AE-TN-KNMI-VAMP-ES

VAMP – Executive Summary

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1 Introduction

The mission objective of ADM-Aeolus is to provide global observations of wind profiles with a vertical and horizontal resolution and coverage satisfying requirements of the World Meteorological Organisation (WMO) [R1]. Accurate wind profile measurements over regions that are sparsely sampled today will help eliminating a major deficiency in the Global Observing System (GOS). The Aeolus mission will demonstrate the impact of these data on operational weather forecasting and on climate research [R2]. Aeolus is a prototype for future operational wind satellites.

The objective of the ADM-Aeolus study Vertical Aeolus Measurement Positioning (VAMP) is to consider the atmospheric dynamical and optical characteristics and their interaction with the ADM-Aeolus measurement system in order to optimize the user benefit of the Aeolus Doppler Wind Lidar (DWL) system. We conclude here with a recommendation for the operation of the instrument spatial and temporal sampling, providing maximum mission benefit.

The VAMP study sets out to explore optional vertical sampling scenarios for Aeolus. The main focus is on heterogeneous atmospheric scenes with large dynamical and optical variability. The quality and coverage of Aeolus winds in such scenes is investigated for a number of proposed sampling scenarios. As a second step, the impact of Aeolus measurements on NWP is estimated for the proposed sampling scenarios taking into account that different climate zones may yield a different optimal sampling. The following tasks have been performed to meet the study objectives:

- Give an overview of the Aeolus instrument operation, commanding and calibration constraints relevant to the spatial and temporal sampling and impact on the L2B data assimilation;
- Map the frequency of occurrence of spatially unrepresentative winds due to strong vertical wind gradients and convective updrafts as a function of height and climate zone;
- Map the frequency of occurrence of strong wind shear or turbulence in combination with strong extinction or backscatter variability;
- Map the frequency of Mie backscatter contamination in the potential upper Rayleigh-only gates, and of lower level range gates where insufficient Mie measurement information is available, e.g. the stratosphere;
- Quantify the quality of the retrieved Horizontal Line-of-Sight (HLOS) winds for Mie only, Rayleigh only (potentially contaminated with Mie scattering) and collocated Mie and Rayleigh (Mie contamination can be corrected for) sampling;
- Investigate the utilization of the Mie core algorithm outputs as quality indicators for Mie channel winds. This may impact the quality of collocated Rayleigh winds as well;
- Quantify the impact of the different vertical sampling scenarios for NWP and for the analysis of stratospheric winds;

2 Documents

Both applicable and reference documents are provided below.

2.1 Applicable documents

	Document	Issue	Title
[A1]	*AE-TN-KNMI-VAMP-001*	1.3	Vertical Aeolus Measurement Positioning - Constraints
[A2]	*AE-TN-KNMI-VAMP-002*	7	Assessment of Optical and Dynamical Atmospheric Heterogeneity
[A3]	*AE-TN-KNMI-VAMP-003*	1.3	Quantification of the L2B HLOS winds accuracies for typical wind shear, aerosol and cloud conditions
[A4]	*AE-TN-KNMI-VAMP-004*	4	Selection and Possible Redefinition of Aeolus Sampling Scenarios for Use in NWP Model Simulation Experiments
[A5]	*AE-TN-KNMI-VAMP-005*	1,0	Impact of Vertical Sampling Scenarios on NWP and on the stratospheric wind analysis

2.2 Reference documents

[R1] ADM-Aeolus Science Report (2007), *ESA-SP 1311*, 121p.

[R2] Stoffelen, A., Pailleux, J.,Källén, E.,Vaughan J.M., Isaksen, L., Flamant, P.,Wergen, W.,Andersson, E.,Schyberg, H.,Culoma, A.,Meynart, R.,Endemann, M., and Ingmann, P. (2005), The Atmospheric Dynamics Mission for Global Wind Field Measurements, BAMS, 86 (1), 73-87.

[R3] The definition of an atmospheric database for ADM-Aeolus (2010), G. J. Marseille, K.Houchi, J. de Kloe, and A. Stoffelen, submitted to AMT.

[R4] Comparison of Wind and Wind-Shear Climatologies Derived from High-Resolution Radiosondes and the ECMWF Model (2010), Houchi, K., Stoffelen, A., Marseille, G.J. de Kloe, J. *J. Geophys. Res.* (accepted for publication)

[R5] On the accuracy and quality control of high-resolution radiosonde wind observations for various wind-finding systems (2010), Karim Houchi, Ad Stoffelen, Gert-Jan Marseille, Jos De Kloe, submitted to *J. Geophys. Res.*

[R6] Stoffelen, A., Flamant, P., Håkansson, M., Källén, E., Marseille, G.J., Pailleux, J., Schyberg, H., Vaughan, M. (2002), MERCI - Measurement Error Correlation Impact on the Atmospheric Dynamics Mission, *KNMI scientific report*, WR-2002-08.

[R7] Tan, D.H., E. Andersson, M. Fisher, and L. Isaksen (2007), Observing-system impact assessment using a data assimilation ensemble technique: application to the ADM-Aeolus wind profiling mission, *Quart. J. Roy. Meteor. Soc.*, 133, 381-390.

[R8] Ad Stoffelen, Gert-Jan Marseille, Karim Houchi, Jos de Kloe, Otto Hooghoudt, Heiner Körnich, Harald Schyberg (2010), ADM-AEOLUS VERTICAL SAMPLING, 10th International Winds Workshop, Tokyo, Japan, 20-26 February 2010

[R9] Poole, L.R. and Pitts, M.C., (1994) Polar stratospheric cloud climatology based on Stratospheric Aerosol Measurement II observations from 1978 to 1989, JGR vol. 99, No D6, pp. 13083-13089, doi:10.1029/94JD00411

Acronyms

ADM	(ESA's Core Earth Explorer) Atmospheric Dynamics Mission
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
DWL	Doppler Wind Lidar
E2S	End-to-End Simulator
ECMWF	European Centre for Medium-range Weather Forecasts
EnDA	Ensemble Data Assimilation technique
ESA	European Space Agency
GOS	Global Observing System
HLOS	Horizontal Line of Sight
L1B	Level 1B
L2B	Level 2B
LIDAR	LIght Detection And Ranging
LIPAS	Lidar Performance Analysis Simulation
LOS	Line-of-Sight
NWP	Numerical Weather Prediction
MERCI	Measurement Error Correlation Impact
PBL	Planetary Boundary Layer
PSC	Polar Stratospheric Cloud
SNR	Signal-to-Noise Ratio
TN	Technical Note
UKMO	United Kingdom Meteorological Office
UTLS	Upper Troposphere - Lower Stratosphere
VAMP	Vertical Aeolus Measurement Positioning
WMO	World Meteorological Organization

3 Instrument operation, commanding and calibration constraints

[A1] provides a detailed overview of the Aeolus instrument operation, commanding, requirements and calibration constraints. These specifications serve as input for the definition of an ensemble of optional vertical sampling scenarios that are further investigated. Vertical sampling scenario in this document refers to the vertical distribution of the 24 bins of the Rayleigh (molecular) channel and Mie (particle) channel, i.e., the respective bin altitude and bin size. Here, the most prominent constraints for the distribution of the bins of these two channels are summarized.

- The mission requirement on the standard deviation of HLOS random wind errors (not including the representativeness error and for a standard reference atmosphere) is 1, 2 and 3 ms^{-1} for the PBL (below 2km), free troposphere (2-16 km) and lower stratosphere (above 16 km), respectively. Aeolus is limited to 24 vertical range bins for both the Fabry-Perot (FP), also denoted Rayleigh channel, and the Fizeau (Fz) spectrometer, also denoted Mie channel. Bin sizes must be multiples of 250 m with a maximum of 2 km;

- Range bins should be large enough to yield sufficient signal (so a good SNR) for good quality HLOS winds. Clouds and aerosols generally yield sufficient signal even for the smallest (250 m) Mie range bins, while Rayleigh bins should be larger than 1 km size. Due to the large heterogeneity of the atmosphere, Mie oversampling results in improved wind profiles due to improved height assignment;

- An exact match of Mie and Rayleigh bins is not possible. At least one Mie range bin below the lowest Rayleigh range bin is required;

- The maximum allowed altitude for the upper range bin is related to the maximum sampling range of 40 km along the laser LOS and the local incidence angle of about 37.5 degrees yielding a maximum vertical range of about 32 km

- The maximum altitude difference between the Rayleigh and Mie channel is 16 km;

- There are 8 switching moments on average per orbit. Since we have 109 orbits per week, this leads to 8*109 = 872 switching moments that may be pre-programmed along the orbits of one week. This table holds the switching definition for 3 weeks, will be uploaded once a week, and must be available 1 week before the actual upload takes place;

- Wind calibration in off-nadir geometry corrects for slowly changing mispointing errors along the orbit. This calibration can be combined with the wind vector measuring mode, provided that a ground echo is measured. This calibration should yield a number of results per orbit high enough to correct for the bias caused by these errors (zero wind calibration through harmonic bias estimation). Current status is that better ground returns are obtained from the Mie than from the Rayleigh channel. For calibration in wind vector measuring mode, at least the lowest Mie bin needs to contain the ground. Rayleigh range bins do not need to reach the ground. Rayleigh channel calibration is foreseen through cross calibration with the Mie channel in the upper part of the PBL with relatively small but sufficient aerosol loading.

- Rayleigh range bins should have precisely overlapping Mie range bins, at least at levels where cloud and aerosol layers occur, to enable cross-talk correction of the Rayleigh signals.

Based on these constraints 10 vertical sampling scenarios were defined in section 6.4 of [A1] and visualized in the Appendix. An additional stratospheric scenario was defined in section 6.5 of [A1] with maximum Rayleigh coverage in the stratosphere extending to 36.5 km altitude, thus violating the maximum altitude requirement of 31.73 km for Aeolus. This scenario is merely to test the impact of additional wind measurements in the stratosphere for an improved description of the stratospheric flow as further evaluated in section 66.

4 Atmospheric heterogeneity

Most of the free troposphere and stratosphere are (almost) free of particles. The Rayleigh channel is then the primary source for wind retrieval by Aeolus. The Rayleigh channel bin size is selected such that retrieved winds meet the mission requirement in these areas. For Rayleigh bins the SNR is directly related to the molecular density that decreases exponentially with altitude. Between 16 and 28 km above mean sea level, range bins of at least 1.5 km are required. Above 28 km, 2 km range bins are required. Below 16 km a minimum 1 km bin size is needed. Cross-talk contamination of Mie signal in the Rayleigh channel is negligible in regions of small aerosol (background aerosol) presence. The typical scattering ratio of background aerosol is below 1.03 [A2]. The resulting bias in Rayleigh channel LOS winds is a function of temperature, giving maximum biases in the stratosphere of about 0.05 ms^{-1}, about 0.02 ms^{-1} in the mid-troposphere and smaller than 0.02 ms^{-1} biases in the PBL [A3].

Rayleigh channel shortcomings are filled in by the Mie channel. About 70% of the earth surface is obscured by clouds, located at different heights and with varying optical thickness. Rayleigh signal extinction in the PBL through aerosol scattering and cross-talk contamination reduces the quality of Rayleigh PBL winds substantially. Thus wind estimates from the Mie channel are needed to retrieve full good-quality wind profiles. Moreover, the Mie channel appears the most favorable candidate for zero-wind calibration. In areas of enhanced aerosol density the Mie channel signal may be sufficient for wind retrieval, wind cross-channel calibration, and/or can be used for cross-talk correction.

The most challenging scenes are those with both relatively large wind and optical variability within one measurement bin. The Mie and Rayleigh channel will both provide a wind estimate that may be very different depending on the location, backscatter and extinction of the particle layer(s) and the wind-shear characteristics within the bin. A possible solution to increase the representativeness of retrieved winds for these scenes is to increase the resolution of the Mie channel to better detect the location of the particle layer(s). Otherwise it is important to be able to detect these scenes from the measurements and to give the retrieved winds less weight in the NWP data assimilation process.

The occurrence of clouds and elevated aerosol layers and their optical properties are a main driver for the vertical distribution of the Mie channel bins. This is true in particular in combination with large atmospheric dynamical variability. Both dynamical and optical variability can be described as a function of climate zone and season. ECMWF model winds were used to generate occurrence statistics of large vertical wind-shear events as well as of up- and downdrafts as a function of altitude, geographical location and season [A2, R3]. The focus was on data void wind profile regions in the current global observing system where maximum impact of ADM-Aeolus is expected. These regions are the stratosphere and the tropospheric Northern Hemisphere oceans (NHO) including the North Pole, Tropics (TR) and Southern Hemisphere (SH). Typical (mean global) values for the wind-shear in the troposphere and lower stratosphere is about 0.004 s^{-1} (i.e., 4 ms^{-1} per km) for the vector wind and 0.0028 s^{-1} for the HLOS wind component, but these values show substantial variability with season, geographic location and altitude [A2]. The occurrence of large wind-shear (exceeding 0.01 s^{-1}) is generally small in the PBL (between the surface and 3 km) and lower troposphere (3-7 km) for all NHO, TR and SH. Only some parts of the SH show occurrence rates of about 50%. The occurrence is substantially larger in the upper troposphere (7-15 km), in particular in the Tropics, subtropics and mid-latitudes. Large occurrence is also found in the UTLS (15-22 km), but limited to the Sub-Tropics and Tropics. In the stratosphere (22-30 km) large occurrence is limited to the tropical region. Most heterogeneous regions were found near the tropopause height. The locations of maximum occurrence shift from the Northern to the Southern Hemisphere with changing seasons.

Current global models tend to underestimate i) the wind variability on horizontal scales smaller than 150 km, ii) the wind variability on vertical scales smaller than 2 km [R4] and iii) the up- and downdrafts (vertical motion). This is due to their smoothness and imposed hydrostatic balance. Also, strong wind shears on top of stabilized boundary layers are underestimated by global NWP models.

To address the shortcomings of the ECMWF model winds, a database of High-resolution (Hi-Res) radiosondes was generated from data sets covering various regions of the globe. Wind (shear) statistics of these additional resources were compared with corresponding collocated ECMWF model statistics and show a 2-3 times smaller wind variability in ECMWF model winds as compared to Hi-Res radiosonde data. This translates to an effective vertical resolution of the ECMWF model of about 1.7 km [A2,R4], i.e., generally smaller than Aeolus' vertical resolution. To account for this effect in the simulations, model winds were adapted in a statistical way, i.e., such that the wind-shear statistics of the adapted model winds agree with Hi-Res radiosondes, but ignoring possible correlation with atmospheric optical structures [A2,R3].

Cloud resolving model (CRM) simulations in the tropics were performed where the vertical winds produced by CRM appeared realistic in scenes of tropical convection. It was found that the mean vertical wind visible along 50 km ADM tracks is generally negligible as compared to the horizontal wind. This included scenes of broken clouds and using classification to discriminate between particle and particle-free measurements. Local effects become more important in heterogeneous scenes and the vertical wind component may contribute substantially to the measured LOS wind, thus introducing biases in the HLOS wind.

To address the atmosphere optical variability an algorithm was developed to retrieve aerosol and cloud optical properties from CALIPSO level-1 attenuated backscatter at 3.5 km horizontal and 125 m vertical resolution, i.e., substantially higher than the typical 50 km horizontal and 1 km vertical resolution of Aeolus wind observations. This enables the simulation of Aeolus interaction with atmospheric processes at (sub-)measurement level. Four months for the year 2007 were investigated. The year 2007 was selected due to the availability of CALIPSO for that year. Statistics of occurrence of large optical variability showed maximum values in the PBL over all oceans. That is explained by the presence of low-level (stratus) clouds. Substantially less variability was found over the continents in the PBL, which is partly explained by a smaller cloud coverage over land due to more intense subsidence and inversion processes during the evening and night. The optical variability in the lower troposphere was small in the Tropics but substantial over the NH and SH mid-latitude regions. However, the occurrence of large vertical shear of the HLOS wind component in these regions at this altitude was small, in particular for the NH summer period (August 2007). In the upper troposphere the occurrence of large optical variability was more concentrated to the continents and parts of the mid-latitude-regions. However, the occurrence of large dynamical variability over the mid-latitudes was small. Opposite, the occurrence of large wind-shear was large in the subtropics, but the optical variability is small in this region, in particular over the oceans. In the subtropical high, the upper air generally descends leading to limited cloud occurrence and stable flow with relatively large shear. Optical variability in the UTLS is mainly limited to cirrus clouds in the Tropics and is mostly concentrated over the continents. Large dynamical variability was also found in these regions. Negligible optical variability was found in the stratosphere except over the South Pole that shows a small occurrence of Polar Stratospheric Clouds (PSC) in August 2007. PSCs over the North Pole in January 2007 were rare and their optical depth much smaller than over the South Pole. Antarctic PSCs are typically observed from mid-May to early November, with a maximum zonal average probability of about 0.6 at 18–20 km in August. The typical Arctic PSC season extends from late November to early March, with a peak zonal average probability of about 0.1 in early February at 20–22 km. There is considerable year-to-year variability in Arctic PSC sightings because of changes in the dynamics of the northern polar vortex. Year-to-year variability in Antarctic sightings is most prominent in the number of late season clouds [R9]. Whether January and August 2007 were typical w.r.t. PSC formation over the North and South Pole regions has not been investigated here. The analysis of the database of high-resolution radiosondes in [A2] shows that the general weather pattern in 2007 is not exceptional and compatible with other years. The 2007 Atlantic hurricane season was an active

Atlantic hurricane season, although not as active as the record 2005 and 2008 seasons. The 2007 season produced 17 tropical cyclones, 15 tropical storms, 6 hurricanes, and 2 major hurricanes[‡].

It is concluded that locations of large optical and dynamical variability are generally of some concern but not highly correlated over the oceans. The small occurrence rates of combined optical and dynamical (from ECMWF) variability with maximum values of about 5% near the tropical tropopause should be considered with care because of the underestimation of the dynamical variability by global models as discussed above. In addition it should be noted that the occurrence rates are based on monthly average statistics (for 4 months) rather than analyzing specific cases such as tropical cirrus, the North Atlantic storm-track region (shear on-top of low pressure systems), and hurricanes (shear on-top of hurricane cloud systems). A specific phenomenon may be averaged out in the large bulk statistics, but still be crucial for NWP. An example is found in [A3] where cross-talk cross correction of Rayleigh winds appeared not efficient on average but very efficient in regions of tropical cirrus clouds. The conclusion on optimized sampling scenarios must thus therefore also take these phenomena, which may be averaged out in monthly statistics, into account.

Adaptation of the model winds as discussed above increases the occurrence rate by a factor of 5-10 with maximum occurrence rates of 20-30% found near the tropopause in the mid-latitude and (sub-) tropical regions. Maximum correlation is found in the Tropical region, in particular over land. The general picture changes with season, following the displacement of the jet stream that is accompanied with strong wind-shear.

The definition of the Aeolus atmospheric data base of combined atmospheric optics (from CALIPSO) and dynamics (from ECMWF, interpolated to CALIPSO locations, and adapted based on Hi-Res radiosondes) is extensively discussed in [A2,R3].

5 HLOS wind quality quantification

The Aeolus atmospheric data base has been further used to quantify the quality of the retrieved HLOS winds for Mie only, Rayleigh only (potentially contaminated with Mie scattering) and collocated Mie and Rayleigh sampling for the ensemble of vertical sampling scenarios defined in [A1]. For the latter, Mie contamination of the Rayleigh channel signal can potentially be corrected for, the so-called cross-talk correction. The dedicated E2S for Aeolus hardware simulation turned out to be too time-consuming for a statistical analysis. Instead, the LIPAS tool was upgraded and verified to be compatible with the E2S-L1B-L2B chain, i.e., simulated winds of LIPAS are close to the latter.

Cross-talk contamination of Rayleigh channel winds is generally not a problem because despite the fact that 70% of the Earth's surface is obscured by cloud, most of the atmosphere (above or below transparent clouds) is (almost) free of particles. It was shown in [A3] that three conditions must apply at the same time to yield substantial biases in Rayleigh channel winds through cross-talk: i) low temperatures (below -20 degrees Celsius), ii) a substantial scattering ratio (larger than 2) and iii) a substantial wind velocity along the laser LOS (larger than 15 ms^{-1}). If either of these conditions does not apply, then the biases will be small, i.e., less than 0.4 ms^{-1} [A2]. For the positioning of the Mie bins one should therefore focus on regions for which all three conditions are most probable to occur and/or where high resolution wind data are needed.

For instance in the PBL the temperature will generally be above -20 °C so Rayleigh channel winds will generally not suffer from large biases through cross-talk, but mainly from extinction. Because a lot of dynamical and optical variability is found in the PBL, mainly over land, it will be hard to get good quality Rayleigh winds in the PBL. Yet, the main objective of ADM is to correct model winds on the synoptic scales rather than mesoscale, thus giving higher priority to tropospheric than PBL winds and priority to ocean coverage rather than land coverage. Given the surface observation network, that is

‡ source: National Hurricane Center, Wikipedia

much denser than the upper air network in all areas, Aeolus PBL observations are expected to be most valuable near the top of the PBL. In the PBL, particularly, near the surface, both the amplitude and the direction of the wind changes, and, combined with the large aerosol variability, it will be very hard to measure representative PBL winds. PBL rolls are particularly expected to have correlated wind and aerosol variability.

A potential valuable region for ADM to measure is the tropopause region (including the jet stream) that shows relatively large dynamical and optical variability. In [A3] the tropical region between 10 and 20 km was more thoroughly investigated in this light. This region is characterized by large cirrus cloud coverage with a mean scattering ratio value of about 4. The mean temperature is about -60 degrees Celsius and the mean zonal wind is close to zero, with +/- 15 ms^{-1} spread. The wind-shear is not excessively high with values between 0.002-0.004 s^{-1} for the HLOS wind. It was found that increasing the resolution of the Mie channel in this region yields an increased data coverage and better quality winds for both Mie and Rayleigh channels. Cross-talk correction appears efficient, reducing the biases in Rayleigh channel winds by about 50% but at the expense of an about 50% increase of the error standard deviation [A3], although the latter is generally still within the mission requirement.

Scenario wvm2_1km (see Appendix) focuses on the lower part of the atmosphere with a high resolution Mie channel in the lowest 5.5 km; 8 bins of size 250 m in the lowest 1.75 km (with 1 Mie bin below the surface to meet the calibration constraint) and 8 bins of 500 m size from 1.75-5.75 km. (The _1km in the scenario names refers to scenarios with Rayleigh channel bin sizes of at least 1 km). This scenario is the most favorable scenario for data coverage. The dedicated extra-tropical tropopause scenario wvm_et_zwc2_1km with an increased resolution of the Mie channel near the extra-tropical tropopause height (500 m bin size between 6 and 11.5 km) has maximum data coverage in this specific region. (The _zwcN_ in the scenario names refers to scenarios with at least 1 Mie channel bin below the surface to meet the calibration constraint as opposed to the _nozwcN_ scenarios. The additional N-value equals 1 or 2 referring to the different scenario variants). The same is true for the dedicated tropical tropopause scenario wvm_tr_zwc2_1km with an increased resolution of the Mie channel near the tropical tropopause height (500 m bin size between 10 and 17.5 km). The (extra-) tropical UTLS, including the jet, has been identified as a target region for Aeolus. Scenarios wvm_et_zwc2_1km and wvm_tr_zwc2_1km appear favorable in this respect when applied to their specific climate zones.

Data coverage and quality are not the only measures to address the information content of Aeolus winds. The use of observations in data assimilation is of at least equal importance. NWP impact of Aeolus winds is discussed in the next section.

6 NWP impact

The use of observations through data assimilation in NWP models, more specifically their degree of positive impact on the forecasts after data assimilation, is probably the most important criterion to judge to added value of observing systems. Two methodologies have been considered: a theoretical assessment based on the analytical analysis equations and an experimental assessment using the Ensemble Data Assimilation technique (EnDA) with the ECMWF model.

6.1 Theoretical tool

The theoretical tool builds on earlier work of the MERCI project [R6] and aims at quantifying the information content of observations in the analysis, i.e., the resulting forecast initial state after data assimilation. Information content of observations should be seen in the context of the other information already available in an assimilation system that is the first guess field from the NWP model. An optimal observing system adds information which is not already present in the first guess field, therefore knowledge of the background errors in the NWP model is crucial in an information content concept to be used for studying various sampling scenarios.

This tool is based upon analyzing average information content of various vertical sampling scenarios in a univariate simplified vertical one-dimensional assimilation system. Such a system does not capture some effects of real NWP systems such as situation dependence of impact and also coupling between horizontal and vertical background error correlations as well as between wind and mass field variables. Nevertheless, it can still give a valuable assessment of the effects of realistic vertical error distribution in NWP systems as well as of corresponding vertical background error correlations. This includes for instance the impact of the vertical distribution of NWP model errors, and the effect of variations between shallowness and deepness of background error structures between latitude zones.

The information content of observations is quantified from the theoretical analysis equations. These relate the analysis error covariance matrix (***A***) to the background error covariance matrix (***B***) and the observation error covariance matrix (***O***). The latter is different for different Aeolus vertical sampling scenarios and takes into account the lack of absolute calibration applicable for some scenarios. The level of decrease of ***A*** relative to ***B*** can be diagnosed with various mathematical expressions which measure the information content of the observations and thus of the sampling scenarios [A5].

A natural ingredient in the assessment is to use the knowledge already available about the vertical distribution of errors in actual NWP models in operational use and about the corresponding vertical background error correlations. These errors are in NWP systems specified as a part of the error covariance matrix used in the assimilation system. These error covariance matrices can be derived in several ways, but are expressions of what is believed to be the best available knowledge of the error magnitudes and structures. Characteristics of the background error have been determined for the ECMWF global model and the limited-area HARMONIE meso-scale model for various seasons and climate zones. This includes the vertical correlation depth of model background error structures that may be very different for different model types (global/meso-scale). The correlation depths for the ECMWF and HARMONIE model typically ranges from 500 m in the PBL to 2500 m in the stratosphere with a local maximum of 1500 m near the tropopause.

The main conclusions from the theoretical tool are:

- The information content of scenarios increases substantially with the ability of absolute calibration (that may be done by either ground calibration or NWP bias correction);
- The ECMWF ***B*** matrix vertical structure shows very little variation north of 45N. Differences are more substantial from 45N to the equator. However, these differences do not show a strong justification for switching sampling scenarios according to latitude band.
- Scenarios with dense Mie sampling in the lower troposphere give better scores than with dense sampling in the upper troposphere when assuming uncorrelated observation errors. This is a bit surprising since background errors are larger at the jet level, and the reason is probably that observations become more complementary to the background because the background error vertical covariance structures extend over more model levels near the surface than at UTLS levels.
- Introducing more realistic (but probably overestimated in the current implementation) vertically correlated observation representativeness errors reduces the information content of Aeolus winds for all scenarios but relatively less for the scenarios with dense sampling in the troposphere.
- It seems more beneficial to sample the troposphere well than the stratosphere, probably due to both lower background wind errors and more shallow background error structures (relative to NWP model sampling) in the stratosphere.

Based on these conclusions the following scenarios show indications of being the most informative: wvm2_1km with dense Mie sampling in the lower troposphere, the extra-tropical scenario wvm_et_zwc1_1km and the tropical scenario wvm_tr_zwc1_1km both with relatively coarse sampling in the UTLS. In addition, for the ECMWF ***B*** matrix, the extra-tropical scenario performs better in the extra-tropics than the tropical scenario and vice versa the tropical scenario performs better in the tropics than the extra-tropical scenario. The scenario definitions are found in the appendix.

6.2 Ensemble Data Assimilation experiments

In addition to the theoretical tool above, comprehensive assimilation experiments have been performed with the operational ECMWF model system. These so-called Ensemble Data Assimilation (EnDA) experiments use real observations from all available observing systems and simulated observations from the future instrument under investigation; Aeolus in our case with different sampling scenarios. For each scenario an ensemble of 10 parallel data assimilation cycles with perturbed observations are performed. The applied observation perturbation causes the different members' analyses and forecasts to diverge from each other. This ensemble spread is used as a measure for the analysis error. Observation information content is expected to improve the forecast quality thus reducing the ensemble forecast spread. The sampling scenario with the largest information content produces the strongest reduction in ensemble forecast spread. More details are found in [A5].

The simulation of Aeolus HLOS winds requires a representation of the (inherently unknown) true atmosphere, both concerning winds and aerosol concentration. For the latter, CALIPSO data is used. For the wind data, UKMO short-range forecasts were chosen and it is assumed that its difference to the ECMWF first guess is comparable to the difference between real Aeolus observations and the ECMWF first guess. For the experiments the period January 2007 was selected because of the availability of CALIPSO data for this period. UKMO model field parameters were interpolated to the CALIPSO orbit and LIPAS used to simulate Aeolus burst mode HLOS wind profiles including random instrument errors and biases through cross-talk and/or incorrect knowledge of aerosol layers in the measurement bins. In addition LIPAS provides an estimate of the observation representativeness error.

The main focus in the experiments is on the stratospheric flow and the troposphere-stratosphere coupling. This answers to one of the recommendations from the Aeolus Workshop in 2006. In the summer Southern Hemisphere (SH) planetary waves hardly propagate vertically leaving the summer stratosphere mainly undisturbed. The coupling between the troposphere and stratosphere is strongest during winter and spring in the Northern Hemisphere, where both topography and land-sea contrasts as well as the strength of the winter storm tracks play an important role. Thus special interest lies on the Northern Hemisphere (NH) in January. Singular vector propagation studies show that the troposphere-to-stratosphere exchange is much larger than vice versa [R8]. Considering also that the HLOS wind quality drops with increasing altitude an interesting question is how to optimally improve the stratospheric flow with Aeolus, either by i) a relatively dense vertical sampling in the troposphere, thus improving the tropospheric flow and implicitly the stratospheric flow through the troposphere-stratosphere coupling or ii) explicitly through a relatively dense and more extended vertical sampling of the stratosphere.

EnDA experiments are computationally intensive and thus only a limited amount of ADM experiments could be performed. These include scenarios wvm2_1km with dense Mie sampling in the lower troposphere, the extra-tropical scenario wvm2_et_zwc2_1km with dense sampling in the mid-latitude UTLS and the stratospheric scenario wvm_stratos_nozwc_1km with maximum data coverage in the stratosphere. This selection was the result of a list of arguments discussed in [A4] and based on results from [A1,A2,A3]. A further experiment was conducted in order to estimate the impact of radiosondes and wind profilers. This impact serves as a reference to the impact of the simulated Aeolus HLOS winds.

It was found that Aeolus impact is comparable to radiosonde impact on average, in agreement with earlier results by Tan et al. (2007). Largest impact occurs in NH high latitudes, in the tropics and over the oceans. As only CALIPSO nighttime data during boreal winter was used here, the southern hemispheric impact was underestimated in the experiments presented. Furthermore, it has to be kept in mind that the simulations were done for the month of January 2007 only. It has not been further investigated here whether this month was a typical winter case, representative of a multi-year, multi month (December, January, February) average containing both typical and extreme storm cases. However, as mentioned above, the 2007 winter weather pattern is representative for a multi-year period.

Information by the simulated ADM observations propagated vertically owing to the dynamical coupling between the troposphere and the stratosphere. On the shorter forecast range up to three days, divergent motion transported impact from the upper troposphere to the middle and upper stratosphere. This fast propagation is probably associated with gravity waves. On the longer forecast times between four and six days, vertically propagating impact was connected to the large-scale planetary waves, with mainly rotational motion and a characteristic westward phase tilt with height. On the longest performed forecasts up to ten days, a downward feedback from the stratosphere onto the tropospheric impact could be observed. However, as the impact displays strongly alternating signs and as one experiment shows degraded impact in spite of an increased number of observations, a larger ensemble and longer time series would be useful to consolidate the results for the longest forecast times.

Besides the missing southern hemispheric observations and extension of the statistics, further shortcomings of the present study are biases of the simulated observations in the stratosphere and the neglected vertical correlation between neighbouring observations that induces correlation of the spatial representativeness error. Interactions with other observing systems can also produce difficulties in comparing different experiments, as different observations might be rejected during the assimilation process. This has not been further investigated.

In order to assess the importance of cross-talk correction of the Rayleigh channel winds, the scenario wvm2_et_zwc2_1km was applied in two experiments with two different options in LIPAS, either only signals from Rayleigh bin measurements classified as particle-free are accumulated, or a perfect cross-talk correction is assumed. The total HLOS wind data coverage for the perfect cross-talk correction is 2.3% larger than for the alternative option. Indeed, the increase in observation number does lead to a reduced forecast spread in the troposphere and lower stratosphere up to 30 hPa for short-term forecasts up to 2 days However, an increased forecast spread is found for 7-10 day forecasts that is not fully understood at this stage but most probably statistically insignificant. Also, it is not clear how the data assimilation system deals with different, but assumed good quality, observations at a single location. For instance in scenes with strong optical variations and large wind-shear the Mie and Rayleigh winds may differ substantially, e.g. on top of tropical cirrus [A3]. This situation may occur in the cross-talk correction experiment. Superobbing by averaging both winds yields a poor wind. Data thinning by selecting one or the other might yield a good or bad wind, depending on the choice made. Data rejection statistics could be used to check the used strategy of the assimilation system and/or its preference for equally located Mie or Rayleigh winds. This has not been investigated.

Based on the EnDA results, the recommendation for the operation mode of ADM-Aeolus can be summarized as follows: For winter in high-latitudes, wvm2_1km performs best, for subtropical winter and tropics wvm-et-zwc2_1km is recommended. For winter in midlatitudes the stratospheric sampling scenario is optimizing the impact. From the possible scenarios of Aeolus, the scenario wvm2_1km optimizes the tropospheric forecast, while the scenario wvm_et-zwc2_1km provides the best stratospheric forecast. In the southern hemisphere summer, wvm2_1km yields generally best impact.

7 Conclusions

The Rayleigh channel bin size is defined by the mission requirement to retrieve HLOS winds with a prescribed quality and by the possible height ranges. Trade-off possibilities for the Rayleigh channel bin size are therefore limited. A minimum Rayleigh bin size of 1000 m is needed in the lower troposphere (with maximum molecular density) to meet the mission requirement. The Rayleigh bin size has to increase with altitude due to the exponential decay of the atmosphere molecular density. The distribution of the Rayleigh channel bins is similar for all proposed scenarios, with the main difference in the position of the lowest bin, i.e., either including or excluding the ground return (for possible Rayleigh channel wind calibration).

Absolute wind calibration improves the Aeolus wind information content substantially. Zero wind calibration is still under study by the L1B team but current knowledge favors Mie channel calibration and cross-calibration of the Rayleigh channel with the Mie channel. These scenarios are annotated as “zwc” here. Alternatively, in case of a stable Aeolus instrument calibration, zero-wind calibration may be attempted by cross-calibrating against a NWP model over many profiles (bias correction). In that case the annotated “nozwc” calibration profilers are preferable. Over the ocean, zero-wind calibration appears unfeasible, i.e., less attractive than NWP bias correction.

Increasing the Mie channel resolution in heterogeneous atmospheric regions of large dynamical and optical variability improves the representativeness of both Mie and, to a lesser extent, Rayleigh channel winds through reduced height assignment errors. As a consequence the wind data coverage is increased in these regions. This is the case for instance near the tropopause where the jet stream resides. An improved characterization of the jet stream is important for better forecasting the location of cyclogenesis.

The theoretical tool shows that most of the impact is obtained near the tropopause. The impact increases when going from the surface to the tropopause and then reduces substantially in the stratosphere. The latter is explained by the small background errors and reduced quality of HLOS winds in the stratosphere. A weakness of the current implementation of the theoretical tool is the assumption of a perfect calibration capability for the “zwc” scenarios. As mentioned in [A1] zero wind calibration (ZWC) is under study but current knowledge shows that ZWC can most likely not be performed over the oceans, with the exception of ice sheets, and is limited to snow, desert and dry regions over land. This finding limits the information content of the “zwc” scenarios substantially to the same level as the “nozwc” scenarios.

The theoretical tool also reveals that the treatment of error correlation is important for the scenario ranking. Ignoring error correlation of (vertically) closely spaced winds yields a good ranking of scenarios with dense Mie winds in the lower troposphere (including the PBL). This is mainly explained through larger data coverage for these scenarios. Taking into account error correlation substantially reduces the ranking of scenarios with dense Mie sampling in the lower troposphere. Yet, maximum information content is obtained for scenarios with relatively dense Mie sampling in the lower troposphere rather than a relatively dense Mie sampling in the UTLS. This may be explained by the deepening of background error structures (relative to NWP model sampling) near the surface. Also the theoretical tool does not explicitly takes into account height assignment errors of optically dense clouds that are mainly found in the lower part of the troposphere.

The EnDA experiments show that a dense Mie sampling is preferred in the lower troposphere in the winter polar region. Moving the dense Mie sampling higher up from the surface to the tropopause is favorable for the winter subtropics and tropics probably by an improved characterization of the subtropical jet. In the mid-latitude region the sampling decision depends on the focus region. For an improved characterization of the stratospheric flow, the sampling of the UTLS is beneficial, i.e., better than directly sampling the stratosphere. This is explained by the dynamical coupling between the troposphere and the stratosphere and the vertical propagation of Aeolus wind information. Lower troposphere sampling provides best impact in the troposphere.

A limitation of the EnDA experiments is neglecting the error correlation of (vertically) closely spaced Aeolus winds. This is true in particular for scenario wvm2. The Mie winds get too much weight in the PBL for this scenario. In operational practice this would result in negative impacts because current NWP models can not resolve small-scale PBL structures such as rolls that are observed by the observing system, for instance the weight of scatterometer winds in the analysis is reduced artificially for this reason. This negative impact is not found in EnDA because the small-scale structures are not simulated in the observations because the artificial true atmosphere is obtained from another NWP model (UKMO in our case) that also does not resolve these small scales. The EnDA system is therefore not penalized for ignoring the error correlation of closely spaced observations. The theoretical tool showed that a correct treatment of error correlations substantially impacts the data information content and subsequent scenario ranking. The generally high ranked scenario wvm2 in EnDA is therefore expected to be less beneficial in operational practice.

Synthesizing the results from all the tasks and taking into account current knowledge on the ZWC capability of Aeolus and the optimal use of observations with correlated errors in NWP systems we recommend the following strategy for operating the vertical sampling of Aeolus:

- Sampling of the UTLS is important, yielding maximum analysis improvement as compared to other altitudes. The resolution of the Mie channel seems of less relevance, but height assignment errors as found in heterogeneous scenes in [A2] have been underestimated in the theoretical tool and EnDA [A5], through an underestimation of model wind-shear.
- Sampling the troposphere is more important than sampling the stratosphere for an improved characterization of the tropospheric and stratospheric flow. The extratropical “zwc1” scenarios benefit from the dense Mie sampling in the lower troposphere, which appeared beneficial in this study.
- Very high (250 m) Mie bin size yields redundant Mie winds (large error correlation) and therefore reduced information content.
- The zwc2 scenarios have limited Mie sampling (and thus data coverage) in the lower troposphere and are therefore less attractive (see above item).
- The extra-tropical and tropical scenarios have dense Mie sampling in the UTLS that reduces height assignment errors of winds near the jet stream, see the first item.
- Since the tropical region is largely ocean or a green vegetation area with large atmospheric humidity, ground calibration opportunities in the tropics are unlikely.

From these items we come to the following recommendation.

- wvm_et_zwc1_1km is recommended in areas with ground calibration opportunity (dry land areas, snow or ice) in particular in the polar (> 70 degrees) and mid-latitude (40-70 degrees). In the sub-tropical region either wvm_et_zwc1_1km or wvm_tr_zwc1_1km is beneficial depending on the location of the ITCZ with clouds at high altitudes. Sub-tropical deserts might be beneficial for ZWC purposes.
- wvm_et_nozwc1_1km in areas with no calibration opportunity and clouds below 15 km (polar and mid-latitude ocean regions).
- wvm_tr_nozwc1_1km for the tropical region.

Starting at the North Pole in ZWC mode (wvm_et_zwc1_1km) we would, for example, switch in one orbit to respectively

i) no-ZWC mode over the NH ocean (wvm_et_nozwc1_1km),

ii) sub-tropics (depending on ITCZ location and/or calibration opportunity either wvm_et_zwc1_1km or wvm_tr_zwc1_1km)

iii) wvm_tr_nozwc1_1km in the tropics,

iv) sub-tropics (depending on ITCZ location and/or calibration opportunity wvm_et_zwc1_1km or wvm_tr_zwc1_1km),

v) no-ZWC mode over the SH ocean (wvm_et_nozwc1_1km)

vi) ZWC mode over the South Pole (wvm_et_zwc1_1km), and vice versa when moving over the South Pole and back to the North Pole. This requires 12 switches, i.e., exceeding the maximum of an average of eight switches per orbit. The switches when entering the sub-tropics may or may not be necessary and could reduce the number of switches. ZWC/no-ZWC switches can be moved in the sequence and to other orbits within one week.

This solution with the above scenarios does not waste Mie range gates at the land surface, but only switches to ZWC when zero-wind calibration over land will be feasible. These areas will be identified by the L1B study team. The polar areas are likely good opportunities for zero-wind calibration in the absence of moderate or strong winds. If ZWC appears ineffective above land, then there appears no strong reason to divert to other scenarios, but rather to minimize the number of switches.

Another issue that needs further research by the L1B study team is the occurrence of both clouds above 15 km beyond 20 degrees latitude and a ZWC opportunity. Indeed, Figures 4.2.3-35 and 4.2.3-40 of [A2] show a substantial 10% cloud occurrence above 15 km between 20 and 40 degrees latitude in the hemisphere summer periods. In combination with substantial ZWC opportunities this would plead for scenario wvm_tr_zwc2_1km (dense Mie sampling in the UTLS) in these regions.

The effect of vertical motion has been studied. The strongest vertical motion (upward convection) occurs below cloud shields and is generally not visible for a DWL. Therefore, vertical motion may be ignored in assimilation of Aeolus wind profiles.

The occurrence of cloud and wind shear may invalidate the DWL winds and influence the choice of vertical sampling. The occurrence of cloud, aerosol stratification and wind shear has been investigated. Representative cases have been used in the simulation of the impact of the vertical sampling scenarios. Moreover, the Mie Core outputs were tested for their utility as quality indicators for Mie channel retrieved winds. For instance Mie signal line-broadening may indicate the sampling of a turbulent region and large residual errors to unreliable winds. Threshold values for the output parameters have been defined to assign a quality measure to the retrieved winds. These are being used in the L2B processing to assign an appropriate weight to the corresponding winds in data assimilation. The most important aspect of this quality control (SNR check) has been accounted for in LIPAS and thus in the choice of the vertical sampling scenarios.

8 Recommendations for future missions

Some limitations due to current instrument constraints were encountered, which cannot be altered at the current stage of the mission. However, they lead to the following recommendations for any future mission.

- The 40 km range constraint along the LOS results in a maximum altitude for wind measurements of 31.73 km (section 5.2 of [A1]). For maximum 2 km bin sizes probably no measurements can be done above this altitude fulfilling the mission requirements on wind quality. Yet, for the dynamics of the stratospheric flow, wind observations above 32 km could still be useful to fill the observation gap at these altitudes.

- The possibility of a top Mie bin with large bin size of for instance 10 km (thus exceeding the 2 km mission constraint) enables to check the upper Rayleigh bins for the presence of cross-talk in the Rayleigh signal.

- Minimization of the vertical cross-talk between range bins (due to ACCD read-out time), which causes loss in wind processing quality.

- Increasing the number of bins, in particular for the Mie channel. From the Mie channel we can expect good returns on cloud tops and optically thin aerosol layers but retrieved winds may suffer from height assignment errors because of missing knowledge of the location of the cloud top or layer inside the bin. Reducing the bin size reduces the height assignment error. The Mie channel is also the most prominent candidate to collect ground returns for zero wind calibration. Reducing the bin size reduces the atmospheric contribution (contamination) in the ground bin. In case of sufficient aerosol loading and cloud (lower troposphere) good quality Mie channel winds can be derived over small vertical range bins. Uncertainty in height assignment remains acceptable when these smaller bins are combined into larger bins in order to provide winds that are vertically representative of the NWP models. More in general, oversampling in the vertical allows improved quality control and a more detailed optical profile for aerosol and cloud assessment. An upgrade of the Mie channel to cover the whole altitude range between the surface and 20 km with 125 m range bins, i.e. 160 range bins, would alleviate the issues mentioned above.

9 Scientific Outreach

The VAMP project has resulted in several peer-reviewed papers [R3,R4,R5] and conference presentations and proceedings. Results have been presented at the ADMAG, SPARC data assimilation workshops, International Winds Workshops and US Lidar Working Group on space-based lidars on various occasions.

Appendix. Overview of vertical sampling scenarios

The appendix provides an overview of the most recent vertical sampling strategies considered in the evaluation tasks described in this Final Report. The annotation in the scenario filenames is as follows:

- wvm refers to wind velocity measurement mode (as opposed to calibration mode)
- _1km to scenarios with minimum Rayleigh bin sizes of 1 km
- _tr refers to tropical scenarios with Mie bins in the tropical UTLS
- _et refers to extra-tropical scenarios with Mie bins in the extra-tropical UTLS
- _(no)zwc refers to scenarios with (no) zero wind calibration ability

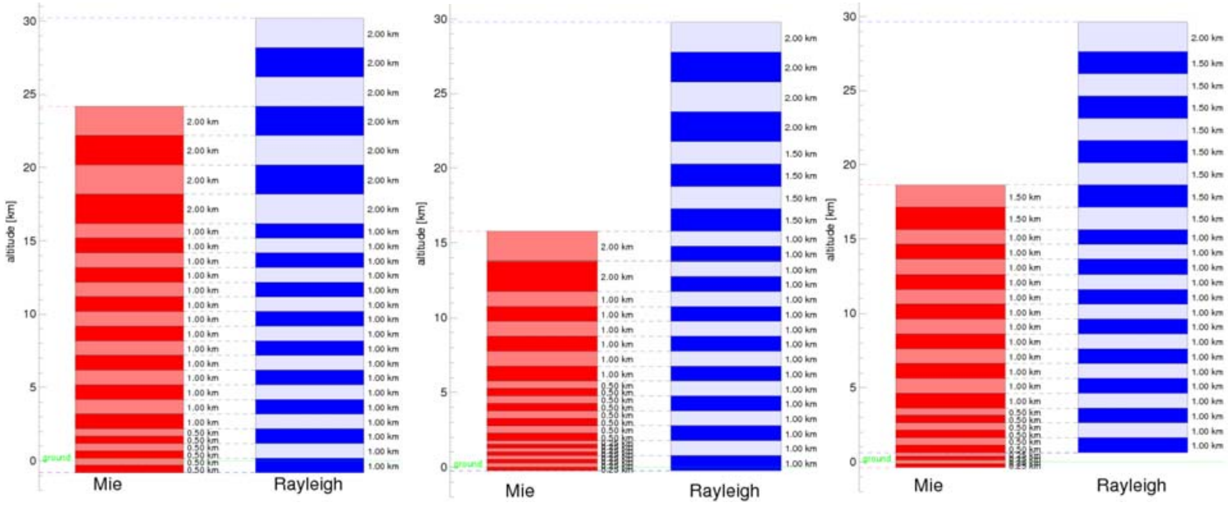

Figure 1. Vertical sampling scenarios from left to right: wvm1_1km, wvm2_1km and wvm_tr_zwc1_1km.

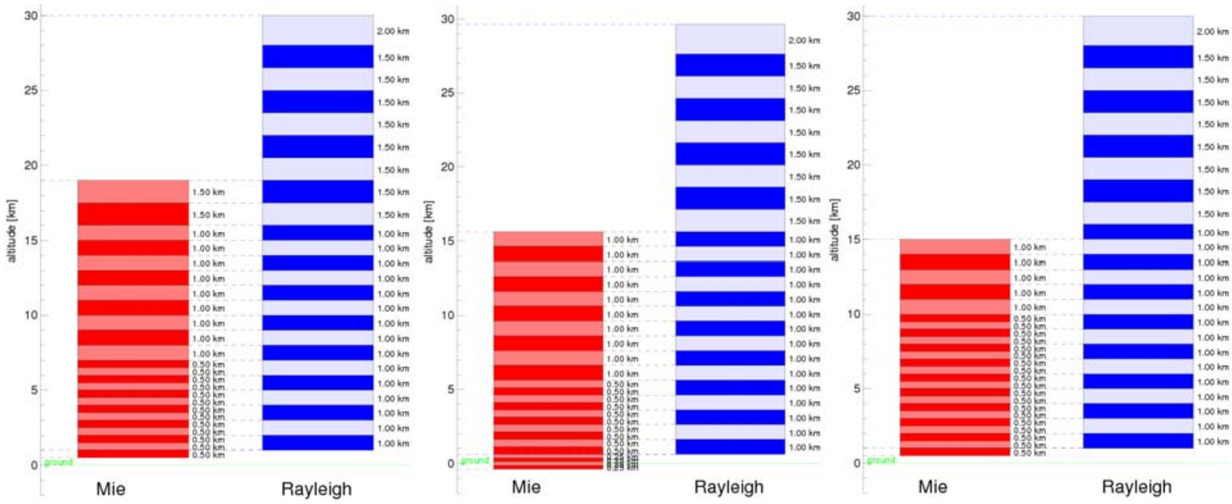

Figure 2. From left to right: wvm_tr_nozwc1_1km, wvm_et_zwc1_1km and wvm_et_nozwc1_1km.

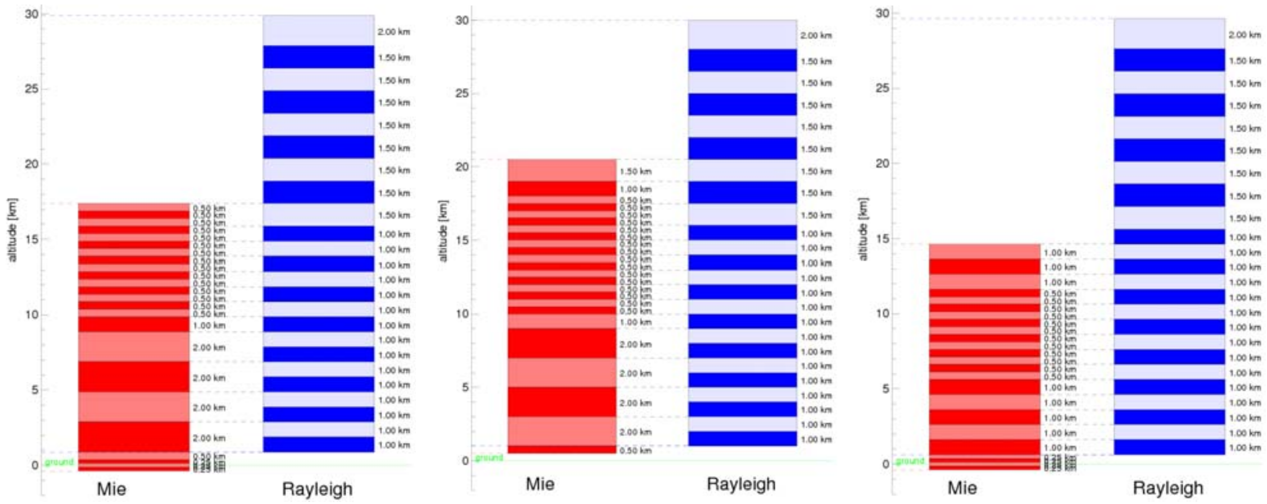

Figure 3. From left to right: wvm_tr_zwc2_1km, wvm_tr_nozwc2_1km, wvm_et_zwc2_1km.

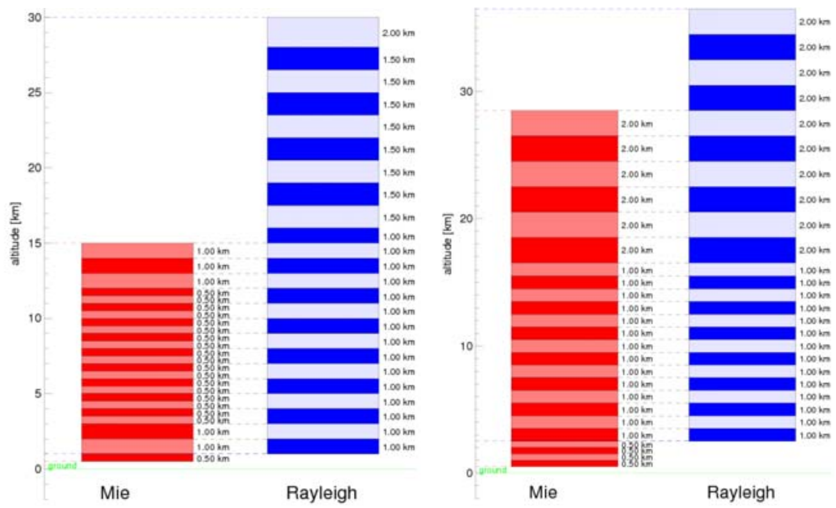

Figure 4. From left to right: wvm_et_nozwc2_1km, wvm_stratos_nozwc_1km. The latter is the stratospheric scenario with maximum data coverage in the stratosphere.