SP-1279 (3)
April 2004

EarthCARE - Earth Clouds, Aerosols and Radiation Explorer
SPECTRA - Surface Processes and Ecosystem Changes Through Response Analysis
WALES - Water Vapour Lidar Experiment in Space
ACE+ - Atmosphere and Climate Explorer
EGPM - European Contribution to Global Precipitation Measurement
Swarm - The Earth's Magnetic Field and Environment Explorers

European Space Agency
Agence spatiale européenne

REPORTS FOR MISSION SELECTION
THE SIX CANDIDATE EARTH EXPLORER MISSIONS

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WALES – Water Vapour Lidar Experiment in Space

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ESA SP-1279(3) – 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 through the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme, where the Earth Explorer missions are completely covered by the EOEP.

Earth Explorer missions are divided into two classes, with Core missions being larger missions addressing complex issues of wide scientific interest, and Opportunity missions, which are smaller in terms of cost to ESA and address more limited issues. Both types of missions address the research objectives set out in the Living Planet Programme document (ESA SP-1227, 1998), which describes the plans for the Agency's strategy for Earth Observation in the post-2000 time frame. All Earth Explorer missions are proposed, defined, evaluated and recommended by the scientific community.

Following a call for Core mission ideas in 2000 and selection of five of the ten proposals for pre-feasibility study, three of the candidates, EarthCARE, SPECTRA and WALES, were chosen for feasibility study in November 2001. In response to a call for Opportunity mission proposals in 2001, which resulted in 25 full proposals being submitted by early 2002, three mission candidates, ACE+, EGPM and SWARM, were also chosen for feasibility study. The Phase-A studies for all six Earth Explorer candidate missions are being finalised by early 2004, forming the basis for the Reports for Mission Selection for all six candidate missions.

This Report for Mission Selection for WALES was prepared based on inputs from the Mission Advisory Group (MAG) consisting of: Edward Browell, Gerhard Ehret, Louis Garand, Elisabeth Gérard, Paolo di Girolamo, Elías Hólm, Ralf Toumi, and Volker Wulfmeyer. Parts of the Report have been made by the Executive based on inputs provided by the industrial Phase-A contractors.

The Report for Mission Selection for WALES, together with those for the other five Earth Explorer candidate missions, is being circulated within the Earth Observation research community in preparation for a User Consultation Meeting at ESRIN, Frascati, Italy, in April 2004.

2. Background and Scientific Justification

2.1 The Role of Water Vapour in Climate and NWP

Society increasingly requires reliable information about the climate system and the impact of anthropogenic as well as natural influences (IPCC 2001). The scientific and engineering community addresses this demand by monitoring the Earth's climate, detecting and quantifying change, modelling the past and current climate, and attempting to predict its evolution. Objectivity is underpinned by continually improving our understanding of atmospheric and surface processes, increasing the realism of climate and forecast models, and quantifying the uncertainties. Not surprisingly, many of these uncertainties relate directly or indirectly to the role of water vapour. Figure 2.1 depicts the central role of water vapour in the climate system. One of the major issues for climate modelling and understanding is to develop parameterisations that accurately account for unresolved water vapour processes, leading to realistic 3-D radiation, clouds and precipitation (Randall et al. 2003). A similar issue arises for numerical weather prediction (NWP) in order to predict weather down to the scale of individual convective events. Humidity fields also impact directly on key weather components such as the surface radiative balance (through downward radiation) and on atmospheric cooling rates.

Quantitative precipitation forecasts (QPF) perhaps represent the routine meteorological product of highest practical and economical value. It stands to reason that better humidity fields should result in improved QPF.

The need to improve the description of the global water vapour distribution extends to the upper troposphere and lower stratosphere (UTLS), as stressed in a recent SPARC report (WCRP 2000) and demands high vertical resolution, notably in the tropopause region. This is needed to improve our understanding of stratosphere/troposphere exchanges. Water vapour is also involved in important chemical processes through the production of hydroxyl radicals (Warneck 1988). In view of the importance of water vapour in the atmosphere, only briefly sketched here, major efforts are needed to improve the quality of global humidity analyses. This applies both to long term (monthly and longer) 3-D fields and individual NWP analyses. Feedback processes linking the various components seen in Figure 2.1 need to be better understood to realistically simulate, for instance, the level of increase of water vapour in a global warming scenario. Uncertainties on the magnitude of the water vapour feedback will persist ‘until observed time series are compiled with sufficient accuracy and length to detect trends in water vapour on a global scale’ (Held and Soden 2000).

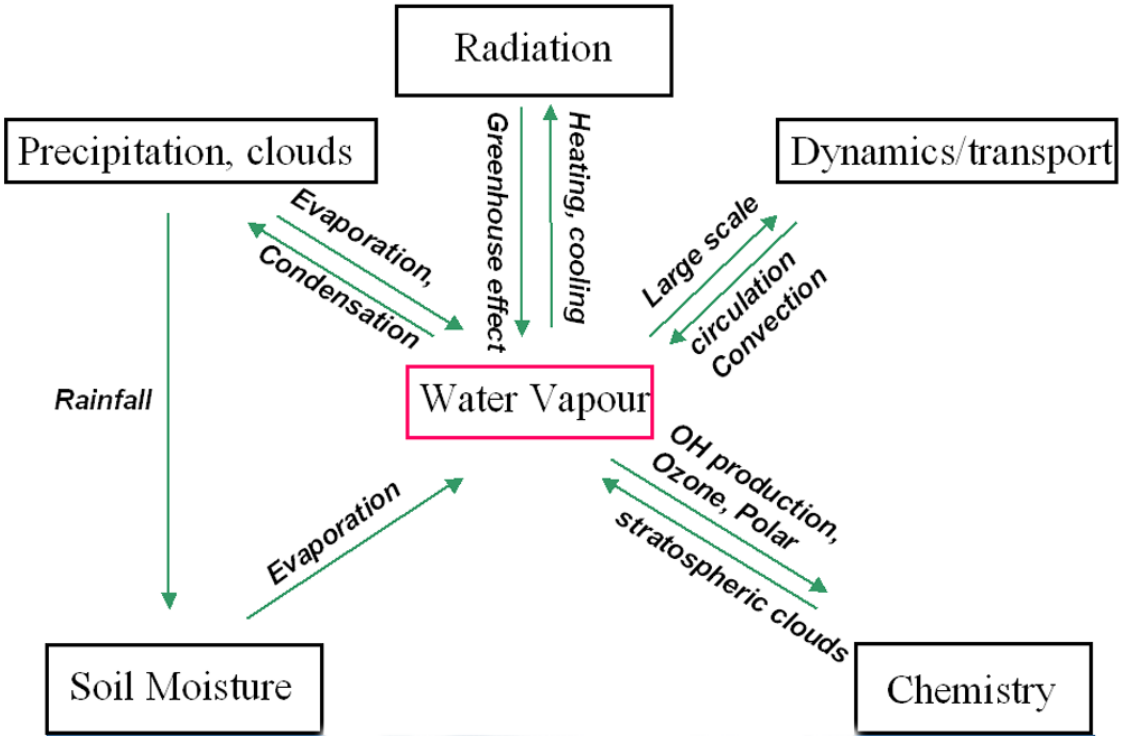

***Figure 2.1**: Main links of water vapour in the Earth's atmosphere.*

2.2 Limitations of Current Humidity Observations

The main sources of humidity data come from surface synoptic reports (land, ships), radiosonde soundings, sparse ground systems (lidars, interferometers, GPS receivers providing total integrated water vapour), and estimates derived from satellite passive infrared and microwave sensors. It is acknowledged that each of these suffers from an incomplete description of the atmosphere in its spatial and temporal dimensions. Furthermore, the combination of all these sources still leaves considerable gaps, notably in the UTLS as well as in the boundary layer. While the horizontal coverage provided by satellite infrared and microwave instruments is impressive, derived profiles are often incomplete and lack vertical resolution.

For both the climate and NWP communities, the specific need for improved vertical coverage and quality of water vapour observations is particularly evident. A satisfying quantitative global description of water vapour is still lacking, for reasons including inadequate accuracy, vertical resolution and coverage, or absolute calibration of observing systems. The archive of radiosonde data, the longest available data source, suffers from the uneven quality of the observations in addition to intrinsic limitations, such as the poor response of radiosonde hygrometers at low temperature. There are also inherent difficulties in calibrating and inter-calibrating passive remote sensing systems

(notably complex and controversial radiance bias removal techniques). 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. While improving the probing of the atmosphere from space is a recognised priority, efforts to improve the humidity field have been slow. More attention has been given to temperature and wind (tracked cloud and moisture features), as these parameters define the atmospheric circulation. It turns out that new 4D-var assimilation systems now make it possible for humidity observations to combine more synergistically with the wind field, leading to improved water vapour convergence governing cloud formation.

Current NWP analyses are characterised by temperature profiles accurate to better than 1.5 K over most of the troposphere in ~1 km layers. In contrast, analyses or 6-h forecasts of specific humidity have relative errors in the range 20-40% (English 1999). Global atmospheric models now have vertical resolutions typically varying from 100 m in the boundary layer to 1 km in the stratosphere. The current observational system is far from providing humidity data reaching such resolutions, yet the scales associated with water vapour and cloud layering are often even finer than this. Climate archives produced by GVaP (GEWEX Water Vapour Project, GEWEX 1998) are based on radiances in the 6.7 μ band, and cover the broad layer 200-500 hPa. Other global datasets strictly based on observations, such as Pathfinder (Susskind et al. 1997) provide humidity in three broad layers only. Currently, the best long time global humidity fields are those obtained from NWP reanalyses, and are largely based on radiosonde and, for the last two decades only, on radiance observations representative of broad layers.

As will be further discussed in this report, the goal of the WALES mission is to address those aspects considered as weakest in the observation of atmospheric humidity: lack of accuracy, vertical resolution and vertical extent. This mission represents an important first step in routinely measuring water vapour profiles on a global scale using an active remote sensing technique. As such, a successful demonstration of this technique from space would represent a breakthrough in the monitoring of the Earth's atmosphere. The mission aims at providing a much needed reference for humidity profiling against which atmospheric models can be evaluated unambiguously and passive remote sensing calibrated. Thus, in addition to the intrinsic value of providing high quality data, WALES will *contribute to a better use of other types of data* characterised by a higher temporal and horizontal coverage.

2.3 Current and Near-Future Programmes

One of the major accomplishments in remote sensing foreseen for the upcoming decade is the exploration of the entire infrared spectrum at high spectral resolution using spectrometers or interferometers. AIRS (Atmospheric Infrared Radiance Sounder, launched in 2002) is the first in a series of spectrometers. IASI (Infrared Atmospheric Sounding Interferometer, launch 2005) and GIFTS (Geosynchronous Imaging Fourier

Transform Spectrometer, launch 2007) are other planned missions based on Fourier transform spectroscopy. With these new passive remote sensing instruments, the vertical resolution for humidity estimates will be typically 1.0-2.0 km and the relative error in the range 15-25%. The most challenging problems for passive IR systems remain, i.e. to avoid the use of radiances contaminated by clouds or dust and to obtain good estimates in the lowest levels. The information on humidity at altitudes above 250 hPa (~10.4 km) from advanced interferometers will be very limited.

Microwave instruments on the other hand 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 that of IR profilers and the vertical and horizontal resolutions are slightly coarser. Over land, the difficult modelling of microwave surface emissivity will continue to limit the retrievals to the middle and upper troposphere. In order to assimilate radiances (IR or microwave), bias corrections must be applied to observations. The standard and convenient assumption made for bias removal is that the overall difference between observed and calculated radiances is zero. Consequently, satellite data used in NWP do not aim at correcting systematic model errors, but rather random errors and local biases. To identify systematic model errors, an independent source of data with high absolute accuracy is urgently needed.

Another instrument is MLS (Microwave Limb Sounder) on EOS-Aura (2004), which is a limb viewing sounder providing observations of the upper troposphere, at a horizontal resolution of about 150 km. GNSS (Global Navigation Satellite System) sounders will be embarked on METOP (2005) and NPOESS (2009) platforms. While the occultation technique appears promising for temperature profiling, its contribution to humidity profiling will likely remain modest, and limited to the range 3-10 km. Because of these and other limitations, notably that water vapour is not measured directly, GPS measurements, like radiance measurements, cannot be considered a reference for humidity.

2.4 Uniqueness of the WALES Mission

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, low bias, and high vertical resolution profiles extending from the ground to the upper troposphere and into the lowermost stratosphere.
- Derived error profile for each retrieved water vapour profile.
- Direct measurement of humidity at all temperatures as opposed to radiosondes.
- Low sensitivity to other parameters (e.g. surface emissivity, temperature profiles, concentrations of other gases, aerosols) needed by other remote sensing techniques.

- Capability to obtain profiles above cloud tops as well as through and below clouds of low optical depths. Potential to sound through holes in scattered or broken cloud fields (individual pulses have a footprint of ~50 m on the ground).
- Enhanced vertical extent with water vapour measurements often exceeding 150 hPa (~13.6 km) (Gérard et al. 2004).
- Simultaneous information on water vapour, cloud top height, aerosol optical depth, and boundary layer height.

2.5 WALES Heritage to Ground-based and Airborne DIAL Systems

The methodology associated with differential absorption lidar (DIAL) remote sensing of water vapour is very mature as it has been developed and evaluated by several groups around the world for nearly three decades. First simulations of the performance of a space-based water vapour DIAL system were presented at ESA twenty years ago (Browell and Ismail 1984, Endemann et al. 1984). WALES draws extensively from the scientific and technological heritage of the European and US airborne water vapour DIAL systems (Browell et al. 1997, Ehret et al. 1999, Wulfmeyer and Bösenberg 1998, Bruneau et al. 2001) and their ground-based counterparts. In 1994, The Max-Planck Institute created the first DIAL system with transmitter and spectral characteristics exceeding the requirements for accurate water vapour measurements in the entire troposphere (Wulfmeyer 1998). The first autonomously operating water vapour DIAL system, called LASE (Lidar Atmospheric Sensing Experiment), was demonstrated from a high-altitude aircraft in 1995 (Browell et al. 1997). During a comprehensive water vapour intercomparison campaign, the LASE system demonstrated that water vapour measurements could be made to an accuracy of better than 6% or 0.01 g/kg, whichever is larger, across the entire troposphere (Browell et al. 1998). To allow water vapour profile measurements across the entire troposphere along the aircraft flight track, the LASE system was modified to interleave 2 to 3 different pairs of water vapour absorption cross sections. An example of these results is shown in Figure 2.2. This multiple-laser-wavelength technique is similar to what WALES will use to achieve continuous atmospheric coverage of water vapour, aerosols, and clouds along its ground track. DLR (Ehret et al. 1998) developed the first airborne water vapour DIAL system operating at the actual proposed WALES wavelengths. Again the capability to obtain highly accurate humidity profiles, down to the level of a few ppm, was demonstrated (Ehret et al. 1999).

The most recent results using water vapor DIAL systems were presented at the 6th International Symposium on Tropospheric Profiling (http://istp2003.tropos.de:8085). Ground-based and airborne water vapour DIAL systems have provided more and more convincing demonstrations of the usefulness of high quality humidity fields for mesoscale assimilation and process studies, in particular for the short time forecasting of convection and frontal systems (e.g. Browell et al. 2003, Flamant et al. 2003).

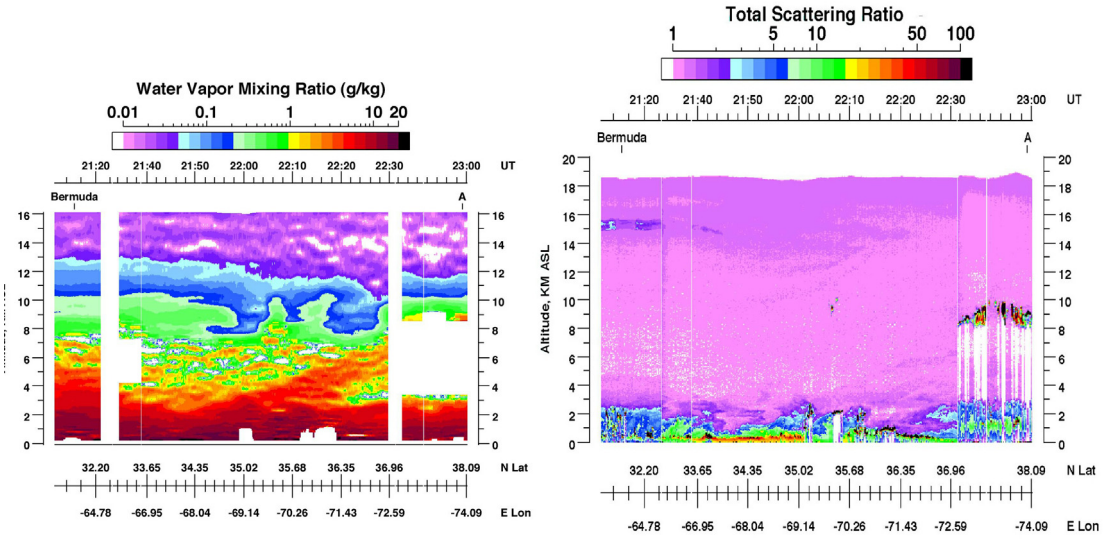

Figure 2.2: *Atmospheric cross sections of water vapour (left) and aerosols/clouds (right) obtained by LASE on a high-altitude ER-2 flight from near Bermuda to Wallops, Virginia on 26 July 1996. The LASE water vapour measurements used two interleaved pairs of DIAL wavelengths and had a vertical resolution of 330 m and a horizontal resolution of about 25 km (data gaps, shown as white regions, are caused by clouds and LASE non-operational times). A stratospheric intrusion of dry air can be seen in the water vapour cross section along with a rising moist layer associated with a front. The aerosol/cloud scattering is defined by the total atmospheric scattering ratio, which is obtained by normalising the off-line lidar return by that expected from a clean (no aerosol) atmosphere. The aerosol/cloud data have a vertical resolution of 30 m and a horizontal resolution of 200 m, and these data reflect the capability to infer the spatial and optical characteristics of cloud and aerosol layers as well as the height of the boundary layer.*

Furthermore, Kamineni et al. (2003) recently demonstrated the positive impact of the assimilation of DIAL measurements on the forecast of a hurricane.

2.6 Expected Impacts

Expected impacts of the WALES measurements include:

- A 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.

- Significantly improved NWP analyses through high quality data with global coverage. The mission will provide about 6000 profiles daily as opposed to ~1200 radiosonde soundings.
- The mission creates a major and most needed reference for validation and calibration of other satellite water vapour measurement techniques, in particular those based on infrared and microwave radiances.
- Improved estimation of the NWP model background error covariance matrix (global map of water vapour error profiles by month). This matrix is fundamental in data assimilation as it determines the weight of the data with respect to the background. Currently there is a large uncertainty associated with model humidity errors. This will impact significantly on NWP analyses, even if the data were not assimilated.
- Microwave and infrared radiances that are sensitive to humidity are also sensitive to temperature as well. Thus, a more subtle, but tangible impact is that a direct measurement of 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 used in NWP (alleviates the problem of non-uniqueness of the solution).

2.7 Outlook

In summary, the Earth Explorer WALES mission will fulfil a long-standing need for a global sampling of high-vertical resolution water vapour profiles. WALES will help to fill major gaps in the measurement of humidity, especially in the upper troposphere and lowermost stratosphere, in partly cloudy situations and below thin clouds. The good along-track resolution will provide valuable information for validating and improving the parametrisation of moist processes as represented in both climate and weather prediction models. As a calibration tool for other remote sensing techniques providing a more complete horizontal and temporal coverage, the WALES mission represents an invaluable data source. In particular, this will allow systematic model biases to be detected with confidence. Anticipating that the proposed new type of observations ultimately becomes a regular element of the Earth's observation system, long-term humidity trends can be inferred. Excellently performing airborne and ground-based DIAL systems have demonstrated the technology to provide water vapour profiles with unique accuracy and resolution.

3. Research Objectives

Climate and NWP objectives largely overlap. As the Earth's observation system reaches its maturity along with data assimilation science, NWP analyses will constitute as the primary climate archive. Nevertheless, it appears useful to present separately those aspects more specific to climate and climate change and those aspects more specific to weather prediction.

3.1 Climate

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

- 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. This relates to major physical processes such as convection, radiation, precipitation, and the troposphere-stratosphere exchange with links to atmospheric chemistry.
- Develop and test methodologies for integrating existing water vapour data sets to facilitate long-term global climate monitoring and trend studies. To that effect, improving the calibration of passive remote sensing systems and validating infrared/microwave techniques represents a major contribution. This should also lead to improved radiative transfer models.
- Signals of climate change are more apparent in high latitude regions (e.g. ice/snow cover). In that regard, humidity data from WALES should again contribute significantly, given the lack of conventional data in these regions combined with the lower quality of passive systems (nearly isothermal atmospheres and variable surface emissivity). Providing high quality profiles with good temporal and spatial sampling over high latitude regions is an important asset of the mission.
- An indirect benefit 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 detection of trends and better understanding of the role of upper tropospheric and stratospheric moisture in climate change.

3.2 NWP

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

- Improving model humidity analyses through constraining the initial state of the models towards highly accurate moisture observations.
- Improving surface fluxes and atmospheric heating/cooling rates.

- Validating numerical weather prediction models.
- Building a more representative NWP humidity background error covariance matrix to optimize the weight of observation and background in the analysis.
- Improving the temperature field by constraining the range of temperature and humidity corrections consistent with observed radiances.
- Improving the physical parameterizations governing the interactions between moisture, radiation and the hydrological cycle leading to improved forecasts.
- Providing high quality humidity data at levels reaching the tropopause or lower stratosphere where most often no other sources of data are available.
- Providing a new reference for calibrating other remote sensing techniques, thereby unifying the global observational network for the humidity variable.

4. Observational Principle and Requirements

4.1 The Observational Principle

The core element of the proposed Earth Explorer mission is a nadir-viewing water vapour differential absorption lidar (DIAL) system. Range-dependent 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 backscattered signals of two laser pulses having slightly different wavelengths. One pulse is emitted on the centre of a water vapour absorption line (on-line wavelength). The second is emitted on the line wing where absorption is negligible or significantly reduced (off-line wavelength). This is shown schematically in Figure 4.1.

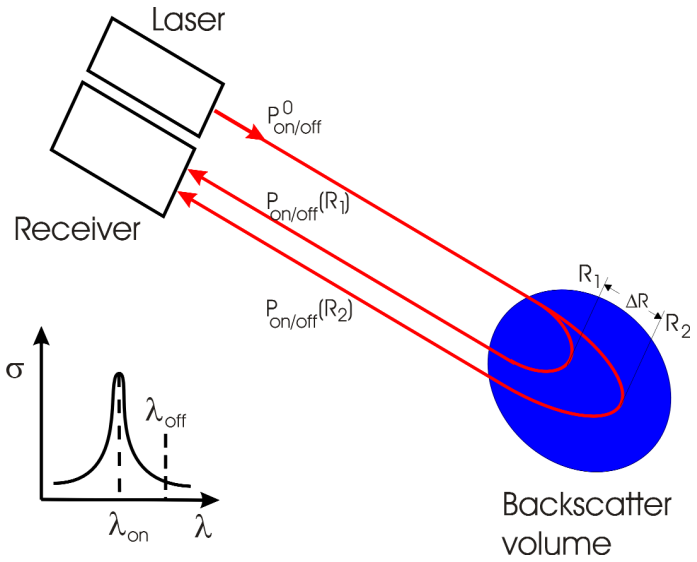

***Figure 4.1**: Conceptual drawing of the DIAL principle*

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

4.1.1 Water Vapour Data Products

The almost simultaneous transmission of the on- and off-line wavelengths allows the direct calculation of the water vapour concentration from backscattered signals by the application of a simplified form of the DIAL equation:

$$n_{H_2O}(R) = \frac{1}{2(\sigma_{on} - \sigma_{off})\Delta R} ln \frac{P_{off}(R_2)\, P_{on}(R_1)}{P_{on}(R_2)\, P_{off}(R_1)} \qquad (4.1)$$

where $P_{on/off}$ is the backscatter power at the on- and off-line wavelengths, respectively, $R_{1/2}$ is the lower and upper level 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 at the on- and off-line wavelengths, respectively.

The equation assumes ideal monochromatic laser pulses (e.g. the line width of the laser pulses is much smaller than the line width of the water vapour absorption line) as well as backscatter and extinction from aerosol and molecules at the on- and off-line wavelengths to be identical. 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, i.e. it does not need any other target for calibration. The measurements rely only on knowledge of the water vapour differential absorption cross-section, which can be precisely determined in the laboratory (Grossmann and Browell 1989). Errors caused by unknown temperature profile can be minimised by selection of temperature insensitive water vapour lines.

High precision with the possibility of trading-off between random error and horizontal /vertical resolution:
The precision of a DIAL measurement can be improved by signal averaging horizontally and vertically. The resulting improvement scales accordingly:

$$\frac{\delta N}{N} \propto (\Delta x)^{-1/2} (\Delta R)^{-3/2} \qquad (4.2)$$

where $\delta N/N$ corresponds to the random error and Δx and ΔR are the horizontal and vertical resolutions of the DIAL measurement, respectively. It is worthwhile to note that signal averaging in the vertical direction is more efficient than averaging horizontally.

High dynamic range:

The water vapour number density measured by DIAL generally scales inversely with the strength of the selected water vapour absorption line as indicated by Eq. 4.1. Strong lines are suitable for measurements at low water vapour concentrations, e.g. in the upper troposphere and lower stratosphere, whereas weak lines are appropriate at high water vapour concentrations in the low troposphere. The WALES instrument will sense the atmosphere at four water vapour lines with different strengths allowing profiling over extended ranges from the surface up to the low stratosphere as depicted in Figure 4.2.

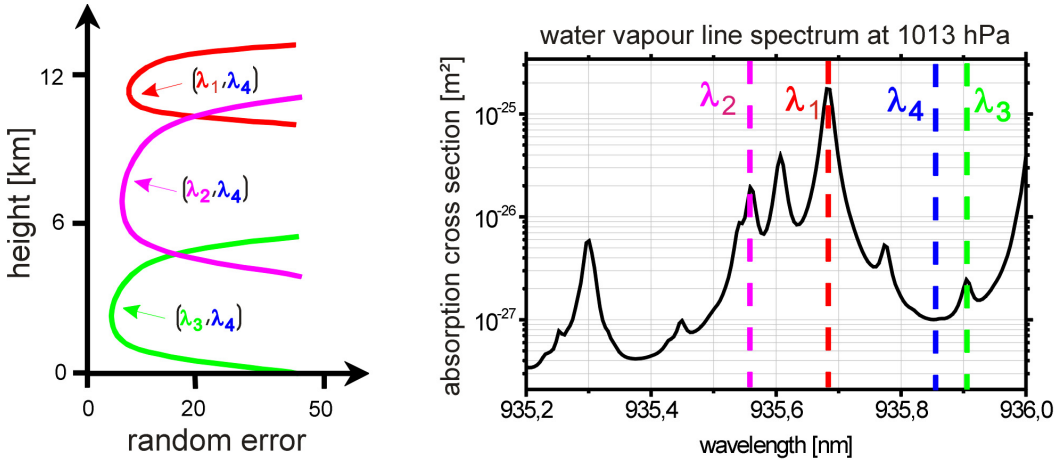

Figure 4.2*: The DIAL transmitter of the WALES instrument will operate at four different wavelengths with different absorption cross sections (right panel). The corresponding lidar signals experience different water vapour optical thicknesses, resulting in different penetration depths. Three combinations of signals using three wavelength pairs, respectively, result in a composite water vapour profile from ground to the upper troposphere. The schematic error profiles for the individual wavelength pairs (on-,off-line) are depicted in the left panel.*

Possibility of data retrieval under cloudy conditions:

Humidity profiles can be measured above the tops of all clouds and, if the optical thickness is low enough (typically below 0.3), the DIAL will penetrate these clouds and measure water vapour below them as well. Measurements are also possible above and between scattered clouds. Examples of this are also shown in Figure 2.2.

4.1.2 Additional Geophysical Products

By analysing the backscattering profiles from off-line channels various additional products can be simultaneously derived from the observations of the WALES mission, namely:

- Aerosol particle backscatter profiles
- Cloud tops and bases (the latter for cloud with low optical thickness)
- Estimates of optical thickness of aerosol and clouds
- Planetary boundary layer height and aerosol spatial distribution in clear-air
- Surface reflectance.

In particular, the simultaneous measurement of both 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 boundaries are associated with large variability (gradients) in particle backscattering. While cloud tops are always determinable, cloud bases can only be estimated if cloud optical thicknesses are small (Winker and Trepte 1998).

The optical thickness of a single aerosol/cloud layer can be estimated if an aerosol-free region is present both above and below the aerosol/cloud layer or the aerosol/cloud extinction-to-backscatter ratio is known. Values of the latter for different aerosol/cloud types are extensively reported in the literature (e.g. Ackermann 1998).

Aerosol and moisture exhibit strong gradients at the top of the boundary layer. In clear air conditions boundary layer height and structure can be estimated from maximum gradients in the backscatter profiles (e.g. Kiemle et al. 1995).

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 (Reagan et al. 1997).

4.2 Generic Observation Requirements for Water Vapour Data

As a guideline for introducing new earth observing instruments, generic requirements for the observation of meteorological parameters are specified by WMO/CBS (World Meteorological Organization/Commission on Basic Systems), see WMO (1998; 2000a; 2000b). In line with these specifications, observational requirements for WALES were defined in order to range between so-called ‘threshold values’, i.e. the minimum requirements for the mission to be worthwhile, and target values, i.e. those currently regarded as yielding maximum benefits to meteorological science. The generic

requirements are listed in ESA (2001) where they have been exhaustively reviewed and discussed. Table 4.1 provides an overview of the WALES observation requirements, discussed in detail in the following subsections.

		Requirement			
Altitude Range	[km]	0-2	2-5	5-10*	10*-16*
Vertical Resolution	[km]	1.0	1.0	1.0	1.5
Horizontal Domain		Global			
Horizontal Integration	[km]	25	100	150	200
Dynamic Range	[g kg^{-1}]	0.01-15			
Precision (1σ)	[%]	20			
Accuracy (bias)	[%]	<5			
Lifetime	[year]	2-3			
Data Reliability	[%]	95			
Timeliness	[hour]	<3			

* altitude subject to fluctuations in compliance with dynamic range.

***Table 4.1**: Observational requirements for the water vapour profiling mission WALES. The altitude ranges are indicative of a tropical atmosphere (0-2 km typical of planetary boundary layer; 2-5 km of lower troposphere; 5-10 of mid-troposphere; 10-16 km of upper troposphere/lowermost stratosphere) and are lower towards the poles. For precision, 1σ denotes 1 standard deviation.*

4.2.1 Vertical Domain, Vertical Resolution and Dynamic Range

Observations of water vapour profiles are needed throughout the atmosphere from the surface up to about 16 km. It should be noted that observational requirements above the upper troposphere/lowermost stratosphere, i.e. in those parts of the stratosphere that are not connected to the troposphere by isentropic surfaces, are beyond the scope of the WALES mission.

The thickness of meteorological model levels typically ranges from 10 to 100 m at low altitudes to 1 to 2 km in the lowermost stratosphere. WMO states a 2 km threshold requirement and a 400 m target requirement in the lower troposphere. In the higher troposphere, the WMO prescribed threshold and target requirements are 3 km and 1 km, respectively. A vertical integration of 1 km in the lower and mid-troposphere and 1.5 km in the upper troposphere/lowermost stratosphere are considered to be appropriate for WALES.

The vertical extent of the WALES measurements is constrained by the dynamic range of the humidity. The dynamic range threshold requirement for WALES is 0.01 to 15 g/kg. The dynamic range target for WALES is 0.001 g/kg (near and above the tropopause) to 25 g/kg (near the Earth's surface) over the entire vertical domain.

4.2.2 Horizontal Domain and Integration

WALES observations are global by design. The overall quality of the data should have measurable impacts everywhere, although perhaps more evidently in data sparse regions. Indirect impacts previously described, such as an improved calibration of passive remote sensing systems and a better definition of model errors needed in NWP data assimilation, will also be obtained on a global scale.

The horizontal scales resolved by the current meteorological analyses are determined by the capabilities of the present global observation system and the data-assimilation methodology used. The water vapour profiles should be provided over areas that are representative of the meteorological model's resolution. A typical horizontal resolution is about 100 km, which is also the reference for WALES. A more stringent requirement is appropriate for the boundary layer to capture small-scale features.

As it is expected that models will have higher resolution in the future (of the order of 20-50 km for global models and 1-3 km for regional models), the processing of the WALES data must be flexible enough to deal with these smaller horizontal resolutions. The representativeness error, as well as other potential error sources like those arising from cloud contamination, could be reduced by performing some more advanced on-ground signal processing on subsamples over a shorter averaging track. Thus, it is required that measurement samples corresponding to a much smaller track length are downlinked, which are then processed on-ground to derive water vapour profiles (see Chapter 5). As the final processing algorithms are not yet known, and since some optimisation of measurement parameters must be possible with WALES, the horizontal subsample length shall be in a range from about 1 km to 5 km.

4.2.3 Water Vapour Accuracy and Precision

Additional input of high quality data that can be assimilated is expected to lead to an improvement in weather prediction skills by both adding more high quality humidity information to the assimilation systems as well as improvement of the physical parameterisation schemes of modern data assimilation techniques. In the present global weather observation network, radiosondes are the key element for water vapour profile measurements. Their quality is not uniform from one type to another and their uncertainty varies between 5 and 10% in the lower/mid-troposphere mainly due to bias. Water vapour observations at higher altitudes (or at higher latitudes, i.e. polar regions)

are of low quality. Indeed atmospheric temperature is a stringent constraint for *in situ* humidity measurements, i.e. no reliable humidity measurements are available at temperatures below 233 K (Elliott and Gaffen 1991; Schmidlin and Ivanov 1998). This means that there are no in situ humidity measurements above ~10 km in tropical regions, ~7 to 9 km in mid latitude regions, ~5 to 7 km in subpolar regions and 0-5 km in polar regions (see Gérard et al. 2004). Furthermore, the quality of radiosondes does not allow identification of systematic humidity biases above 500 hPa (Ross and Elliott 1996). The lack of accuracy in the existing humidity measurements is critical in near-saturation regions. For example, a large positive bias in the analysis can systematically create spurious large-scale precipitation, inducing a modification of the general circulation after a few days of assimilation. Thus, in order to improve the hydrological cycle and better determine the general circulation, humidity measurements with a bias of less than 5% are necessary.

A requirement of less than 5% bias is critical for climate research also. Climate uses of observational data include analysis of trends and processes contributing to variability on all spatial and temporal scales and to validation of climate models (Karl 1996). A low and time independent bias is essential for an absolute standard and relates to climate needs: 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).

A strong requirement on the humidity measurement bias is also needed to provide a new reference for bias correcting other remote sensing techniques, in particular those based on infrared and microwave radiances. As mentioned in Chapter 2, bias correction schemes often assume that the overall model bias in radiance units is zero. Other schemes are based on the comparison of observed and calculated radiances, with the latter derived from radiosonde profiles. The drawback of these approaches is that they rely on the quality of model results or radiosonde measurements, which are both subject to systematic or intrinsic errors.

A random error of less than 20% is required over the whole vertical domain, as prescribed by WMO and proven to be beneficial to NWP by Gérard et al. (2004). In this, the representativeness error is not taken into account. If this threshold happens to be exceeded, the vertical resolution can occasionally be degraded in the processing of the data, in order to recover the random error performance.

4.2.4 Mission Lifetime

The expected lifetime of 2 to 3 years for the mission covers several seasonal cycles and is considered sufficient to demonstrate its benefits. This is also in accordance with the expected lifetime of the high power laser transmitter, which is the key component of the mission payload.

4.2.5 Data Reliability

Data reliability describes the probability that errors remain within the 3-sigma limit of the expected normal error distribution. Gross errors and transmission problems can potentially damage the objective analysis, leading to an incorrect picture of the state of the atmosphere. Gross errors can partially be avoided by applying a good quality control procedure during the measurement processing. Experience with conventional observation systems and associated quality control in operational meteorological analysis indicate that the rate of gross errors presented to the analysis should be only a few percent. Based on this experience, the observations from WALES are required to have a data reliability of 95%.

4.2.6 Timeliness

While timeliness is not that critical for climate research, it is an important issue for NWP. In a meteorological data-assimilation system, the observations must be available for each run of the forecasting model. The analyses start at pre-specified times and a data cut-off time is applied. For numerical weather prediction, acceptable data delivery times for short- and medium-range forecasting vary generally between 30 minutes to more than 6 hours, depending on the analysis time window and analysis cut-off delay. A data-delivery requirement of 3 hours is specified, as is common for polar-orbiting operational meteorological instrumentation.

4.2.7 Summary of Requirements

For a mission intended to demonstrate the feasibility of a full-scale space-borne water vapour observing system to improve global atmospheric analyses, the requirements on data quality and vertical resolution are the most stringent and most important to achieve. Under this assumption, the cross-track sampling and repeat cycle needs are the least stringent.

For global observations, WMO (1998, 2000a, 2000b) has suggested of the order of 500 to 1000 water vapour profiles per hour with a precision of better than 20% as a threshold operational requirement. As a pre-operational demonstration mission, WALES should provide at least 250 profiles of that quality per hour, assuming a 100 km integration length (i.e. ~6000 profiles per day as opposed to ~1200 currently available soundings from radiosondes). Because of the high quality of the data with respect to that of the background fields, the impact on NWP analyses is expected to be very significant, especially where these two sources disagree. Profiling above clouds and below optically thin clouds will also be possible.

Information on additional geophysical parameters will also be derived from WALES observations and made available to users. These parameters include cloud top and boundary layer heights, aerosol distributions and optical depths. As the provision of

such information does not drive the WALES mission, requirements specific to the determination of these additional parameters are not specified here. However, the impact of aerosols and/or clouds on WALES humidity retrievals is fully taken into account, as detailed in the end-to-end processing methodology presented in Chapter 6.

5. Data Processing Requirements

5.1 Data Format

WALES will collect lidar backscatter signals at four different wavelengths simultaneously, with a repetition rate of 25 Hz and a range resolution of 50 m. An advanced data processing scheme has been developed within the Phase A End-to-End Simulator Study performed by Università della Basilicata, University of Hohenheim and DLR (Di Girolamo et al. 2003). The performance analyses and evaluations concluded that hardware averaging on the spacecraft is not appropriate. Therefore, the raw data including time and location of the footprint have to be transmitted to the ground station.

5.2 Production of Calibrated Lidar Backscatter Profiles

The data processing scheme is presented in Figure 5.1. Interfaces to external data sources as well as the potential usage of researchers and NWP centres are also shown. After collection of the lidar return signals, the data are digitized to at least 14 bits and transferred to a ground station. After receipt of the data on the ground, the raw data are stored. Spikes and saturated data are detected and excluded in the data analysis scheme. Clouds are also detected. Regions with low signal within and below clouds will be excluded. At this stage, raw backscatter lidar data with quality control are provided to the user.

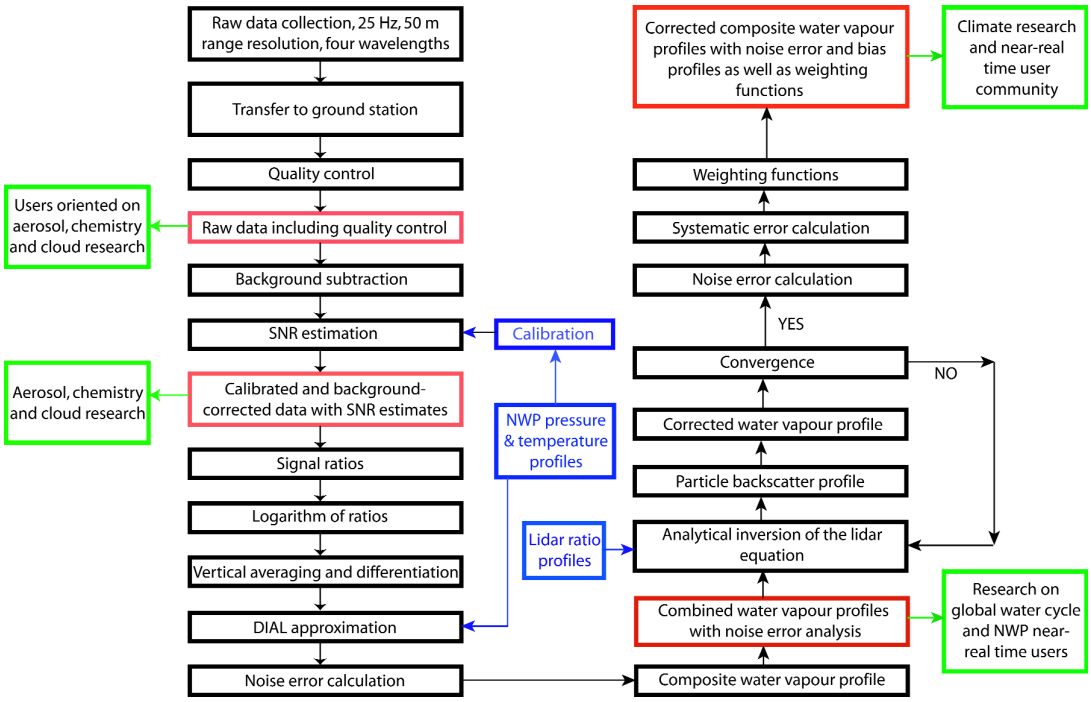

Figure 5.1*: WALES data processing scheme. The blue boxes show the interfaces where external data are incorporated. Different data levels are indicated in red. The green boxes show the data flow to the user community.*

A calibration of the lidar data will be performed. This is one of two stages where data from other sources are needed. Temperature and pressure profiles will be provided by analyses or short-range forecasts in stratospheric regions. Using post-processing modules, molecular backscatter profiles are simulated along the WALES track. By analysing the WALES backscatter signals, regions are identified where the signals are dominated by molecular backscatter. Combining the theoretical calculations, the measurements of the backscatter signals, and a laser power measurement, yields the system constant with high accuracy. This is possible due to the high average power of the WALES laser transmitter. It is expected that this calibration procedure will only have to be repeated occasionally.

The background signals are subtracted from the lidar signals at each wavelength. The lidar signals are calibrated and inserted into an analytical model. This model prescribes the system parameters and yields estimates of the SNR of the raw lidar signals. At this stage, calibrated lidar backscatter data with background subtraction and SNR estimates are provided.

5.3 First-estimate Water Vapour Profiles

An adaptive approach is applied for further data averaging and processing. This is necessary, as the resulting bias and the noise errors are interrelated at low SNR. Increasing the SNR to a certain level by a certain amount of time (horizontal) averaging, this bias can be virtually eliminated (see Chapter 6). This results in a constant weighting function within the horizontally averaged region. Errors of different profiles which are calculated after horizontal averaging are not correlated.

Before any vertical averaging, the ratios of the on-line and the off-line signals are taken for each wavelength pair. Afterwards, the logarithms of these ratios are calculated for each wavelength pair. This procedure minimizes the bias. Subsequently, differentiation of the ratios is performed. As the derivatives will still be noisy, this operation has to be combined with vertical averaging. Either block averaging or linear regression can be applied. In both cases, the corresponding vertical weighting function can be defined. For calculating a first estimate of a water vapor profile using Eq. 4.1, knowledge of the corresponding water vapour absorption cross section profiles at each wavelength is required. Therefore pressure and temperature profiles have to be prescribed for this purpose. Similar to the procedure discussed above for system calibration, the data shall be provided via analyses or short-range forecasts. The pre-calculated orbits for WALES can be used as an input to an atmospheric forecast model. During the forecast, model columns of atmospheric data are interpolated to the horizontal and time location of the WALES measurements, and subsequently used in the WALES retrievals. Remaining errors are expected to be very low, due to the low cross-sensitivity of the water vapour absorption cross sections to temperature and pressure.

Using an appropriate line shape function, the water vapour absorption cross sections are calculated in the spectral region of each WALES transmitter wavelength, taking into consideration the altitude dependence of the temperature and pressure profiles. Line parameters are determined via dedicated laboratory spectroscopic measurements. A similar approach has been applied for other wavelength regions (e.g. Grossmann and Browell 1989). This procedure ensures calculation of cross sections with an accuracy of about 2%. The same accuracy can be achieved for the WALES wavelengths.

Using analytical error propagation methods, water vapour noise error profiles are calculated. Finally, a composite water vapour profile is determined using the retrieved water vapour profiles from each wavelength pair and using a weighted average with noise errors. At this stage, composite water vapour profiles with noise errors are available.

5.4 Final-level Water Vapour Profiles

To improve the accuracy of the water vapour profiles, the data have to be corrected for spectral broadening in the scattering volume, which is also called the Rayleigh-Doppler effect. This correction requires an estimate of the particle backscatter coefficient profile. This profile can be calculated by an analytical inversion of the off-line lidar signal using the first estimate of the composite water vapour profile. At this stage, a profile of the *lidar ratio*, which is the ratio between the lidar particle extinction and backscatter coefficients, has to be prescribed for the inversion of the lidar equation. Two approaches are possible to access the required data. One approach is to develop a global lidar ratio database, which will take into account the variability of the lidar ratio in dependence of cloud and aerosol particle properties. Here WALES can benefit from ongoing efforts in connection with spaceborne lidar systems, as these data are also essential for missions such as CloudSat and Calypso. The other approach is the use of global aerosol and cloud model data, where several projects are currently ongoing. There is no doubt that both approaches will provide the required data by the proposed launch time for WALES. If the lidar ratio profile is chosen, the analytical inversion can be performed resulting in a profile of the particle backscatter coefficient.

The water vapour profile determined with the DIAL approximation is used in combination with the particle backscatter profile to correct for Doppler broadening. This is an iterative procedure that usually needs 2-3 cycles (see Figure 5.1 and Chapter 6). The retrieved water vapour, particle backscatter and particle extinction profiles are stored, including the noise error analyses discussed above. Horizontal and vertical weighting functions are also specified.

For estimating bias profiles, results of analytic error propagation as well as end-to-end performance simulations are sufficient (Wulfmeyer and Walther 2001a, Di Girolamo et al. 2003). Using these techniques, the expected range of systematic errors due to system parameters and atmospheric effects is calculated for each profile. At this final stage,

water vapour profiles will be provided with an extended analysis with respect to systematic and noise errors as well as weighting functions.

5.5 Summary

This Chapter and Figure 5.1 have presented the complete data analysis procedure for WALES. The processing is simple and straightforward. For most processing steps, no external data are needed. NWP analyses or short-range forecasts of temperature and pressure profiles along the WALES track are required to infer absorption cross-sections and to assist in system calibration. Lidar ratio analyses will be used for Rayleigh-Doppler correction of the water vapour profiles. It has to be noted that the cross-sensitivity of the WALES retrievals to the accuracy of these external data sets is very low. The non-ambiguous nature of lidar signals, with their well-isolated sensitivity to humidity, allows measurements of water vapour profiles with unprecedented high accuracy. This statement is confirmed in Chapter 6.

In the final stage of the data analysis, water vapour profiles including profiles of:

- overall accuracy or rms errors
- noise errors
- maximum bias
- corresponding range and horizontal resolutions including the shape of their weighting functions

are provided. The shape and width of the weighting functions relates the real data profile with the measured one by means of horizontal and vertical convolution. This weighting function is fundamental to the construction of the error correlation.

The detailed specifications of the water vapour profiles will ensure applications in a variety of projects in weather and climate research. Particularly, the fast and robust data analysis procedure ensures a that less than 3 h is needed for data assimilation into NWP models. Investigation of WALES data over monthly and seasonal periods should demonstrate the capability of these observations to detect model biases and climatic trends.

6. Performance Estimation

6.1 Introduction

This chapter provides an assessment of WALES performance based on the application of a recently developed comprehensive water vapour DIAL end-to-end model. The model represents an important advance in comparison with analytical models (see e.g. ESA 2001), as it provides a more realistic and extended error analysis. For instance, atmospheric inhomogeneities as well as non-linear effects within the retrieval algorithm can be investigated. System, platform, orbit and atmospheric parameters correspond to the values chosen in industry Phase-A studies (see Table 8.2 of the technical and programmatic attachment).

Additionally, results of two scientific studies are presented: an impact study comparing the information content of WALES water vapour profiles and IR passive remote sensing, and an analysis of the performance and coverage of WALES measurements in the presence of clouds.

6.2 Determination of Random and Systematic Errors (1D Case)

Based on the application of the end-to-end model, we provide an assessment of systematic and noise errors dependent on altitude and SNR for three selected reference atmospheric models (tropical, sub-Artic winter and US Standard Atmosphere).

Concerning the systematic error, several components have been considered: the error associated with the laser spectral specifications (line bandwidth, spectral stability and spectral purity), the effects associated with uncertain knowledge of water vapour spectroscopy and atmospheric temperature, the effects associated with Doppler broadening of the backscatter signals, as well as the effects associated with the application of different non-linear operators present in the DIAL equation. A detailed budget of the different error sources is provided in the technical and programmatic attachment. Assuming these sources to be independent, the overall mean bias is less than 4%.

Figure 6.1 illustrates the vertical profiles of bias and random errors for the three selected reference atmospheric models. Borderline values for laser specifications are considered (laser linewidth 160 MHz, laser frequency stability 60 MHz, spectral purity 99.9%), while contributions from water vapour spectroscopy as well as the effects associated with temperature uncertainty are not included. The solid lines in the figures refer to the horizontal and vertical resolutions specified in the requirement Table 4.1. For the US Standard Atmosphere and the tropical atmosphere, the random error does not exceed 15% and 11%, respectively, up to 14 km, while for the sub-Artic atmosphere the random error is smaller than 18% in the free troposphere up to approx. 12 km

(Figure 6.1b). The peak bias does not exceed 4% throughout the troposphere for the three selected reference atmospheric models (Figure 6.1a). Mean and standard deviation of the bias up to 13 km are -0.7±0.6%, -2.4±1.0% and -1.3±1.4% for the US Standard Atmosphere, the tropical atmosphere and the sub-Artic, respectively.

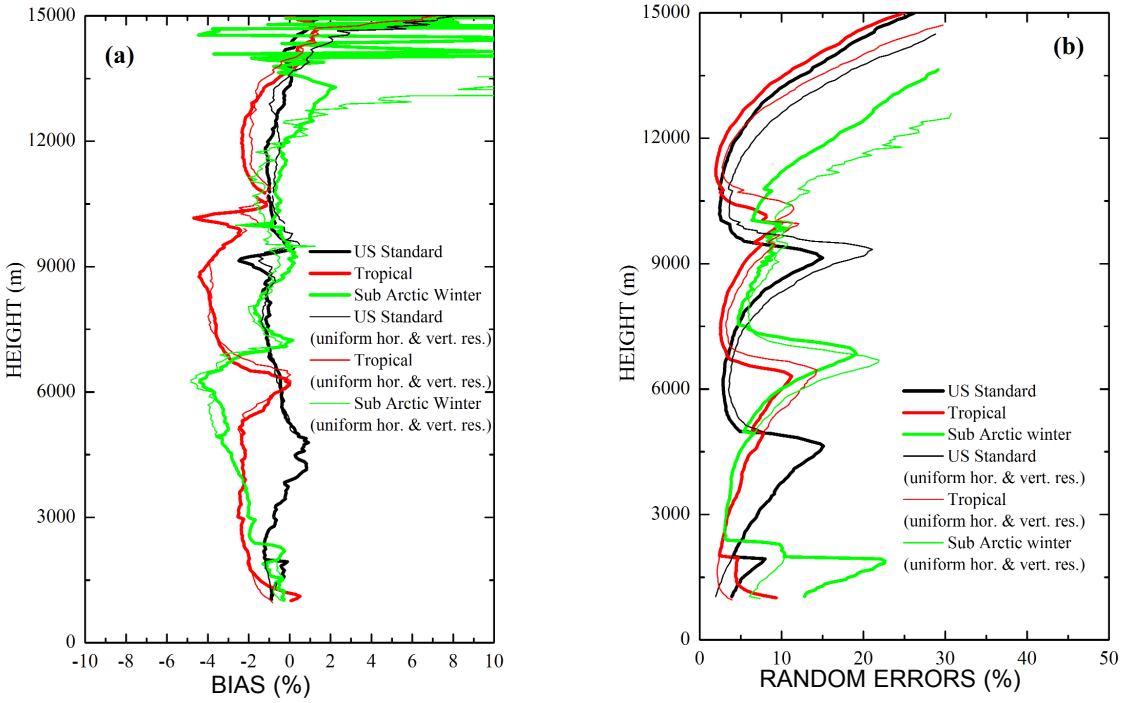

***Figure 6.1**: (a) Bias and (b) random error profiles. The solid lines in the figures refer to the altitude dependent horizontal and vertical resolutions as specified in the requirement Table 4.1, while the thin lines represent the errors in the case of a uniform horizontal resolution of 100 km and vertical resolution of 1 km. Bias and random errors can be traded off by choosing different combinations of horizontal/vertical resolutions.*

6.3 Effects of Clouds on WALES Performance

Clouds influence the SNR of WALES backscatter signals as well as the background signal level. Two cloud layers, a cirrus cloud at 9 km and an alto-stratus at 4 km, were considered, each with a lidar optical thickness of 0.3. The simulations show that WALES is able to measure above and below cirrus clouds, with a random error of less than 20% and a mean bias < 5%. Further simulations demonstrated that the instrument is capable of providing precise measurements above clouds with only small degradations with respect to cloud-free conditions.

In the frame of Phase-A, specific studies have been carried out on the statistical impact of cloud on WALES performance. A one-year simulation of WALES orbiting using ECMWF archived 6 hourly cloud fields has been used. The results demonstrate that measurements satisfying the 20% precision requirement can be performed with a global mean coverage of about 85% at altitudes above the 700 hPa level, and a coverage of

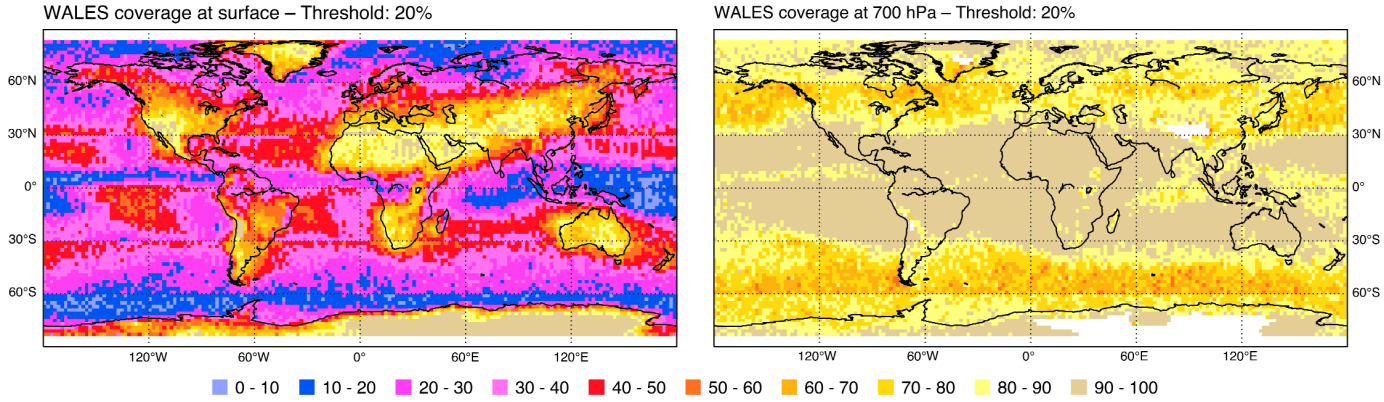

***Figure 6.2**: WALES coverage (percentage of measurements satisfying the 20% random error requirement) (a) above the surface, and (b) above 700 hPa*

about 40% above the Earth's surface (Figure 6.2). By using a higher threshold of 50%, the coverage increases to about 50% above the surface.

6.4 2D cases: NWP Scenes and Inclusion of Real Data from Airborne H_2O DIAL Systems

2D simulations improve the insight into WALES performance in the presence of inhomogeneous atmospheric conditions. Figure 6.3a shows a latitude/height cross section of a 6 h forecast (90°S-90°N cross section) valid for 24 May 2001 at 06 UTC, and Figure 6.3b represents the corresponding WALES reconstruction based on the use

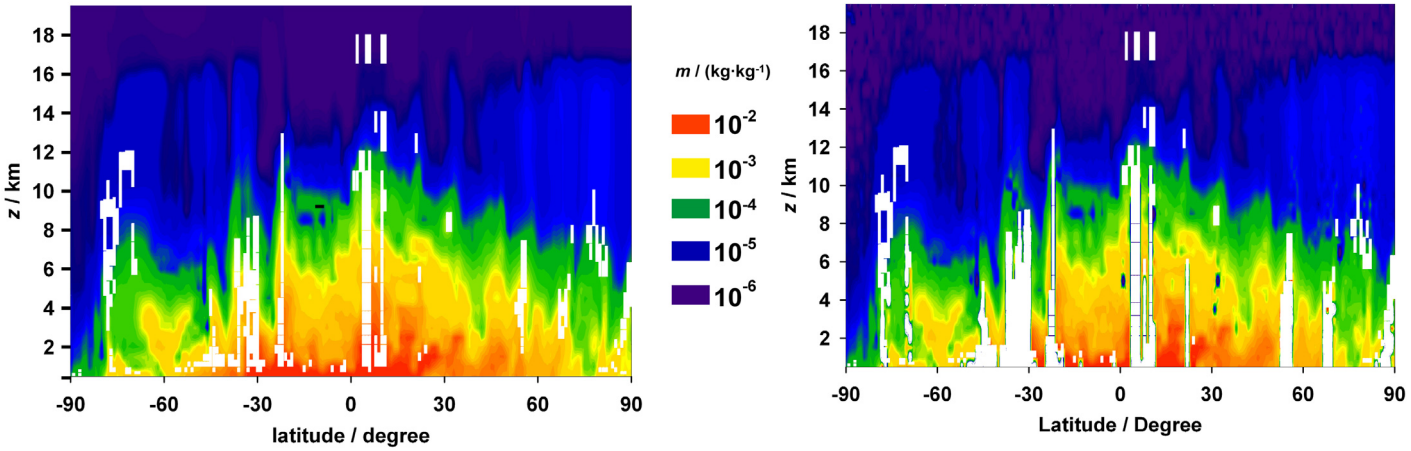

***Figure 6.3a**: MSC 6-h forecast for 24 May 2001 (06 UTC) at longitude 122 W. White stripes represent clouds.*

***Figure 6.3b**: WALES reconstruction for the data in Figure 6.3a. White stripes represent clouds or signal degradation.*

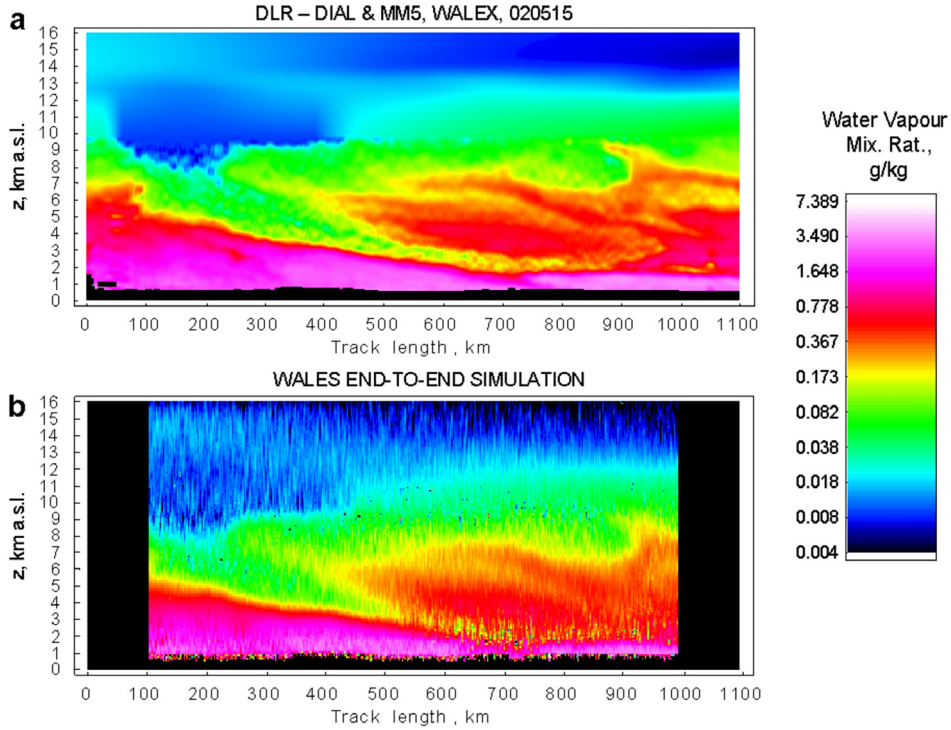

***Figure 6.4**: (a) Original water vapour field, (b) and end-to-end simulation. Horizontal resolution is 25 km.*

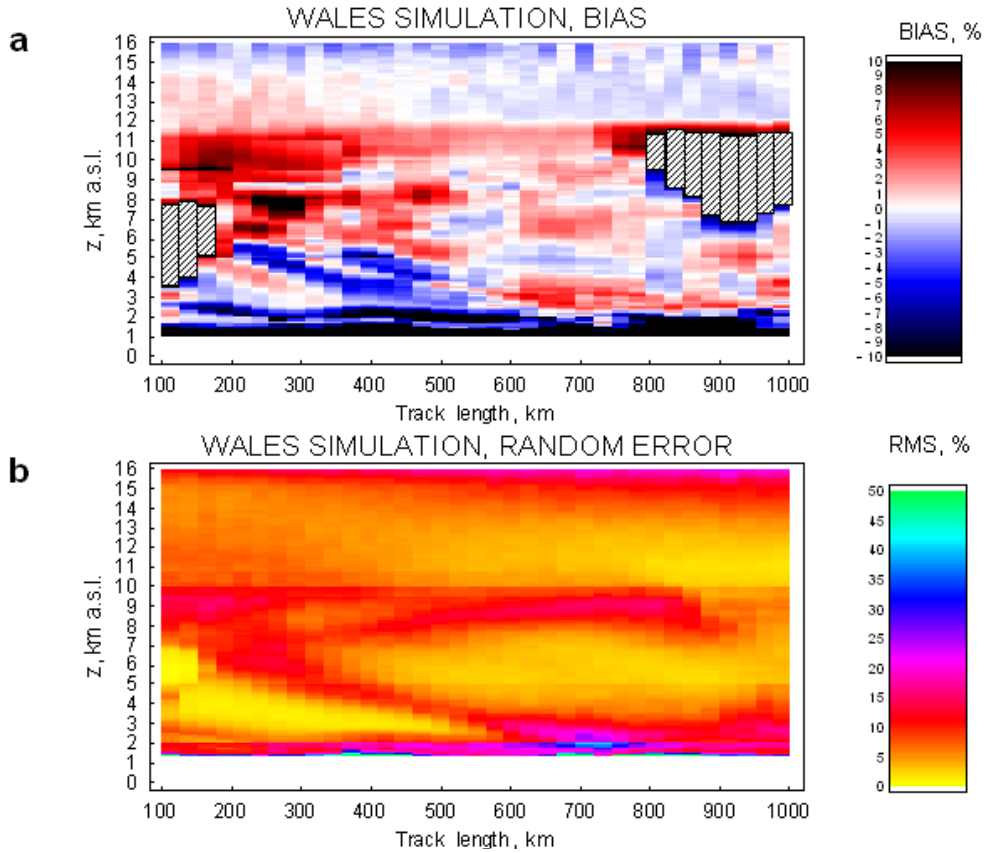

***Figure 6.5**: (a) Bias and (b) random error fields as calculated by the end-to-end simulator for the cross-section of Figure 6.4. Grey areas in Figure 6.5a are affected by cloud.*

of an analytical model. The water vapour field is reproduced correctly, with limited loss of information in cloudy areas. The random error is 5-15% up to 15.5 km. Useful data can be collected up to ~16.5 km (random error <50%).

Figure 6.4 shows the simulations for WALES based on real atmospheric measurements carried out with the DLR Falcon water vapour DIAL system during the Walex experiment. Figure 6.4a represents the original water vapour fields as measured by the DLR DIAL, while Figure 6.4b represents the corresponding WALES reconstruction based on the end-to-end performance simulator. The water vapour field is obtained in great detail.

Figure 6.5 shows the corresponding systematic error field and the noise error field. The maximum systematic error is less than 5% up to 16 km, except in the presence of thick cirrus and mid level clouds and occasionally inside the dry stratospheric intrusion (left portion of Fig. 6.5a), while the random error is less than 20% up to 16 km (Fig. 6.5b).

6.5 Vertical Extent and Resolution

An impact study was specifically performed in order to assess the benefits of WALES data to NWP through quantitative analysis of information content. Good vertical resolution and low random errors are shownm giving substantial improvements in analysis error and vertical resolution in 1D-var comparisons with IASI and other advanced infrared sounders (Gérard et al. 2004). The results show that WALES globally performs better than IASI, especially in the lower troposphere. The analysis relative error threshold of 20% is exceeded at altitudes above 150-200 hPa (12-14 km) for WALES and above 200-250 hPa (10-12 km) for IASI. Below 250 hPa where both instruments meet the 20% accuracy threshold, the mean relative error for WALES retrievals is 7.2%, while that for IASI is 11.4%. The analysis vertical resolution resulting from the assimilation of WALES data (see Fig. 6.6) is twice as fine as that in the case of IASI (0.5 to 1 km for WALES versus 1 to 2 km for IASI).

The vertical extent of WALES was compared to that of AIRS and radiosondes (Gérard et al. 2004) (Fig. 6.7) based on simulations from the NWP forecast in Figure 6.3a. The mean vertical extent for a particular cross-section is found to be 15.4 km (114 hPa) for WALES, well above the AIRS vertical extent (10.3 km or 252 hPa) and the radiosonde vertical extent (7.9 km or 363 hPa). The vertical extent of WALES profiles is found to be well above the limit of radiance assimilation (13 km or 200 hPa). These results confirm the obvious and very significant advantage of WALES, particularly in high latitude regions.

6.6 Summary

Analyses performed using end-to-end models confirm that low biases and noise errors can be achieved in WALES water vapour retrievals. Outcomes of the 1D and 2D simulations

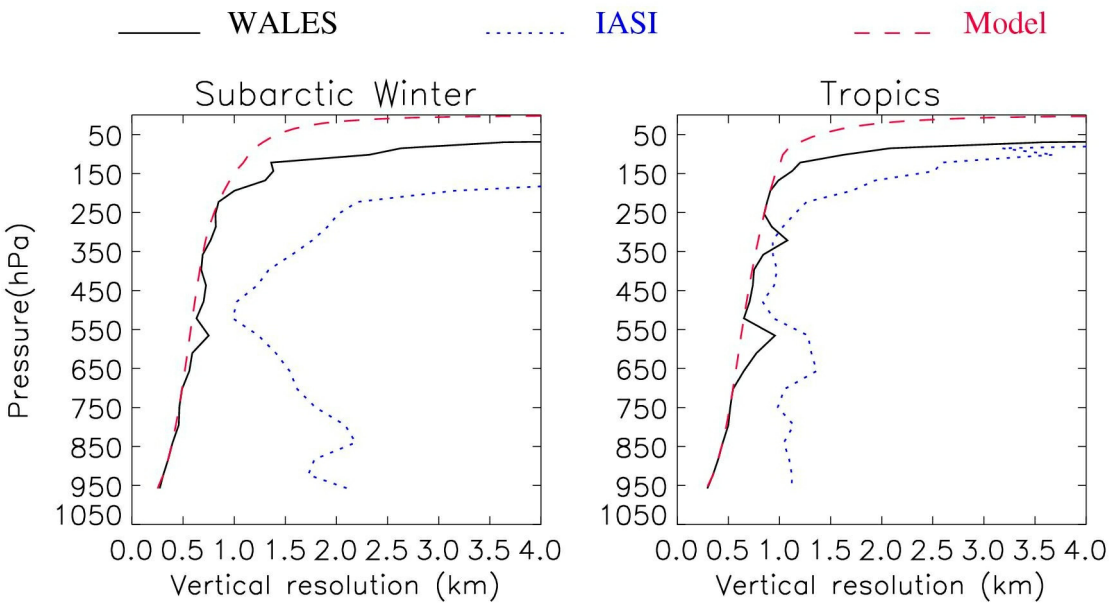

***Figure 6.6**: WALES (solid lines) and IASI (dotted lines) specific humidity analysis vertical resolution for sub-arctic and tropical conditions. The model vertical resolution is dashed.*

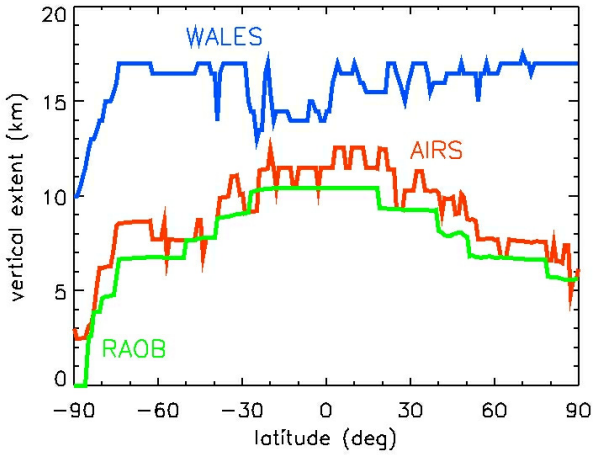

***Figure 6.7**: Comparison of the vertical extent of WALES (top curve), AIRS (middle curve) and radiosondes (RAOB) (bottom curve); same cross-section of Figure 6.3a was considered.*

of WALES performance clearly show that the observational requirements are met (Table 4.1). WALES will perform low-bias (<4%) measurements of water vapour covering the whole dynamic range specified in the requirements. Less than 20% random error in a cloud free atmosphere is maintained even in the case of a very humid atmosphere. In the presence of clouds, WALES will provide precise measurements (<20%) below thin cirrus clouds and above cloud decks, as well as make measurements through gaps between clouds. Table 6.1 compares the expected performances of WALES with the water vapour observational requirements. It shows that WALES performance exceeds the requirements. The vertical and horizontal resolutions can be scaled to meet the

	Requirement	WALES Expected Performance
Dynamic Range [g/kg]	0.01-15	0.005-16
Precision (1σ) [%]	20	5-18%
BIAS [%]	5	<4%

***Table 6.1**: Expected performances of WALES versus water vapour observational requirements*

desired NWP and climate research precision in the water vapour measurements. Specific studies have been performed which confirm the strong impact of WALES data on NWP and climate research.

7. Readiness of the User Community

7.1 Users

The primary objective of the Earth Explorer mission WALES is the measurement of high vertical resolution water vapour profiles on a global scale. This highly accurate data collected over a period of 2-3 years of operation will be of great importance for the validation of global climate models, better understanding of atmospheric processes, and improvement of numerical weather forecasting skills. Other geophysical parameters that can be derived from WALES measurements, referred to as secondary data products, are specified in Chapter 4.

Two different classes of users can be identified:

- Near-real-time users (e.g. national meteorological services, ECMWF) assimilating data into operational numerical weather prediction models.
- Research oriented users (e.g. universities, meteorological research centres, government agencies) using both primary and secondary data products from WALES observations for improved understanding of Earth's atmosphere in climate and meteorological studies.

7.2 Near-Real-Time Users

Weather service centres will request WALES data products in near real-time (not longer than 3 hrs after the observation) throughout the mission. They will combine these data with products from other meteorological observations to obtain a complete set of meteorological state variables. Additionally, WALES data products will be used synergistically for the calibration of future water vapour measuring instruments, as summarised in Chapter 8. The atmospheric lidar remote sensing community will devise the processing routines for their implementation at dedicated NWP and ground processing centres.

Preparations by near-real-time users at NWP centres will benefit from the ADM/AEOLUS mission where the ECMWF is currently developing data assimilation and quality control for data provided by the incoherent Doppler wind lidar. Similarly, the ECMWF, as well as a number of national weather services have indicated their interest in using WALES data products operationally.

It is worthwhile noting that the radiative transfer scheme for the WALES measurements is straightforward. WALES data reduction will not require exhaustive processing routines. Moreover, the methodology for processing DIAL data products has been extensively analysed in the past using data from ground-based and airborne measurements, as mentioned in Chapter 2. Hence, real data sets as well as data

evaluation algorithms already exist that will help in implementing and testing the complete processing chain outlined in Chapter 5. Details concerning ground processing can be finalised in the early phases of the mission in such a way as to allow timeliness of delivery while minimising data losses. This is a big advantage of the whole mission concept.

7.3 Research Oriented Users

WALES data at various processing levels will be requested by atmospheric research centres and universities. For this type of user, off-line data will be accepted that have a much longer delay between data generation and delivery. Data acquired during the lifetime of the mission will be used in re-analysis studies to validate climate models. Extended atmospheric re-analysis projects (ECMWF, i.e. ERA 15, ERA 40, NCEP) have already demonstrated their valuable contribution to the climate research community through the consistent data set they provide. To facilitate re-analysis studies, WALES data products will be archived.

Preparation of the scientific community for the usage of WALES data products will be accomplished by field campaigns prior to the mission. Data products derived from airborne and ground-based water vapour DIAL measurements are increasingly used in applied research. Examples are the Mesoscale Alpine Project (MAP), the Convection and Moisture Experiment (CAMEX), and the International H_2O Project (IHOP) where lidar experts and meteorologists worked together on sensor validation and meteorological studies. Further campaigns are in preparation where water vapour DIAL experts will interact with a broad user community studying deep convection in the tropics (TROCCINOX), climate-related processes in the upper troposphere and lower stratosphere (SCOUT), the West African monsoon (AMMA), and quantitative precipitation forecasting in complex terrain (The International Field Experiment of the German Science Foundation (DFG) Priority Programme 1167 “QPF”).

7.4 User Programmes Supported

The research objectives of the WALES mission have a strong synergy with the primary goals of long-term user programmes established by WMO. In particular, the WALES mission will contribute to:

- *The World Climate Research Programme (WCRP) and its Sub-Programmes: GEWEX and GvaP* (Global Water Vapour Project), by improving the understanding of atmospheric water vapour processes and observations; *CLIVAR* (Climate Variability and Predictability), by providing quality-controlled water vapour data sets and aerosol/cloud information that help to improve knowledge about water vapour feedback and radiative forcing caused by aerosols and optically thin cirrus clouds; and *SPARC* (Stratospheric Processes and their Role in Climate), by

providing global water vapour data for the upper troposphere and lower stratosphere (UT/LS).

- *The World Weather Research Programme (WWRP)* and its Sub-Programme *THORPEX* by improvement of NWP accuracy in the 1-14 day time domain.
- *The International Geosphere-Biosphere Programme (IGBP)* and its *Sub-Programme IGAC* (International Global Atmospheric Chemistry Project), with special emphasis on atmospheric water vapour, clouds and aerosols that have a role in global climate control.

In summary, a high level of readiness of the weather services and scientific user communities can be expected before launch. There will therefore no delay before the usage of WALES data. The objectives of the WALES mission are also very well supported by long-term user programmes established by WMO.

8. Global Context

8.1 Water Vapour Information Context in 2010

Atmospheric humidity is currently measured by about twenty different satellite instruments, which give near-complete global coverage every twelve hours. The number of humidity measuring instruments is expected to increase to more than thirty by 2010, based on the preliminary launch dates for all approved satellite missions (CEOS, 2003). All of these instruments are descendants of today's microwave and infrared nadir and limb sounders, except for the new GPS radio occultation instruments, and so the problems apparent in the use of infrared and microwave radiance data in present weather prediction models will remain in 2010. Despite the huge satellite coverage, most infrared instrument humidity information comes from the 250-600 hPa region with vertical resolution limited to ~1.5 km, with microwave instrument humidity information extending down to the surface but with lower vertical resolution.

The foremost of these problems is the lack of a common reference for evaluating the biases of the water vapour information from all the satellite instruments. A set of reference measurements with high absolute accuracy, providing a global coverage of high-resolution vertical water vapour profiles from the ground to the tropopause, would revolutionize the use of data from infrared and microwave sounders. The biases of all humidity observations could be evaluated in a consistent way, harmonizing the humidity levels given by the different instruments (see Chapter 2). This would enable the synergetic use of all observations to accurately resolve horizontal and vertical gradients in the humidity field.

For the infrared sounders (CrIS, GIFTS, GOES, HIRS, IASI, SEVIRI, TES), which have channels sensitive simultaneously to water vapour and temperature, the quality of the retrieved temperature would also improve. For the microwave sounders (AMSU, ATMS, MHS, SAPHIR, SSMIS), which have channels sensitive to humidity, temperature, liquid water, ice and rain, the retrievals would benefit from better humidity background fields.

None of the approved or planned satellite missions including the GPS mission (COSMIC and GRAS) can provide the reference needed for atmospheric humidity. A single water vapour lidar in space that meets the accuracy requirements of the WALES mission would provide the reference needed to integrate the humidity, cloud and rain information from future satellites. An important contribution of WALES is therefore its provision of better rather than more observations of atmospheric water vapour.

Humidity information will be available from infrared and microwave limb-sounders (TES, HIRDLS, MLS) in the upper troposphere and throughout the stratosphere, and

these measurements will overlap with WALES in the upper troposphere and lowermost stratosphere region. WALES can also act as a reference for these instruments in this region.

WALES will also be able to provide measurements of aerosols and clouds, and this will complement similar information from other instruments (possibly including the lidar on ADM and CALIPSO).

8.2 Research Context in 2010

The increase in computer power will allow both researchers and operational centres to use models at higher resolution by 2010. For global weather forecasting, 10 km horizontal resolution is planned, and regional models will be on the kilometre scale. At this resolution, clouds and precipitation are better resolved, and the use of information on humidity in all its phases will be a central research topic. Instead of assimilating humidity into models, total water will be assimilated. The main contribution to total water is humidity, with contributions from cloud liquid water and ice. This integrated treatment of water in the atmospheric models will make better use of humidity, cloud, and rain data. Another change that will take place by 2010 is the integration of global and regional meteorological, chemical transport, and aerosol models. This will make global humidity information readily available to atmospheric chemistry and aerosol researchers.

The main users of the WALES water vapour data will be the operational meteorological weather centres, as described in Chapter 7, but other user groups include:

- Data producers and retrieval algorithm developers who will be able to use the lidar data for intercomparison and quality checks on their own humidity data and algorithms.
- Atmospheric chemistry researchers who have many uses for lidar data, not only for the water vapour information, but also for example the use of backscatter information for identifying polar stratospheric clouds.
- Researchers and instrument developers involved in field campaigns for testing instruments who will make use of the lidar data for intercomparison and quality checks on their instruments.
- Aerosol modellers will also use these lidar data for checking their models, assimilating the data into their models, and combine the data with that from other sensors to gain insight into aerosol properties.

9. Application Potential

9.1 Operational Forecasting

- The direct measurement of high quality water vapour profiles as provided by WALES observations is not covered by the present NPOESS and MetOp baseline concepts. The WALES mission would come in the right time frame (~2010) to complement the planned deployment of the future Joint Polar System that includes the American NPOESS and the EUMETSAT Polar System EPS with the MetOp satellites.
- As explained in the previous section, the use of water vapour lidar data in operational weather forecasting (global and regional) would bring many benefits. In addition to being an accurate source of humidity information in the troposphere, the measurements can act as a common reference for all other water vapour measuring instruments. This would bring a new level of synergy to the operational use of satellite data, not only humidity, but also temperature, cloud and rain data, most of which are sensitive to humidity. Background error descriptions for humidity would also be improved by calibration against global water vapour lidar data. Better background error data translate into more accurate use of all available humidity data in the analysis. Another benefit of adding lidars to the existing satellite data sets is the potential for improved hurricane forecasts, as illustrated by Kamineni et al. (2003). The continuous cross-sections provided by WALES, combined with its high vertical resolution, make these data particularly well suited for impact-weather or targeting studies as envisioned by THORPEX.
- In 2010, we will be seeing operational (global and regional) aerosol and chemical transport models issuing daily forecasts (see Errera and Fonteyn 2001, for a stratospheric prototype). A driving force in these developments is the Global Monitoring for Environment and Security initiative (GMES). A backscatter lidar can be used as input in the preparation of the initial conditions of these models just as for weather prediction, providing information on water vapour, clouds, and aerosol backscatter. This will provide additional information for the prediction of aerosols and pollutants spreading from volcanoes, biomass burning, sand storms, and anthropogenic emissions, which can also greatly benefit many aspects of society, including air safety.
- Through more accurate information on humidity and clouds, the Earth's exposure to radiation in different wavelength bands will be better known, and this will provide a better input to ancillary models related to human health issues (e.g. UV exposure), biology, and agriculture.

9.2 Climate Monitoring

Water vapour lidars have important potential for climate monitoring, both alone and through their use in a reanalysis of the atmospheric circulation. The advantage of monitoring through re-analyses using atmospheric models and data assimilation is that observational information about one component of the atmosphere spreads to all other components.

The availability of long time series of high quality water vapour profiles would benefit re-analysis projects covering several decades of observations. One of the largest difficulties in such projects, which have been performed at NCEP and ECMWF, is the calibration of observations across different instruments and satellites. The introduction of instruments with the coverage, resolution and accuracy planned for WALES would make it possible to interpret changes in the water vapour distribution in future re-analysis in terms of physical processes. There is no data processing technique (data assimilation or otherwise) that can substitute for accurate observations when it comes to determining the correct level of humidity from a mixture of different observations and models, which each have their own particular bias.

Unless a reference measurement is available, there is always an ambiguity as to what the absolute level of humidity is, which can mask the real trend or create apparent trends. Since humidity and temperature are tightly coupled in meteorological analyses and radiance observations, which are sensitive to both humidity and temperature, the determination of accurate temperature trends is also dependent on determining accurate humidity trends. The interaction of radiation with clouds is one of the largest sources of uncertainty in temperature trend studies, and an accurate humidity distribution is a prerequisite for determining accurate cloud distributions. In addition, the lidar data can be used to determine the heights and optical characteristics of high-level clouds, which would also further the understanding of cloud-radiation interactions.

9.3 Spin-off from WALES

Climatological applications require long-term measurements, and it is expected that the WALES mission would be followed up by other active global humidity observation systems. It is also expected that the accuracy requirements for reference quality humidity measuring instruments will become more stringent, as models improve in accuracy with time. A unique feature of water vapour lidars is their scalability with respect to transmitter average power and efficiency of the receiver. Consequently, they can meet the increasing accuracy requirements of follow-on missions through advanced technology developments in more powerful transmitters and larger receiver systems.

While horizontal coverage is not an issue for WALES in its role as a reference instrument, we can foresee that higher horizontal coverage of lidar profiles is needed in future for better vertical resolution on a global scale. Deploying lidars on a few satellites would give global high vertical resolution humidity coverage every twelve hours.

Lidars are also being considered for remote sensing of gases on other planets in the Solar System, including the mapping of water vapour in the atmosphere of Mars. Although different in size and power requirements, future lidar systems for planetary exploration would benefit greatly from the demonstration of global water vapour measurements by WALES.

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Acronyms

ACE+	Atmospheric and Climate Explorer
ADM	Atmospheric Dynamics Mission
AEOLUS	Atmospheric Explorer for Observations with Lidar in the Ultraviolet from Space
AIRS	Atmospheric Infrared Radiance Sounder
AMMA	African Monsoon Multidisciplinary Analysis
AMSU-A/B	Advanced Microwave Sounding Unit-A/B
ATMS	Advanced Technology Microwave Sounder
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection And Moisture Experiment
CBS	Commission on Basic Systems of WMO
CEOS	Committee on Earth Observation Satellites
CLIVAR	WCRP Programme on Climate Variability and Predictability
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CrIS	Cross-track Infrared Sounder
DFG	Deutsche Forschungsgemeinschaft
DIAL	Differential Absorption Lidar
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EarthCARE	Earth Clouds, Aerosol and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
EGPM	European contribution to the Global Precipitation Mission
EOEP	Earth Observation Envelope Programme
EOS	Earth Observing System
EPS	EUMETSAT Polar System
ERA	ECMWF Re-Analysis Data
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GEWEX	Global Energy and Water cycle Experiment
GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GMES	Global Monitoring for Environment and Security initiative
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GRAS	GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding
GVaP	GEWEX Water Vapour Project

HIRDLS	High-Resolution Dynamics Limb Sounder
HIRS	High-Resolution Infrared Sounder
IASI	Infra-red Atmospheric Sounding Interferometer
IGAC	International Global Atmospheric Chemistry project of IGBP
IGBP	International Geosphere-Biosphere Programme
IHOP	International H_2O Project
IR	Infra-Red
LASE	Lidar Atmospheric Sensing Experiment
MAG	Mission Advisory Group
METOP	Meteorological Operational polar satellites of EUMETSAT
MHS	Microwave Humidity Sounder
MLS	Microwave Limb Sounder
NCEP	National Center for Environmental Prediction
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NWP	Numerical Weather Prediction
QPF	Quantitative Precipitation Forecast
RAOB	Radiosonde Observation
SAPHIR	Sondeur Atmospherique du Profil d'Humidite Intertropical par Radiometrie
SCOUT	Stratosphere-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SNR	Signal-to-Noise Ratio
SPARC	WCRP Programme on Stratospheric Processes and their Role in Climate
SPECTRA	Surface Processes and Ecosystem Changes Through Response Analysis
SSMIS	Special Sensor Microwave Imaging Sounder
TES	Tropospheric Emission Spectrometer
THORPEX	The Observing System Research and Predictability Experiment
TROCCINOX	Tropical Convection, Cirrus Clouds and Nitrogen Oxides Experiment
UTC	Universal Time Coordinated
UTLS	Upper Troposphere / Lower Stratosphere
UV	Ultra-Violet (radiation)

WALES	Water-vapour Lidar Experiment in Space
WCRP	World Climate Research Programme
WWRP	World Weather Research Programme

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