End-to-end model for DIAL systems

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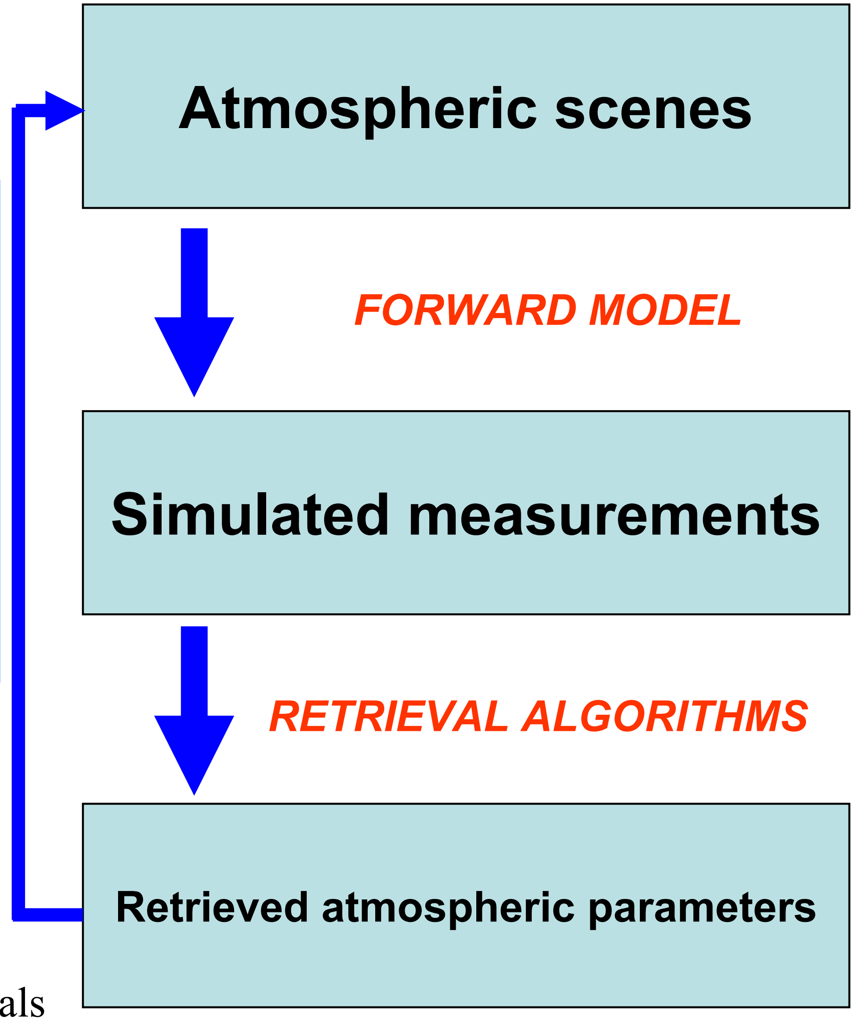
End-to-end simulators may be used to *size* passive and active remote sensors for space-borne, air-borne and ground-based applications.

May be used to size DIAL systems.

End-to-end simulators of DIAL systems

End-to-end simulators are capable to generate synthetic measurements by *numerically simulating* :

- **mechanisms of interaction of laser radiation with atmospheric constituents**
- **behaviour of all devices in the experimental setup.**



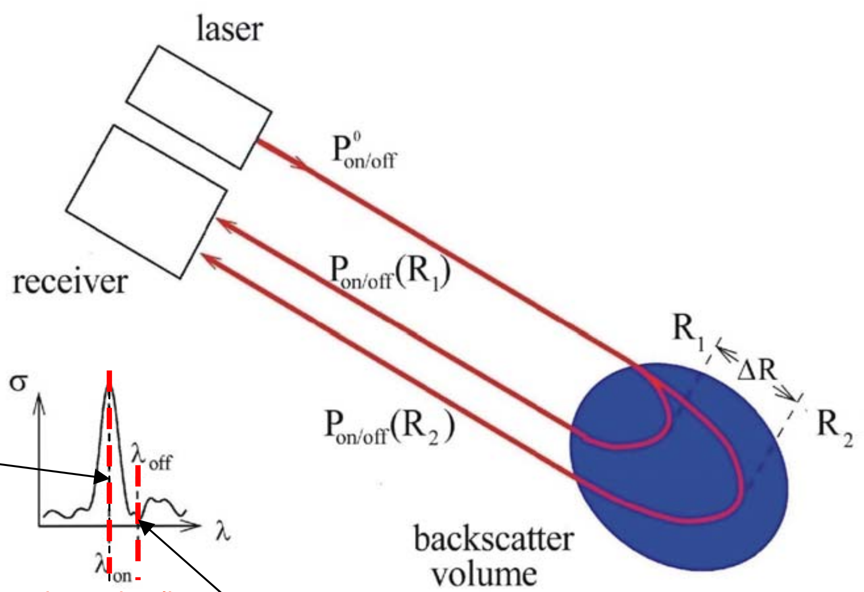
End-to-end models include:

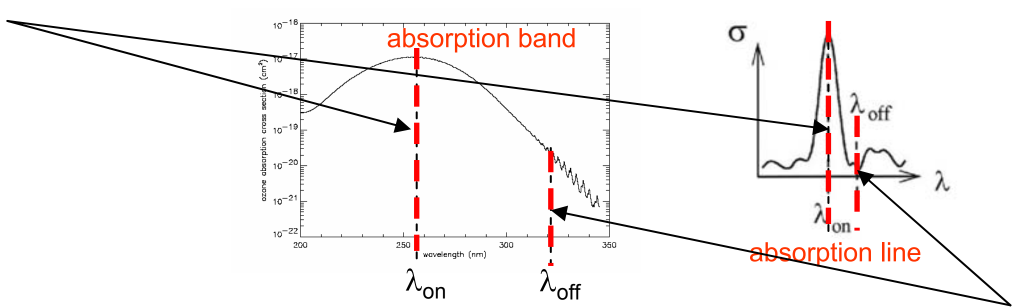
Forward model → generate synthetic lidar signals

Retrieval module → application of the DIAL equation

DIAL methodology

- DIAL Technique is based on:
  - Transmission of two laser pulses throughout the atmosphere.
  - Comparison of the intensities of the backscattered radiation.





- The range-resolved profile of the concentration of the molecular species under investigation n_{sp} is directly derived from the on- and off line lidar signals through the equation:

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

Measured parameters:

- **Atmospheric constituents**

  - **H_2O** (for example: online 723.59 nm, offline 723.7 nm; online 935.31 nm, offline 935.6 nm)
  - **CO_2** (for example around 2.0 mm)
  - **CH_4** (for example: online 310 nm, offline at 355 nm)
  - **O_3** (for example: online at 310 nm, offline at 355 nm)
  - **NO_2** (for example around 450 nm)
  - **SO_2** (for example around 300 nm and 7.4 mm)

- **Atmospheric state variables**

  - **Temperature**
  - **Pressure**

Atmospheric temperature measurement based on the selection of specific O_2 absorption lines characterized by a large temperature dependence.

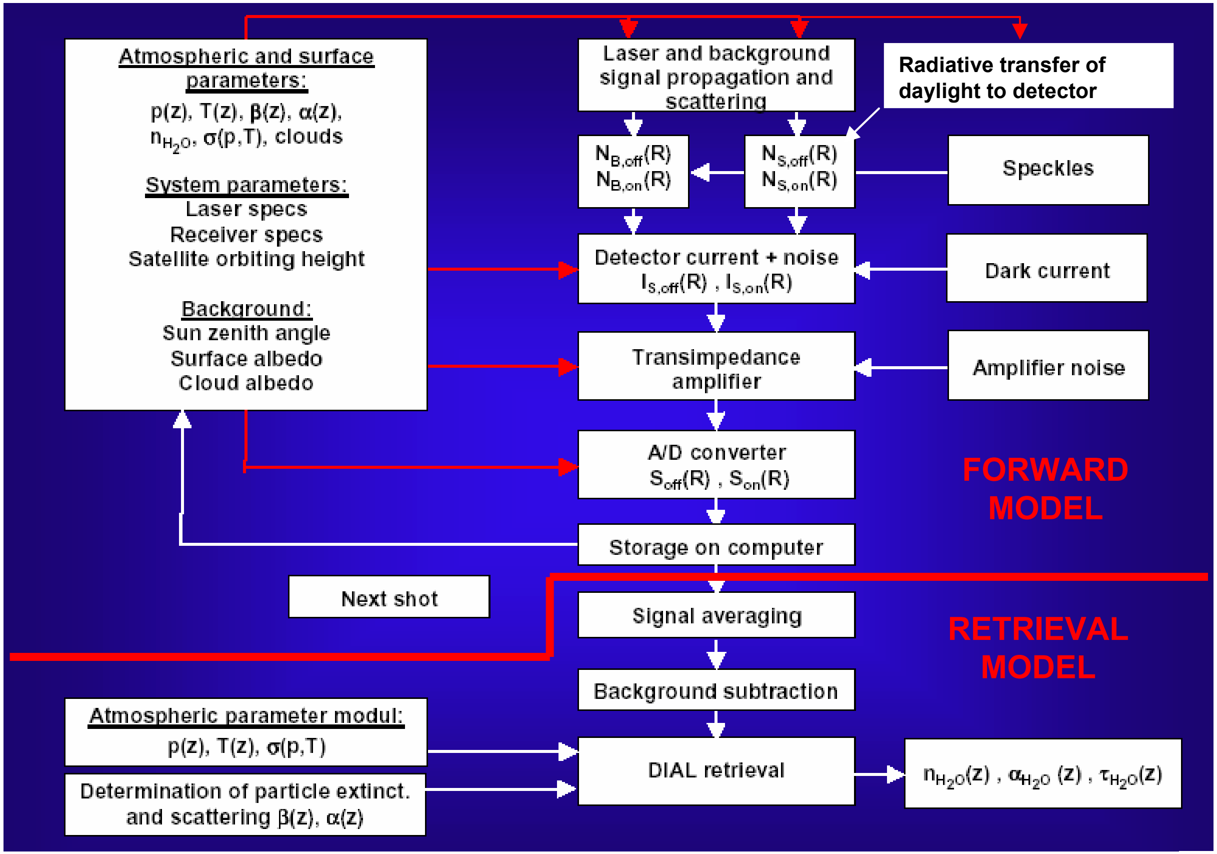
$$\frac{d\alpha}{\alpha} = \frac{dT}{T}\left[\frac{\varepsilon}{kT} + c\right]$$

Relative changes of O_2 absorption coefficient $d\alpha/\alpha$ with temperature dT/T

High temperature sensitivity for lines with high initial state energy ε

WALES = Water Vapour Lidar Experiment in Space

ESA Earth Explorer Core Mission



End-to-end model

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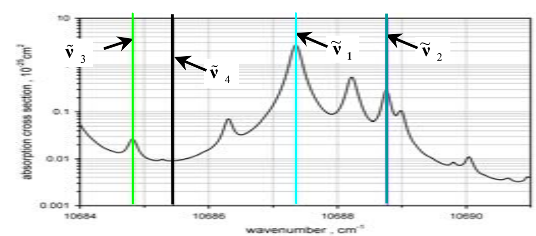
Block diagram

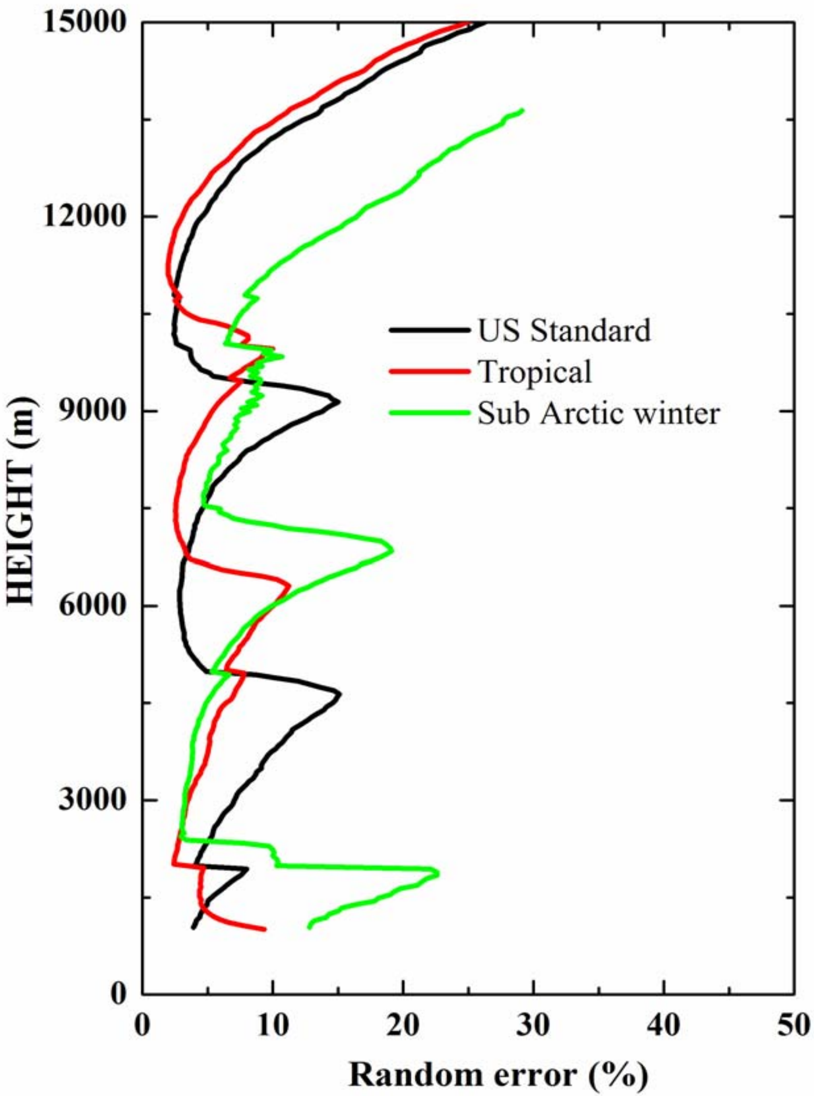
Laser wavelengths: λ_{off}=935.6 nm
λ_{wk}=935.66 nm
λ_{med}=935.31 nm
λ_{st}=935.43 nm

Pulse energy = 75 mJ
Pulse rep. rate= 25 Hz
Telescope diameter=1.7 m



Mission performance

Clear sky performances from end-to-end simulation



Random Error

US Standard Atmosphere:

Peak random error < 15 % up to 14 km

Mean random error = 6.6 % up to 14 km

Tropical atmosphere:

Peak random error < 11 % up to 14 km

Mean random error = 5.4 % up to 14 km

Sub-Artic winter atmosphere:

random error < 18 % up to 12 km

Mean random error = 8.8 % up to 14 km

Solar off-nadir angle = 75^0

Ground albedo = 0.35

Orbit altitude = 450 km

Δx=25 km, 0.5 < z < 2 km,
Δx=100 km, 2 < z < 5 km,
Δx=150 km, 5 < z < 10 km,
Δx=200 km, 10 < z < 16 km

Δz=1.0 km, 0.5 < z < 2 km,
Δz=1.0 km, 2 < z < 5 km,
Δz=1.0 km, 5 < z < 10 km,
Δz=1.5 km, 10 < z < 16 km

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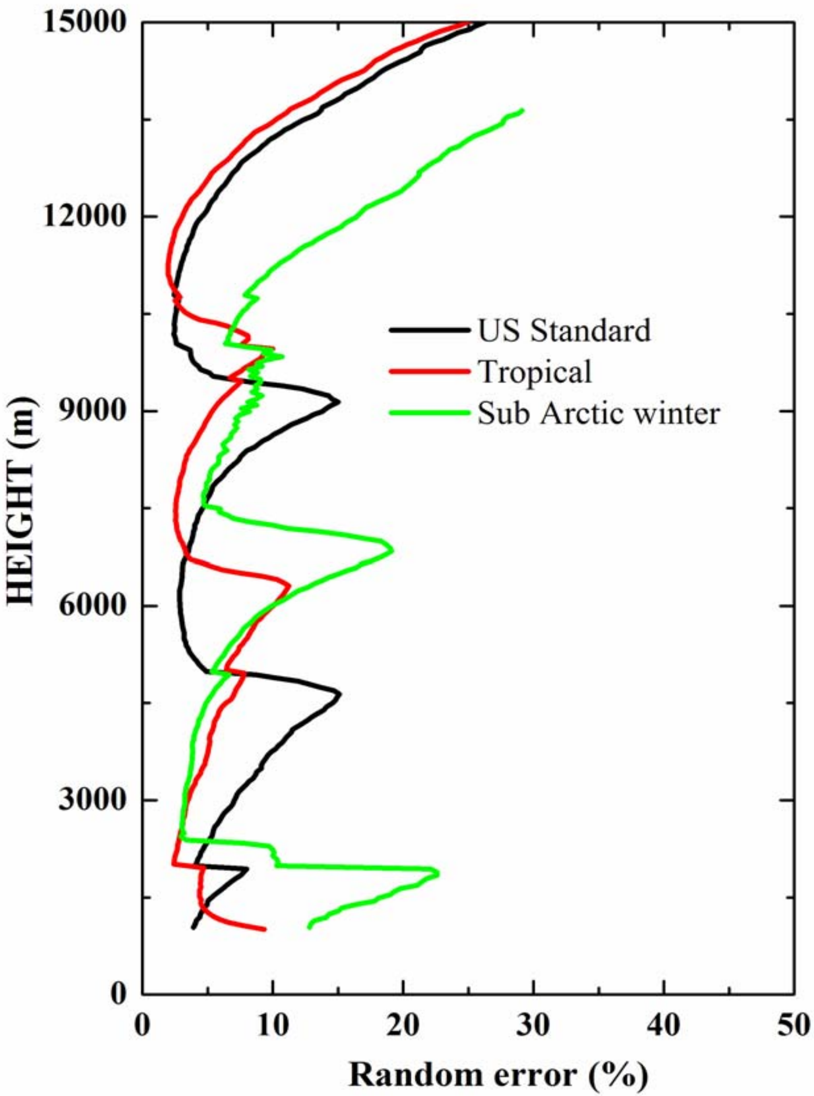

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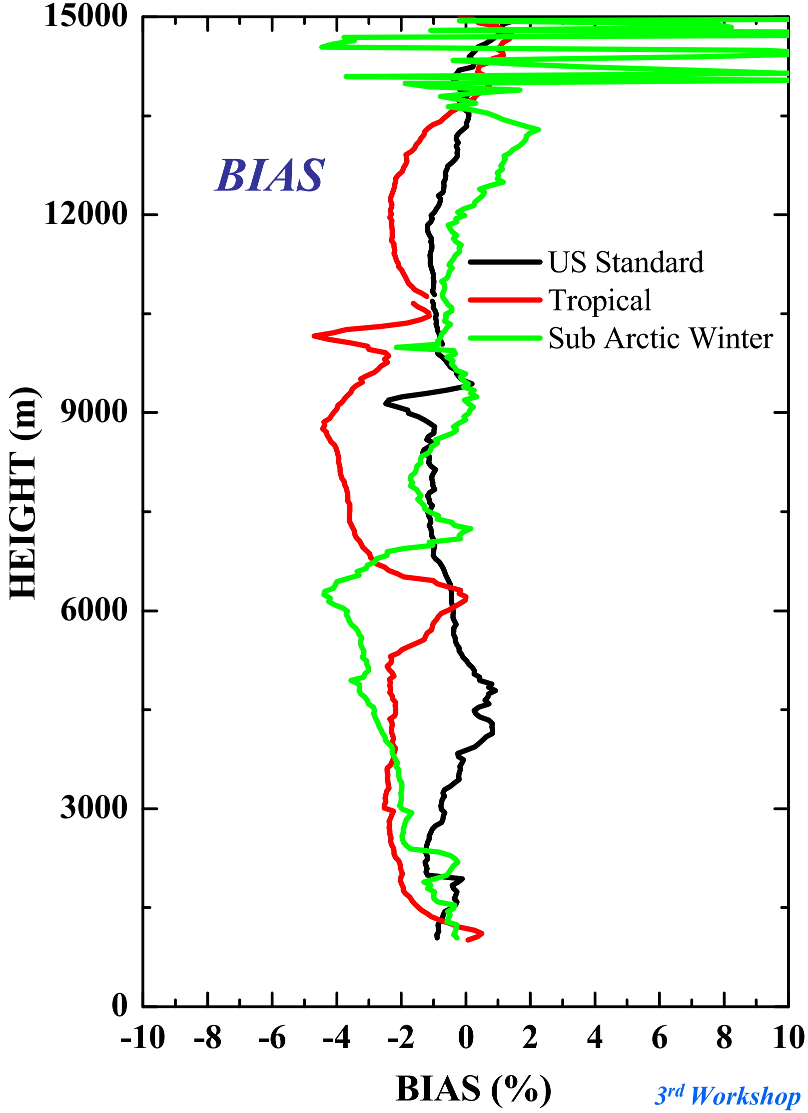
Mission performance

Clear sky performances from end-to-end simulation



BIAS

Peak BIAS < 4 % throughout the troposphere

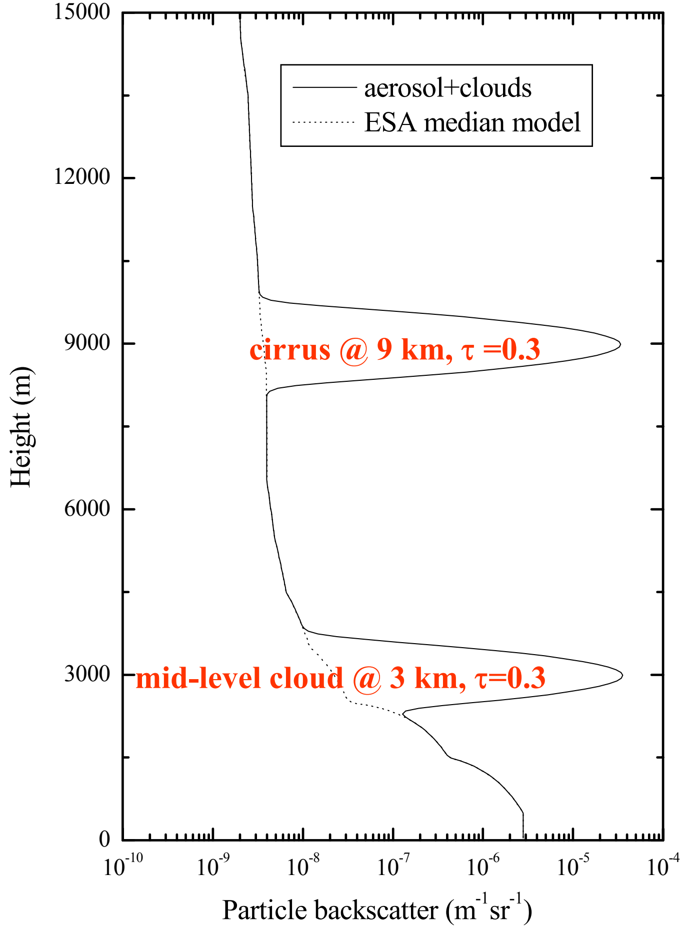
Mean and standard deviation of the BIAS up to 13 km:

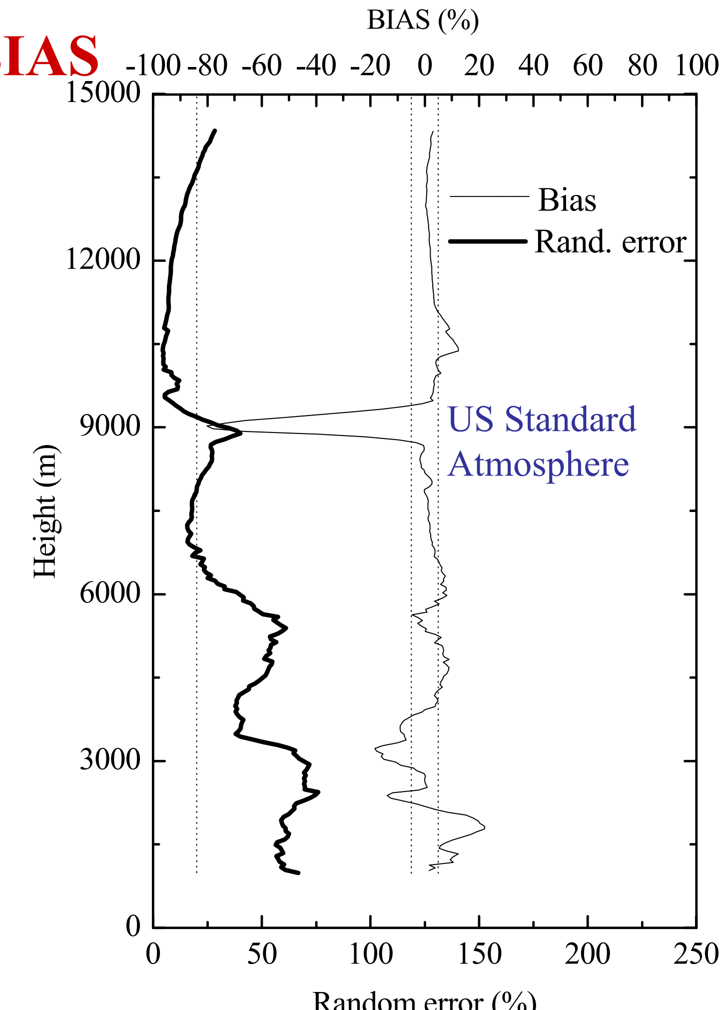
- -0.7±0.6 % for US Standard Atmosphere
- -2.4±1.0 % for Tropical atmosphere
- -1.3±1.4 % for Sub-Artic winter

Contribution from water vapour spectroscopy as well as the effects associated with temperature uncertainty are not included.

Mission performance

Performances in presence of clouds: effect of clouds on random error and BIAS





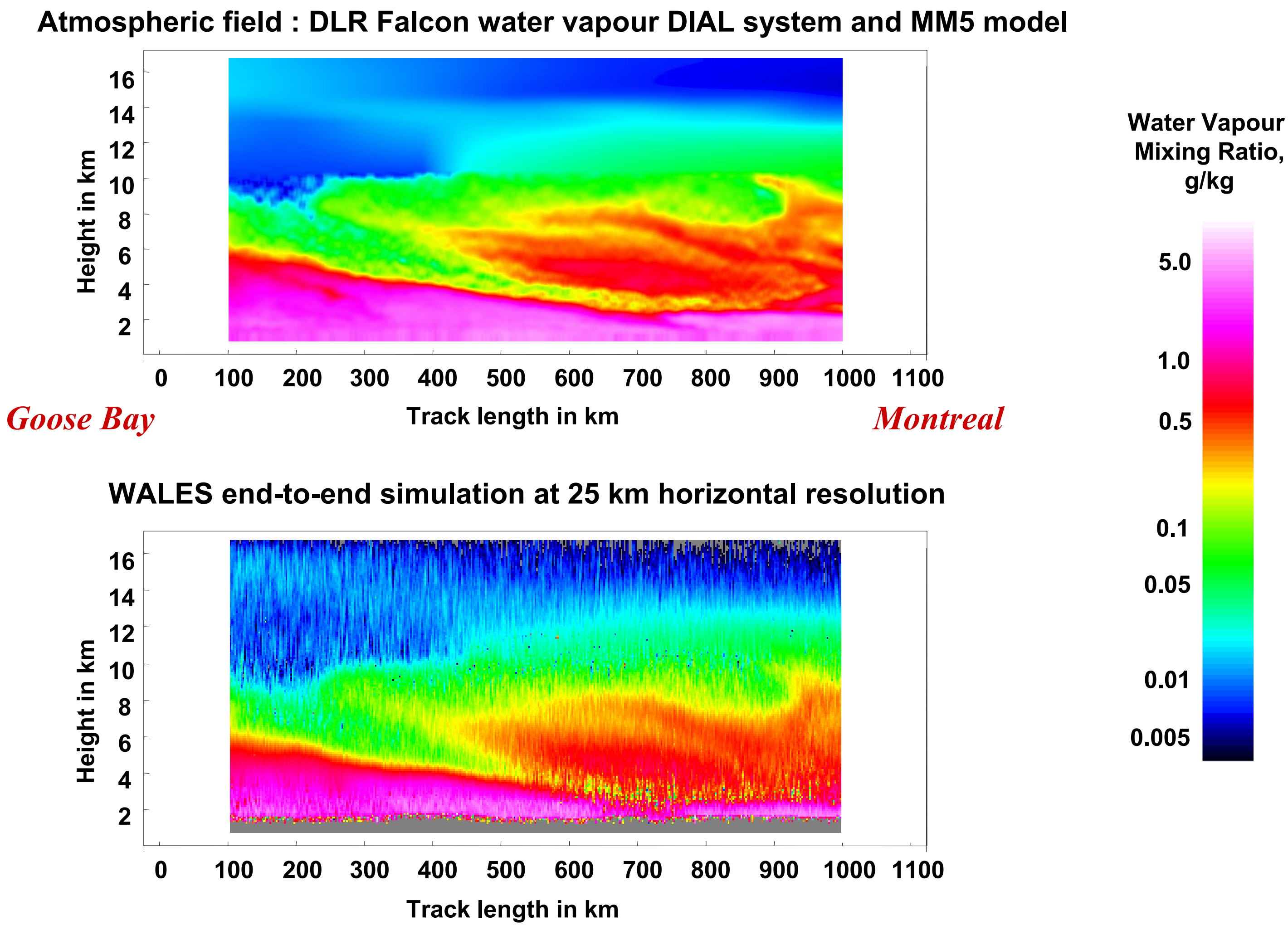
WALES is able to perform measurements above and below thin cirrus clouds, down to the top of mid-level clouds:

peak BIAS < 5-6 %, rand. error < 20-30 %

Mission performance:

Performances of WALES in variable atmospheric conditions

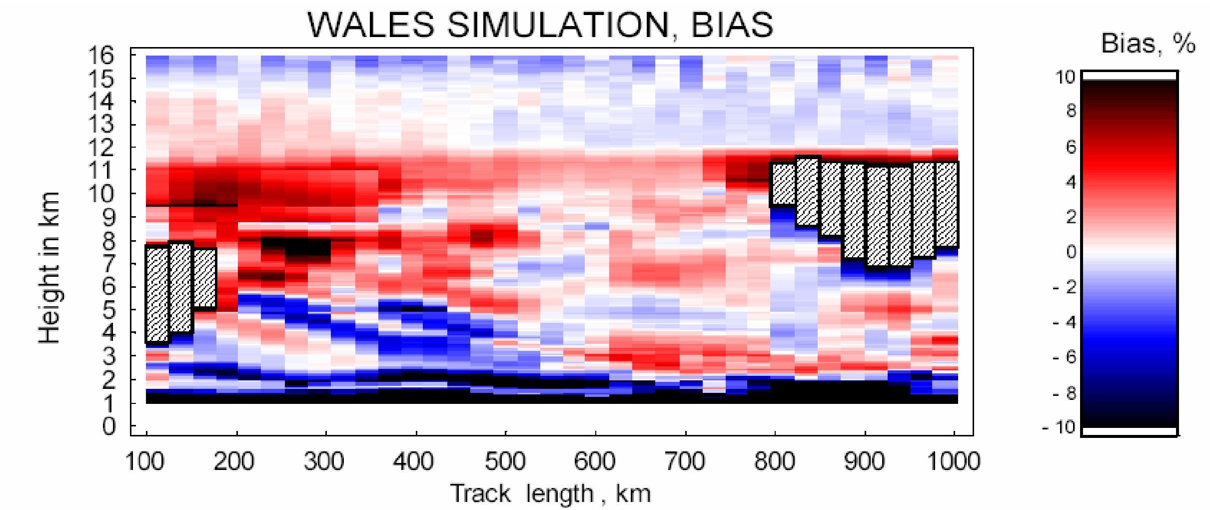
WALES 2-D simulation from observed airborne DIAL data

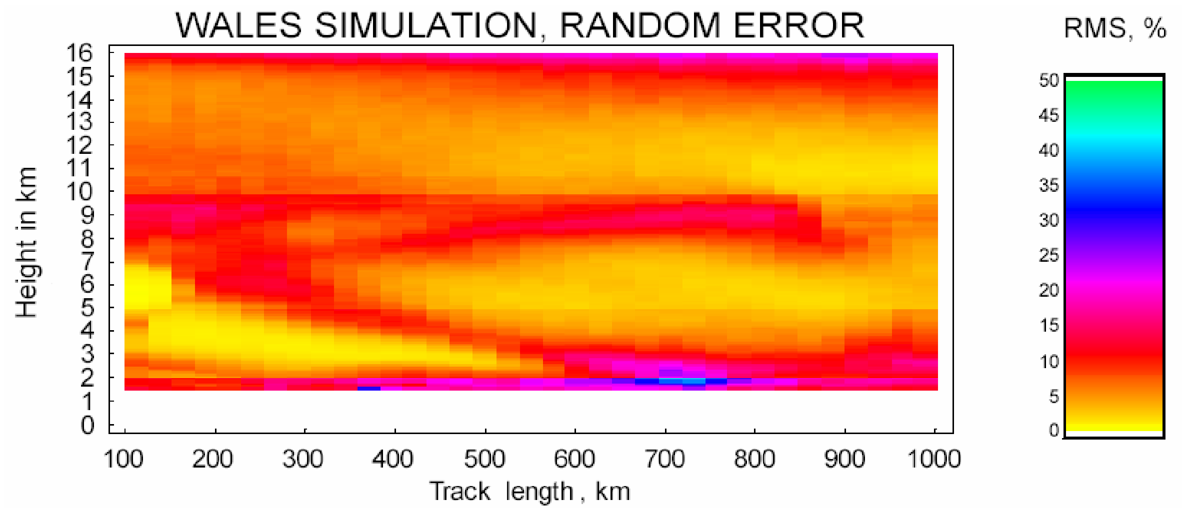


Mission performance

2D simulation of bias and random error from end-to-end model

Atmospheric field : DLR airborne DIAL and MM5

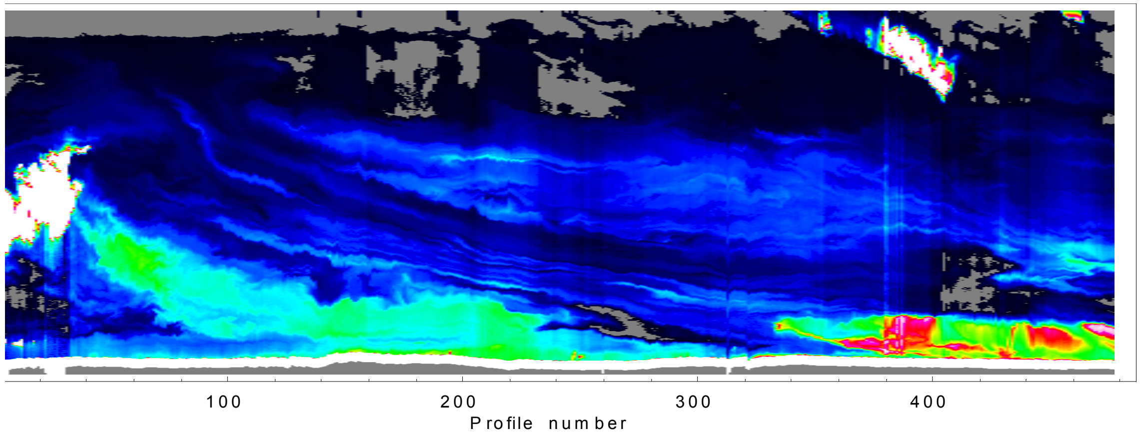




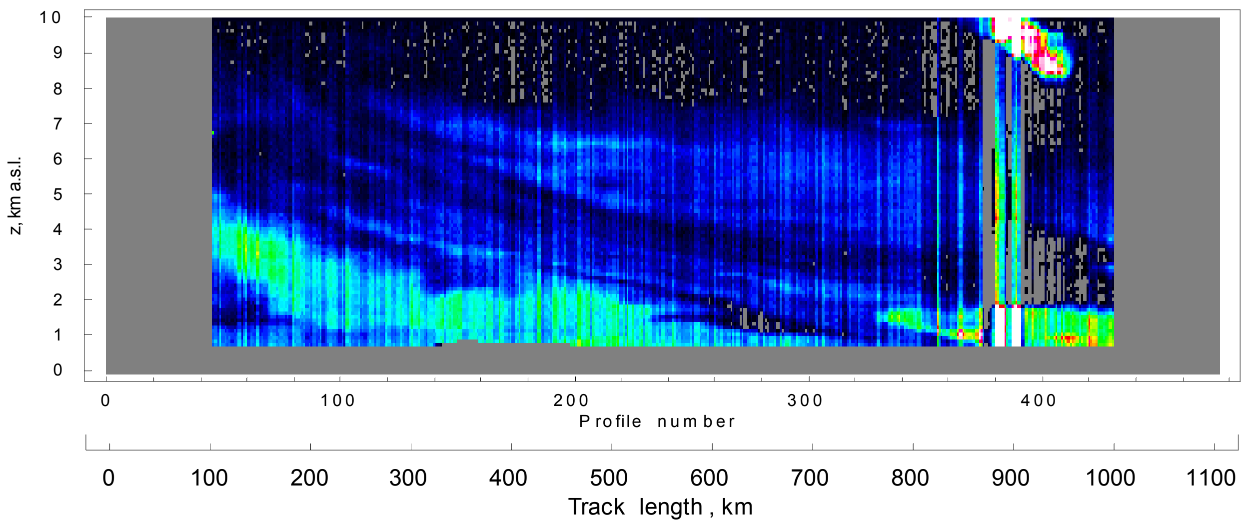
Mission performance

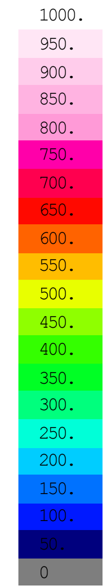
Particle backscatter: 2D simulation

Original DLR Falcon particle backscatter field



WALES simulation, 25 km hor. res.





Particle Back. Coeff., 10^{-9}/(m sr)

Mission performance

Systematic error budget

Contributors	Comment	Mean BIAS up to 14 km	Standard deviation of the BIAS up to 14 km
Frequency stability	considering 60 MHz laser detuning	1.2 %	1.1 %
Line-width	considering 160 MHz laser linewidth	1.2 %	0.9 %
Spectral purity	considering 99.9 % laser spectral purity	1.0 %	1.0 %
H_2O Spectroscopy knowledge	considering 2 % uncertainty on vapour vapour spectroscopy	2 %	2 %
Temperature knowledge	considering 2 K temperature uncertainty	1.1 %	0.4 %
Rayleigh-Doppler broadening effect	Corrected through an iterative approach, assuming an error of 30 % on lidar ratio	0.4 % clear air, 0.5 % in clouds	0.3 % clear air, 0.4 % in clouds
Application of non-linear operators		0.4 %	0.9 %
Overall BIAS		**3.1 %**	

Pure Rotational Raman lidar measurements of atmospheric temperature from space

Analytical model simulations

$$\Delta T(z) = \frac{\partial T(z)}{\partial R} R(z) \sqrt{\frac{P_{loJ}(z) + bk_{loJ}}{P_{loJ}^2(z)} + \frac{P_{hiJ}(z) + bk_{hiJ}}{P_{hiJ}^2(z)}}$$

Simulation using the residual laser power at 355 nm being left by the Nd:YAG laser source used in the WALES experiment.

P_{trasm}=30 W @ 355 nm

A_{tel}=2.4 m^2

FOV=105 μrad

Clear-sky performances:

Altitude range = 0-16 km

Horizontal Integration = 200 km

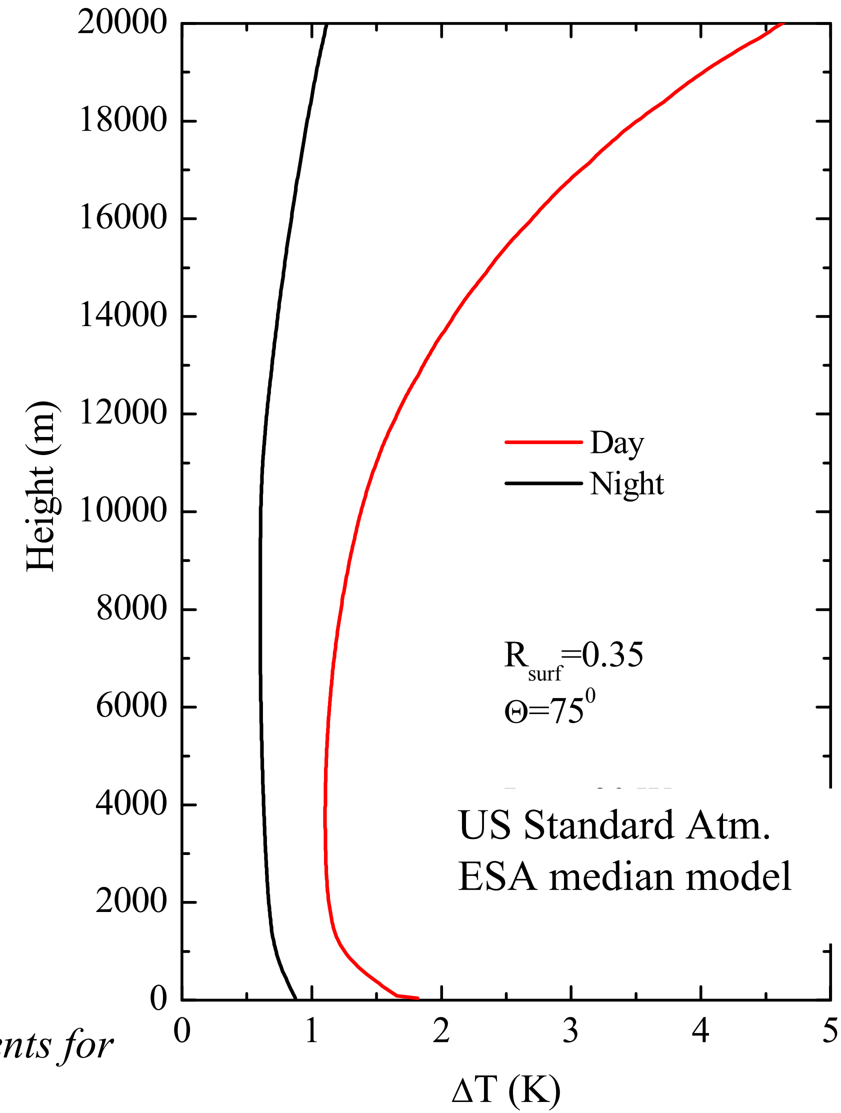
Vertical Resolution = 1 km

Precision throughout the troposphere

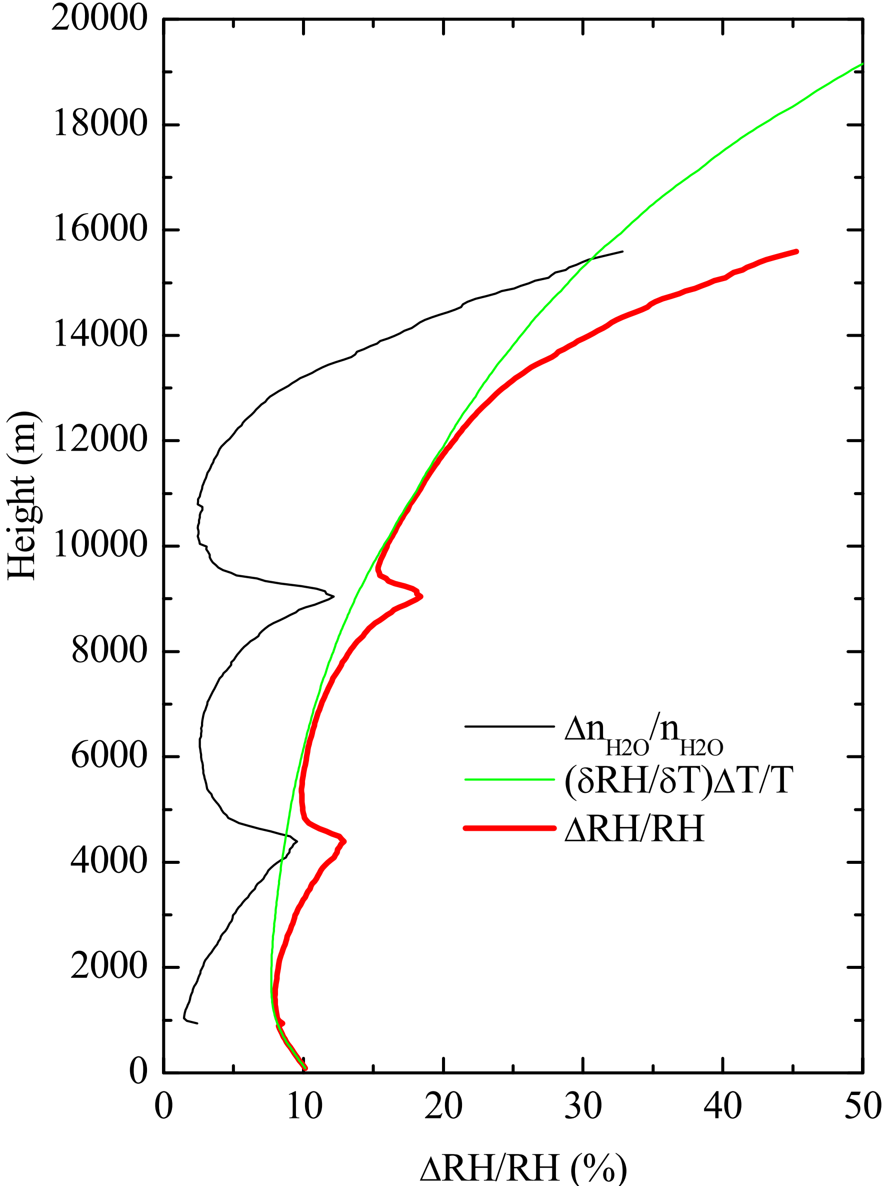
< **1 K (max precision 0.6 K) night**

< **2 K (max precision 1.2 K) day**

fulfilling WMO threshold observational requirements for most NWP and climate research applications



Lidar measurements of relative humidity from space



$$RH(z) = \frac{e(z)}{e_S(z)} = \frac{n_{H_2O}(z)kT(z)}{c \cdot \exp\left[\frac{a(T-273.15)}{T-273.15+b}\right]}$$

$$\Delta RH(z) = \sqrt{\left(\frac{\partial RH}{\partial n_{H_2O}}\right)^2 \Delta n_{H_2O}^2(z) + \left(\frac{\partial RH}{\partial T}\right)^2 \Delta T(z)}$$

$$\frac{\Delta RH(z)}{RH(z)} = \sqrt{\frac{\Delta n_{H_2O}^2(z)}{n_{H_2O}^2(z)} + \left(1 - \frac{abT}{T-273.15+b}\right)^2 \frac{\Delta T^2(z)}{T^2(z)}}$$

8 %<**ΔRH/RH**<45 %, 8<z< 16 km

max.precision in the PBL

mean random error = 11.3 % up to 10 km
mean random error = 16.6 % up to 16 km

Coarse characterization of cloud development processes, not accurate enough for cloud microphysical studies (particle nucleation, etc.).

Summary

End-to-end simulators may be used to size DIAL systems for space-borne, air-borne and ground-based applications.

An end-to-end model was successfully applied to simulate the performances of WALES

End-to-end simulations show that a space-borne DIAL systems with the specifications of WALES may:

- provide low bias (< 5 %) high precision measurements (random error<20 %) of the water vapour distribution throughout the troposphere with high vertical resolution, in clear sky conditions and in presence of clouds.
- provide accurate estimates of additional geophysical parameters as particle backscatter.

Analytical simulations of Rotational Raman lidar measurements of atmospheric temperature using the residual laser energy at 355 nm being left by the WALES transmitter show night-time precision throughout the troposphere better than 1 K and daytime precision better than 2 K.

Future work

- Inclusion in the simulator of additional atmospheric data sets coming from existing lidar systems to:
  - get a more complete and exhaustive assessment of the performances of WALES in variable atmospheric conditions and the effects associated with atmospheric inhomogeneities and variable cloud scenes.
- Modify the simulator to use it for sizing ground-based DIAL systems and to verify the feasibility of other space applications (CO_2, temperature)
- Development of an Observing System Simulation Experiment (OSSE)
  - To assess the impact of a WALES like system on NMP and Climate studies,
  - To test the benefit in term of NWP and climate research of assimilating data from a space-borne water vapour DIAL system into GCMs and smaller scale models.

Earth Observation Envelope Programme – 3

expected End 2004