SIMULATION OF THE PERFORMANCE OF WALES BASED ON AN END-TO-END MODEL

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ABSTRACT

WALES (Water Vapour Lidar Experiment in Space) is one of the experiments considered by ESA for selection as Earth Explorer Core mission in the frame of the *Earth Observation Envelope Programme*. WALES is expected to provide accurate and global 4-d water vapour fields with high vertical resolution from a low Earth orbit satellite.

The expected performances of WALES have been simulated through the application of an end-to-end model. In this work we provide an assessment of WALES daytime performances in clear sky and cloudy conditions. Expected performances are expressed in terms of systematic and noise errors in dependence of altitude and SNR for three selected reference atmospheric models (tropical, sub-Artic winter and US Standard Atmosphere). An estimate of the major components of the systematic error is also provided.

Real atmospheric data from existing lidar systems have also been considered to estimate the performances of WALES in variable atmospheric conditions, as well as to determine the effects on system performances associated with atmospheric inhomogeneities and variable cloud scenes.

1. INTRODUCTION

The high variability of atmospheric water vapour in both space and time, as well as its large dynamic range, represent a major challenge for its observation. The need for improved coverage and quality of water vapour observations is particularly felt by both the climate and the numerical weather prediction (NWP) community.

The European Space Agency's Water Vapour Lidar Experiment in Space Mission aims to meet this need by providing high-quality water vapour profiles, globally and with good vertical resolution, using a differential absorption lidar (DIAL) system on a low Earth orbit satellite. With launch envisaged around 2010-2012 and a duration of 2-3 years, the primary mission goal of WALES is to demonstrate the feasibility of a longer-term operational mission.

In December 2000 WALES was selected by ESA for assessment studies (pre-phase A), while in October 2001, an additional selection took place in Granada based on a public consultation meeting, as a result of which WALES was one of three missions selected for "Phase A".

In the context of WALES pre-A phase studies, WALES instrument requirements were defined through the application of approximate analytical models and results were summarized in the WALES Assessment Report [1]. DIAL measurements were simulated considering analytical expressions for random and systematic measurement errors [2, 3, 4, 5]. This approach was tested [5] and was found to lead to highly reliable results at high signal-to-noise (SNR) of the backscatter signals.

However, whereas analytical models are a convenient way to predict DIAL system performances, several approximations are made which may not be valid for WALES. These include certain assumptions on errors' statistics and their propagation, approaches to combine different random error sources and the disregard of several effects due to small-scale atmospheric variability. Furthermore, in analytical models instrument biases are treated separately and the overall accuracy of the measurements is determined by the propagation of systematic errors.

The above limitations can be overcome through the development and application of an end-to-end performance simulation model. End-to-end performance simulators are capable to generate realistic synthetic DIAL signals by properly simulating all steps of the measurement procedure, i.e. numerically reproducing the different mechanisms of interaction of laser radiation with atmospheric constituents, as well as the behaviour of all devices included in the experimental setup.

The use of end-to-end models allows to simultaneously estimate random and systematic errors, distinguishing the effects on measurement bias associated with different atmospheric effects, system parameters and data analysis strategies.

2. MODEL SETUP AND RESULTS

An end-to-end model has been recently developed in a joint effort between Università della Basilicata, University of Hohenheim and DLR [6]. This numerical model includes a forward model, used to generate the lidar synthetic signals, and a retrieval module for the application of the DIAL equation. A block diagram of the simulator is shown in fig. 1.

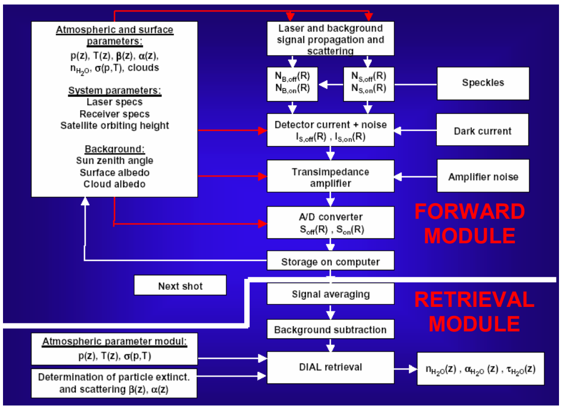

Fig. 1: Block diagram of the end-to-end simulator

Laser spectral specifications as the laser line spectral profile, the frequency stability and the spectral purity are properly modelled in the simulator, as well as are the different mechanisms of interaction of laser radiation with atmospheric constituents and the behaviour of all devices present in the water vapour DIAL system (telescope, optical reflecting and transmitting components, narrow band etalons, avalanche photodiodes and ACCDs) and the acquisition system. All devices are simulated together with their statistical behaviour. Specifically photon statistics, represented by Poisson distribution, is considered for both backscattered and background photons. Avalanche photodiodes' statistics, the so-called Conradi-McIntyre distribution [7], as well as random and systematic errors associated with amplification, signal digitisation and background signal subtraction are also accounted for.

WALES synthetic signals are then fed into the retrieval module, which is a completely independent model dedicated to the application of the DIAL equation.

According to the horizontal resolution chosen, a certain number of on-line and off-line sampled signals are averaged and the DIAL equation is applied to the averaged signals. For the application of the DIAL equation to lidar signals, different vertical averaging schemes and differentiation algorithms can be considered and tested. A modified version of the traditional Schotland equation is applied, accounting for Doppler broadening and Brillouin scattering [6].

System parameters used in the model for both the transmitter and the receiver, as well as design driving parameters (like orbit type and altitude and platform velocity), are those specified in the context of Phase A System Studies carried out from industry (Astrium and Alcatel). Main system and orbit parameters considered in Astrium Phase A study are summarized in table 1.

Table 1: Main system and orbit parameters considered in the Astrium Phase A study.

Parameter	**Value**
Orbit altitude	450 km
Solar angle	75^0
Ground albedo	0.35
Laser energy	72mJ
Laser rep. frequency	25 Hz
Laser wavelengths	λ_1=935.685 nm λ_2=935.561 nm λ_3=935.906 nm λ_4=935.852 nm
Laser frequency stability	< 60 MHz
Laser linewidth	<160 MHz
Laser spectral purity	>99.9 %
Detector type	L3CCD
Detector gain	50
Detector quantum efficiency	0.6

3. SIMULATIONS

In what follows we provide an assessment of systematic and noise errors in dependence of altitude and SNR for three selected reference atmospheric models (tropical, sub-Artic winter and US Standard Atmosphere), as well as an estimate of the major components of the systematic error. Among these: 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. Table 2 includes all different contributions to the systematic error expressed in terms of mean bias and its standard deviation up to 14 km. The overall mean bias is smaller than 4 %.

Fig. 2 and 3 illustrate the vertical profiles of bias and random error for the tropical atmosphere, the sub-artic winter atmosphere and US Standard atmosphere. Aerosol backscatter and extinction data were taken from the ESA ARMA median model. Borderline values for laser specifications are considered (laser line-width: 160 MHz, laser frequency stability: 60 MHz, spectral purity: 99.9 %), while contribution from water vapour spectroscopy as well as the effects associated with temperature uncertainty are not included in the figures.

Table 2: Contributions to the systematic error

	Mean bias up to 14 km	**Standard deviation of the bias up to 14 km**
Line-width	1.2 %	0.9 %
Frequency stability	1.2 %	1.1 %
Spectral purity	1.0 %	1.0 %
Temperature knowledge	1.1 %	0.4 %
Use of non-linear operators	0.4 %	0.9 %
Spectroscopy uncertainties	2 %	2 %
Doppler broadening	0.4 % clear air, 0.5 % in clouds	0.3 % clear air, 0.4 % in clouds

The solid lines in the figures refer to an horizontal resolution of 25 km up to 2 km, of 100 km up to 5 km, of 150 km up to 10 km and of 200 km up to 16 km, while the vertical resolution is 1.0 km up to 10 km and 1.5 km above. 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 then 18 % in the free troposphere up to approx. 12 km. Additionally, the peak bias is found to not exceed 4 % throughout the troposphere for the three selected reference atmospheric models. 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 atmosphere, respectively.

A better assessment of trade off capability between bias and random error, and horizontal/ vertical resolution is obtained by representing WALES performances at uniform horizontal and vertical resolution. Dotted lines in fig. 2 and 3 represent the vertical profiles of bias and random error for the three selected reference atmospheric models at a uniform horizontal resolution of 100 km and vertical resolution of 1 km.

Effects associated with the application of the different non-linear operators present in the DIAL equation are found to cause an increase in random error and bias in the transition regions between different wavelength pairs (around 6.5 and 11 km), regions where the signal-to-noise ratio (SNR) for the stronger pair is smaller than 3-5, while local optical thickness for the weaker pair is smaller than 0.02.

The presence of clouds influences the signal-to-noise ratio level of the backscatter signals, as well as the background signal level. The effect of cirrus and mid-level clouds on random error and bias has been simulated for the US Standard Atmosphere. Two cloud layers, a cirrus at 9 km (peak scattering ratio 540) and a mid-level cloud at 3 km (peak scattering ratio 290), were considered, each with an optical thickness of 0.3.

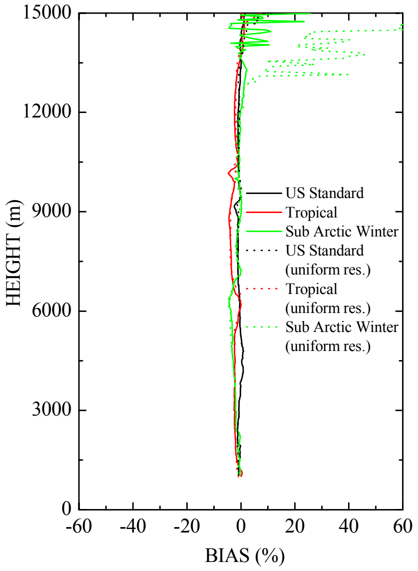

Fig. 2: Bias profile for tropical, sub-Artic and US Standard Atmosphere in clear sky conditions.

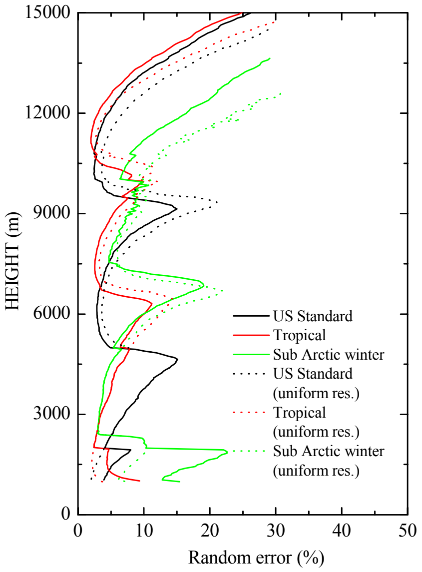

Fig. 3: Random error profile for tropical, sub-Artic and Standard Atmosphere in clear sky conditions.

Simulations show that WALES is able to measure above and below the cirrus cloud, down to the top of the mid-level cloud, with a peak bias not exceeding 5-6

% (fig. 4). The random error is found to be < 20 % above and below cirrus clouds, down to an altitude of 7 km, while it is larger (up to 50 %) below.

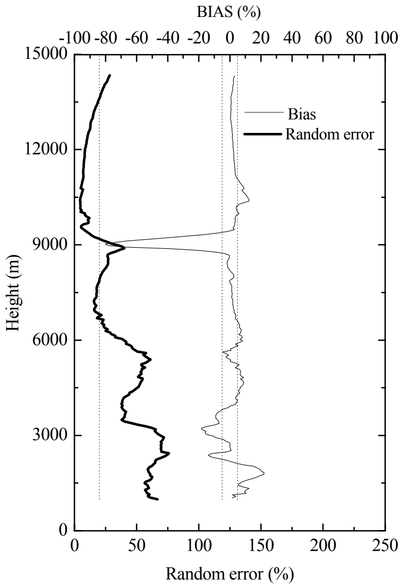

Fig. 4: Random error and bias in presence of clouds (US Standard Atmosphere, cirrus centered at 9 km, mid-level cloud centered at 3 km). Dotted lines indicate 20 % for random error and ± 5 % for bias.

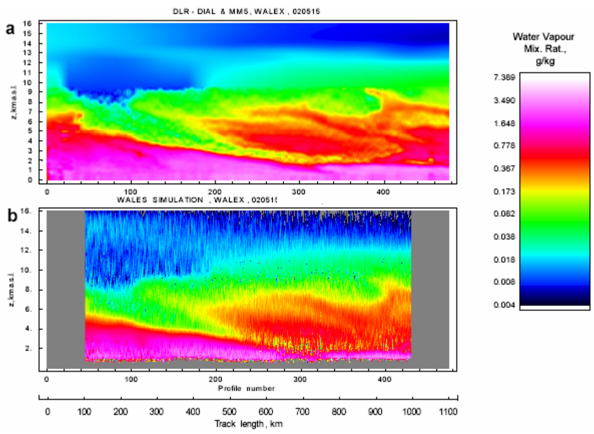

Fig. 5: Original water vapour field (a) and WALES end-to-end simulation (b). Hor. resolution is 25 km.

Real atmospheric measurements carried out by the DLR Falcon water vapour DIAL system during the Walex experiment (15 May 2002) have also been considered to estimate the performances of WALES in variable atmospheric conditions and determine the effects on system performances associated with atmospheric inhomogeneities and variable cloud scenes. Fig. 5 shows the original DLR DIAL water vapour field, together with the WALES end-to-end simulation. These and other results, revealing the capability of WALES to reproduce the fine structure of the water vapour and particle backscatter fields, as well as its capability to provide low bias measurements with high precision in presence of clouds, will be discussed in detail at the conference.

4. SUMMARY

Simulations performed with an end-to-end model show that WALES is expected to provide low bias (< 4 %) measurements of the water vapour content throughout the troposphere, with less than 20 % random error in cloud free conditions even in the case of a very humid atmosphere. Simulations also show that, in the presence of clouds, WALES is expected to provide accurate measurements above and below thin cirrus clouds and above stratiform cloud decks.

ACKNOWLEDGEMENTS

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