a central role in climate processes. Its radiative properties make it the major greenhouse gas in cloud-free sky. Changing humidity by just a few percent affects the spectrum of outgoing long-wave radiation by an amount of similar magnitude to that caused by doubling carbon dioxide in the atmosphere (Harries, 1997). Thus the radiative balance of the atmosphere depends strongly on feedbacks associated with the water vapour distribution. Furthermore, the water vapour distribution is determined by the hydrological cycle, and is much less well-mixed than other greenhouse gases because of its link to temperature and because of the interactions between clouds, convection and atmospheric transport, especially in the upper troposphere and lower stratosphere.

Society increasingly requires reliable information about the climate system and the impact of anthropogenic influences (IPCC, 1996; IPCC, 2001). The scientific and engineering community fulfils this demand by monitoring the Earth's climate, detecting and attributing change, modelling the current climate and predicting climate change. Objectivity is underpinned by continually improving our understanding of the climate system, increasing the realism of climate models, and quantifying the uncertainties, many of which relate to the role of water vapour. Observations of water vapour play a vital part in all of these activities and are an essential component of the Global Climate Observing System (GCOS, Karl, 1996).

An adequate qualitative, let alone quantitative, global description of water vapour for climate science is still lacking, for a number of reasons:

- The dynamic range of specific humidity varies with height over four orders of magnitude. The largest values of specific humidity, of the order of 20 g/kg, occur near the Earth's surface, while the lowest values, of the order of 0.001 g/kg, occur near and above the tropopause.

- High spatial and temporal variability of humidity. There are sharp vertical gradients on scales of a kilometre or less, and horizontal contrasts on scales of tens of kilometres. Temporal variations range from minutes for convective processes to decades for climate change.

- Lack of accuracy, coverage or absolute calibration of observing systems. The archive of radiosonde data for instance, the longest available data source, suffers from the uneven quality of the observations in addition to intrinsic limitations.

The high variability just mentioned is best illustrated from a typical humidity analysis (a sophisticated combination of model simulation and observational data, explained in more detail in Sections 2.2.3 and 2.3.1). Figure 2.2a shows such an analysis at a level near 700 hPa over the Eastern Pacific Ocean. Even at a single level, the specific humidity varies over three orders of magnitude, locally over short horizontal distances. Especially in mid and high latitudes, there are often narrow dry structures next to humid ones. Figure 2.2b shows the humidity cross-section for the path indicated by the arrow in Figure 2.2a. The two dry intrusions are striking features (the first one down to 900 hPa). The moist ascending air next to the second dry intrusion (see the 5 g/kg contour in Figure 2.2a) is associated with strong convection and intense precipitation

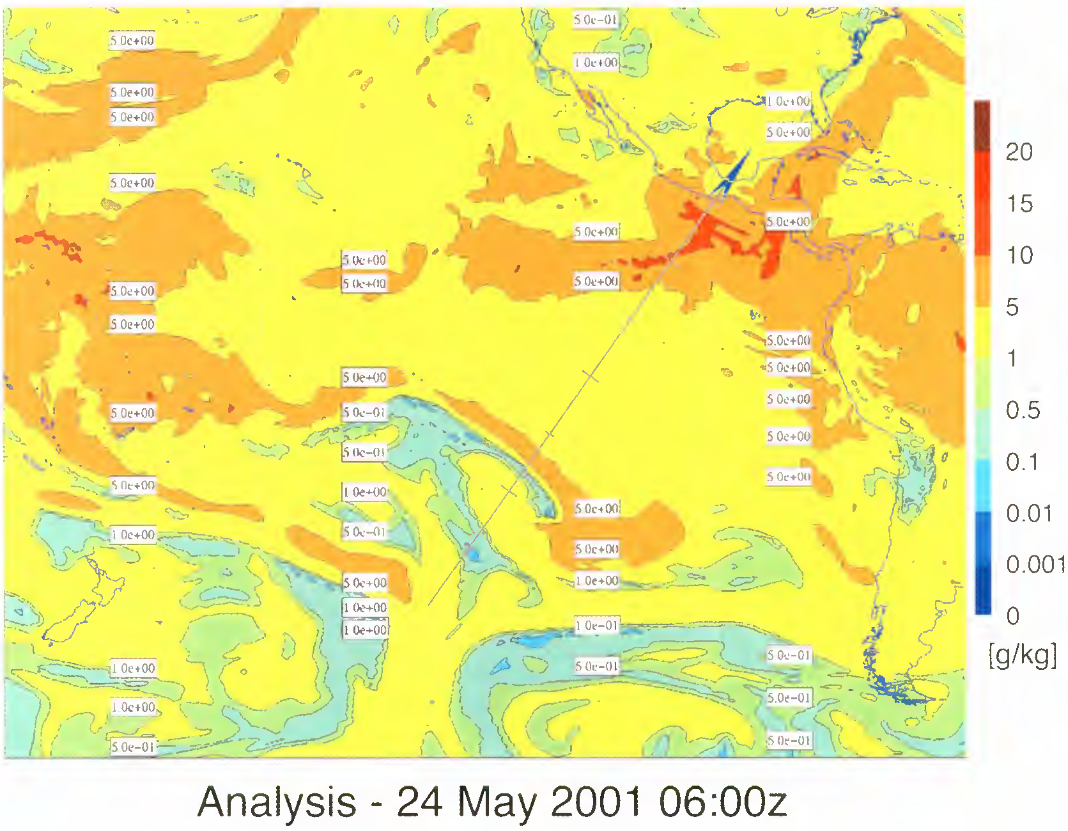


Figure 2.2a: *Specific humidity (g/kg) analysis at a level near 700 hPa for 24 May 2001, 06 UTC. The arrow represents the path of the cross-section shown in Figure 2.2b.*

in the model (not shown). Higher in the model, the convection injects 0.01 g/kg into the stratosphere. While this amount is small relative to surface values of specific humidity, it represents a substantial moistening of the lowermost stratosphere, with potentially significant implications for chemistry. In the tropical portion to the right of the cross-section, the humidity varies from 1 g/kg to 10^{-3} g/kg in the layer 100-300 hPa. Above 300 hPa, the analysis is actually extrapolated as there are no observations available.

Figure 2.2 shows vivid examples of fine scales captured by NWP models, but regional models of improved resolution reveal even finer structures. Climate models are limited in this regard due to their coarser resolution. This leaves the possibility of systematic errors in climate modelling. Hence, one of the major issues for climate modelling and understanding is to develop parameterisations that accurately account for unresolved water vapour processes, down to the scales relevant to individual convective events, condensation, precipitation, and cloud microphysics. A similar issue arises for numerical weather prediction, since neither climate models nor NWP models will resolve all these scales in the near future. Water vapour observations leading to improved climate model parameterisations will therefore also benefit NWP.

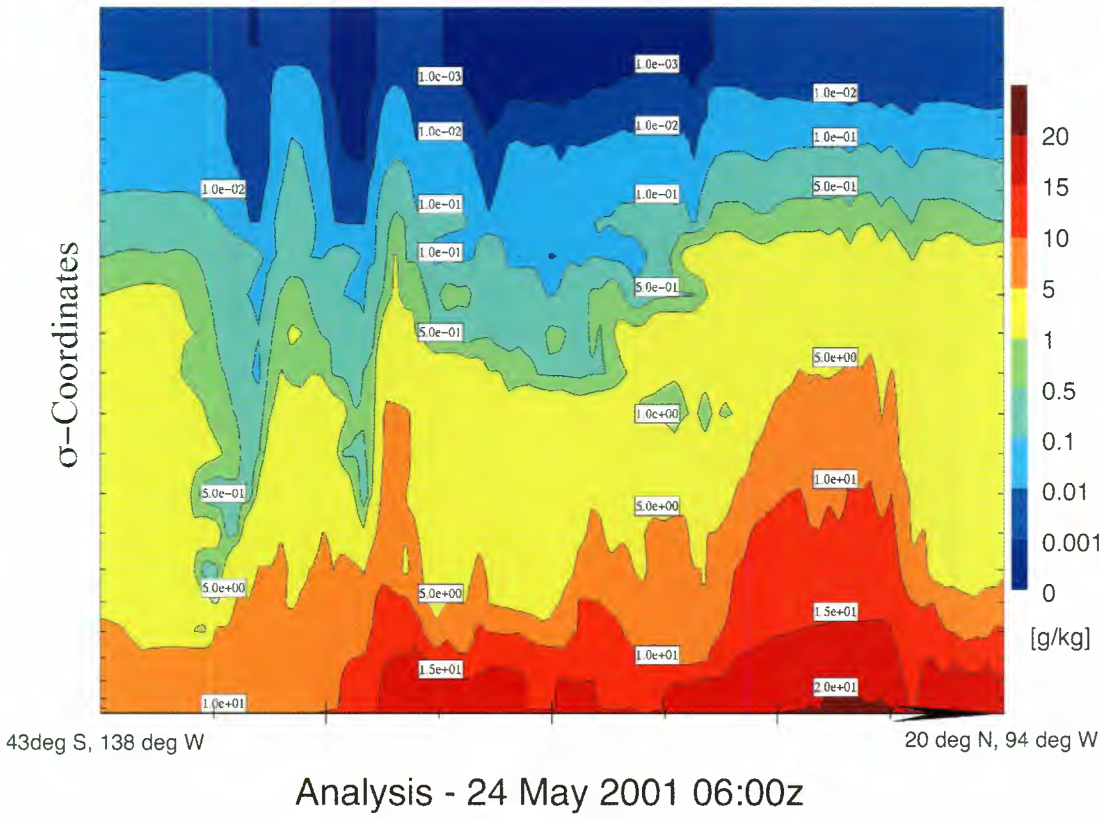


Figure 2.2b: *Specific humidity (g/kg) cross-section for the path shown in Figure 2.2a. Vertical coordinate is* $\sigma = p/p_0$ *where* p_0 *denotes surface pressure. The cross-section extends from 43 S, 138 W to 20 N, 94 W.*

The large dynamic range, the large range of horizontal and vertical scales, and the need to account for the influence of many different transport and physical processes present a severe challenge to understanding the impact of water vapour in climate. There is therefore a pre-eminent need for high quality water vapour observations. The need to improve the description of the global water vapour distribution, particularly in the upper troposphere and lower stratosphere (UTLS), has recently been stressed in the SPARC report (WCRP, 2000) and demands high vertical resolution (notably in the tropopause region) and coverage of a large dynamic range. In the UTLS, stratosphere-troposphere exchange can occur rapidly through motions along isentropic surfaces (i.e. isosurfaces of potential temperature, see the review by Holton et al., 1995). Such exchange is therefore another process that results in sharp contrasts in the water vapour distribution, and contributes to the high spatial and temporal variability of water vapour referred to above. The uses of water vapour observations vary according to the precise aspect of climate being considered, and are given in more detail below.

2.2.2 The Need for Water Vapour Observations

On the timeframe of the proposed Earth Explorer WALES mission, the main specific priorities for improved water vapour observations for climate purposes are as follows.

Model Validation

Observations are used to validate the overall performance of general circulation models and to constrain key model components such as the radiation scheme and the parameterisation of sub-grid processes. Zonal means and coarse resolution diagnostics will continue to be used together with analysis of modes of variability on regional, interannual, seasonal and intraseasonal scales, and increasingly will be complemented by quantitative validation of radiation and atmospheric transport focused on finer details of vertical and horizontal structure.

Observations with global coverage are therefore required with vertical and horizontal resolution comparable to that of general circulation models. Advances in computing power indicate that the most advanced climate models will soon have vertical resolutions of about 1 km throughout the troposphere and horizontal resolutions of 100 km.

Efforts to validate models are on-going in the context of the Atmospheric Model Intercomparison Project (AMIP, e.g. Gates et al., 1999) and its successor AMIP-II, both projects of the WCRP and of its Working Group on Numerical Experimentation (WGNE). Water vapour was the focus of AMIP subproject 11 and is continued in AMIP-II as subproject 27 (tropospheric humidity and meridional moisture fluxes). First results have been published by Gaffen et al. (1997) indicating that the representation of water vapour in GCMs was poor in several respects, with few obvious links to details of model formulation.

One outstanding example of the usefulness of remotely sensed water vapour data in understanding atmospheric processes and validating models comes from the Halogen Occultation Experiment (HALOE, Russell et al., 1993) on the Upper Atmosphere Research Satellite (UARS), which is also mentioned below in the context of climate trends. Time-height plots and meridional cross-sections of HALOE data in the stratosphere illuminate the processes influencing the abundance and transport of water vapour in the stratosphere (see WCRP 2000 and references therein for details of the meaning procedures). The rate of ascent through the tropical stratosphere, and the amplitude of the seasonal signal (the so-called 'tape-recorder' signal, Mote et al., 1996) provide valuable information for validating GCMs.

Monitoring and Trends

In the last decade, major efforts were made to launch observation and modelling programmes aiming at understanding better the role of water vapour in climate change.

A special programme known as GVaP (GEWEX water Vapor Project, GEWEX 1999a, 1999b) was designed in the early 1990s to improve the global mapping of water vapour in order to study climatic trends. The satellite component of GVaP put the emphasis on upper tropospheric humidity (200-500 hPa) using observations in the 6.2-6.8 μm region available from both geostationary and polar orbiting satellites. Several channels were eventually used to get the relative humidity in broad layers (Soden and Bretherton, 1996). A radiative transfer model was used to link (via regression) observed radiances and the mean relative humidity in broad layers. The influence of the quality of the radiative transfer model was shown to be significant (Soden et al., 2000), especially for the determination of long term climatic trends and anomalies. Difficulties arise due to multiple factors such as the indirect nature of the measurements and the calibration/intercalibration of the various satellites used in the global monitoring over a long time period. The radiative transfer model is subject to biases, which are air-mass type dependent (see Stephens et al., 1996). Nevertheless, this effort led to a much clearer global view of the synoptic scale variability of water vapour, and its link to large scale signals such as those of El Niño episodes. GVaP also created a 1 by 1 degree global daily analysis called NVAP (NASA Water Vapor Project) based on various sources of observations (no NWP background) for the period 1988-1996. Products include the integrated water vapour or total precipitable water (TPW) and humidity estimates in three broad layers 1000-700 hPa, 700-500 hPa, and 500-300 hPa (Randel et al., 1996). Another data set is 'Pathfinder' (Susskind et al., 1997), based on TOVS (TIROS Operational Vertical Sounder) data for the period 1985-1993. Humidity integrated over five layers is available. Greater vertical resolution and accuracy are highly desirable.

Long term radiosonde data sets have been used to infer trends in humidity and temperature. Gaffen and Ross (1999), for instance, inferred increases in surface specific humidity of several percent per decade over the United States, in line with an increase of atmospheric temperature. Similarly, Ross and Elliott (1996) inferred trends in surface to 500 hPa integrated water vapour. Changes in relative humidity were smaller and more difficult to detect. Problems arise due to intrinsic limitations as well as variations in the quality of radiosonde humidity measurements, but the most severe limitations are the sparse horizontal coverage and limited vertical extent of these measurements.

An increasing trend in stratospheric water vapour was first noticed in radiosonde data (Oltmans and Hofmann, 1995) and subsequently in data from HALOE (Nedoluha et al., 1998, Evans et al., 1998, Randel et al., 1999). A more recent analysis of a longer time series of HALOE data (Smith et al., 2000) showed a smaller trend. They suggested that stratospheric moistening is linked to changes in the increased convection in the second half of the Asian summer monsoon.

Cloud Physical Processes

Clouds represent a key forcing and feedback component in the climate system. Their role in climate change is only partially understood (Cess et al., 1996). Physical process studies are required for a better understanding of radiative transfer in cloudy atmospheres, as well as for improved parameterisations to model feedback mechanisms adequately. Observational requirements for water vapour include measurements below clouds. Figure 2.3 shows clouds as detected by the LITE (Laser In-space Technology Experiment) mission. Not only will an active technique provide data above cloud tops (as for passive techniques), it will extend coverage considerably by measuring below optically thin clouds as well as between clouds. This is indicated by the hatched area in Figure 2.3.

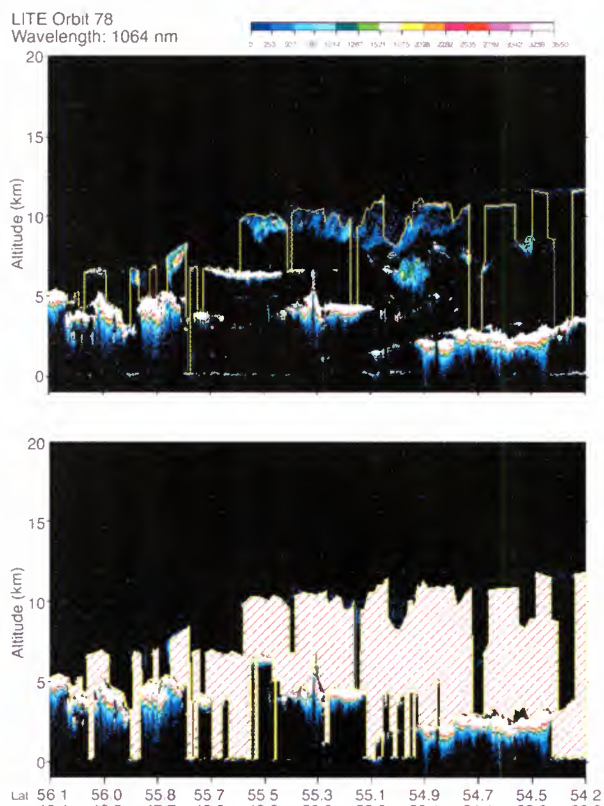


Figure 2.3: *Backscatter signals of the LITE (Laser In-space Technology Experiment) instrument measured in 1994. These data are used to derive a comparison of passive and active sounding from space. A passive system does not penetrate cloud and will provide observations only above the yellow curve in the upper panel. An active system can penetrate thin cloud layers and can measure in gaps between clouds to provide additional profile information under cloudy conditions as well, i.e. throughout the hatched region in the lower panel). The hatched regions are very interesting meteorologically and hence where data are urgently requested.*

Water vapour is also the most significant source of the OH^- radical in the upper troposphere and further observations would benefit studies of chemical processes. Polar Stratospheric Clouds (PSCs) play an important role in the heterogeneous chemistry processes associated with ozone depletion in the polar regions (Hamill and Toon, 1991; Solomon, 1988). A large fraction of these clouds (i.e. type-I PSCs) is located in the altitude range between 10 and 16 km. Water vapour observations provide valuable information about PSC formation and evaporation, at the high and low parts of the range, respectively. The modelling of cirrus clouds is particularly challenging. In humid areas, relative humidity near and exceeding saturation plays a central role in the formation of cloud and raindrops. Hence, for understanding cloud physical processes in general, accurate high relative humidity measurements are needed.

2.2.3 Observation Limitations

Presently, no single instrument is capable of covering the high dynamic range of specific humidity while providing a global view at high horizontal, vertical and temporal resolution. With the progress in satellite meteorology, the horizontal and temporal aspects of the observational system have been very much improved. However, with the observation data sets presently available, it is difficult to blend them into a global product with the accuracy and the spatial and temporal resolution required to meet climate user needs. The weakest aspects are clearly the lack of accuracy, the lack of vertical resolution, and the difficulty of measuring humidity in the upper troposphere. New measurement techniques are undoubtedly needed to address these limitations.

At this point it is appropriate to elaborate on the important contribution to climate research made by the analysed fields produced by numerical weather prediction models. By assimilating observational data, analysed fields represent a highly processed form of observations. Such fields are used routinely to initialise climate models and provide useful estimates of, for example, parameterised fluxes. In the absence of sufficiently comprehensive directly observed datasets, they are also used for climate model validation and identification of climate model biases. Their main drawback is that the assimilation process itself depends on numerical models that have their own systematic biases. Indeed, the physical parameterisations in NWP models are often very similar to those in climate models and require analogous validation against independent observations.

2.2.4 Summary of Climate Related Goals

To meet the need for reliable information about climate and the impact of anthropogenic influences, the candidate Earth Explorer mission WALES must aim towards:

- a better knowledge of the water vapour distribution at the highest possible horizontal, vertical and temporal resolutions,
- the design of new sources of measurements with improved absolute accuracy in order to measure long-term trends and validate infrared/microwave techniques,
- a better understanding of the physical processes responsible for the distribution of water vapour and the highly non-linear interactions between these processes.

As shown below, the aims and concerns of climate research share much with the priorities in weather prediction.

2.3 Water Vapour in NWP

2.3.1 General Characteristics of NWP Models

NWP models are of two types: global and regional. The horizontal resolution of global models is typically of the order of 100 km. Regional models cover a portion of the Earth at higher resolution. On continental grids, the typical resolution of the models is 20 km, while in research 1 km is not uncommon, especially over complex terrain. In the vertical domain, between 25 and 100 levels are used with a model top between 0.1 hPa and 10 hPa, but often higher for so-called GCMs. The dynamics part of the model, governing the motion of the atmospheric fluid, may be identical for all horizontal scales. The physics part often differs for several processes, notably those related to clouds and precipitation and to surface energy exchange.

Forecasts start with an estimate of the state of the atmosphere, called an analysis. An analysis usually consists of corrections to a six hour forecast from six hours earlier, serving as the so-called background field (or first guess). Available data are used to modify the background field in a physically and statistically consistent manner. This process is called data assimilation. In such a six hour data cycle, data within three hours of the analysis time are assimilated as if they were all at analysis time, causing some smearing of rapidly evolving phenomena. In more advanced 4-dimensional variational systems, observations are also fitted in time (assuming the model trajectory as realistic). The weight given to the observations is determined by the ratio of observation to background error. This is what is meant by 'statistically consistent'. Physical consistency on the other hand means that the laws of stability, saturation, continuity and geostrophy, among others, are respected. There is no doubt that archived NWP analyses of uniform quality represent a major tool for climate research. To reach an advanced stage of uniformity, re-analyses can be done using the same software and resolution over decades of raw data (Kistler et al., 2001). However, data availability from different epochs does differ, and satellite data, for instance, will soon increase in volume by an order of magnitude. It can be argued that at some time in the future, when the Earth's observational system has reached maturity, climate monitoring and NWP analyses will be largely synonymous. Similarly, on the modelling aspect, the difference between forecast models and GCMs is becoming smaller and limited to spatial resolution and vertical extent.

2.3.2 Importance of Humidity Data in NWP Models

As expressed in Section 2.2, humidity plays a central role in the radiative balance as well as in precipitation processes through cloud formation and dissipation and direct impact on solar energy input. However, because of its high spatial variability at all scales, the background estimate of humidity is often poor, evidencing the need for improved coverage with high quality measurements.

Table 2.1 shows the value of the relative error dq/q assigned to the background field for specific humidity q at the Canadian Meteorological Center (CMC) and the UK Met Office (UKMO, English, 1999) for a few representative levels. Note that relative errors often approach or exceed 40% and are even assumed to become fixed above a certain level (UKMO, above 300 hPa). Moreover, significant differences exist between the two estimates. The large differences, for example above 300 hPa, are not physically justified. These differences are due in part to the differences in the forecast models, but a larger portion of the difference is due to *ad-hoc* procedures used to estimate the

Level (hPa)	Altitude (km)	CMC (%)	UKMO (%)
100	16.0	74	46
135	14.3	114	46
150	13.5	88	46
200	11.5	99	46
250	10.4	74	46
300	9.0	68	46
400	7.2	58	40
500	5.6	55	37
600	4.2	49	38
700	3.0	46	35
850	1.5	30	32
920	0.8	21	31
1000	Surface	18	19

Table 2.1: *Relative error on specific humidity associated with the background (6-h forecast) field used in data assimilation at the Canadian Meteorological Center (CMC) and UK Met Office (UKMO) NWP centres for a few representative pressure levels.*

background error in regions devoid of data. CMC estimates for instance are modelled from the difference between 24-h and 48-h forecasts valid at the same time. Clearly if observations with relative error of 15-25% were available, the NWP analysis error, which combines observations and background, would be largely improved. Figure 2.4 shows this, assuming a random observation error of 25% and using the CMC model humidity error. Even at this relatively high level of observation error, the improvement of the analysis over the background is substantial. Humidity soundings over oceans are badly needed, among other applications, to better evaluate the part of the background error covariance matrix pertaining to humidity. Not only the diagonal terms of the background errors need to be evaluated, but the off-diagonal terms as well. Figure 2.5 shows the level-to-level humidity error correlation used at the MSC. This correlation is used globally, while variances vary with latitude. Again this modelled correlation needs to be validated with real observations and eventually refined by making it dependent on the synoptic situation. Flow-dependent background errors represent a very important research topic in data assimilation.

In NWP, humidity statistics suggest a radius of influence of about 200 km, i.e. a single datum of humidity will influence the analysis over these horizontal scales. Higher

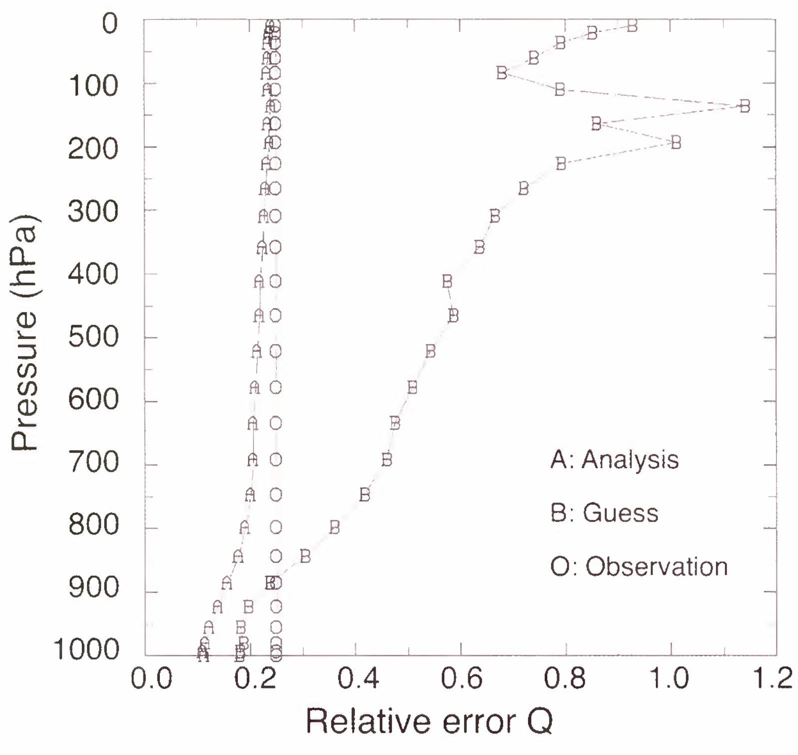


Figure 2.4: *Resulting analysis error (A) obtained from combining an observation error (O) constant with height at 25% with the MSC (Meteorological Service of Canada) humidity background error (B). The error in specific humidity q is expressed in terms of d(log(q)) = dq/q as a function of pressure level (hPa).*

resolution than this is needed, particularly in regions of 'active weather' such as near disturbances or fronts. Ahead of warm fronts, for instance, high cirrus clouds are typically present while the lower atmosphere is quite dry. Observational systems capable of detecting such structures will help to improve the short-term evolution of frontal systems. Over land, the early detection of moisture convergence in clear air and, in particular, at low levels is essential for the prediction of thunderstorm and squall lines. The literature on meso-scale meteorology is full of examples demonstrating the need for an accurate 3-D moisture field to forecast severe weather (see, e.g. Koch et al., 1997; Bell and Hammon, 1989; Crook, 1996 and, more generally, AMS, 1999). Since the most intense weather phenomena (squall lines, tornadoes) occur on short horizontal scales, the need for observations that resolve these scales is obvious.

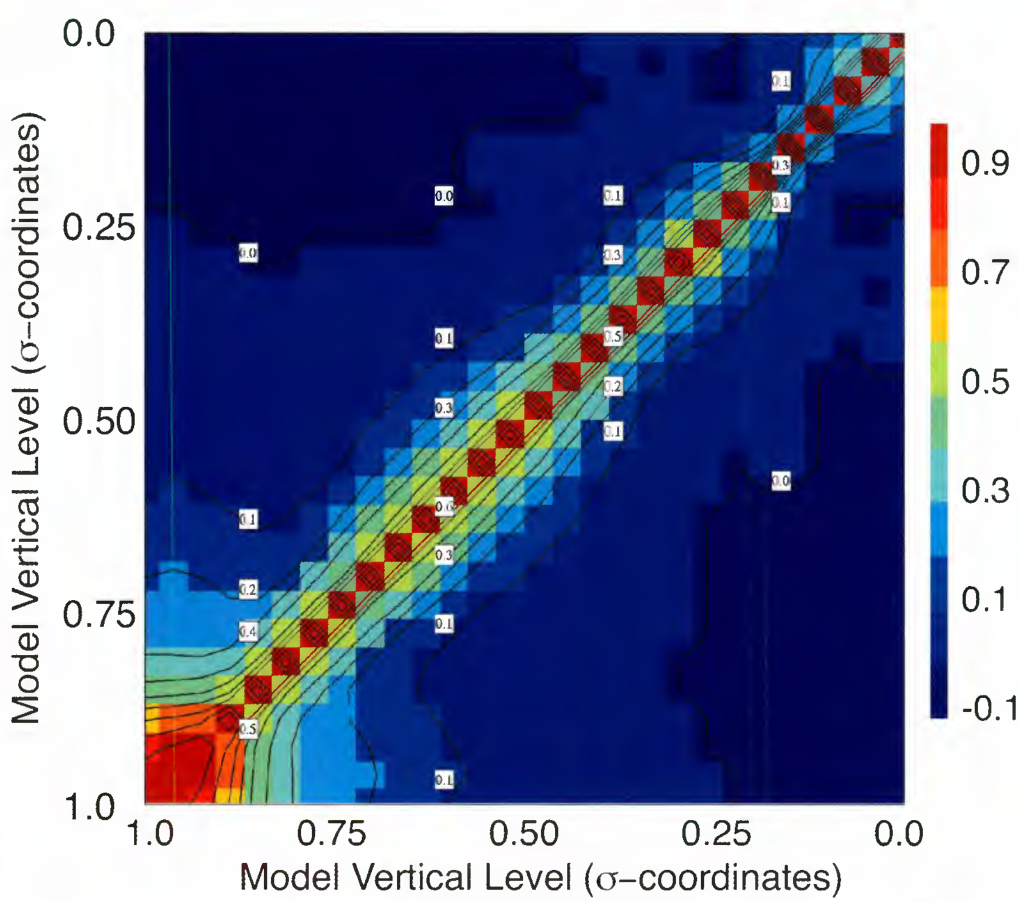


Figure 2.5: *Background vertical error correlation matrix for the humidity variable used at the MSC. The bottom-left corner represents the surface-surface component and the upper-right corner the top-top component (at 10 hPa). There are 28 vertical levels.*

2.4 Observational Sources

2.4.1 Current Data Sources

As mentioned earlier, the SPARC project recently summarised the status of observational data sets of water vapour and noted their limitations for climate use (WCRP, 2000). The main arguments have already been presented in Section 2.2. More details on the technical reasons for these limitations are given here, together with the main implications for weather prediction.

The traditional source of humidity measurement is radiosondes, being part of the GOS. They are launched once or twice daily from about 650 sites, non-uniformly distributed over land regions. This information is limited, but of fairly good quality, by itself and because it is accompanied by temperature and wind measurements. An important limitation is that humidity estimates from radiosondes become unreliable at temperatures below 233 K, which means that there are no *in-situ* humidity measurements above ~300 hPa (see Figure 2.2). Over most of Antarctica, no radiosonde humidity measurements are possible at any height since the air temperature is below 233 K for the entire atmosphere. Radiosonde stations are costly to operate and their cost has to remain low. It is difficult to produce them with uniform quality and characteristics, and different companies produce various types.

Figure 2.6 compares four commonly used sondes on the same balloon ascent. The sondes show various errors throughout the profile. At levels below 300 hPa, large systematic differences (exceeding 20%) are noted between the sondes. The humicap sonde for example (widely used in Europe) has a significant dry bias, and Guichard et al. (2000) showed how this error impacts negatively on the available potential energy necessary for deep convection. Related problems were noted in the past, notably the difficulty for some sondes to measure humidity near saturation (see, e.g. Garand et al., 1992; Schwartz and Doswell, 1991). Elliott and Gaffen (1991) concluded that it was difficult to infer a reliable water vapour climatology from radiosondes above 500 hPa. Relying on radiosondes to detect long-term trends or to calibrate remote sensing techniques may lead to significant biases. In addition, the trend is for the total number of radiosonde sites to decline. Figure 2.7a shows the average data availability of radiosondes at the ECMWF for a period of six hours centred on 8 July 2001: 00 UTC.

Another type of *in-situ* humidity measurement is that obtained from ground stations, typically hourly. Figure 2.7b shows the coverage of synoptic reports in a manner similar to that in Figure 2.7a. Fixed and drifting buoys are also available, although not all report humidity. These data are of good quality. Over land, one difficulty is that the model topography often differs significantly from the true topography (up to 500 m at the model horizontal resolution of 100 km), requiring extrapolation rules to provide the humidity estimate at the model level.

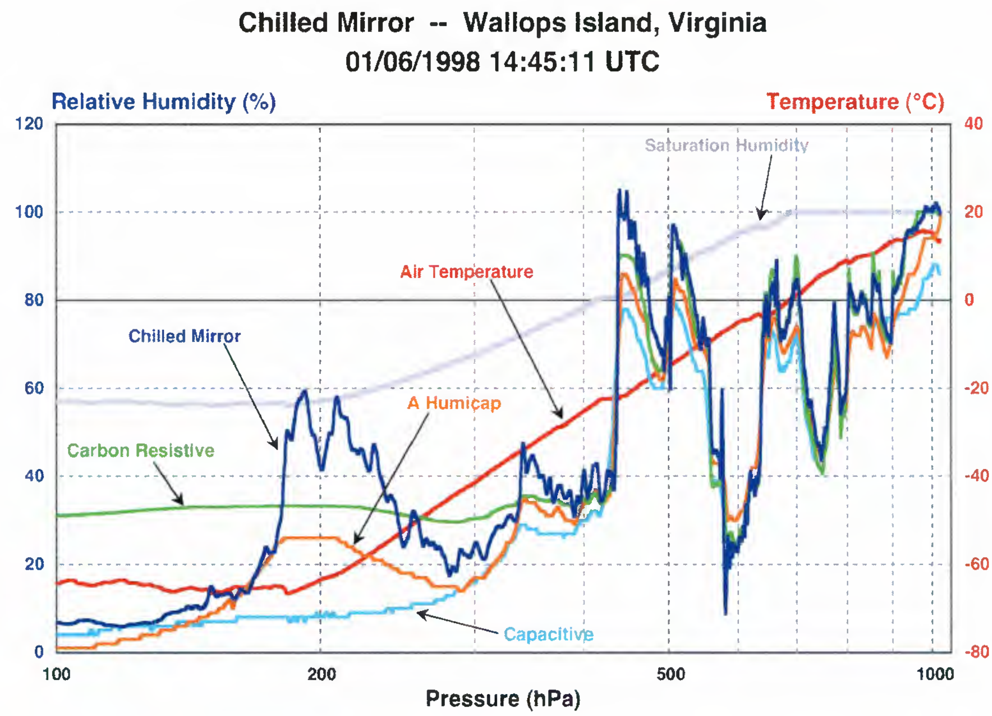


__Figure 2.6:__ Comparison between humidity soundings made at Wallops Island on 1 June, 1998 for four different sensors launched on the same balloon (courtesy: F. J. Schmidlin). Three of these sensors (A-humicap, carbon resistive and capacitive) have been or are currently routinely used by US or European weather services.

Commercial aircraft provide temperature, wind and humidity estimates along the flight path. The main limitation of these data is their availability at a single height mainly above 8 km. Over oceanic routes that height is nearly the same for all aircraft and the range of routes used is limited. Currently, humidity data from aircraft are not used in NWP. However, this situation is likely to change soon and the volume of available data from sensors on regional aircraft (e.g. MOZAIC, Measurement of OZone on Airbus In-service airCraft, Gierens et al., 2000) will increase. Over regions such as Europe or the USA, aircraft data will represent a relatively dense source of humidity profiles with frequent ascents/descents from airports separated by distances of the order of 150 km (Fleming, 1996, 2001). Figure 2.7c shows a typical example for currently available aircraft data.

Other ground measurements are, for example, those from microwave radiometers, infrared (IR) spectrometers and lidars (see Weckwerth et al., 1999). These data are very useful for NWP model validation, but represent a marginal input to a global analysis.

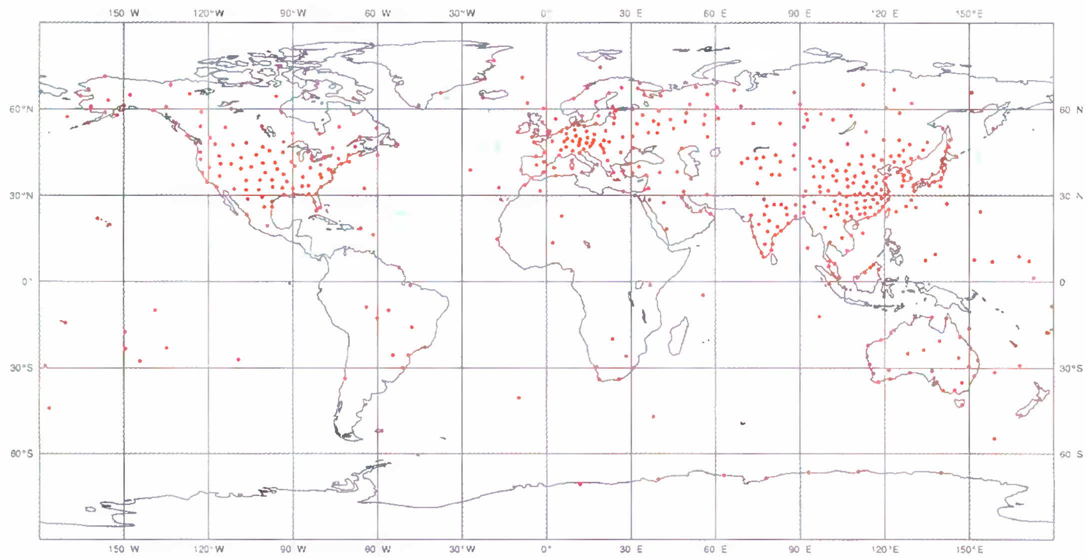


Figure 2.7a: *Radiosonde (TEMP) reports available at ECMWF for the 6-h period centred on 8 July 2001: 00 UTC (courtesy: ECMWF).*

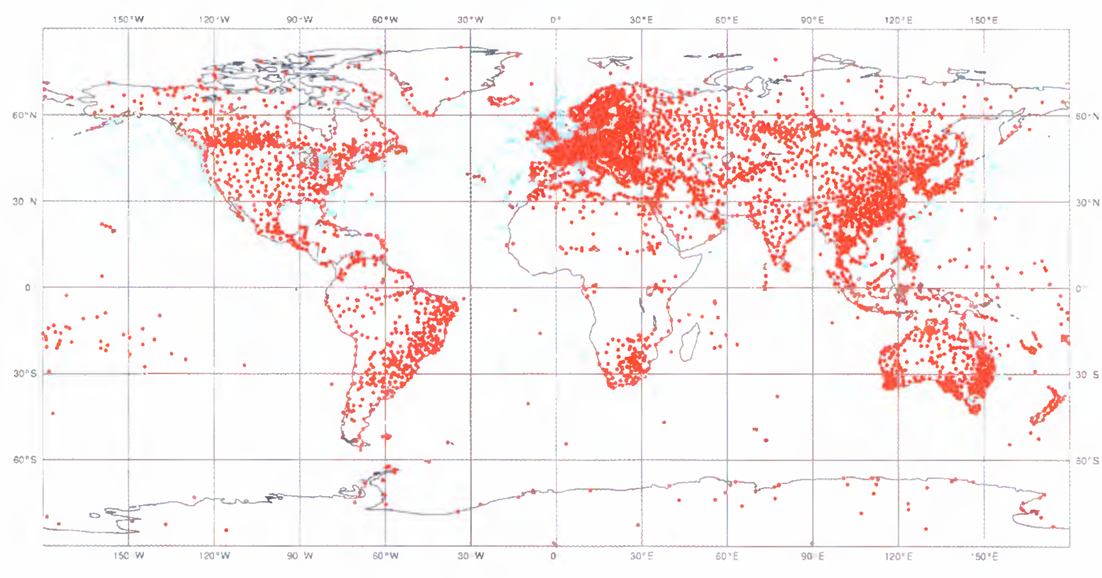


Figure 2.7b: *Same as Figure 2.7a, but for surface synoptic reports from ground stations and ships (courtesy: ECMWF).*

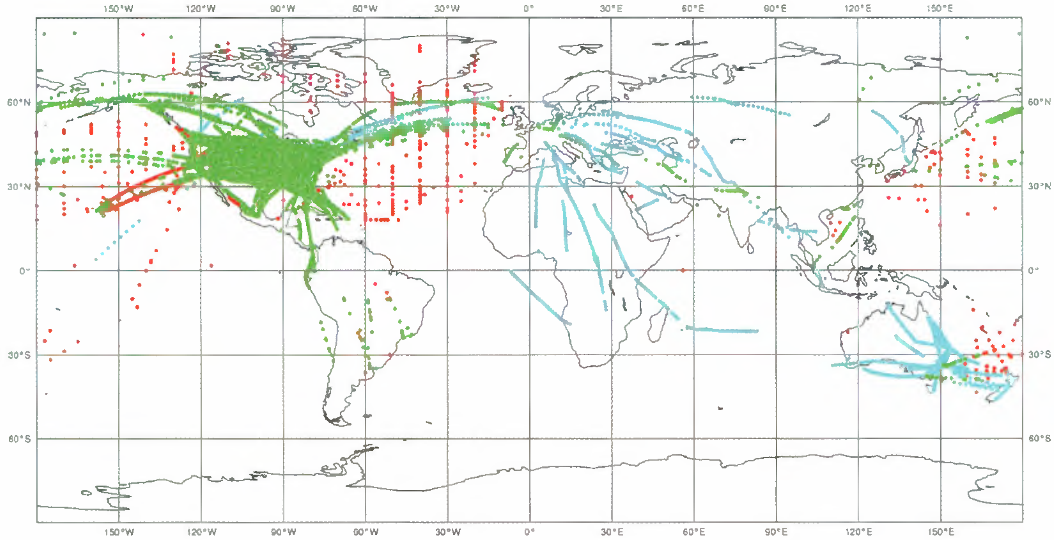


Figure 2.7c: *Same as Figure 2.7a, but for aircraft reports (AIREP). Currently, only wind and temperature data are used in NWP (courtesy: ECMWF).*

Satellite observations, no doubt, represent the unique means to achieve global coverage with good horizontal and temporal resolution. Recently, significant progress was made in assimilating infrared radiances, which are sensitive to both temperature and humidity. Figure 2.7d shows the relatively good coverage from two operational NOAA satellites providing ATOVS data. Currently, estimates are limited to clear air and, over land, to channels that are not affected by the surface. Systematic errors in infrared passive remote sensing systems can be large whenever scattered clouds, e.g. low level cumuli, are present and not detected. The impact of this source of data is mainly important between 200-500 hPa. This is especially true for humidity sensing channels. In addition to data from polar orbiting platforms, observations from geostationary satellites in the 6.7 µm water vapour band are available at high temporal resolution. Figure 2.7e shows an observed radiance field from the water vapour channel onboard Meteosat. As for TOVS channels, the details of the vertical distribution cannot be recovered due to the sensitivity of the radiances to broad layers. Yet, as already shown in Figure 2.2, upper-tropospheric humidity varies over three orders of magnitude. In order to assimilate radiances, bias corrections must be applied to radiative transfer schemes simulating those radiances. Bias correction schemes assume that the overall model bias in radiance units is zero. Consequently, satellite data used in NWP do not aim at correcting systematic model errors. To make sure that systematic model biases are accounted for, an independent source of data with high absolute accuracy is needed. Such absolute 'truth' does not exist for the humidity variable in the upper troposphere and is extremely limited at all heights over oceans.

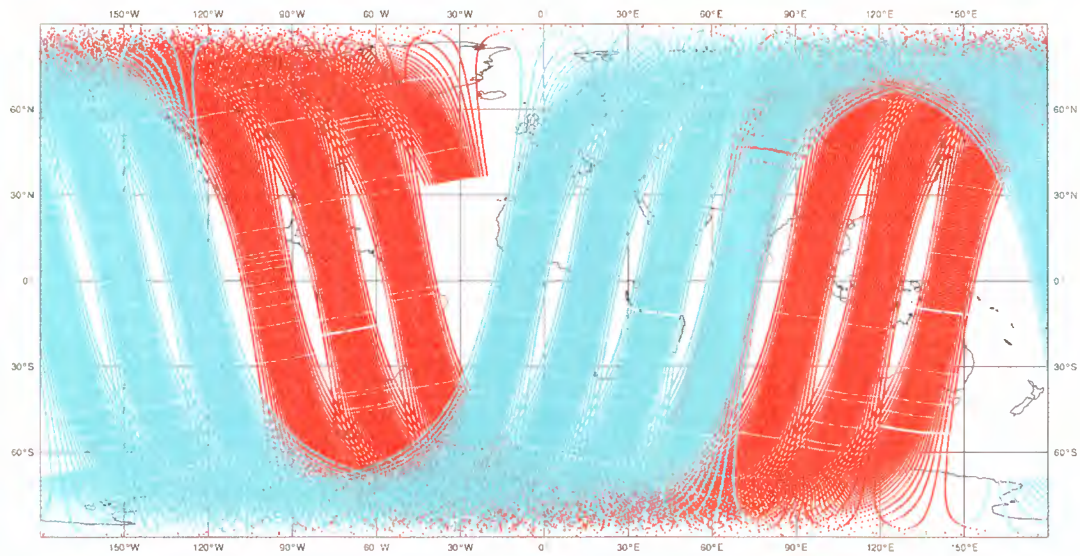


Figure 2.7d: *Same as Figure 2.7a, but for advanced TOVS (TOVS, TIROS-N Operational Vertical Sounder, ATOVS) data available from NOAA-15 and NOAA-16 satellites (courtesy: ECMWF).*

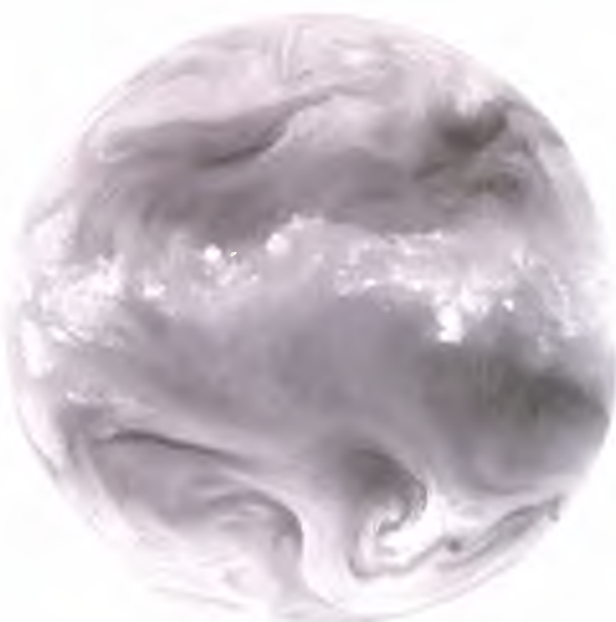


Figure 2.7e: *Meteosat water vapour image (position: 0 deg / 0 deg) from 8 July 00 UTC (copyright: 2001 EUMETSAT).*

Similarly microwave data, especially imager radiances from SSM/I (Special Sensor Microwave Imager), were used over oceans to infer the total water vapour column content (TPW). The vertical structure is imposed by the NWP first guess. These data help in improving the horizontal distribution of integrated water vapour from the surface to about 500 hPa (see Hou et al., 2001; Gérard and Saunders, 1999 or Deblonde, 1999, for a demonstration of impact in NWP). Thus, this type of data complements the upper tropospheric information provided by IR radiances. Profiling in broad layers is also possible from microwave radiances. Figure 2.7f shows an example of SSM/I coverage. No estimates are available over land.

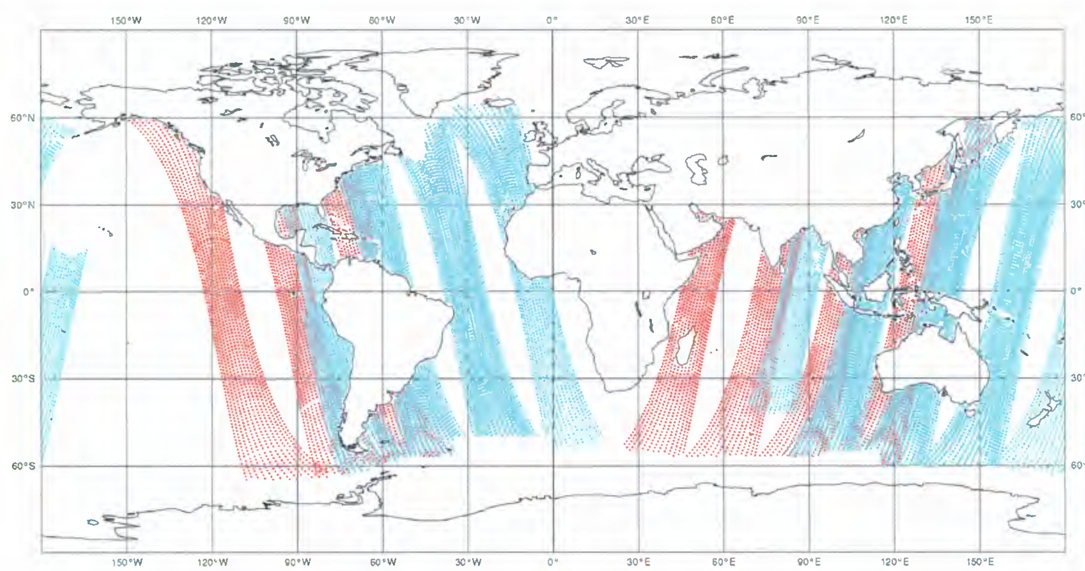


Figure 2.7f: *Same as Figure 2.7a but for SSM/I data available from DMSP (Defense Meteorological Satellite Program) satellites (courtesy: ECMWF).*

GNSS (global navigation satellite system) data also provide TPW at ground sites equipped with an appropriate receiver. A system like GPS/MET (Global Positioning System for Meteorology) or the Blackjack GNSS receiver on CHAMP (Challenging Minisatellite Payload) provides humidity profiles, not only TPW, from an occultation technique. The disadvantages of these systems lie in the limited horizontal resolution (~300 km) and vertical range (above a few km). Furthermore, the technique requires a good a priori estimate of the atmospheric temperature profile (see Rocken et al., 1997).

2.4.2 Planned Sources

One of the major accomplishments in remote sensing foreseen for the upcoming decade is the exploration of the entire infrared spectrum at unprecedented spectral resolution using spectrometers or interferometers. AIRS (Atmospheric Infrared Radiance Sounder, e.g. Aumann and Strow, 2001) is the first in a series of spectrometers, with a launch scheduled for December 2001. IASI (Improved Atmospheric Sounding in the Infrared, launch 2005, Diebel et al., 1997, Centre National d'Etudes Spatiales CNES, 2001) and GIFTS (Geo-synchronous Imaging Fourier Transform Spectrometer, launch 2004, National Aeronautics and Space Administration, NASA, 2001) are other planned missions. In contrast, AMLS (Advanced Microwave Limb Sounder) on EOS-Aura is a limb viewing sounder providing observations of the upper troposphere, but at comparatively low horizontal resolution. GNSS sounders will be embarked on Metop (GRAS, GNSS Receiver for Atmospheric Sounding) from 2005 and NPOESS (GPSOS, Global Positioning System Occultation Sensor) from 2009.

With these instruments, the vertical resolution for humidity estimates will be typically 1-2 km (closer to 2 km for humidity) and the relative error in the range 15-25%, with a coverage possibly reaching 75% of the Earth (for IR, no use in fully overcast areas below clouds, difficulties above clouds where thin cirrus is present; for microwave, lower horizontal resolution). The most challenging problems for passive IR systems are to obtain good estimates in the lowest levels, above clouds and to avoid the use of radiances contaminated by small or thin clouds. Currently, the quality control for infrared radiances in NWP centres tends to be very severe, which results in accepting a limited number of observations departing significantly from the first guess leading to a reduced impact. The information on humidity above 150 hPa from advanced interferometers will also be very limited. Remarks previously made on the need for independent data with high absolute accuracy remain. Accurate radiative transfer models are essential for the assimilation of radiances. In addition, good estimates are needed of the concentrations of all gases affecting a given channel.

As for infrared instruments, microwave instruments will continue to evolve and to provide improved humidity and temperature estimates in regions where non-precipitating clouds are present. The vertical extent of the information is similar to or slightly coarser than that of IR profiles. Over land, the difficult modelling of microwave surface emissivity will continue to limit the retrievals to the middle and upper troposphere.

2.5 Uniqueness of the WALES Mission

2.5.1 Nature of the Data

The Earth Explorer WALES mission will use an active technique and will provide numerous important advantages with respect to current observational techniques for water vapour. Among these are:

- High accuracy profiles extending from the ground to the upper troposphere and into the lowermost stratosphere where current knowledge is most limited.

- Direct measurement of humidity at all temperatures as opposed to, for example, radiosondes.

- Low sensitivity to other parameters (e.g. surface emissivity, temperature profiles, concentrations of other gases, aerosols) that are needed by other techniques.

- Unbiased vertical profiles above cloud tops and, for the first time, well resolved profiles below clouds of low optical depth such as thin cirrus.

- High precision.

- High vertical resolution.

- Possibility to get estimates of the variability within the chosen average distance (flexible, currently ~100 km is proposed).

- In broken clouds, possibility to keep only the measurement data originating from clear spots.

- Availability of an estimated random and systematic error profile for each sounding to be used in data assimilation.

- Simultaneous information on water vapour, clouds and aerosols.

The mission creates a major and much needed reference for validation of other water vapour measurement techniques, in particular those based on infrared and microwave radiances.

The proposed mission provides water vapour measurements with unprecedented accuracy. In contrast, errors associated with radiosondes are not as stable: they depend on the type of sonde, with variations from lot to lot for the same type of sonde. Similarly, radiance measurements require continuous bias error corrections relying on, for example, radiosondes or model output. Thus, radiance assimilation is meant to correct random errors, not systematic errors. WALES will be a unique data source for the identification of systematic model biases.

The ability to take measurements above, near, between and to some extent below clouds, was demonstrated by the LITE mission. Figure 2.3 shows an example of this unique capability.

2.5.2 Expected Impacts

The most important impact on climate research will be better understanding and modelling of climate feedbacks by providing accurate and high resolution water vapour observations in the upper troposphere and lowermost stratosphere, where no sufficiently reliable observational datasets currently exist. The high-quality data at high vertical resolution will provide valuable insights into the processes controlling the abundance of water vapour, particularly in those regions where the water vapour, ice and cloud feedbacks on climate are not only significant, but also most uncertain.

The most important impact on NWP will be significantly improved analyses through high quality data with global coverage. The mission will provide about 6000 soundings daily (assuming a 100 km integration length) as opposed to the ~1200 currently available radiosonde soundings. Because of the high quality of the data with respect to that of the first guess (Figure 2.4), the impact on NWP analyses is expected to be very significant, especially where these two sources disagree. Based on the results of a

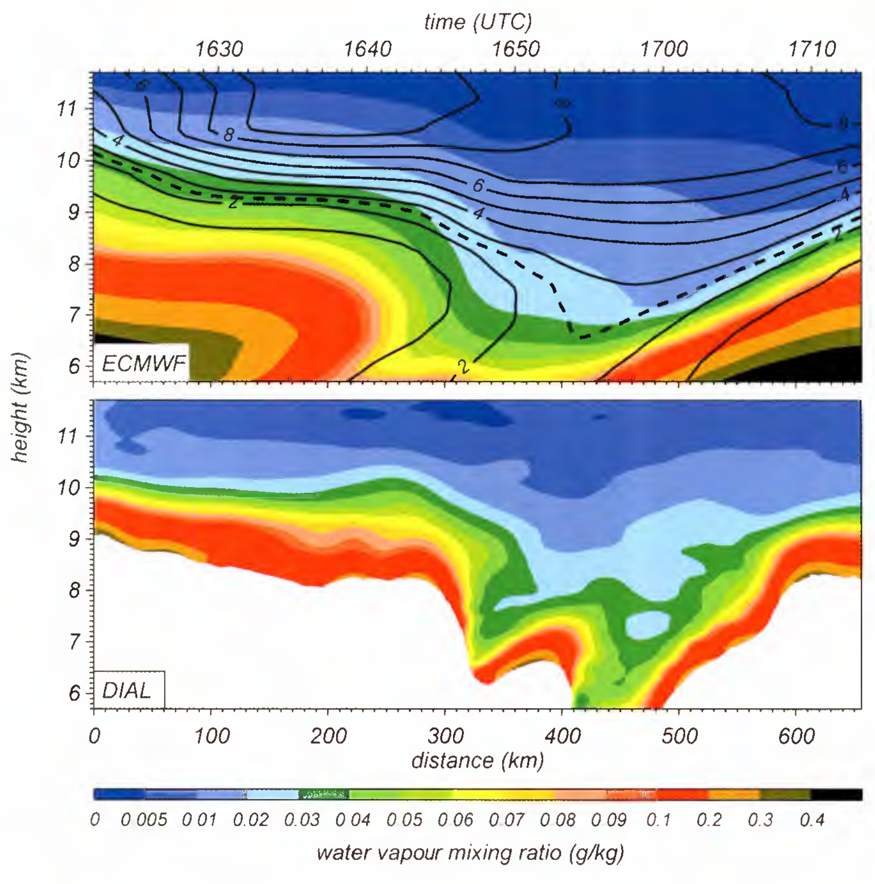


Figure 2.8: *Comparison of ECMWF analysis with DIAL observations – Cross-sections of water vapour mixing ratio (g/kg) on 12 November, 1998, between 43.8 N 1.4 E (left side) and 47.0 N 7.7 E (right). Top: data taken by the airborne H_2O-DIAL of DLR between 1622 UTC and 1713 UT; Bottom: operational analysis provided by ECWMF (T213, i.e. 62 km). There is a significant jump in scaling at the 0.1 g/kg isoline: the increment is 0.005 or 0.01 g/kg below it and 0.1g/kg above it. The full lines indicate the potential vorticity unit (pvu) increment. The tropopause is indicated by the dashed line (2.5 pvu).*

recent Observing System Simulation Experiment (OSSE), conducted at MSC for ORACLE (Ozone Research and Cooperative Lidar Experiment) and which has clearly shown a large impact worldwide (not only in the vicinity of the track), an analogous positive impact from WALES is expected. Even closer to the actual WALES mission, proof of concept has been established both from ground and airborne systems (see Figure 2.8, Ehret et al., 1999; Browell and Ismail, 1995; Wulfmeyer and Bösenberg, 1998; Bruneau et al., 2001a/b), providing representative demonstrations of the capability of the proposed active system to measure complete and accurate water vapour profiles.

Other major impacts and benefits include:

- A significant improvement in the vertical resolution of humidity profiles (better than 1 km) compared to that provided by infrared and microwave sounders (a few km). Hence vertical cross-sections will reveal major variations in the vertical distribution of humidity, as demonstrated with similar airborne systems.

- The vertical extent of the profiles will often reach the lower stratosphere.

- The accuracy of the profiles will be unprecedented, of the order of 5%.

- The data will help modellers to improve NWP/GCM physical parameterisations.

- The high vertical resolution and quality of the new observations will help to better estimate a representative NWP background error covariance matrix. This matrix is fundamental in data assimilation as it determines the weight of the data (from the ratio of the background to observation error). Currently, there is a large uncertainty on this matrix for humidity (variations of the order of 20-50% from centre to centre, see Table 2.1). Through improving the quality of the estimates in that matrix, the new data will have a significant impact on NWP analyses, even if the data were not assimilated (see Figure 2.5).

- The basic advantage of an active over a passive system is that it will provide data not only above but also below thin cloud, and it can 'see' through cloud layers as shown in Figure 2.3.

- Radiances that are sensitive to humidity are always sensitive to temperature as well. Thus, a more subtle impact is that improving the humidity field will also lead to an improved temperature field by constraining the range of temperature and humidity corrections that satisfy the observed radiances (this alleviates the problem of non-uniqueness of the solution, see e.g. Garand, 2000).

- Simultaneous measurements of aerosols and relative humidity will provide unique information on particle hygroscopic growth.

- Humidity retrievals above and near clouds will be greatly improved.

2.6 Conclusion

The Earth Explorer WALES mission will fulfil a long-standing need for global, high-vertical resolution, water vapour measurements. WALES will help to fill major gaps in the measurement of water vapour (humidity), especially in the troposphere and lowermost stratosphere, in partly cloudy situations and below thin clouds. The system will be highly accurate and very robust, resulting in reliable long-term data. In addition, the good along-track resolution will provide valuable information for validating and improving the parameterisation of moist processes, including convection and detrainment, as represented in both climate and weather prediction models.

As a verification tool for other remote sensing techniques, the WALES mission represents an invaluable data source. In particular, its high accuracy will allow systematic model biases to be detected with confidence, not only for the total vertically-integrated humidity, but also as a function of height. Anticipating that future refinements of the WALES instrument will ultimately be regular elements of the Earth observation system, long-term humidity trends can be inferred.

The Earth Explorer WALES mission is unique among missions aimed at improving humidity datasets. Active remote sensing appears to be the most promising approach for obtaining high-quality water vapour data at high vertical resolution. As demonstrated by airborne and ground instruments, technology is now mature for the realisation of a water vapour DIAL in space.

3 Research Objectives

3.1 Introduction

The Earth Explorer WALES mission will fulfil a long-standing need for highly accurate and high vertical resolution humidity measurements on a global scale, from the surface up to the lowermost stratosphere (i.e. ~16 km). Assuming measurements representative of 100 km Earth segments, more than 6000 profiles will be available daily, as opposed to the ~1200 currently available soundings from radiosondes. Each profile will in general be complete and accompanied by a corresponding error profile. In the presence of dense clouds, humidity profiling above cloud tops as well as in cloud gaps will be possible. Humidity profiling will also be possible above and below optically thin clouds. The WALES mission will provide simultaneous information on water vapour, clouds and aerosols. Thus, the mission will fill major gaps in the observational system needed for climate and NWP applications. No other planned satellite missions can provide observations of comparable quality.

3.2 Climate and NWP Research Objectives

Water vapour plays a prominent role in climate and NWP. It impacts on the radiative balance as well as on precipitation processes through cloud formation and dissipation and has a direct impact on solar energy input. The WALES observations will be characterised by their global coverage and high vertical resolution, the large vertical extent of the retrieved water vapour profiles at all temperatures, from the surface up to the lowermost stratosphere, and the coverage of a wide dynamic range with high precision and very high accuracy. In contrast to passive sounders, the humidity data provided by the active instrument underpinning the WALES mission will not be biased by the first-guess water vapour required for passive retrievals.

3.2.1 Climate

The key science issues summarised in the previous chapter translate readily into the following climate research objectives:

1) Improve our knowledge of the role of water vapour in the global water and energy cycle for a better understanding of the water vapour feedback. Improve the measuring, understanding and modelling of the greenhouse effect, the radiative balance and radiative transfer of the atmosphere, the physical processes responsible for the water vapour distribution and the highly non-linear interactions between these processes, particularly the hydrological cycle, with more emphasis on the upper troposphere and lowermost stratosphere, where no comparable data set exists.

2) Develop and test methodologies for integrating existing water vapour data sets to facilitate long-term global climate monitoring and trend studies. Improve the calibration of passive remote sensing systems and validate infrared/microwave techniques.

3) Improve the representation of water vapour feedback in climate prediction models. This requires better modelling of radiative transfer and physics parameterisations and quantitative validation of the overall performance of general circulation models on a fine vertical and horizontal scale.

4) Improve our understanding of convective processes and water vapour feedbacks on aerosol particles and atmospheric chemistry.

The WALES mission climate objectives resonate strongly with the primary goals of GVaP (GEWEX 1999a; GEWEX 1999b). It is proposed on the grounds that any strategy to achieve these objectives must include high-quality observations of water vapour. The need to improve the description of the global water vapour distribution in the upper troposphere and lowermost stratosphere has been emphasised (SPARC – WCRP, 2000; GVaP Science and Implementation Plan – GEWEX 1999a, 1999b) and demands high vertical resolution and coverage of a large dynamic range. Such data sets are essential for analysing and understanding variability on a range of spatial and temporal scales, as required in Objective 1. The same datasets can also be exploited for Objective 2, provided their biases and error characteristics are sufficiently well known. Furthermore, they provide data for validation of global climate models and process studies, and are thus vital for Objectives 3 and 4.

A significant impact of WALES on climate research is expected, due to the high quality and coverage of the data. The benefits of the WALES mission include enabling scientists to make more confident predictions about future climate, as required by society (IPCC, 2001), and contributing to better understanding of atmospheric chemistry (SPARC – WCRP, 2000). An indirect benefit, but perhaps one that is ultimately more valuable, is that by demonstrating the value of active remote sensing of humidity from space, WALES will establish the basis for future missions of longer duration, as required for the detection of trends and better understanding of the role of upper tropospheric and stratospheric moisture in climate change.

3.2.2 NWP

The Earth Explorer WALES mission will contribute to the alleviation and solution of key problems in NWP by:

1) Improving model humidity analyses through constraining the initial state of the models towards highly accurate moisture observations.

2) Validating numerical weather prediction models.

3) Building a more representative numerical weather prediction background error covariance matrix to optimise the weight of observation and background in the analysis.

4) Improving the temperature field by constraining the range of temperature and humidity corrections consistent with observed radiances (humidity-sensitive radiances are always sensitive to temperature).

5) Improving the physical parameterisations governing the interaction between moisture, radiation and hydrological cycle for improving the model humidity forecast.

6) Validating remote sensing techniques such as those using infrared and microwave satellite radiances.

7) Providing a new reference for calibrating other remote sensing techniques. WALES can provide independent measurements of water vapour to improve the interpretation of passive satellite sounding systems.

3.3 Conclusion

The Earth Explorer WALES mission is expected to answer a long-standing need for humidity observations in climate and NWP applications. Indeed these data will help in improving the understanding, modelling and validation of water and energy cycle, radiative transfer, physical processes, aerosol, clouds and atmospheric chemistry, as well as in the calibration of passive remote sensing techniques.

The feasibility of the required type of observations has been proven recently by ground and airborne systems. In view of this and the considerable scientific benefits expected for climate and NWP, it is a very timely moment to implement the WALES mission.

4 Observational Requirements

This chapter defines the specific observation requirements that are necessary in order to address the scientific questions and research objectives of the climate and NWP communities that have been defined for the WALES mission (Chapters 2 and 3). To provide some context, Section 4.1 recalls some generic requirements for water vapour measurements, independent of any particular technology, which are important for advancing climate research and NWP. Section 4.2 presents the WALES mission observational requirements.

Two classes of requirements, namely threshold and target requirements, have been defined by international programmes. Threshold requirements are defined as those leading to an impact on climate and NWP. The target requirements are the ideal performances that will lead to maximum impact in climate research and NWP.

4.1 Generic Requirements for Water Vapour Data

4.1.1 Introduction

Generic requirements for the observation of meteorological parameters are specified by WMO/CBS (Commission on Basic Systems) and are expressed by the World Meteorological Organization (WMO, 1996) (with minor updates in WMO, 2000a and WMO, 2000b) in terms of:

- **Accuracy and Precision**
  Data must be provided with a detailed error analysis with respect to systematic errors (accuracy, bias) and random errors (precision). The bias of measurements must be as low as possible and time independent. No distinction is made between systematic and random errors in the generic requirement tables; indeed they are merely combined in a single RMS measure of error.

- **Resolution** (horizontal and vertical sampling)
  The threshold requirements with respect to the spatial scales roughly correspond to the present spatial resolution of models. The target requirements mainly correspond to the expected spatial resolution of future models.

- **Coverage**
  Data are requested globally and continuously, i.e. even when clouds are present. Measurements in clear air are a must.

- **Time Sampling**
  This is the time interval between two measurements of the same region. It should be short enough to observe atmospheric processes with sufficient time resolution.

- **Timeliness** (the delay from observation to delivery)
  Whereas the timeliness is not that critical for climate research, it is an important issue for NWP. To provide data to operational NWP centres for initialisation and assimilation, timeliness should be of the order of a few hours.

The WMO documents (1996, 2000a, 2000b) synthesise a consensus view of the whole user community – represented by WMO Members – at that time. Observation requirements are always evolving due, for instance, to developments in climate models and assimilation and forecasting systems. The WMO updates the requirements regularly in response to these changes. This is known as the 'rolling requirements review' (RRR).

Additionally, requirements have been discussed within the scope of GVaP (GEWEX 1999a, GEWEX 1999b) and SPARC (WCRP, 2000). The need for highly accurate and highly resolved global water vapour measurements has been stressed, focussing on a reduction of the present high uncertainty of water vapour profiles in the upper troposphere as well as in the lower stratosphere.

4.1.2 Climate Modelling and Prediction

Generic resolution requirements on specific humidity measurements for climate applications are summarised in Table 4.1. The specifications also fulfil many of the requirements for coupled models of climate and the chemistry of long-lived atmospheric constituents, but do not of course have the time sampling necessary to resolve short-lived chemical species.

For many climate GCM runs, observational data are not assimilated directly, but pre-analysed three-dimensional fields are used for initialisation. These fields often come from operational NWP analyses or – for long-term consistency – off-line analyses, for instance the ECMWF or NCEP re-analysis products (cf. Section 2.1). For these applications, the requirements for analysis are the drivers, and are addressed next.

4.1.3 Atmospheric Analysis and NWP

Atmospheric analysis and modelling applications include both operational meteorology and atmospheric process studies using NWP models. These applications cover a wide spectrum of activities related to the prediction of how the atmosphere and, in particular, the associated weather conditions, change with time. A summary of the requirements (see references as above, but also e. g. Weckwerth et al., 1999) is shown in Table 4.2.

Without going into further detail than has been provided in Chapter 2, it suffices to state that, in spite of the major achievements of the current Earth observational system, there is still a substantial gap between generic observation requirements and the datasets currently available.

		Specific Humidity Requirements	
		Threshold	Target
Horizontal Domain		Global	
Horizontal Sampling	LT	100 km	50 km
	HT	100 km	50 km
	LS	250 km	50 km
Vertical Domain		Surface to 10 hPa	
Vertical Sampling	LT	2.0 km	0.5 km
	HT	2.0 km	0.5 km
	LS	2.0 km	0.5 km
Time Sampling		12 h	3 h
RMS Error	LT	20%	5%
	HT	20%	5%
	LS	20%	5%
Timeliness		60 days	30 days
Time Domain		> 10 years	
Long-term Stability		< 2% RH/decade	

Table 4.1: *Generic observation requirements for climate modelling and prediction (LT = lower troposphere, 0 to 5 km; HT = higher troposphere, 5 to 15 km; LS = lower stratosphere, 15 to 35 km). Note that long-term stability is defined in terms of relative humidity. In the worst case and neglecting any temperature errors, this corresponds to a long-term stability in specific humidity of 2%.*

		Specific Humidity Requirements	
		Threshold	Target
Horizontal Domain		Global	
Horizontal Sampling		250 km	50 km
Vertical Domain		Surface to 10 hPa	
Vertical Sampling	LT	2.0 km	0.4 km
	HT	3.0 km	1.0 km
	LS	-	-
Time Sampling		12 h	1 h
RMS Error	LT	20%	5%
	HT	20%	5%
	LS	-	-
Timeliness		3 h	1 h

Table 4.2: *Generic observation requirements for atmospheric analysis and NWP (for the meaning of LT, HT, LS, see Table 4.1).*

4.2 WALES Mission Specific Requirements

The observation requirements specific to the WALES mission are given in Table 4.3. They have been designed to meet the climate and NWP research objectives put forward in Chapter 3, which require an observing system that can provide high accuracy water vapour profiles globally. It is important to note that, in addressing the regions corresponding to the WMO's generic definitions of lower troposphere and higher troposphere (Table 4.1), the WALES observation requirements in fact extend into the lowermost stratosphere. This report has already remarked several times on the importance placed by SPARC (WCRP, 2000) on the UTLS region, and Table 4.3 acknowledges this by referring separately to the mid-troposphere (MT) and the upper troposphere/lowermost stratosphere (UTLS). Observational requirements above the UTLS, i.e. in those parts of the stratosphere that are not connected to the troposphere by isentropic surfaces, are beyond the scope of this report.

		Threshold			Target		
		LT	HT		LT	HT	
			MT	UTLS		MT	UTLS
Vertical Resolution	[km]	1.0	1.0	2.0	0.5	1.0	2.0
Horizontal Domain		Global					
Horizontal Integration	[km]	100	150	200	10	50	100
Dynamic Range	[g kg^{-1}]	0.01 - 15			0.001 -25		
Random Error (1 σ)	[%]	20			5		
Systematic Error	[%]	< 5			< 2		
Timeliness	[hour]	< 3					

Table 4.3: *WALES mission threshold and target observational requirements. LT and HT as in Table 4.1. HT consists of the mid-troposphere (MT, approximately 5 km to 10 km, 500 hPa to 300 hPa) and the upper-troposphere/lowermost-stratosphere (UTLS, approximately 10 km to 16 km, 300 hPa to 100 hPa). For random errors, 1 σ denotes 1 standard deviation. Compliance with the random error value is required for the entire horizontal domain and the given dynamic ranges.*

The WALES research objectives place extremely demanding requirements on the vertical resolution of water vapour observations, well below the generic threshold requirements. This is particularly challenging in view of the fact that the WALES mission demonstrates a new observing concept for space-borne remote sensing.

It is worth mentioning that other information such as aerosol particle backscatter and cloud tops as well as cloud bases and derived variables such as relative humidity will be made available by WALES. Therefore, WALES will provide a large amount of data on additional parameters and will complement other missions. However, as the provision of such information does not drive the WALES mission, requirements are not imposed here.

As an Earth Explorer mission demonstrating a new technique, the WALES mission does not have any particular requirements on the sampling except that global data are required. As it is expected that three- and four-dimensional data assimilation systems will be used for processing the data, there is no requirement on the preferred local time of the observation.

In order to obtain observations during all seasons at least twice (this will broaden the statistical basis), a minimum mission duration of two years is required.

5 The Mission Elements

5.1. Introduction

The main data products provided by the WALES mission will be vertical profiles of absolute humidity throughout the troposphere and the lower stratosphere up to an altitude of 16 km, as well as vertical profiles of tropospheric and stratospheric aerosol. Additional geophysical products will be cloud boundaries, primarily of cirrus and mid-level clouds, planetary boundary layer height and structure, and occasionally surface reflectance and albedo. These data products will be assimilated by NWP centres to improve the accuracy of weather forecasts and atmospheric analysis. Moreover, these data will improve climate research capabilities, with particular emphasis on the role of water vapour in atmospheric forcing, in the Earth's radiation budget and in water-vapour/cloud interactions. Through its anticipated impact on NWP and climate research, the WALES mission is expected to become an important and innovative element of the GOS.

This chapter outlines the architecture of the candidate Earth Explorer WALES mission including its space and ground segments, and identifies ancillary data necessary for data processing; the chapter also briefly illustrates other missions that will benefit from or provide benefits to WALES.

WALES will have:

- a space segment, consisting of a satellite carrying a water vapour Differential Absorption Lidar (DIAL) system, used to perform measurements of the vertical profiles of atmospheric water vapour, aerosol and clouds

- a ground segment, required to accomplish data processing and delivery to NWP and climate modelling centres.

Ground system and operational satellites, as well as outputs from NWP models, will provide auxiliary data to support the processing of WALES data.

5.2 The Space Segment

The core element of the proposed Earth Explorer mission is a nadir-viewing water vapour DIAL system. Differential absorption of laser radiation by water vapour represents a selective and sensitive method for measuring the vertical profile of absolute humidity. In principle, the DIAL technique is based on comparing the attenuation, throughout the atmosphere, of two laser pulses of slightly different wavelength. One pulse is emitted on the centre of a water vapour absorption line (on-line wavelength, λ_{on}). The second is emitted on the line wing (off-line wavelength, λ_{off}), where absorption is negligible or significantly reduced. This is shown schematically in Figure 5.1.

As the laser pulses propagate through the atmosphere, part of their energy is backscattered to the instrument by particles – typically aerosols or hydrometeors – and by the molecules of the gas species comprising the atmospheric mixture.

The length of the laser pulse transmitted into the atmosphere defines the scattering volume. The location of this volume is very precisely determined by the travel time of the laser pulse from the transmitter to the scattering volume and back to the receiver.

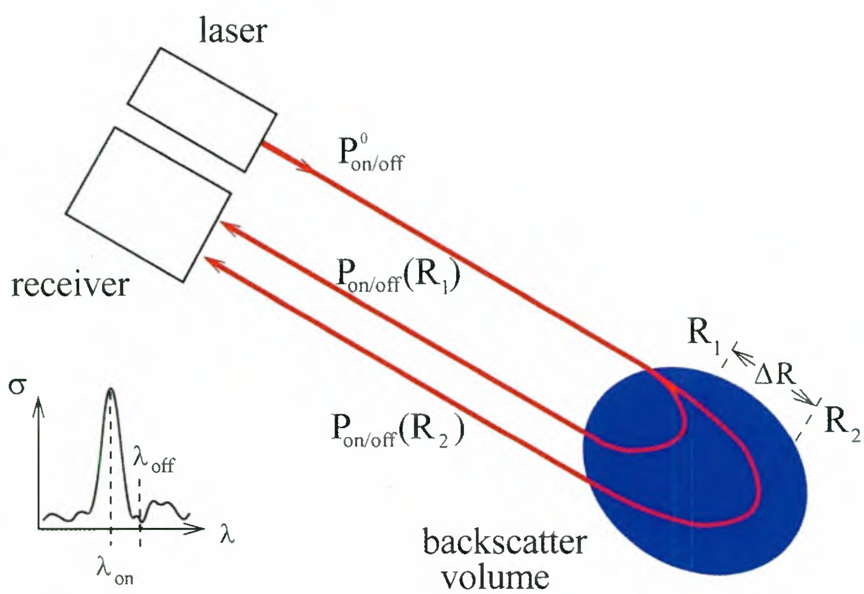


Figure 5.1: *Conceptual drawing of the DIAL principle.*

The almost simultaneous transmission of the on- and off-line wavelengths allows the application of a simplified form of the DIAL equation, specifically

$$n_{H_2O}(R) = \frac{1}{2(\sigma_{on} - \sigma_{off})\Delta R} \, ln \frac{P_{off}(R_2)\, P_{on}(R_1)}{P_{on}(R_2)\, P_{off}(R_1)} \tag{5.1}$$

where $P_{on/off}(R_{1/2})$ are the backscatter powers at λ_{on} and λ_{off}, respectively, $R_{1/2}$ are the lower and upper levels of the scattering volume, respectively, $n_{H_2O}(R)$ is water vapour number density, $R = (R_1 + R_2)/2$ and $\sigma_{on/off}$ is the water vapour absorption cross-section.

The equation assumes backscatter and extinction from aerosol and molecules at the on- and off-line wavelengths to be identical, thus implying that the difference in amplitude of the on- and off-line signals is to be totally ascribed to water vapour absorption.

From the above equation it follows that the WALES mission will provide numerous advantages with respect to currently operational water vapour sensors. Among these are:

Small and Time-independent Bias

The DIAL technique is self-calibrating: the measurements depend only on knowledge of the water vapour differential absorption cross-section. This quantity is well known in the near infrared spectral region, having been extensively measured and reported in the literature (Grossmann and Browell, 1989); furthermore, this quantity is almost independent from ancillary data, provided the absorption lines selected are among those largely independent of temperature. Hence, it is possible to perform direct measurements of humidity with low sensitivity to ancillary parameters. Because of the possibility to select water vapour absorption lines in a spectral region containing only a few absorption lines from other gas species, interference from other trace gases is negligible (Ambrico et al., 2000).

High Precision with the Possibility of Trading-off between RMS Error and Horizontal/ Vertical Resolution

Due to the large scattering cross-section of aerosol and gas species at the laser wavelength and to the large power aperture product, the collected signals are large enough to guarantee a high signal-to-noise ratio and, consequently, high precision measurements. Precision can be further increased by reducing vertical and/or horizontal resolution. Conversely, vertical and/or horizontal resolution can be increased if lower precision is acceptable.

High Dynamic Range

Precise water vapour DIAL measurements are obtained in atmospheric regions characterised by a differential optical thickness in the range 0.02-0.1. Such values of differential optical thickness can be maintained at any humidity level by selecting absorption lines with different absorption cross-sections. The simultaneous transmission of, for example, three on-line wavelengths allows coverage of up to four orders of magnitude in absolute humidity and sounding of the atmosphere from the surface up to 16 km.

The considered spectral region (925-940 nm) includes absorption lines that allow comprehensive coverage of the troposphere and the lowermost stratosphere. The strongest lines, with attenuation cross-sections in the range 1 to 2 x 10^{-25} m^2, can be used to sound the upper troposphere and lowermost stratosphere, the medium strength lines (1 to 6 x10^{-26} m^2) to sound the middle troposphere, and the weakest lines (1 to 6 x 10^{-27} m^2) to sound the planetary boundary layer. Different on-line wavelengths can be selected depending on the geographical region monitored (Tropical, Mid-latitude, Sub-Arctic) and the season of the year. Figure 5.2 shows water vapour absorption cross-sections in the spectral interval 925-940 nm.

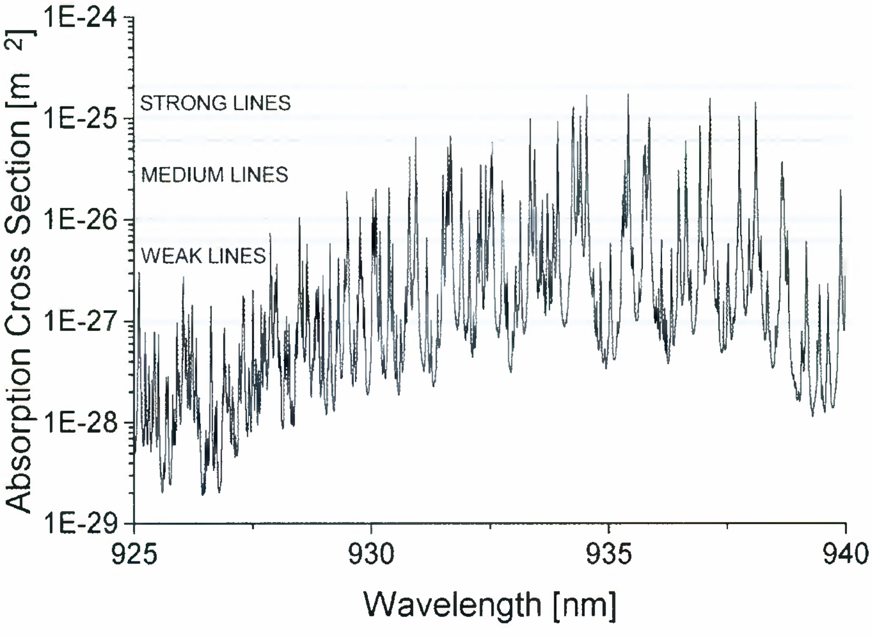


Figure 5.2: *Water vapour absorption cross-section versus wavelength in the spectral region 925-940 nm. Horizontal lines highlight the cross-section ranges suitable for measurements in the upper, mid and low troposphere. Lines with strong absorption are suitable for sensing the upper troposphere/lowermost stratosphere (UTLS) region, medium absorption for the middle troposphere (MT) and weak absorption for the lower troposphere (LT).*

Low Vertical and Horizontal Error Correlation

Data from adjacent vertical layers are uncorrelated, as are error estimates from adjacent horizontal pixels.

Possibility of Data Retrieval Under Cloudy Conditions

Humidity profiles can be measured above the tops of all clouds. Furthermore, if optical thickness is low enough (typically below 0.3), the DIAL will penetrate these clouds and measure water vapour below these clouds. Measurements are also possible above and between scattered clouds. This benefit of the WALES mission is illustrated in Figure 2.3.

5.3 Ground Segment

The ground segment concept includes receiving stations located at high latitudes. The mission and satellite operations control will be at ESOC in Darmstadt (D). Data will be processed at the stations or in separate scientific centres, to provide quasi-real-time data delivery to NWP centres. Processed data will be archived for ten years. Data processing includes the retrieval of the vertical profiles of absolute humidity, the correction of systematic errors, and the estimation of random and residual systematic errors. The retrieval of particle backscattering profiles is also performed at this stage, leading to estimates of cloud boundaries, planetary boundary layer height (at about 1.5 km altitude) and optical thickness of aerosols and clouds. The data will be processed to Level-1b within three hours of observation.

5.4 Processing Requirements and Products

The high-level requirements for the processing of WALES data and the products for end-users are:

- Backscatter profiles (Level-1b products);

- Retrieved profiles of water vapour extinction coefficients and their error estimates as a function of height (Level-2a products);

- Retrieved profiles of absolute humidity and their error estimates as a function of height (Level-2b products).

All of these products will be made available to appropriate end users and archive centres and should be made available in near real-time.

- Data sets for climate research (Level-3 and -4, i.e. gridded fields, monthly and seasonal means).

The WALES data will be made available to facilitate the generation of additional geophysical products specified in Section 5.6 below.

5.5 Validation

In the initial phase of the mission, an important activity will be validation via data from ground-based or air-borne observations. Due to the horizontal resolution of WALES (between 100 and 200 km), ground based lidar systems will be of limited use for correlative measurements, but airborne systems flying along the satellite ground-track will be a more reliable tool. Several airborne systems can provide the required support. Potential candidates are the DLR airborne DIAL system, the NASA/LARC (Langley Research Center) experiment Lidar Atmospheric Sensing Experiment (LASE), the Raman Airborne Spectroscopic Lidar (RASL) being developed by NASA/GSFC (Goddard Space Flight Center) and the Hohenheim/NCAR (National Center for Atmospheric Research) airborne WV DIAL, which is also under development.

5.6 Additional Geophysical Products

Various additional products will be derived from the observations of the WALES mission, namely:

Aerosol Particle Backscatter Profiles

Backscattering profiles from aerosol and cloud particles can be retrieved from the off-line lidar signal. Off-line signal statistics are expected to be large enough to guarantee high precision both in the troposphere and in the stratosphere. In particular, the simultaneous measurement of absolute humidity and particle backscattering profiles allows inference of important information on the microphysical properties and hygroscopic growth of aerosol particles (Wulfmeyer and Feingold, 2000).

Cloud Tops and Bottoms (the Latter for Cloud with Low Optical Thickness)

Backscattering profiles can be used to estimate cloud boundaries. Cloud boundaries are associated with large increases or decreases of the particle backscattering, i.e. with large backscattering gradients. While cloud top is always determinable, cloud bases can only be estimated if cloud optical thickness is small (e.g. McCormick, 1997; Winker and Trepte, 1998).

Optical Thickness of Aerosol and Clouds

The optical thickness of aerosol layers and thin clouds can be estimated from the off-line signal if an aerosol-free region is present both below and above the aerosol/cloud layer. Alternatively, the optical thickness of aerosol and clouds can be determined from the backscattering profiles if the extinction-to-backscatter ratio (or lidar ratio) for the sounded particles is known. Values of the lidar ratio for different aerosol and cloud types are extensively reported in the literature (e.g. Ansmann et al., 1992; Ackermann, 1998).

Planetary Boundary Layer Height and Structure in Clear-Air

Aerosol and water vapour tend to be trapped within the planetary boundary layer and can be used as tracers for the study of boundary layer vertical structure. In particular, aerosol and moisture exhibit strong gradients at the top of the boundary layer. In clear-air conditions, both in stable and unstable conditions, the boundary layer height can be identified as a minimum in the backscatter gradient (Devara et al., 1995, Wulfmeyer 1999).

Surface Reflectance and Albedo

In situations where the DIAL system sounds an atmospheric column of limited optical thickness, the surface reflectance and albedo can frequently be determined from off-line signals (e.g. Reagan et al., 1997, cf. those parts of Figure 2.3 where the hatched region reaches the ground).

5.7 Relation with Other Missions

WALES is expected to provide valuable data to be included in the GOS. On the other hand, GOS will provide auxiliary data to be used in the processing and monitoring of WALES data. WALES will benefit from and be of benefit to all GOS system elements, the environmental observation satellite network, the surface observing network, the upper-air observing network and the aircraft-based meteorological data relay system.

The measurements of this mission will be used synergetically with traditional meteorological and operational satellite observations to provide data for calibration of present and future water vapour observing systems (SEVIRI on MSG, IASI/AMSU on Metop, TOVS, SSM/I, and AIRS). WALES humidity sounding will facilitate improvements in the interpretation schemes for high-resolution passive sounding measurements. In particular, a co-located space DIAL system may improve IASI and AIRS performances in terms of temperature profiling accuracy (0.8 K to 0.4 K at 600 hPa; Smith, 1998).

WALES will benefit from and be of benefit to ORACLE, a series of ozone DIAL missions scheduled between 2003 and 2013. Combined WALES and ORACLE measurements will substantially improve the understanding of the interactions between water vapour and ozone in the troposphere, and will also help in assessing stratosphere-troposphere exchange.

WALES will also benefit from results of the ESSP-3/CENA mission, flying in formation with EOS-PM (or EOS-Aqua). The combination of these two systems, providing accurate measurements of radiative fluxes in the atmosphere, of cloud cover and estimates of the aerosol direct and indirect radiative forcing, will complement

WALES measurements. Similar arguments hold for EarthCARE, one of the other candidate Earth Explorer Core missions.

WALES may fly for some time simultaneously with ADM/Aeolus. The combination of data from these two Earth Explorer Missions will allow testing of GCM performance, primarily the consistency between the water vapour distribution and the dynamical variables of the atmosphere.

5.8 Proof of Concept by Ground-based and Airborne Measurements

The methodology of water vapour DIAL has been the subject of many studies in the past. DIAL systems have been used for measurements of water vapour from ground-based and aircraft platforms for two decades. Recently, it has been demonstrated that water vapour DIAL measurements with an overall error of less than 5% are feasible in the entire troposphere (Wulfmeyer and Bösenberg, 1998). Successful autonomous DIAL measurements of water vapour, aerosols, and clouds have been made from a high-altitude aircraft operated by NASA (Browell et al., 1998). The proposed DIAL instrument has its roots in the various ground-based and airborne lidar systems that are operational throughout Europe as well as the LITE experiment and the airborne LASE instrument of NASA. It will draw extensively on the scientific and technological heritage from European airborne water vapour DIAL systems (DLR-H_2O, Germany, Ehret, et al., 1999; CNRS-Leandre II, France, Bruneau et al., 2001a/b) and their ground-based counterparts (MPI, Germany; IMAAA-CNR/Unibas, Italy) and will take advantage of the associated technological achievements.

Figure 5.3 demonstrates the measurement capability of water vapour DIAL in the lower troposphere. An excellent agreement between DIAL and radiosonde profiling was found by Wulfmeyer and Bösenberg (1998). The difference between the mean values was merely 0.06 g/m^3, which corresponds to 2.7%. There was no evidence to suggest a systematic error in the DIAL system higher than 2.7%.

Furthermore, the capabilities of an airborne water vapour DIAL in the upper troposphere and lowermost stratosphere have already been demonstrated by Ehret et al. (1999) and are illustrated in Figure 2.8.

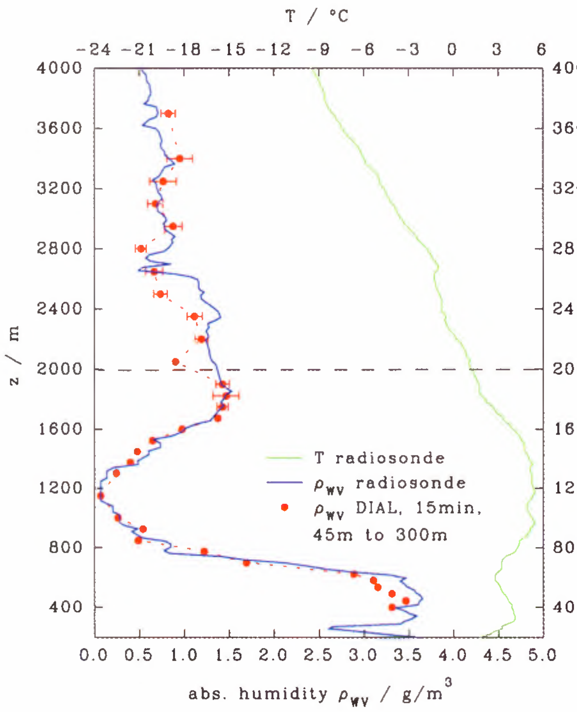


Figure 5.3: *Water vapour and temperature profiles measured during the comparison experiment on 1 December 1994 at 19:13 UT. The DIAL profile was calculated without Doppler correction. Indicated in the DIAL profile are the statistical errors that are often less than the diameter of the circles. Excellent agreement between the water vapour profiles was achieved. Note the extended dry layer between 800 and 1400 m, which was very well captured by the DIAL.*

6 System Concepts

6.1 Introduction

The WALES mission addresses the measurement of water vapour concentration profiles in the troposphere and lower stratosphere. It is a single payload mission operating a nadir viewing water vapour Differential Absorption Lidar (DIAL) instrument.

6.2 Payload

The measurement requirements for WALES are high vertical resolution, small correlated errors, and low time-independent bias. A DIAL instrument is ideally suited for this purpose because its measurement principle combines the good definition of the measurement volume inherent in pulsed lidar measurements with the self-calibration property of a differential absorption measurement. Direct detection DIAL operated in the 925-940 nm spectral range is the most suitable concept to provide low statistical errors and bias.

6.2.1 Observational Principle

WALES is intended to profile the atmosphere in a nadir-viewing configuration as depicted in Figure 6.1. The DIAL technique compares the attenuation of two laser

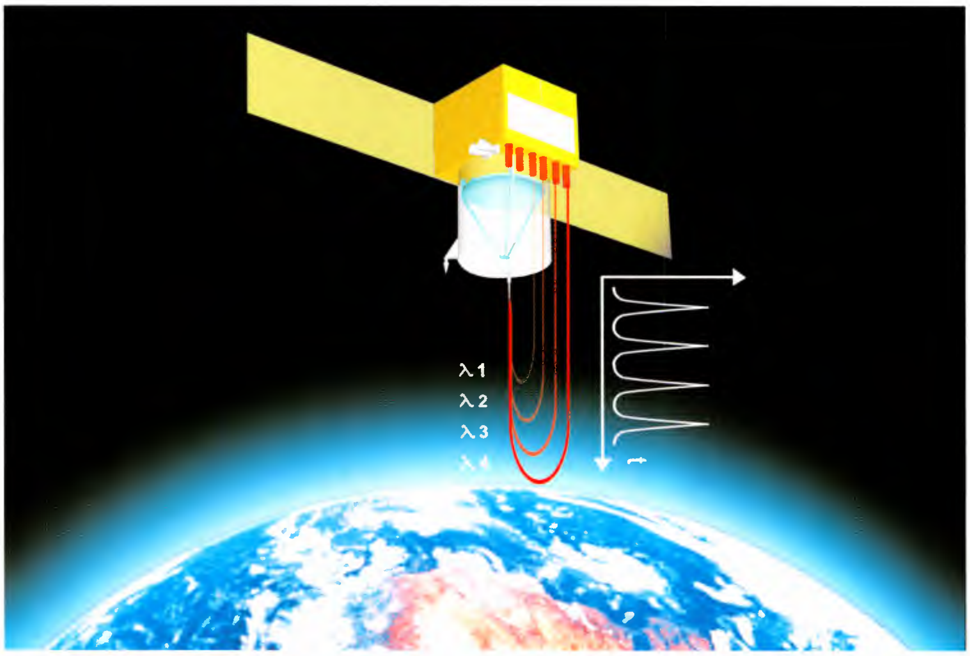


Figure 6.1: *Observational principle of WALES.*

pulses emitted at different wavelengths. The on-line wavelength falls on the centre of a water vapour absorption line and the off-line wavelength falls on the line wing, where absorption is significantly reduced.

The large dynamic range of water vapour is addressed with a DIAL instrument by using different on-line wavelengths λ_1, λ_2, λ_3 with different (water vapour) attenuation cross-sections, and one off-line wavelength λ_4, as depicted in Figure 6.2. In this way, different sub-intervals of the dynamic range are addressed by dedicated on-line wavelengths. For typical water vapour profiles the different on-line wavelengths have different penetration depths, thus allowing for measurements in different altitude intervals. The location of these intervals varies with climate zone. The strongly absorbing water vapour lines are used for higher altitudes (low water vapour concentration) and the weakly absorbing lines are used for lower altitudes (high water vapour concentration). From near-simultaneous sounding with all four wavelengths, complete profiles across the entire altitude range are obtained. Note that the on-line measurements and the separate off-line measurements are used in a cascaded way. That is, for each on-line measurement, the measurement on the next weaker line serves as its off-line measurement.

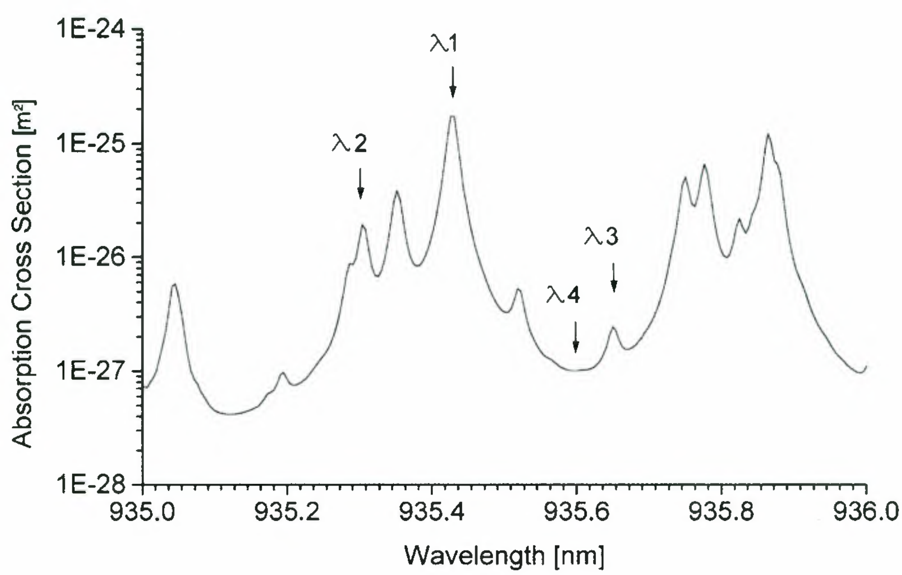


Figure 6.2: *Selected water vapour lines.*

Suitable water vapour absorption lines for an instrument with three on-line wavelengths and a separate off-line wavelength have been identified in the region around 935 nm. A close spacing between on- and off-line is always desirable to minimise any wavelength dependence of the backscatter coefficient. There are several possible combinations of water vapour absorption lines and different strategies can be followed to optimise the selection, either for best match to desired absorption cross-sections or for improved insensitivity to atmospheric temperature variations. As a consequence, the instrument will be designed to allow a variable set of wavelengths to be selected from a wavelength range rather than specifying a small set of fixed wavelengths.

6.2.2 Performance Requirements

The main error source that drives the design of a spaceborne DIAL instrument is the statistical noise from the relatively small number of received photons. This section outlines the most critical design parameters that determine the RMS error and gives bounds for system design parameters.

Apart from the selection of appropriate on-line wavelengths at suitable water vapour absorption lines, the DIAL measurement precision is determined by the instrument properties and the measurement resolution. In particular, the random error is inversely proportional to the power-aperture factor $\sqrt{A_{Tel} . P_{av}}$, where A_{Tel} denotes the telescope aperture area and P_{av} the laser average power.

Noise from background light is a particular problem for water vapour DIAL observations from space. Suitable wavelength ranges are in the near infrared region (e.g. around 935 nm as adopted for WALES). At these wavelengths eye-safety considerations, rather than technical limitations or performance considerations, limit the energy density of the beam and determine the transmitter and hence the receiver field of view. Consequently, the only viable technical solution to reduce the background noise level is the use of narrowband filters. About 40 pm FWHM (full width at half maximum) filtering is needed. The impact of background light is minimised by flying on a dawn-dusk orbit and pointing the instrument to the dark side.

Wavelength Calibration

The DIAL measurement principle does not require radiometric calibration. However, accurate control of the transmitted wavelengths is required. Knowledge of both the absolute wavelength and the transmitter spectral shape determines the achievable systematic measurement error (bias). To achieve a low bias, the transmitted wavelengths must be locked to an absolute frequency reference with high accuracy (<60 MHz).

Spectral Purity

In addition to accurate knowledge of the centre frequencies of the transmitted beams, the spectral shape must either be known or the signal energy must be confined to a sufficiently small frequency interval. The reference interval for spectral purity is approximately equal to FWHM (~1 GHz) of the strongest attenuation line at the highest measurement altitude. To avoid the need for characterising and monitoring of the spectral shape, the principle of using a narrow bandwidth signal of high spectral purity is preferred. For the stipulated level of systematic errors, a laser line width of <160 MHz and a spectral purity of 99.9% are needed. As for the frequency accuracy, the requirements on beam quality are driven by the measurements in the lower stratosphere (using the strongest absorption line).

Raw Data Spatial Resolution

Because of the vertical variation of aerosol backscatter and the non-linearity of the DIAL equation, the vertical resolution of the raw data must be higher than the intended vertical resolution of the water vapour retrieval, to allow for effective cancellation of the on-line and off-line backscatter coefficients. Analysis shows that the raw data vertical resolution should be about 20 times higher than the intended resolution of the water vapour profile for typical aerosol variability.

The raw data horizontal resolution, set by the on-board along-track averaging, is driven by the need to provide measurement data under broken cloud conditions. The horizontal resolution should be commensurate with the size of cloud free patches under typical broken cloud conditions. Thus, about 1 km horizontal on-board averaging is appropriate.

Pointing

Absolute pointing is not critical to a spaceborne DIAL application. Pointing away from nadir would need compensation in the data processing if the resulting Doppler shift exceeds acceptable values. The pointing values identified in Table 6.1 are sufficient for ensuring that no Doppler compensation is required. Stronger requirements, however, have to be considered regarding the relative alignment of the different receiver channels and the corresponding alignment of the transmitted laser pulses. It must be ensured that on- and off-line pulses probe the same air volume and that the receiver field of view is illuminated in the same way for all channels.

Background Subtraction

The useful echo signal must be extracted from the detector signal. It is thus necessary to compensate for the receiver offset and background light. This is achieved by recording the receiver signal after reception of the ground echo, i.e. at a time where no contamination by backscattered photons is possible.

Receiver Linearity

The DIAL equation requires a linear relationship between the receiver response and the received echo signal power. Non-linearities of the detector and its electronics affect the overall linearity of the echo signal measurement. For the relevant dynamic range of the echo signal and the allowable bias error, a preliminary non-linearity requirement of 10^{-3} (30 dB relative amplitude error for signals in the dynamic range) has been identified.

Table 6.1 summarises the main instrument requirements derived from the observational requirements.

Parameter	Value
Transmitter	
Number of wavelengths	3 on-line and 1 off-line to be transmitted as a burst of 4 pulses
Inter pulse separation within burst	200 μs (=1.5 m on ground)
Wavelength range	935.5 nm ± 0.4 nm
Laser frequency locking accuracy and stability	< 60 MHz
Laser line-width (FWHM)	< 160 MHz
Laser spectral purity within 1GHz	> 99.9%
Absolute pointing accuracy	± 3 mrad
Spatial alignment of probed volumes	< ±10 μrad
Alignment of transmitter and receiver	< 20 μrad
Receiver	
Detector field of view	matched to transmitter FOV within 0.05 mrad
Receiver nonlinearity (over 30 dB dynamic range)	< 0.1%
Raw data altitude resolution	< 50 m
Raw data along track onboard integration	< 1 km

Table 6.1: *Summary of the instrument requirements.*

6.2.3 Instrument Description

The instrument principle is based on the emission of four wavelengths, serving as three pairs of on-and off-line wavelengths in a cascaded manner (Section 6.2.1 and Figures 6.3 and 6.4).

The main subsystems are:

- four separate telescopes (bistatic configuration) to transmit the different wavelengths
- two transmitter units capable of emitting two wavelengths each, in the form of pulse pairs with a separation between the individual pulses of a few hundred μs

- a 1.5 m diameter receiving telescope
- four direct detection receivers with blocking filters to reduce the background noise level
- instrument control electronics to monitor equipment, control mode switching and provide measurement timing.

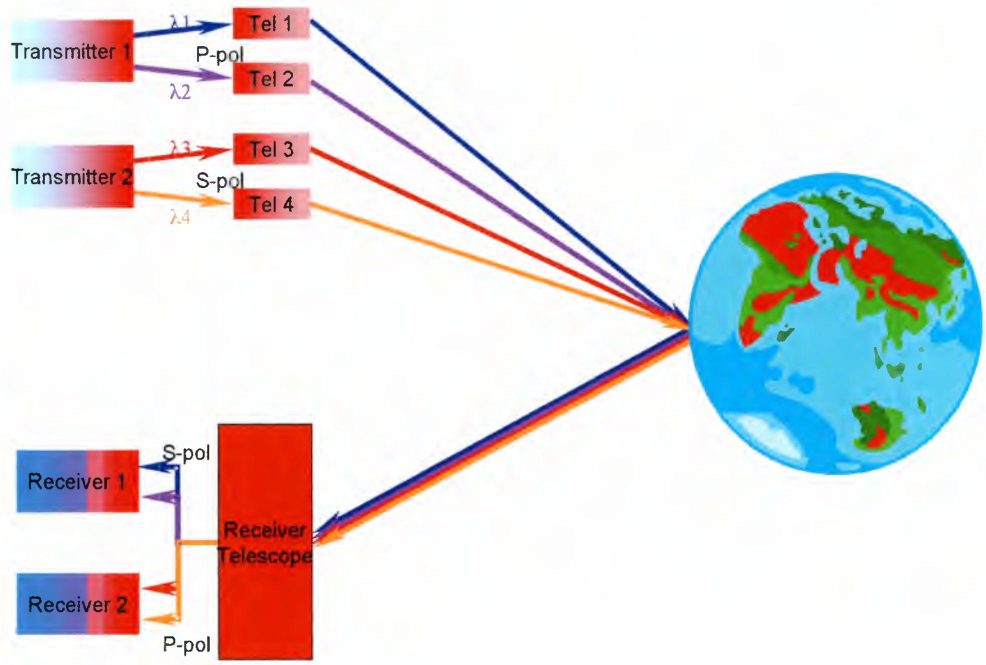


Figure 6.3: *Overview of the proposed concept.*

The laser operation and pulse emission principle are described in the temporal diagram shown in Figure 6.4.

The instrument provides 50 m vertical sampling from ground to 16 km altitude and 1 km horizontal sampling.

Figure 6.5 shows the different subsystems in a functional block diagram of the instrument. The transmitter system consists of a pump unit, a laser source, a frequency reference stage and a transmitter telescope. These units must be replicated to allow the quasi-simultaneous operation of the four wavelengths.

The receiver system comprises the receiver telescope, the receiver optics (including blocking filter and etalons for background-light suppression and wavelength separation) and the detector assembly.

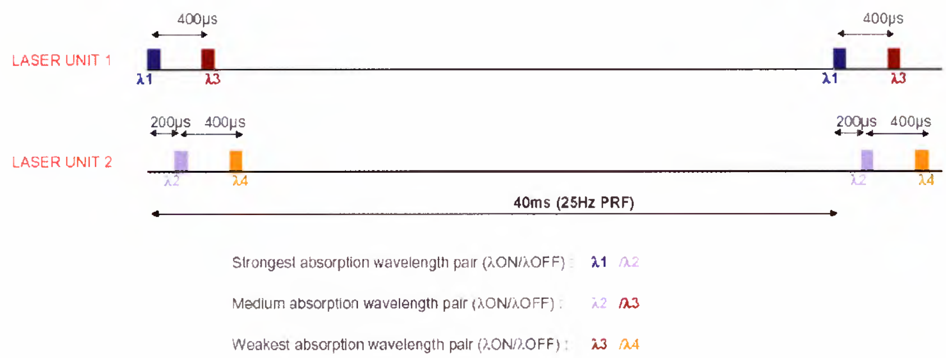


Figure 6.4: *Operation principle and temporal diagram of emitted wavelengths. A train of pulses is emitted in burst mode at a 25 Hz pulse repetition rate. Pulses are emitted in a cascade with a delay of 200 μs, allowing the on-line and off-line pairs to probe essentially the same volume.*

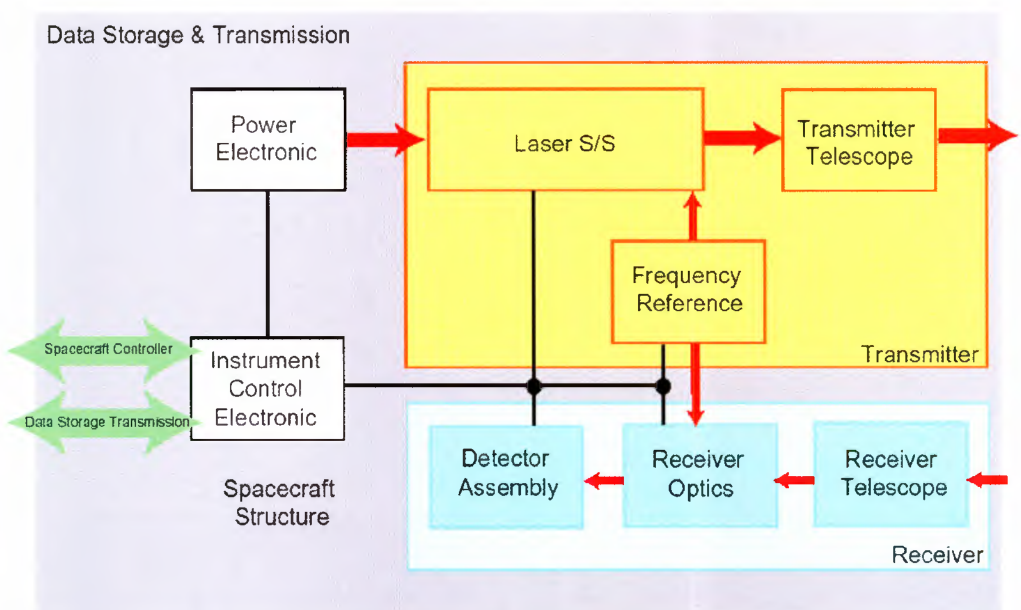


Figure 6.5: *DIAL instrument functional block diagram.*

The overall instrument and data-management functions are included in the dedicated instrument control unit, interfacing with the spacecraft controller.

The power electronics, the pump unit, the detector assembly and the instrument control unit are cooled by a dedicated heat-pipe assembly connected directly to the satellite radiator.

Transmitter

Candidate laser sources are shown in Table 6.2.

Wavelength	Cr:LiSAF	Ti:Sapphire	Nd:Mixed Garnet	OPO
830 nm	Yes	Yes	No	Yes
925 nm	Yes	Yes	No	Yes
935 nm	Possible	Yes	Possible	Yes
940 nm	Possible	Yes	Yes	Yes
Properties				
	Pumping by flashlamp or Diode at 670-690 nm. For this spectral range only cw-diodes are commercially available.	Pumping by flashlamp or frequency doubled Nd-lasers	Pumping by flashlamp or Diode at 808 nm	Pumping by frequency doubled Nd-lasers
	Spontaneous lifetime of 67 μs	Spontaneous lifetime of 3.7 μs	Spontaneous lifetime of 270 μs	
	Soft and mechanically weak crystal	Hard and mechanically strong material	Hard and mechanically strong material	Hard and mechanically strong material
	No high energy laser reported	Lasers up to 240 mJ are reported	Only laboratory demonstrator at NASA exists	Systems up to 100 mJ are reported

Table 6.2: *Candidate laser sources and overview of trade-off issues.*

The laser material investigation can be summarised as follows:

- In terms of pure laser performance two comparable materials, the Ti:Sapphire laser and the OPO, are available.
- Cr:LiSAF does not seem to be a promising material.
- The Nd:mixed garnet concept has the potential to be a good transmitter, but the heritage is limited and much technological investigation must be performed to advance this concept to practical use for spaceborne systems.

In conclusion, these reasons lead to the selection of the Ti:Sapphire and OPO lasers as the best candidates for a spaceborne DIAL.

A possible configuration for the laser transmitter is shown in Figure 6.6. It has an actively controlled seeded OPO system pumped by a frequency-doubled high power Q-switched Nd:YAG laser. An alternative setup using a Ti:Sapphire could be used in the same instrument architecture; in particular the pump laser could be the same.

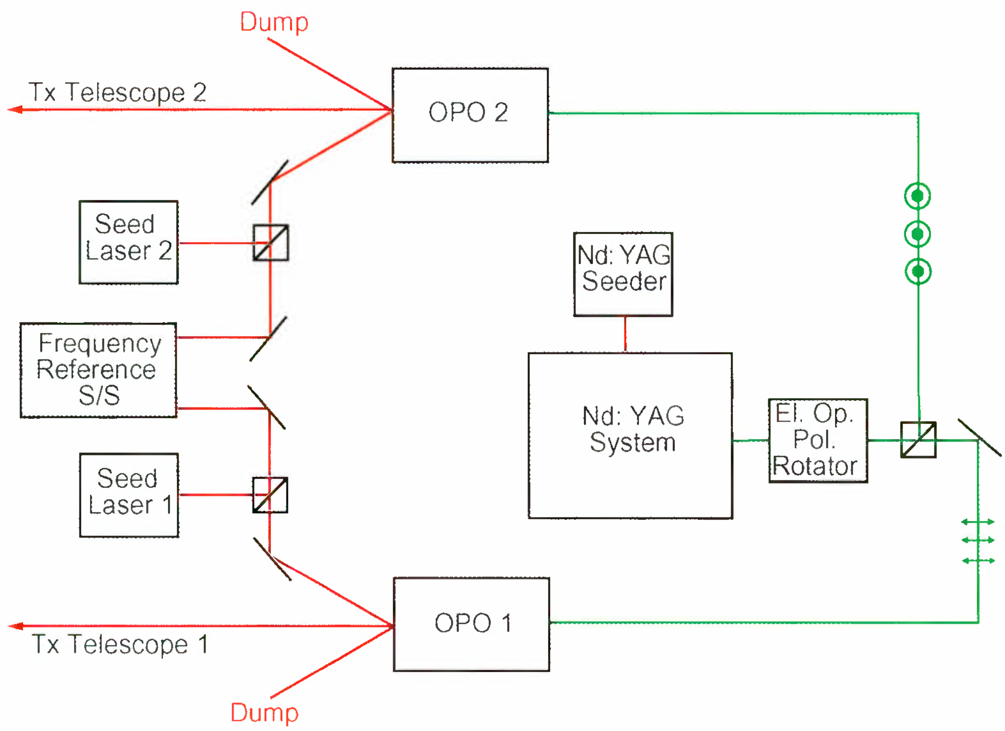


Figure 6.6: *Principle of one transmitter unit.*

The pump unit consists of a Master Oscillator with Power Amplifier (MOPA) laser for the power pulse generation, together with a frequency stabilised seed laser to secure the spatial and spectral beam quality. The laser source is seeded by an actively controlled (frequency stabilised) laser to reach the required performance for the transmitter pulse.

The operational principle for the transmitter is to use one pump source that can generate pulse pairs with 400 µs pulse separation. With the electro-optical polarisation rotator the beam polarisation switches between s and p polarisations. With this configuration the pump pulse can be routed to one of the two independent laser sources (OPO or Ti:Sapphire). Each of the OPO cavities is optimised for one wavelength. The laser source output is directed to the individual transmitter telescopes. The seeder is coupled through the output coupler to the laser and one part of the seed frequency is guided to the frequency stabilisation stage. In an OPO configuration, the idler beam can be absorbed in a beam dump, or alternatively guided to deep space.

The pump unit outlined here benefits from a very good heritage, because the required performance analyses lead to a pump source with requirements almost identical to the actual ADM-Aeolus transmitter breadboard (Table 6.3).

Parameter	Value
Wavelength	1064 / 532 nm
PRF	25 Hz double pulses with 500 μs delay
Output Energy	> 500 mJ @ 1064 nm / ≈300 mJ @ 532 nm
Spatial Mode	TEM_{00}
Longitudinal Mode	Single-frequency
Beam Quality	$M^2 < 3$
Spectral Purity	99% in 90 MHz

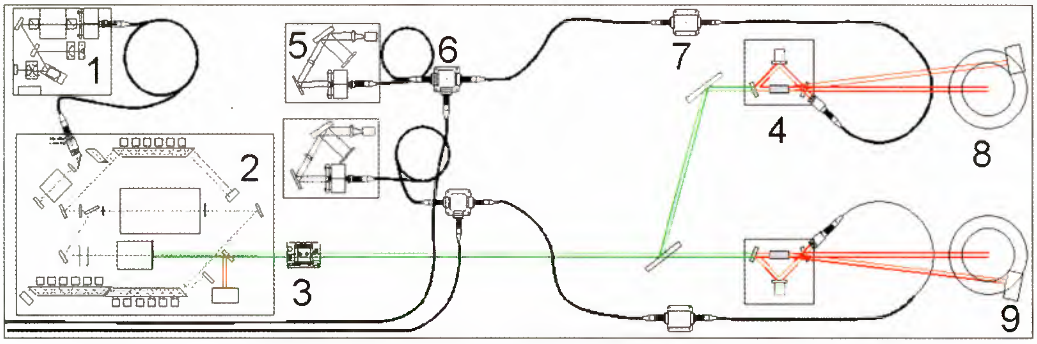
Table 6.3: *WALES MOPA performance prediction.*

The pump unit power electronics are based on the ATLID laser-diode power-supply breadboard in the form of a pulse-forming network. This design must be adapted to the special WALES needs by doubling the number of power storage cells (due to the pulse pairs) and optimising for the low PRF of 25 Hz.

The overall transmitter layout is shown in Figure 6.7, assuming an OPO laser source. The assembly consists of two transmitters with seeders and a single pump source. The complete transmitter subsystem of the WALES instrument would consist of three such assemblies operated in a two out of three cold redundancy configuration. This implies that the tuning range of each laser source covers the entire wavelength range considered for all four operational wavelengths.

In order to ensure high spectral purity, the laser source must be injected with a laser seeder of high spectral purity. The two solutions identified involve an external cavity diode laser and a DFB/DBR diode laser, respectively.

Moreover, the emitted wavelength properties must include very narrow bandwidth (<160 MHz) and high spectral stability (<60 MHz). The frequency stabilisation cannot be done by using water vapour cells as reference for all employed wavelengths. The absorption lines employed have absorption cross-sections varying by over two orders of magnitude and the off-line wavelength is not centred at all on a water vapour absorption line. In addition to a water vapour cell, a wavemeter based on a Fizeau or Fabry-Perot interferometer to determine wavelength differences is needed. The on-line wavelength with the largest absorption cross-section is then locked to the absorption cell (multiple-pass vapour cell with a optical path length of about 35 m) while the other wavelengths are offset-locked to this stabilised signal using the wavemeter, as shown in Figure 6.8.



1) Pump Unit/Seeder
2) Pump Unit/Power Laser
3) E/O Polarization Rotator
4) Laser Source/OPO
5) Frequency Reference/Seeder
6) Fibre coupled Beam Splitter
7) Fibre coupled Optical Isolator
8) Transmitter Telescopes
9) Beam Dump

Figure 6.7: *Transmitter sub-unit pre implementation.*

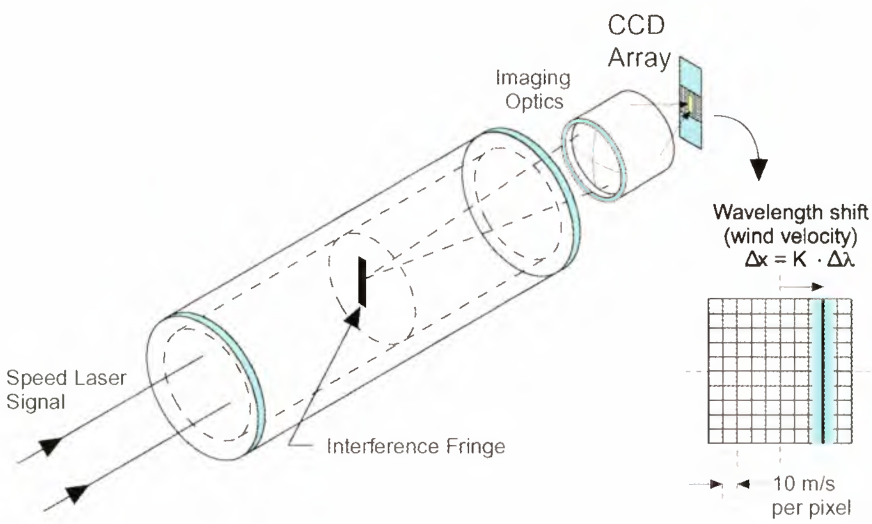


Figure 6.8: *Wavemeter principle.*

Receiver

The receiver concept consists of a receiver telescope, a polarisation and spectral pre-selection unit and two receiver units, each with a high resolution spectral filter stage and a detector assembly.

The concept for the receiver telescope is an afocal parabolic design with an f-number of 1 (see Figure 6.9). A very stiff CSiC plate is used as the baseplate for the receiver.

This plate supports the struts for the secondary mirror and the tripod for the 1.5 m CSiC primary mirror.

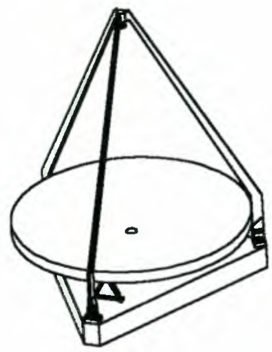


Figure 6.9: *1.5 m diameter telescope. All ceramic CSiC design.*

A deployable telescope (see Figure 6.10) providing a large aperture could be an option to provide margins to reduce the laser power required. The alignment requirements on the telescope deployment are relaxed considerably by using a secondary stage mechanism. Such a concept has been studied for the ozone DIAL ORACLE programme (Mark et al., 1999).

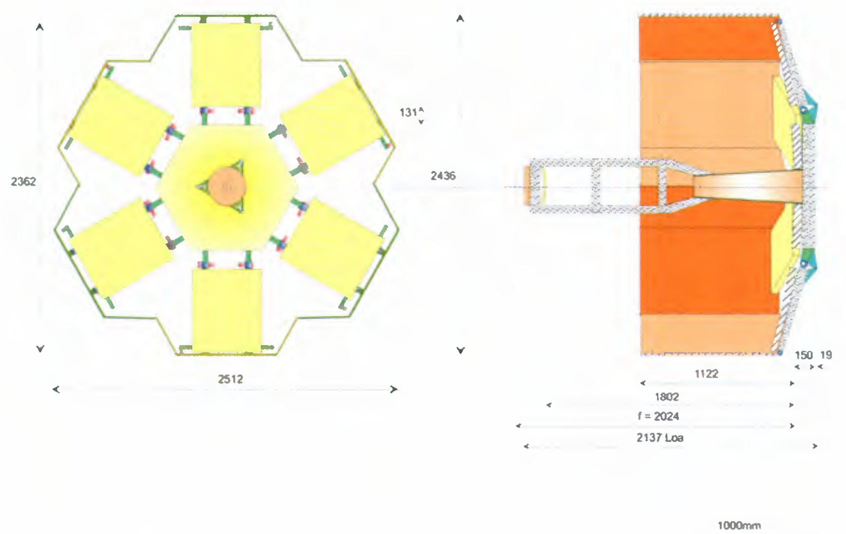


Figure 6.10: *Alternative telescope option: a deployable telescope.*

Figure 6.11 shows the receiver principle. The four wavelengths received from the telescope are first split by a polarising beam-splitter into two pairs. The signal is then spectrally filtered by a coarse bandpass filter for initial background signal suppression.

The next stage is a narrowband etalon, where one wavelength is transmitted and the other reflected. The transmitted frequency is received on the detector assembly. The reflected part goes through the second etalon and is collected by the other detection assembly. This configuration provides high background signal suppression and high receiver transmission for useful wavelengths.

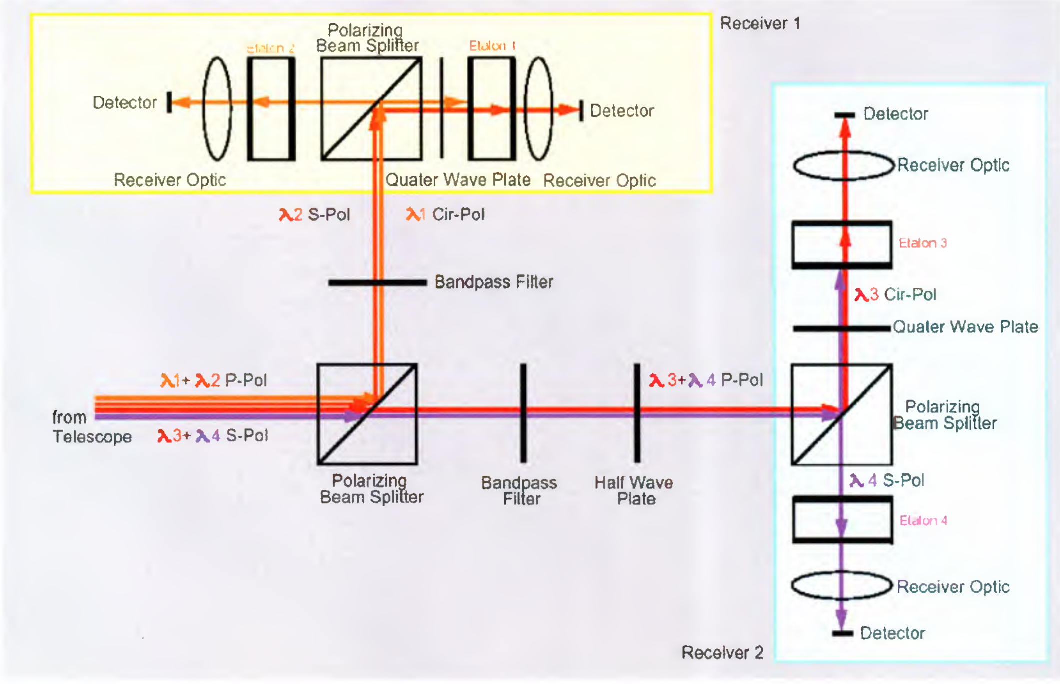


Figure 6.11: *Receiver principle.*

The narrow bandwidth etalon is a key element in the receiver chain to separate any particular wavelength and block the background radiation. An active adjustable design concept is proposed with 50 mm aperture and 40 pm bandwidth (see Figure 6.12 and Table 6.4). The active cavity adjustment by piezo-electric drivers allows the etalon peak transmission to be tuned to the selected laser wavelength. The system provides four tuneable wavelengths, addressing in-flight optimised absorption lines with respect to the probed atmosphere. For the detector, both Avalanche Photo Diode (APD) and Accumulation CCD are worth considering.

Instrument mechanical design

A candidate instrument concept is shown in Figure 6.13. The instrument consists of a receiver telescope and six emitter telescopes (four transmitter channels and two for the laser unit, implemented in cold redundancy).

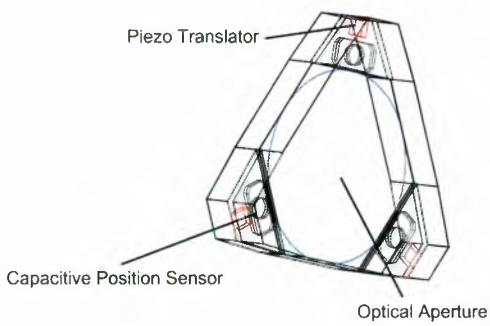


Figure 6.12: *Etalon proposed design.*

Parameter	Value
Material	Fused silica
Clear aperture	50 mm
Cavity adjustment	Piezo controlled
Cavity control	Capacitive position sensor
Control range	± 0.3 μm (> ± 3 nm wavelength shift)
Performance	
Optical transmission	> 50%
Spectral transmission	40 pm (goal 200 pm)
Free spectral range	6 nm

Table 6.4: *Etalon performance and design values.*

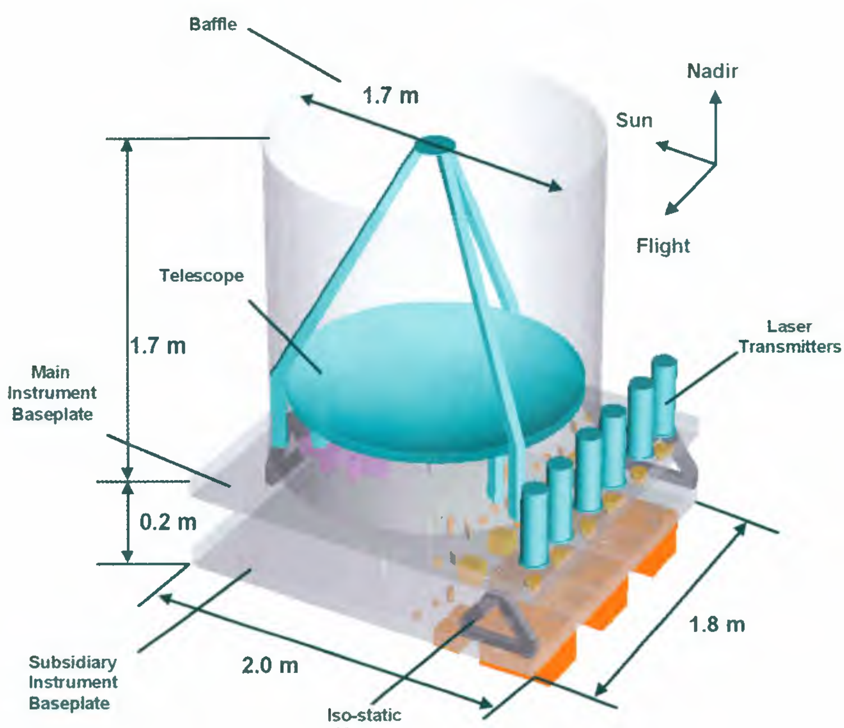


Figure 6.13: *Instrument mechanical layout.*

6.3 Mission Analysis

To meet the global coverage requirement, a polar orbit is required. Best performance is achieved at the lowest feasible orbit altitude that can be maintained with reasonable propellant demand. To minimise background radiation, the solar incidence angle should be as low as possible. A Sun-synchronous orbit with 450 km altitude and a local time for the ascending node of about 06h00 (dawn-dusk orbit) has been selected. It results in a maximum eclipse time of 24 min during the Northern Hemisphere winter period.

The global coverage resulting from the orbit selection is shown in Figure 6.14, which depicts the number of observations obtained per day.

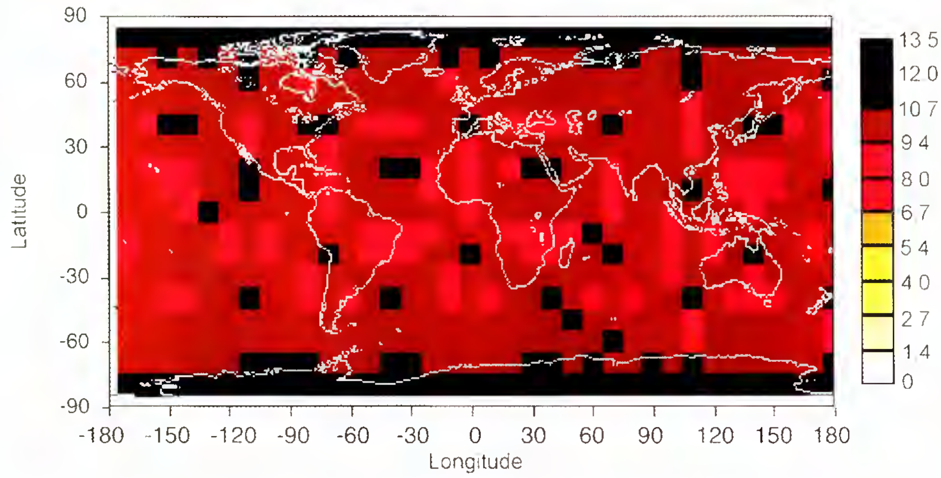


Figure 6.14: *Average number of observations per day in 10° by 10° cells.*

At least two ground stations in the Northern Hemisphere are required to ensure ground contact every orbit. Ground stations at Kiruna (Sweden) and Barrow (Alaska) are proposed. The visibility area of each ground station is shown in Figure 6.15.

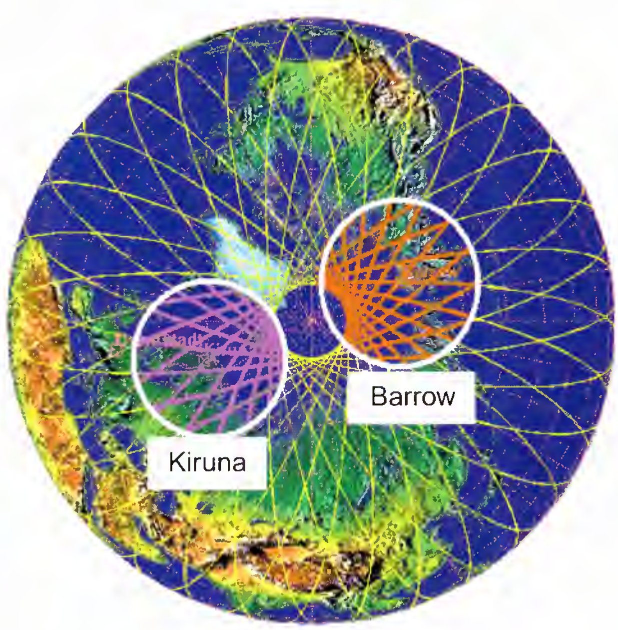


Figure 6.15: *Visibility of ground stations.*

6.4 Satellite Concept

The satellite configuration is driven by the size of the DIAL telescope. The dawn-dusk orbit at 450 km altitude allows application of a relatively simple design (Figure 6.16).

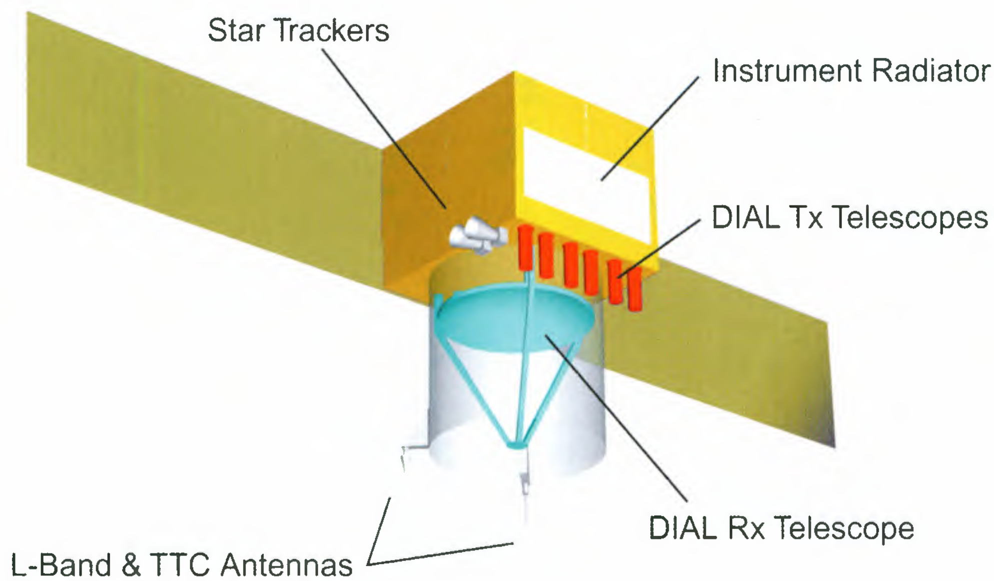


Figure 6.16: *Spacecraft in deployed configuration.*

All transmitter and receiver parts of the instrument that require close co-alignment are located on a common lower baseplate. On the other side a transmitter panel (upper baseplate) with high-dissipating units is attached. Internally, the platform is made of a central tube core structure, allowing a circular interface to a standard launcher adapter. The upper end of this tube provides a load path for attaching the instrument to the bus.

The spacecraft must radiate heat amounting to about 945 W for the instrument and about 250 W for the platform. To provide best temperature conditions, the instrument heat will be dumped via heat pipes to a radiator panel on the anti-Sun side. Because of the selected dawn-dusk orbit, the satellite bus provides a cold space view for the accommodation of the radiator. The dissipation heat of the platform will be radiated with two radiators mounted on the flight and anti-flight sides and thermally connected with heat pipes.

The power consumption during the Sun-illuminated phase is about 1428 W and increases during eclipse by only 15 W. Fixed orientation solar arrays can be used. The area of the solar array with GaAs cells is about 17 m^2. In addition NiH_2 batteries will provide 40 Ah.

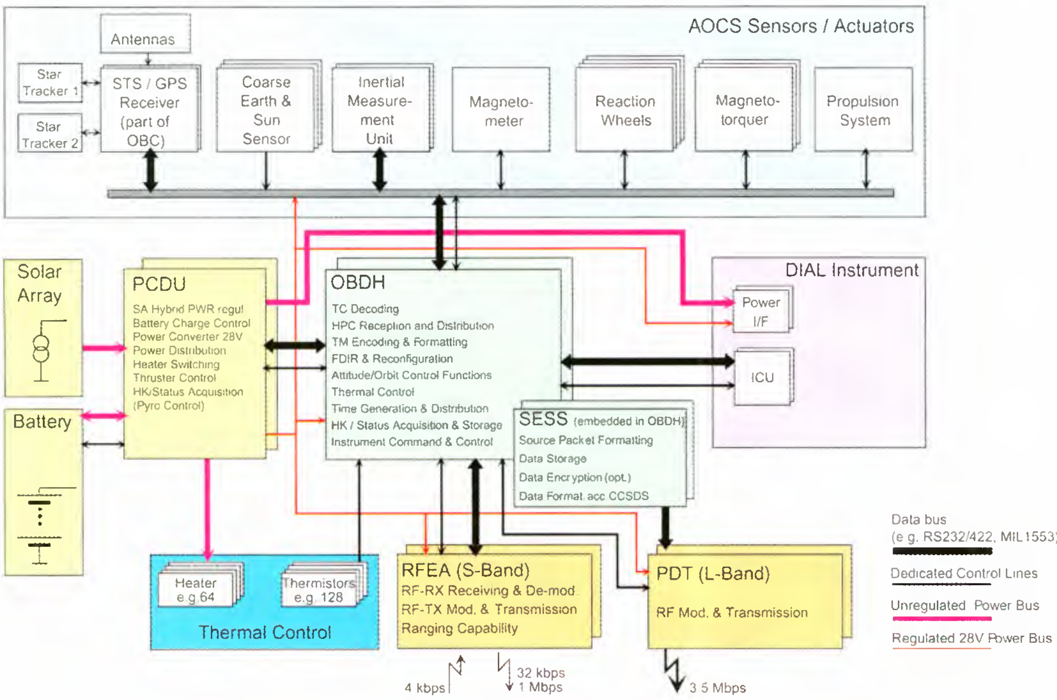


Figure 6.17: *Satellite functional block diagram.*

A functional block diagram of the satellite is shown in Figure 6.17.

The on-board data handling system provides all necessary processing and interface resources for safely commanding, controlling and monitoring the overall spacecraft. The data rate of the instrument is low, about 250 kbit/s equivalent to 1.4 Gbit of raw data per orbit. The OBDH mass memory allows the storing of data from several consecutive orbits.

In order to benefit from existing ground and on-board terminals, the METOP L-band link – applied for high rate picture transmission (HRPT) and planned also for ADM-Aeolus – is proposed for WALES Payload Data Transmission.

Attitude estimation is performed with gyros and star trackers, and altitude control with reaction wheels and magneto-torquers in nominal mode. Orbit determination is provided by GPS receivers, while orbit control is ensured by a hydrazine propulsion system. In acquisition and non-nominal modes, attitude estimation and control can be provided by magnetometers and coarse Sun (Earth) sensors and magneto-torquers.

The power demand, mass and data rate budgets of the WALES instrument and satellite are presented in Table 6.5.

	Mass (kg)
Instrument	590
Satellite (dry mass)	1220
Including system margin	1340
Fuel (3 years)	150
Total mass	1490

	Power (W)	Data rate
Instrument	140	250 kbit/s
Satellite (including margins)	1430	1.4 Gbit/orbit

Table 6.5: *Instrument and satellite budgets.*

6.5 Launcher

The launcher choice is driven by the satellite dimensions. Soyuz IKAR is assumed as a reference (Figure 6.18).

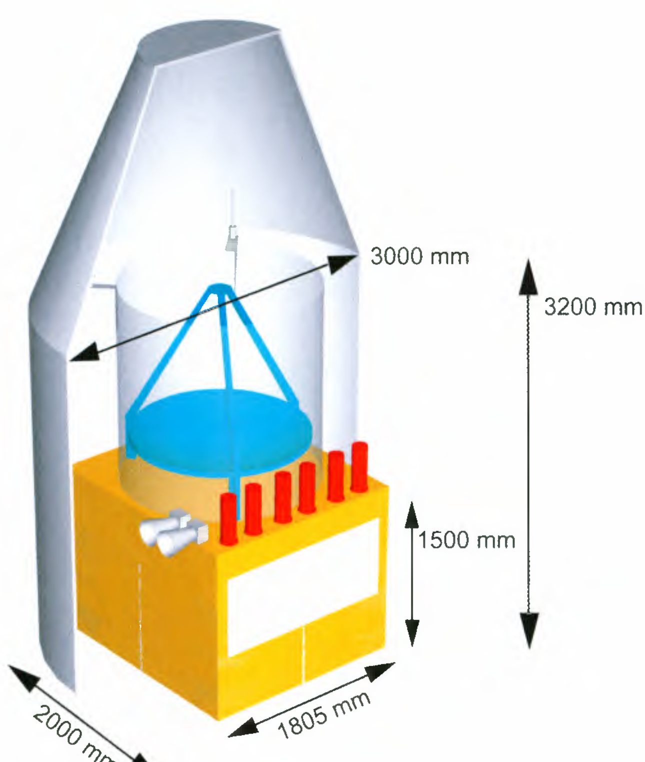


Figure 6.18: *Satellite stowed configuration in Soyuz IKAR launcher.*

6.6 Ground Segment

6.6.1 Architecture

The proposed ground segment architecture is shown in Figure 6.19. The main elements are:

- CDAE (Command & Data Acquisition Element)
- MSCE (Mission Operations & Satellite Control Element)
- PAC (Processing & Archiving Centre)
- Communications Networks.

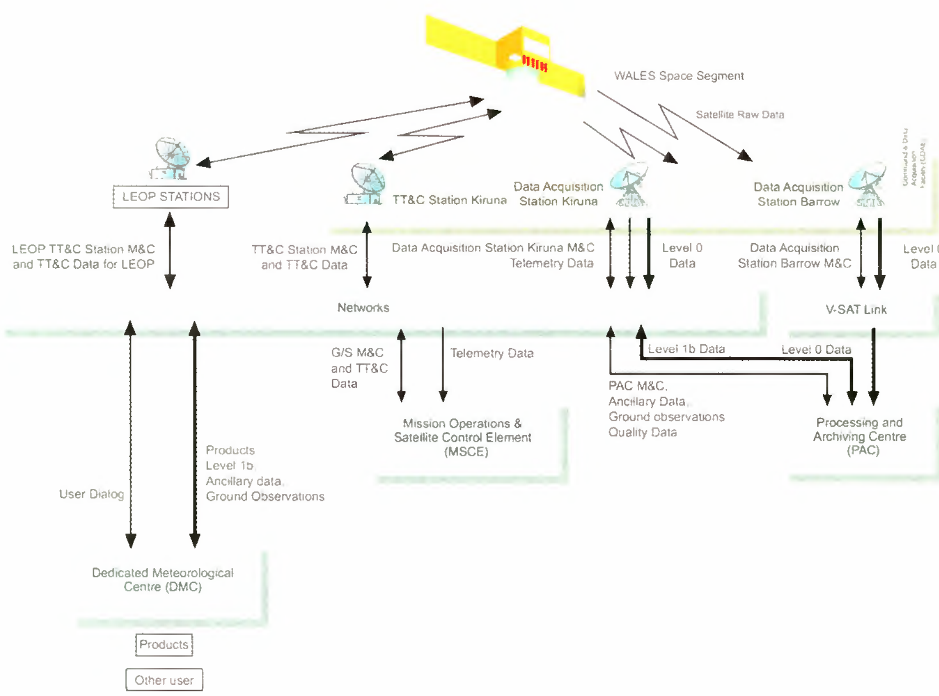


Figure 6.19: Ground segment architecture.

The CDAE could consist of stations in Kiruna and Barrow (Section 6.3). The MSCE would be ESOC. The best location for initial data processing has yet to be defined. The level and location of data archiving will be the result of further study and trade-offs. It is assumed that all measurement data will be delivered to and archived at a Science Data Centre, which could be a European weather service. The overall concept could be similar to that for ADM-Aeolus as the same user community is being served. Hence maximum use can be made of available ESA facilities and infrastructure for implementing CDAE, MSCE and the Communications Networks.

6.6.2 Data Products and Processing

The data processing flow is shown in Figure 6.20.

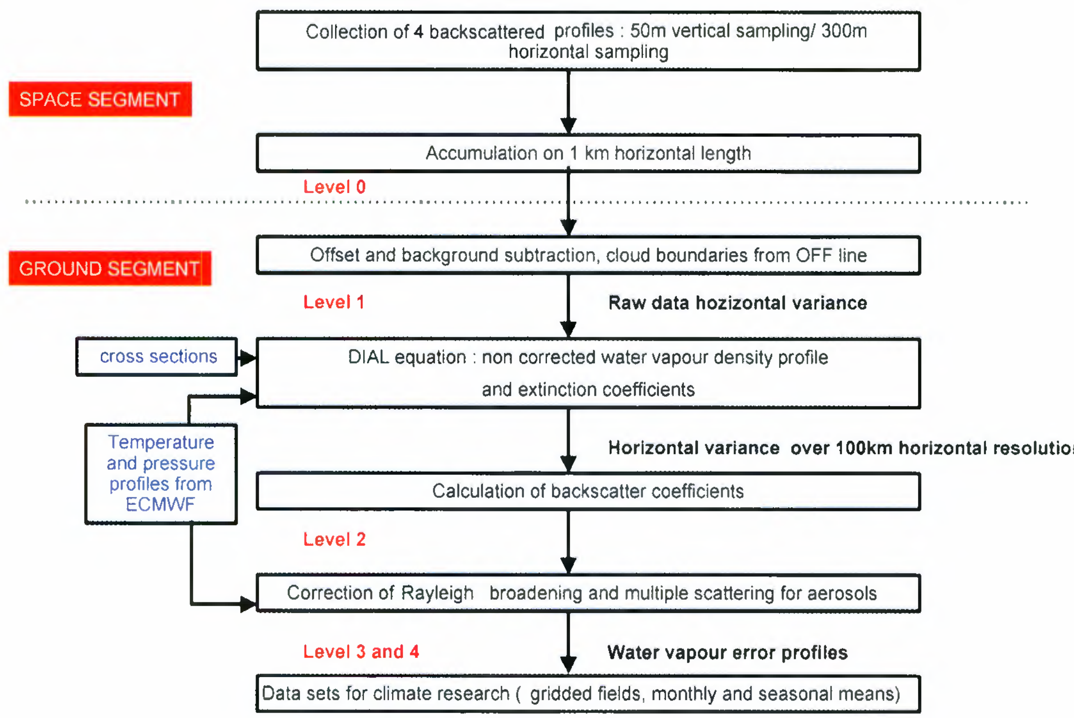


Figure 6.20: *Data processing flow diagram.*

The first data processing steps must be performed on board; subsequent steps can be done on the ground. The Level-0 data products are the pre-accumulated backscatter profiles together with auxiliary data such as laser pulse energy, time, position, and wavelength. Due to the simplicity of the DIAL equation, the Level-1 data products already contain water vapour vertical profiles along with error estimates. The cross-sections of the selected absorption lines are calculated using temperature and pressure profiles from ECMWF.

Data processing includes correction for Rayleigh-Doppler broadening of the narrow-band laser line profile caused by backscattering due to the 'thermal' motion of molecules. Although molecular scattering is regarded as an elastic scattering process, random thermal motion of the molecular constituents of the atmosphere induces a significant Doppler broadening of the scattered light. This effect influences the absorption cross-sections along the path from the scattering volume to the receiving telescope. It is worth noting that (predominantly systematic) errors can be introduced and consequently that correction can be required, especially in the presence of large backscatter gradients from aerosol or clouds. Auxiliary data such as aerosol backscatter profiles obtained from WALES off-line measurements, together with temperature profiles obtained from NWP models (for example, the ECMWF model), will permit proper correction of the effect (Ansmann, 1985; Ansmann and Bösenberg, 1987). The backscatter profiles will be retrieved through analytical inversion of the off-line signal or from the Klett solution of the Bernoulli equation (Fernald, 1972).

The retrieved aerosol profiles must also be corrected for the effects of multiple scattering. This phenomenon is particularly important within clouds or aerosols with optical depths in excess of unity (Bruscaglioni et al., 1998). Analytical approaches, like the one proposed by Bissonnette (1996), can be used for the correction.

6.7 Performance

6.7.1 Assumptions

A suitable set of line parameters is given in Table 6.6; it has been identified from the HITRAN 96 data base (updated by Schermaul et al., 2001a/b).

	Wavenumber $1/\lambda^{vac}$ [cm^{-1}]	**Wavelength λ^{air} [nm]**	**Lower state rotational energy E" [cm^{-1}]**	**Absorption cross-section σ^0_L[m^2]**
Weak line	10684.830	935.657	382.517	1.38×10^{-27}
Medium-strength line	10688.772	935.307	488.108	1.77×10^{-26}
Strong line	10687.364	935.427	136.762	1.89×10^{-25}
Off-line	10685.456	935.6		Line wing $< 8 \times 10^{-28}$

Table 6.6: *Line parameters used for the performance studies. Data taken from HITRAN 96 database.*

The desired water vapour lines have been carefully selected such that only lines with lower state rotational energy values in the range 100 cm^{-1} < E" < 500 cm^{-1} are considered. For these lines, the DIAL measurement error due to uncertainty in atmospheric temperature is < 0.5% K^{-1}).

Three reference water vapour profiles (tropical, sub-Arctic winter and US standard) have been used for the performance simulations and instrument sizing. These reflect large variations of water vapour content (from 0.002 g/kg to 15 g/kg) and cover the major part of the global humidity range (see Figure 6.21).

The instrument parameters used for the performance assessment are listed in Table 6.7.

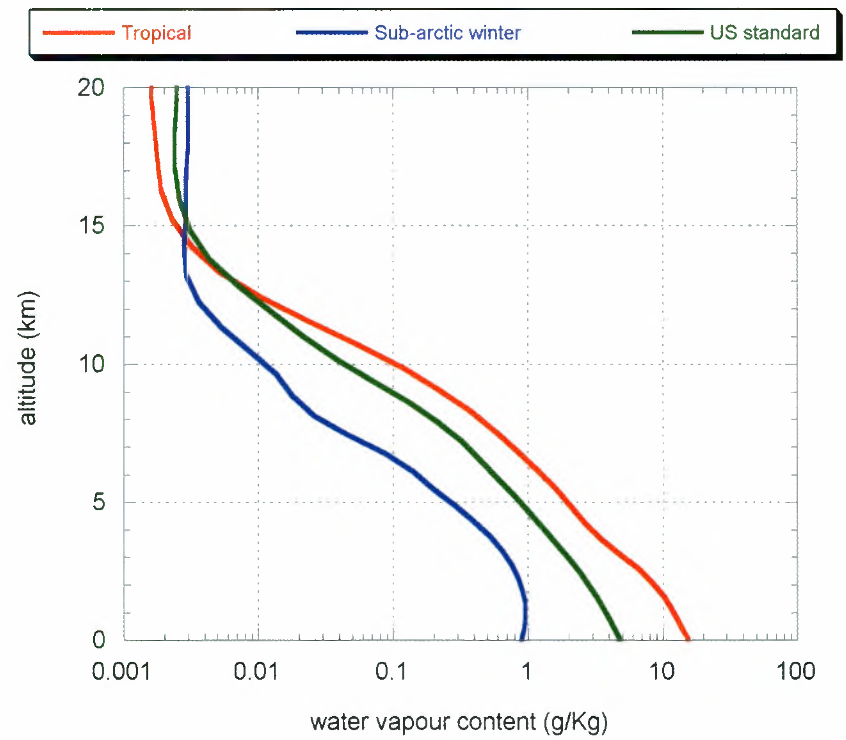


Figure 6.21: *Reference water vapour profiles used for simulation.*

Parameter	**Unit**	**Value**
Vertical resolution [0-5 km/5-10 km/10-16 km] (*)	km	1 / 1 / 2
Horizontal resolution [0-5 km/5-10 km/10-16 km] (*)	km	100 / 150 / 200
Observation condition	-	Daytime
Spacecraft altitude	km	450
Receiver telescope optical (circular) aperture	m	1.50
Laser pulse energy (for each wavelength)	mJ	120
Transmitter FOV (set according to eye safety)	µrad	138
PRF (double pulse repetition frequency)	Hz	25
Spectral filter width	pm	40
Spectral filters transmission	-	0.45
Telescope transmission	-	0.91
Receiver field of view	µrad	178
APD effective NEP	fW/√Hz	1.33
APD quantum efficiency	-	0.9

(*) Horizontal and vertical resolutions are set according to the WALES threshold observational requirements for NWP from Table 4.4.

Table 6.7: *Summary of DIAL performance parameters.*

6.7.2 Results

The results for random error are presented in Figure 6.22 for clear air and in Figure 6.23 with cirrus and alto-stratus clouds. The relative statistical water vapour error (or random error) is displayed as a function of altitude and for different climates. The specified random error (vertical line; constant 20 percent) and threshold lower limit of the dynamic range (horizontal line; corresponding to 0.01 g/kg) are also shown in the plots.

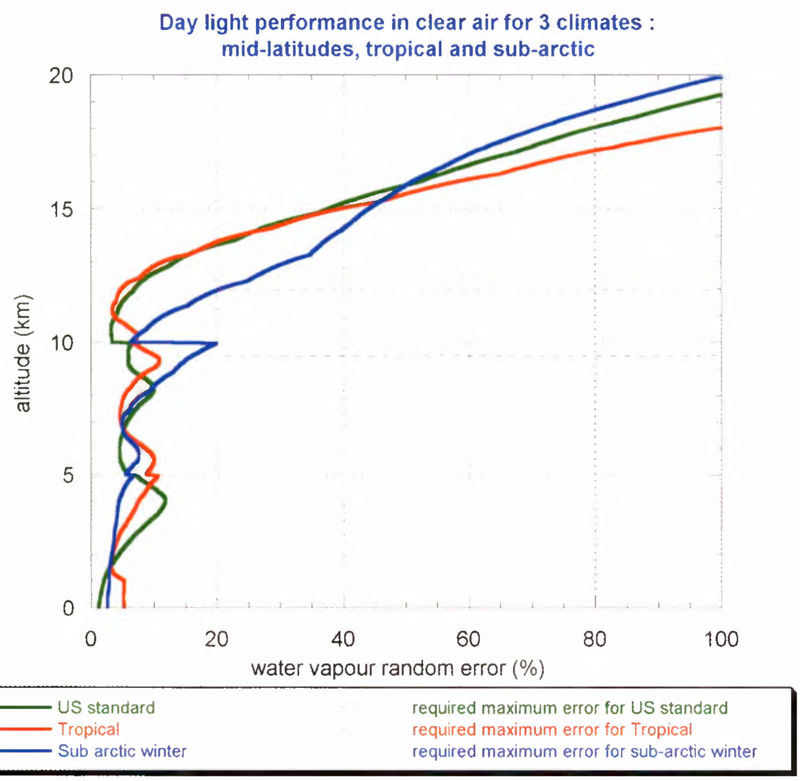


Figure 6.22: *Relative random error performance computed for the three reference profiles of water vapour, clear air conditions. Vertical and horizontal resolution are changed at 5 and 10 km (according to Table 6.7), explaining the jumps in the curves at these altitudes.*

In clear air, the average performance over the whole dynamic range specified in the threshold requirements (Table 4.4) is better than 10% for the three water vapour profiles considered. The instrument is able to measure up to around 14 km with a relative random error of less than 20%, for mid-latitudes and tropical climates. The error is about 50% at 16 km, this is due to the very low humidity at this altitude (about 0.002 g/kg). Remarkably good performance is achieved for very moist conditions of the tropical profile close to the surface (errors are lower than 5%).

A single set of four wavelengths has been used for this simulation, meaning that such performance is achieved for different climates without the need to tune the lasers. The instrument tuning capability is, however, proposed to allow an optimum set of wavelengths with respect to the probed atmosphere to be selected in-flight.

The effect of cirrus and alto-stratus clouds on the random error performance has been simulated and is displayed in Figure 6.23. Simulations have shown that the instrument is able to measure below thin clouds. The performance simulation between 5 and 13 km gives a relative error of less than 20%. The main difference from Figure 6.22 is caused by a loss of signal due to the cirrus transmission and larger background radiance due to a cloud deck at 5 km.

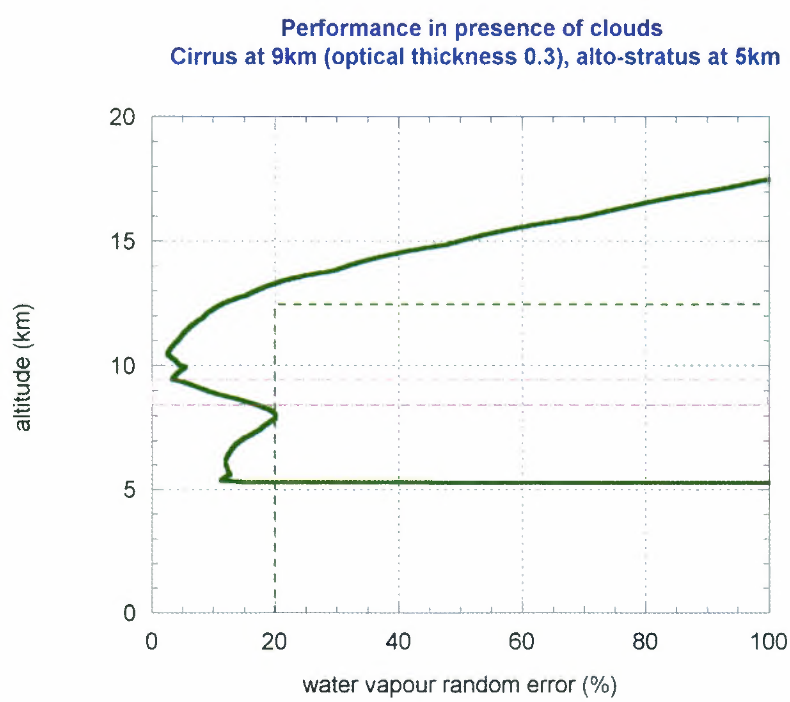


Figure 6.23: *Random error performance computed for the US standard profile of water vapour in case of clouds. This set of simulations assumes a cirrus cloud, 1 km thick at 9 km altitude and with an optical thickness of 0.3 (shown on the graph in red dashed line), and alto-stratus at 5 km altitude.*

In addition, the simulation demonstrates that with a cloud deck at 5 km, the instrument is able to provide precise measurements above the clouds with only small degradations with respect to cloud-free conditions.

Table 6.8 shows a detailed budget for the bias performance.

Contributors	Impact on bias budget
Temperature knowledge (5 K)	2%
Cross-section characterisation (spectroscopy measurements accuracy)	2%
Laser spectral purity	1%
Laser frequency linewidth	1%
Laser frequency stability	0.5%
Other contributors (misalignment, pointing, background subtraction, linearity)	1%
Overall performance	3.4%

Table 6.8: *Bias or systematic error budget.*

Concerning the performance of WALES, the threshold requirements (see Table 4.4) are met with large margins. WALES will be able to measure water vapour content with less than 10% random error in a cloud free atmosphere, even in the case of a very humid atmosphere (see Figure 6.22, red curve). In the presence of clouds, WALES will be able to provide precise measurements below thin cirrus and above cloud deck. For cloudy scenes, WALES will provide profiles through gaps between clouds (similar to LITE, see Figure 2.3) The vertical and horizontal resolutions can be scaled to meet the target NWP and the desired climate research precision of the water vapour content. Measurement of the water vapour content with a precision of better than 20% will be reached for 500 m vertical resolution and 100 km horizontal resolution.

7 Programmatics

7.1 Introduction

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

7.2 Technical Maturity, Critical Areas and Risk

The technical maturity of the WALES mission is compliant with a launch in the timeframe of the second cycle of the Earth Explorer Core missions. The required technology preparatory activities indicate, however, that a launch in 2008 is challenging in terms of development schedule.

The clear separation of the platform and the (single) DIAL instrument and the relative simplicity of the ground processing allow for parallel developments of instrument, platform and ground segment. The development risks are associated with a number of well-identified elements of the instrument, as outlined in Table 7.1. The main critical element concerns the transmitter subsystem, where the capabilities to provide the required performance remain to be demonstrated. The development of the laser transmitter has already been initiated.

The instrument development will draw substantially from the experience accumulated in Europe with the ALADIN lidar for the Atmospheric Dynamics Mission (ADM) / Aeolus and the pre-development of the ATLID lidar for the EarthCARE mission. Useful experience that can be enlisted also includes NASA's lidar In-space Technology Experiment (LITE). It should be further mentioned that in-depth experience at instrument system level exists from the various ground and airborne experiments, as noted in Section 5.8.

Assuming that preparatory work on key instrument items will successfully take place, there is good confidence that the number of instrument models can be kept to a minimum during the development phase. For the platform, a strong heritage exists from the on-going Earth Explorers and other missions and no critical element has been identified.

Table 7.1 summarises the preliminary risk assessment for the most critical elements.

Unit	Heritage/Risk
Transmitter	
Laser source	Commercially available with reduced performance values. *OPO:* required power level not yet demonstrated; spectral behaviour demonstrated by ground-based, airborne systems. *Ti:Sapphire:* required power level and spectral behaviour demonstrated; implementation and thermal control to be demonstrated
Wavemeter/ vapour cell	Commercially available components. Design to be adapted to stabilise four wavelengths and to be enhanced for space environment.
Frequency reference seeder	Commercial systems for different wavelength available and space qualified. Availability of 935 nm diodes to be clarified.
Receiver	
Telescope	Technology demonstrated. Scaling to the required size and mass to be demonstrated.
Fabry-Pérot etalon	Commercially available with reduced performance values.

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

7.3 International Cooperation and Related Missions

Because of its expected role in collecting key information to understand the global climate and its changes, WALES is clearly of global interest and can play a major role in the international effort to further our understanding of atmospheric processes. There is therefore a strong potential for scientific and technical cooperation.

Cooperation can be envisaged with other European organisations, Eumetsat in particular, as their infrastructure could be used for the data archiving and near-real-time distribution to operational users. Useful cooperation with ECMWF can also be envisaged.

Cooperation with NASA/NOAA could be sought for the provision of a high-latitude data acquisition station, e.g. Barrow in Alaska, to allow near-real-time provision of data.

The missions most closely related to WALES have been discussed in Section 5.7. The role of WALES in the GOS cannot be over-emphasised, considering the stress put by many scientific and operational bodies on the need to fill the gap in the observation of the Earth's atmosphere caused by the present lack of water vapour data of the required quality. In this respect, the strong analogy of WALES to ADM/Aeolus is worth noting. Their data have been requested in particular by the meteorological and atmospheric science community for a long time and, although both missions are clearly pre-operational, they will be implemented in the framework of an operational set-up, based on the near-real-time data assimilation into state-of-the-art numerical models of the atmospheric dynamics.

WALES will also strongly support and complement other missions aimed at observing other atmospheric processes, in particular those driving the Earth's radiation budget. WALES will provide both water vapour and aerosol profiles as well as cloud top information that will re-inforce the modelling of atmospheric processes observed with EarthCARE and ESSP-3/CENA.

7.4 Enhancement of Capabilities and Potential for Applications

The expected advances in science have been discussed in previous chapters. As also shown in previous chapters, this mission is also very relevant to the enhancement of capabilities to enable applications (NWP and future operational systems). The potential for application of a mission dedicated to water vapour mapping has been recognised for many years. WALES will be another application of the long lidar development effort in Europe, already at the basis of the ADM/Aeolus and EarthCARE missions, so confirming and consolidating the excellence of the European scientific and technical communities in the field of active optical remote sensing.

The data from WALES will be fundamental for the calibration of the observations from operational meteorological sensors, both present and planned. It is also likely to become essential for the long-term monitoring of climate evolution, thanks to its high accuracy and vertical resolution.

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Acronyms

ACECHEM	Atmospheric Composition Explorer for CHEMistry and climate interaction
ADM	Atmospheric Dynamics Mission
AMIP	Atmospheric Model Intercomparison Project
AIREP	WMO code for aircraft report
AIRS	Atmospheric Infrared Radiance Sounder
APD	Avalanche Photo Diode
ATLID	ATmospheric LIDar
ATOVS	Advanced TOVS
CBS	Commission on Basic Systems
CCD	Charged-Coupled Device
CDAE	Command and Data Acquisition Element
CENA	Climatologie Etendue des Nuages et des Aerosol
CEOS	Committee on Earth Observing Satellites
CHAMP	CHAllenging Minisatellite Payload
CMC	Canadian Meteorological Center
CNES	Centre National d'Etudes Spatiales
DBR	Distributed Bragg Reflector
DFB	Distributed Feedback Bragg
DIAL	DIfferential Absorption Lidar
DMSP	Defense Meteorological Satellite Program
EarthCARE	Earth Clouds Aerosol and Radiation Explorer
ECMWF	European Centre for Medium-range Weather Forecasts
E/O	Electro-Optical
EOEP	Earth Observation Envelope Programme
ERA	ECMWF Re-Analysis
ESA	European Space Agency
ESOC	European Space Operations Centre
ESSP	Earth System Science Pathfinder
FOV	Field-Of-View
FWHM	Full-Width at Half-Maximum
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water cycle EXperiment
GIFTS	Geo-synchronous Imaging Fourier Transform Spectrometer
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GOS	Global Observing System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GPS/MET	GPS for Meteorology

GPSOS	GPS Occultation Sensor
GRAS	GNSS Receiver for Atmospheric Sounding
GSFC	Goddard Space Flight Center
GVaP	GEWEX water Vapor Project
HALOE	HALogen Occultation Experiment
HRPT	High Resolution Picture Transmission
HT	Higher Troposphere
IASI	Infrared Atmospheric Sounding Interferometer
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
LARC	LAngley Research Center
LASE	Lidar Atmospheric Sensing Experiment
lidar	light detection and ranging
LITE	Lidar-In-space Technology Experiment
LS	Lower Stratosphere
LT	Lower Troposphere
MOPA	Master Oscillator Power Amplifier
MOZAIC	Measurement of OZone on Airbus In-service airCraft
MSCE	Mission operations and Satellite Control Element
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NVAP	NASA water VApor Project
NWP	Numerical Weather Prediction
OBDH	On-Board Data Handling
OPO	Optical Parametric Oscillator
ORACLE	Ozone Research And Cooperative Lidar Experiment
OSSE	Observation System Simulation Experiment
PAC	Processing and Archiving Centre
PRF	Pulse Repetition Frequency
PSC	Polar Stratospheric Cloud
RASL	Raman Airborne Spectroscopic Lidar
RMS	Root Mean Square
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal-to-Noise Ratio
SPARC	Stratospheric Processes And their Role in Climate
SPECTRA	Surface Processes and Ecosystems Changes Through Response Analysis
SPG	Scientific Preparatory Group
SSM/I	Special Sensor Microwave/Imager
TEM	Transverse Electric and Magnetic
TEMP	WMO code for conventional wind, temperature and humidity sounding
TOVS	TIROS-N Operational Vertical Sounder

TPW	Total Precipitable Water
UARS	Upper Atmosphere Research Satellite
UKMO	United Kingdom Met Office
UTC	Universal Time Coordinated
UTLS	Upper-Troposphere/Lowermost Stratosphere
WALES	WAter vapour Lidar Experiment in Space
WATS	WAter vapour and temperature in the Troposphere and Stratosphere
WCRP	World Climate Research Programme
WGNE	Working Group on Numerical Experimentation
WMO	World Meteorological Organization

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