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DOCUMENT

ADM-Aeolus
Mission Requirements Document

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1 INTRODUCTION

The European Space Agency has been dedicated to observing the Earth from space since the launch of its first meteorological mission, Meteosat, in 1977. Following the success of this first mission, the subsequent series of Meteosat satellites, together with ERS-1, ERS-2, Envisat, and MetOp, have provided a wealth of valuable data characterizing meteorological conditions as well as the Earth's climate and changing environment. ESA's Living Planet Programme has subsequently established the framework for the development of science-driven Earth Explorer missions. The Earth Explorers are designed to address critical and specific challenges that are raised by the science community, while at the same time demonstrating breakthrough technology and new observing techniques.

The first European satellite-based wind lidar (Light Detection and Ranging) concepts were developed by the so-called Doppler Lidar Working Group. These preparatory activities, including theoretical studies, technical developments and field campaigns, are described in the ESA "Report for Mission Selection" (European Space Agency, 1999). This report was presented to the Earth Observation community at the Earth Explorer User Consultation Meeting in 1999, after which the Atmospheric Dynamics Mission (ADM) wind lidar mission was selected by ESA for implementation as the second Earth Explorer Core mission.

The mission name was extended to ADM-Aeolus, where the name Aeolus is adopted from the ruler of the winds in Greek mythology. In this document, the mission name is hereafter abbreviated to Aeolus. The Aeolus mission shall demonstrate the capability of a space-borne high spectral resolution Doppler wind lidar to make accurate global measurements of wind profiles in the troposphere and the lower stratosphere (0-30 km). The mission thus addresses one of the main deficiencies of the current Global Observing System (GOS), as identified by the World Meteorological Organization (WMO, 2004). Additional geophysical products that will be retrieved from the Aeolus measurements are cloud and aerosol optical properties. The Aeolus mission shall, furthermore, demonstrate the impact of its wind profile data on operational weather forecasting and climate research.

The purpose of this document is to define the mission objectives and scientific requirements of Aeolus, and to provide guidelines for the technical implementation of the mission. The document has been divided into 8 sections and two Appendices with introduction, references and definitions sections followed by sections addressing the scientific background of the mission (section 5), the mission objectives (section 6), user information requirements (section 7), observation requirements (section 8), the ADM-Aeolus mission elements (section 9), and data use and synergies with other observing systems (section 10).

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3 DEFINITIONS

A summary of definitions valid for this document is given here. The first four definitions are based on ISO standard 3534-1 (ISO, 1993).

Accuracy:

The closeness of agreement between a measurement and the accepted reference value. The term accuracy, when applied to a set of measurements, involves a combination of random components and a common systematic error or bias component, and can be expressed as follows:

$$Accuracy = \sqrt{(Precision^2 + Bias^2)} \qquad \text{(Eq. 1)}$$

Bias:

The difference between the expectation of measurements and the accepted reference value. The bias is the total **systematic error**. There may be one or more systematic error components contributing to the bias.

Free Troposphere:

The Earth atmosphere between 2 km above the surface and 16 km. Please note that this definition is specific to this document and not fully in-line with the exact definition of the free troposphere in meteorology (e.g. Wallace and Hobbs, 1977).

Instrument related observation error:

The root of the sum of the observation precision squared and the observation systematic error squared.

Level 0:

Instrument source packet (ISP) data with raw Aladin measurement data, instrument housekeeping data and Aeolus platform housekeeping data, vertical sampling grid information, calibrated housekeeping data and instrument health parameters.

Level 1:

Geolocated measurement data including processed ground echo data, preliminary HLOS wind measurements and observations (zero wind correction applied), viewing geometry & scene geolocation data, and annotation data including processed calibration data, product confidence data and calibrated housekeeping data

Level 2:

Fully processed wind (Level 2B), ECMWF forecast model winds on the location of the Aeolus L2B observations after assimilation of Aeolus L2B data (L2C), and optical properties profile (Level 2A) data, fully processed error information and product confidence data.

Measurement:

Horizontal average of the atmospheric backscattered signals from a number of laser pulses from a vertical bin. The horizontal averaging laser pulses from Aeolus takes place on-board the spacecraft to reduce the data size before data downlink.

Medium-range forecast:

Forecast for the following 72 to 240 hours, see http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Observation:

In order to achieve sufficient signal-to-noise levels, Aeolus measurements are further horizontally averaged by the on-ground Level 1 and Level 2 data processors within a vertical bin. The resulting product is called an observation. Adjacent observations in the vertical form an observation profile.

Observation profile:

An observation profile is a collection of adjacent observations along the lidar line-of-sight from the surface up to the highest vertical bin.

Observation representativeness error:

When observations are assimilated into numerical weather prediction models, the associated observation error is increased adding the so-called observation representativeness error to the instrument-related error. This is done to compensate for the introduction of an observation with a given geographical representativeness in a discretized numerical representation of the atmosphere by the forecast models. The total associated observation error is mostly defined through the use of statistics, comparing the observations with the model first guess and analysis.

Phase E1:

The commissioning phase. For Aeolus, this is defined as the first 3 months after launch. Within this period the instrument will be switched on and the platform, instrument and ground segment operation and performance is calibrated and/or validated.

Phase E2:

The operational phase of the Aeolus satellite. In this phase, the instrument is assumed to operate in a stable measuring mode. Routine instrument calibration and product validation is performed. Only minor changes to the instrument settings, measurement modes, and algorithm updates are expected.

Planetary Boundary Layer (PBL):

Earth atmosphere between the surface and 2 km above the surface. Please note that this definition is specific to this document, and not fully in-line with the exact definition of the planetary boundary layer in meteorology (e.g. Wallace and Hobbs, 1977).

Precision:

The closeness of agreement between independent test results obtained under stipulated conditions. It depends only on the distribution of the **random errors**. It is computed as the standard deviation of the measurements.

Precision of a lidar observation:

The random part of the wind-speed estimation error. It is defined as the standard deviation of the estimates (σ_{LOS}) (good estimates) falling under the bell shape part of the Probability Density Function (PDF) described below, and is hence the calculated precision after the removal of gross errors.

Probability Density Function (PDF) of a line-of-sight wind speed:

For wind observation by Doppler Wind Lidars in the low-backscatter regime, the number of events (photons) per measurement interval, detected at receiver level, can be close to the number of 'noise' events. The retrieved wind speeds from measurements with a low signal-to-noise ratio (SNR) are less accurate, especially for cases where the noise resembles the measured signal characteristics. A PDF of the Line-Of-Sight wind speed (V_{LOS}) can be estimated by retrieving the wind speed from a synthetic measurement applying the estimated error distribution. The resulting wind speed distribution looks like a cluster of localised good estimates (bell shape) around the defined true mean speed (V_{true}), as shown in Figure 1.

An approximate model of the estimated PDF for any observing system – here with terminology appropriate for Aeolus-type line-of-sight winds – is as follows:

$$PDF(V_{LOS}) = \frac{P_{ge}}{V_S} + \frac{1-P_{ge}}{(2\pi)^{\frac{1}{2}}\sigma_{LOS}} \exp\left[\frac{-(V_{LOS}-V_{true})^2}{2\sigma_{LOS}{}^2}\right] \qquad \text{(Eq. 2)}$$

where σ_{LOS} is the random part of the wind-speed estimated error (precision of a lidar observation), P_{ge} is the probability of gross error of a lidar observation, and V_s is the wind search window (horizontal axis in Figure 1).

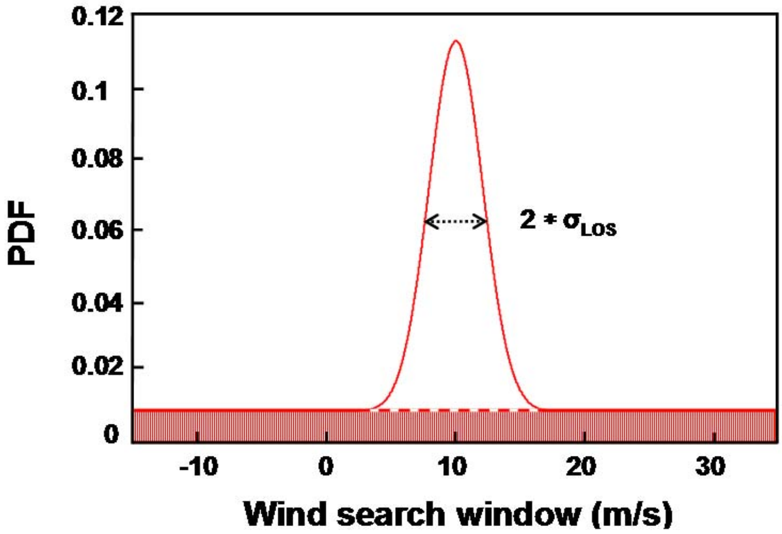

Figure 1: *The PDF of wind estimates looks like a cluster of localised good estimates (bell shape) around the true mean speed (here 10 m/s) sitting on a pedestal of uniformly distributed bad estimates (shaded zone), or gross errors, extending over the wind search window. Here the systematic error equals 0. The wind search window is linked to the LOS dynamic range (± 90 m/s).*

Probability of gross error (P_{ge}) of a lidar observation:

The complement to unity of the percentage of estimates (bad estimates) contained in the pedestal of uniform distribution over the 'search window' wind speed range (V_S). This is shown by the shaded area in Figure 1. Estimates outside the search window should always be considered 'bad' and thus rejected. It is expected that the on-ground data processing will be able to remove most gross-errors through quality control (QC). The requirement in this document refers to the maximum amount of gross errors not being detected by the data processing and QC.

Short-range forecast:

Forecast for the following 12 – 72 hours (see http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html

Stratosphere:

The Earth atmosphere between about 16 and 50 km. Please note that this definition is specific to this document and not fully in-line with the exact definition of the range of the stratosphere in meteorology (e.g. Wallace and Hobbs, 1977).

Systematic error of a lidar observation:

Originated from the instrument and platform characterization, calibration and data processing. In the case of Aeolus, this will include **biases** due to undetected/uncorrected instrument misalignments, platform miss-pointing and errors in the instrument response calibration.

Trueness:

The closeness of agreement between the average value obtained from a large series of measurements and an accepted reference value. The measure of trueness is in the document expressed in terms of bias.

Vertical bin:

The return signal from an emitted laser pulse can be averaged over time on the detector, resulting in an atmospheric return signal representative of an atmospheric layer with a thickness equal to the speed of light divided on the averaging time.

4 ACRONYMS

ADM-Aeolus	Atmospheric Dynamics Mission - Aeolus
Aladin	The ADM-Aeolus Doppler Wind Lidar Instrument
AMV	Air Motion Vector
AOD	Atmospheric Optical Depth
ATOVS	Advanced TIROS Operational Vertical Sounders
BM	Burst Mode
CAT	Clear Air Turbulence
CM	Continuous Mode
DWL	Doppler Wind Lidar
ET-EGOS	Expert Team on Evolution of the Global Observing System
EARS	EUMETSAT Advanced Retransmission Service
Lidar	Light Detection and Ranging
ECMWF	European Centre for Medium-range Weather Forecasts
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GCOS	Global Climate Observing System
GOS	Global Observing System
GRAS	Global Navigation Satellite System Receiver for Atmospheric Sounding, a Global Navigation Satellite System receiver that operates as an atmospheric sounder, flying on board the MetOp satellite
HLOS	Horizontal Line of Sight
L1B	Level 1B
L2A	Level 2A
L2B	Level 2B
L2C	Level 2C
LOS	Line of Sight
MetOp	Meteorological Operational satellite programme (MetOp), which is the space segment of Eumetsat's Polar System
NRT	Near-Real-Time (within 3 hours of sensing)
NWP	Numerical Weather Prediction
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
PBL	Planetary Boundary Layer
PDF	Probability Density Function
QC	Quality Control
QRT	Quasi Real Time (within 30 minutes of sensing)
RMS	Root-Mean-Square
SATEM	Radiance measurements from satellites that have been converted to temperature and humidity profiles
SATOB	Satellite Observations
SNR	Signal to Noise Ratio
SSM/I	Special Sensor Microwave / Imager
TOVS	TIROS Operational Vertical Sounder, aboard NOAA's TIROS series of polar orbiting satellites

VAMP	Vertical Aeolus Measurement Positioning
VHAMP	Vertical and Horizontal Aeolus Measurement Positioning
WMO	World Meteorological Organisation
WCRP	World Climate Research Programme

5 SCIENTIFIC BACKGROUND AND JUSTIFICATION

Continuous measurements of winds throughout the atmosphere are crucial for Numerical Weather Prediction (NWP) and the modelling of global climate, its variability, predictability and change. Reliable instantaneous analyses and longer term climatologies of winds are also needed to improve our understanding of atmospheric dynamics and global atmospheric transport and cycling of energy, water, aerosols and chemicals. This includes observations of winds at all levels in the atmosphere (primarily troposphere and stratosphere) and at the Earth's surface.

Meteorological observations have been carried out from space for several decades, including indirect measurements of the atmospheric wind field through temperature soundings, from which the geostrophic wind field can be inferred outside the tropics. Direct wind measurements of the global, three-dimensional wind field are, however, still outstanding, including small-scale and tropical winds. Deficiencies in the current observing system, including coverage and frequency of observations, are impeding progress in both operational weather forecasting and climate-related studies (WMO, 1998). Furthermore, there is a tendency to reduce the number of conventional observation sites (e.g. radiosonde stations) primarily for cost reasons. Improvements in the available wind data are needed urgently to exploit the full potential of recent advances in NWP (e.g. improvements in spatial resolution and data assimilation techniques). Only a Doppler Wind Lidar (DWL) has the potential to provide the requisite data by means of accurate observations of wind profiles in the atmosphere, globally and down to the surface or to the top of optically thick clouds (ESA, 2008).

A DWL will not only provide wind data but also ancillary information derived from the measured atmospheric backscatter, such as cloud top height, vertical distribution of clouds, aerosol and cloud optical depths, atmospheric extinction, the altitude of the Planetary Boundary Layer (PBL) etc. The spin-off products can be used for scene classification in the retrieval of the wind products, as well as stand-alone products for cloud and aerosol related research and applications.

There is a strong relationship between advances in NWP and those in climate-related studies. Climate studies are using analyses of atmospheric fields from NWP data assimilation systems, originally designed to provide initial conditions for operational weather forecasting models. The understanding of the atmosphere and its evolution is to a large extent based on analysed fields from a succession of data assimilation cycles, carried out at operational weather centres. Progress in climate analysis is thus closely linked to progress in NWP. This is an important guideline when defining the mission requirements for Aeolus in this document.

Wind fields generally need to be given as a three-dimensional representation. However, while the vertical wind component can be significant for local phenomena, the average vertical wind component is negligibly small over a typical meteorological grid box (Courtier *et al.*, 1992, Marseille *et al.*, 2011). The Doppler wind lidar technique determines the wind velocity only along its Line-Of-Sight (LOS). Thus to determine the horizontal components of the wind vector, a given air volume would have to be observed from multiple directions assuming the net vertical wind velocity to be negligible. Ways to achieve this have been investigated in great detail (ESA, 1987), but all lead to inherently complex instrument concepts and/or substantial cost increase.

Lorenc *et al.* (1992) showed that NWP models can also assimilate single wind components taken relative to an instrument LOS direction and that measurements of a single Horizontal LOS wind component (HLOS) improve weather forecasting skill. A series of impact studies have further confirmed the improvement of NWP forecast skill when adding simulated Aeolus HLOS wind observations to the existing GOS (e.g. Marseille *et al.*, 2008a, 2008b, Stoffelen *et al.*, 2006, Tan *et al.*, 2005 and 2007, Žagar, 2004). In the tropics, single HLOS winds have clear skill, but a combination of both zonal (along longitudes at one latitude) and meridional (along latitudes at one longitude) LOS winds would be more beneficial (Žagar *et al.*, 2008, Riishøjgaard *et al.*, 2004, Stoffelen *et al.*, 2005). A different conclusion was drawn by Horanyi *et al.* (2013 and 2015a) from a limited number of single observation experiments; "The single component (HLOS) wind data can represent approximately 75% of the full vector wind information (both in the extra-tropics and tropics) as far as their forecast impact is concerned. This is because the ECMWF model is capable of deriving the true wind vector from a single line-of-sight observation to a 75% level."

Based on these results, mission requirements for single LOS wind observations will be outlined here.

6 MISSION OBJECTIVES

The primary objective of the Atmospheric Dynamics Mission, Aeolus, is to demonstrate the Doppler Wind Lidar technique for measure wind profiles from space. The mission sets out to provide observations of global wind profiles along the instrument LOS direction over a minimum lifetime of 3 years. The data are intended for assimilation into NWP models, improving the analyses and forecasting of the 3-D vector wind field.

A secondary mission objective is to provide data sets suitable for the evaluation of climate models. Reliable short-term wind "climatologies" are needed to improve our understanding of atmospheric dynamics and the global atmospheric transport and cycling of energy, water, aerosols, chemicals and other airborne materials. The mission would, thus, provide data needed to address some of the key concerns of the World Climate Research Programme (WCRP) i.e. the quantification of climate variability, evaluation and improvement of climate models and process studies relevant to climate change. The newly acquired data would also help realise some of the objectives of the Global Climate Observing System (GCOS) i.e. (i) the study of the Earth's global energy budget (by measuring wind profiles globally), and (ii) the study of the global atmospheric circulation and related features such as precipitation systems, the El Niño and the Southern Oscillation phenomena and stratospheric/tropospheric exchange.

The Aeolus mission objectives can be further detailed as follows:

a) improving NWP analyses and forecasting of the 3-D vector wind field,

b) improved medium-range forecasts for the extra-tropical region through a better definition of planetary-scale waves,

c) improvements in forecasts of intense wind events through measurements of vertical wind shear (vertically resolved HLOS wind observations),

d) improved modelling and forecasting of tropical dynamics through the provision of direct wind observation profiles,

e) provide data sets suitable for the evaluation of climate models,

f) improvements of the knowledge of the atmospheric state through the provision of atmospheric optical properties (cloud and aerosol spin-off products derived from the measured atmospheric backscatter)

7 USER INFORMATION REQUIREMENTS

The WMO has defined rolling requirements for wind profile observations, depending on whether they should be used for NWP or for the modelling of climate change. Quoting from WMO (1996):

"*Various statements of requirements have been made, and both needs and capability change with time. The statements given here were the most authoritative at the time of writing, and may be taken as useful guides to development, but are not fully definite*".

The WMO requirements are defined by the Expert Team on Evolution of the Global Observing System (ET-EGOS), and its designated focal points for each of the WMO application areas. The realisation of WMO requirements would represent a major step forward for the analysis of atmospheric flows. In order to better guide developers of observation systems, the WMO has used the current satellite capability to set a threshold below which no impact is expected from additional wind measurements. Current satellite capabilities for the measuring of wind profiles consist of image-derived Atmospheric Motion Vectors (AMVs), and space-borne observations of the mass field together with geostrophic adjustment theory. Table 1 lists the WMO observation requirements for Global NWP horizontal component of wind profiles from February 2011.

		Ideal requirements			Breakthrough			Threshold requirements		
		LT	**HT**	**Strat**	**LT**	**HT**	**Strat**	**LT**	**HT**	**Strat**
Vertical Resolution	[km]	0.5	0.5	0.5	1	1	1	3	3	3
Horizontal Domain		global			global			Global		
Horizontal resolution (spacing)	[km]	15	15	15	100	100	100	500	500	500
Temporal Sampling	[hour]	1			6			12		
Accuracy (Component)	[ms^{-1}]	1	1	1	3	3	3	5	8	5
Timeliness	[hour]	0.1			0.5			6		

Table 1: *WMO observation requirements for* ***Global NWP*** *for the horizontal component of wind profiles (WMO, 2011). LT: Lower troposphere, HT: Higher Troposphere, Strat: Stratosphere. Accuracy is here defined as the sum of the absolute value of the systematic (bias) and random (precision) observation errors (E. Andersson, personal communications 2011).*

Requirements are expressed for geophysical variables in terms of six criteria: vertical resolution, horizontal domain and resolution, temporal sampling, accuracy and timeliness (Andersson *et al.*, 2009). For each of these criteria the table indicates three requirement levels:

- "ideal" is a goal requirement, above which further improvements are not necessary
- "breakthrough" is an intermediate level between "threshold" and "ideal" which, if achieved, would result in a significant improvement for the targeted application. The

breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems

- "threshold" is the minimum requirement to be met to ensure that data are useful

These WMO requirements shall serve as a guide for the further definition of the Aeolus Mission Requirements below.

Two different classes of users of satellite-based wind profile observations can be identified:

- near-real-time users (e.g. national meteorological services and the European Centre for Medium-Range Weather Forecasts (ECMWF)), assimilating the data into the operational numerical weather prediction models for improved weather forecasting

- research oriented users (e.g. universities, research centres) using the global wind profiles and secondary data products for improved understanding of the Earth atmosphere for climate and meteorological studies.

The first group for operational applications require access to the Level 1B (L1B) data product in Near Real-Time (NRT, < 3 hrs after sensing) and a fast Level 2B (L2B) processor, or the L2B data product in NRT, globally, throughout the mission. Some users would also prefer a Quasi-Real-Time delivery (QRT, < 30 minutes after sensing) of data from at least certain relevant geographical regions (see Table 1). The NWP centres may then process the L1B data to L2B pressure and temperature corrected wind profiles, and assimilate these and other observations from the GOS, to derive a complete picture of the state of the atmosphere. At the time of writing (v2.0 of this document), ECMWF assimilates GOS data once every 12 hours.

For research applications, any processing level may be required, from Level 0 (L0) data to level 2. For most studies, it is acceptable to have a much longer delay between data generation and delivery (e.g. within two weeks). Continuous data is desirable for the building of time series.

Data shall be made available both to national NWP centres and to scientific users.

The L0, L1B, L2B, L2C, calibration and auxiliary data products should be archived to allow off-line use and reprocessing. The threshold for the data storage is 5 years beyond the mission lifetime (GR-7 , ESA, 2014), but the goal is more than 20 years (FURD-ES-0020, ESA, 2011). Archived and reprocessed data should be available to the NWP centres and the scientific users on request.

MR-10: ESA shall implement NRT delivery of L1b data to users, delivery of a L2B processor and L2A, L2B, L2C, calibration and auxiliary products, relevant product and processing-related documentation, and a long-term archive of the mission L0, L1B, L2A, L2B, L2C, calibration and auxiliary data

8 OBSERVATION REQUIREMENTS

8.1 Measurement Technique

The user information requirements for a quasi-global coverage, NRT data delivery and frequent revisits (see Table 1), can be fulfilled by a DWL embarked on a free flyer designed in such a way that the observations can be exploited operationally.

The Doppler Wind Lidar technique provides measurements of the frequency shift of the emitted laser light, which is being backscattered by atmospheric air molecules (Rayleigh scattering) and/or aerosol and cloud particles (Mie scattering). The frequency shift is caused by the Doppler effect due to the relative motion of the scatterers along the LOS direction of the laser. Rayleigh scattering increases in strength inversely proportional to the fourth power of the light wavelength, thus strongly favouring short wavelengths. Mie scattering occurs when the scattering wavelength and the size of the scatterer are of comparable sizes.

The frequency distribution of laser light, backscattered by the air molecules, can be described by so-called 'Rayleigh-Brillouin scattering theory', where Rayleigh scattering is related to the local temperature and Brillouin scattering to local pressure fluctuations (e.g. Witschas *et al.*, 2010). The temperature-dependent Brownian motion of air molecules causes scattered light to become broadened in frequency. Pressure fluctuations by acoustic waves cause an additional modulation to the frequency distribution of the scattered light, which is described by Brillouin scattering theory. The higher the temperature and atmospheric pressure, the broader and more modulated the backscattered laser signal becomes. Backscattered laser light, thus, needs to be temperature and pressure corrected before the Doppler shift between the emitted and received laser light can be determined. The resulting Doppler shift is used to retrieve the speed of the air molecules along the one-dimensional lidar LOS.

The Mie backscatter from aerosols and clouds is used to determine the wind speed in layers with sufficient particle loading or down to optically thick clouds. Again, the Doppler shift between the emitted and relatively frequency-narrow Mie backscattered laser light, is used to determine the wind speed along the lidar LOS. Aerosol concentrations are highly variable, and show large concentrations mainly in the PBL (0 to 2 km altitude) and in thin elevated layers often connected to fire episodes or volcanic eruptions. Correspondingly, the backscatter from aerosols varies significantly with altitude and region, and is difficult to predict. Also thin cirrus clouds near the tropopause will contribute to the signal.

To obtain reliable wind profiles from higher regions of the troposphere and the lower stratosphere, the use of molecular backscatter is mandatory since only few particles exist at these altitudes. On the other hand, the attenuation of molecular scattering is quite high at low altitudes, and in and near the PBL a detection method using aerosol and cloud backscatter is clearly complimentary. Thus it becomes essential that both Mie and Rayleigh backscatter measurements are performed by the Aeolus mission. This also implies that Aeolus must work at a short wavelength ensuring a sufficient molecular backscatter.

MR-20: The measurement technique shall provide accurate wind observation profiles in clear atmosphere, within and below optically thin clouds, and at the top of optically thick clouds

8.2 Orbit

The user requirement for the Aeolus orbit is that the mission will provide quasi-global coverage, which means that measurements shall be taken around the globe within one day.

There are no specific requirements as to the exact diurnal timing of the Aeolus wind measurements. However, the user requirements on the product accuracy and orbit stability are high which shall be reflected in the orbit choice.

MR-30: The orbit shall provide globally distributed measurements within one day allowing the necessary pointing and instrument stability to meet MR-75, MR-80, MR-100 and MR-110

8.3 L2 data requirements

8.3.1 Wind observation type

In NWP models, the horizontal wind vector is decomposed into two independent wind components representing the south to north (meridional, denoted as v) and west to east (zonal, denoted as u) directions. The vertical atmospheric motion (denoted as ω) is on average one order of magnitude smaller than the horizontal winds. However, on small horizontal scales (e.g. within the footprint of a DWL) in areas with strong vertical motion (e.g. in turbulent conditions and within convective clouds), the vertical component of the wind may dominate. Neglecting the vertical motion is in such cases not strictly valid. However, current NWP models cannot resolve these small scales. Therefore the vertical motion on sub-grid scales is regarded as an unwanted component of the measurement and it is rather treated as a part of the so-called representativeness error, which is further discussed below. Furthermore, strong updrafts often cause the formation of optically thick convective clouds. A lidar can only penetrate optically thin clouds. Therefore, strong updrafts are not likely to be detectable by DWLs, except in turbulent conditions (in the PBL, above and in lee of topography, clear-air turbulence (CAT), in the convective outflow above and next to convective clouds, and around the jet-stream). The average vertical wind component seen by a DWL from space is on average small over a typical meteorological model grid box (Courtier *et al.*, 1992, Houchi *et al.*, 2011). Furthermore, although a three-dimensional wind vector can be assimilated into any NWP model, the assimilation of the horizontal wind component is simpler to implement. Therefore, it is an advantage to provide NWP users with the horizontally projected component of the DWL LOS wind. It is also important to identify areas with strong turbulence and convection in the data assimilation process, in order to attribute an appropriate observation representativeness error to the DWL measurements.

Lorenc *et al.* (1992) verified the hypothesis that single-component wind observations by DWLs are sufficient to ensure NWP forecast impact, by performing a so-called Observing System Experiment (OSE) where either none (control experiment), one, or two components of AMV wind observations were assimilated. They found that the impact of introducing two-component wind observations in the OSE is twice as large as the impact of introducing one-component wind observations only. In an additional experiment, 50% of the available AMV observations were randomly removed, resulting in a 50% reduction of the OSE impact compared to the impact when all AMVs were used. The conclusion was that the expected analysis and forecast impact is the same for two collocated orthogonal components as for twice as many spatially well-separated single-wind component observations. Similar conclusions were also made in Marseille *et al.* (2008a). The Lorenc *et al.* (1992) study implicitly assumed that the meridional and zonal components are of equal importance (e.g. Hollingsworth and Lönnberg, 1987, Horanyi *et al.*, 2013 and 2015a), though Žagar (2004) suggests that for tropical analyses zonal wind observations are slightly favoured if only one wind component can be measured.

To launch a space-based lidar, measuring two components of the wind instead of one, is costly and adds complexity to the mission. The user requirement is therefore to provide at least one LOS component of the wind, which can be projected to the horizontal plane by the on-ground data processor.

MR-40: Profiles of horizontally projected line-of-sight wind observations shall be provided, preferably in the zonal direction

8.3.2 Resolution

The measured Doppler wind lidar pulse returns need to be horizontally and vertically averaged in order to obtain a sufficient SNR. As defined in section 3, the detected atmospheric return of the ALADIN laser pulses are averaged on-board to so-called measurements in order to reduce the size of the data to be downlinked. These measurements are averaged further during the on-ground processing to so-called observations to obtain sufficient SNR. Requirements for the horizontal and vertical averaging of the wind measurements are therefore established here.

8.3.2.1 Horizontal

The horizontal scale used in current meteorological analyses partly depends on the current GOS and on the data assimilation methodology. Experiments with reduced grid sizes have demonstrated positive benefits as smaller scale features are better represented (Simmons and Hollingsworth, 2002, Abdalla *et al.*, 2012). Operational NWP model grids scales are in practice limited by computing resources. Although both meteorological models and analysis methodologies are evolving, it is noted that the spatial extent of the horizontal error correlation structures is to some extent determined by the density of the GOS observation network. If a much denser observation network were available, smaller scales could be resolved.

The model grid resolution of state-of-the-art NWP models is on the order of 10 and 30 km (March 2014), and the minimization of the cost function is normally performed on scales of 30-80 km. An observation resolution on the order of 15-100 km is therefore considered appropriate. For scales around 50 km, a -5/3 slope of the kinetic energy density spectrum as a function of wave number has been observed (Nastrom and Gage, 1985, Marseille *et al.*, 2013). Averaging over longer horizontal scales thus leads to an increase in atmospheric variability.

Two scientific studies were initiated in 2011, with the aim of consolidating the Aeolus Mission Requirements. The first study, called VHAMP, was performed by a consortium led by the Royal Netherlands Meteorological Institute (KNMI) and a second study was performed by ECMWF. The VHAMP study (Marseille *et al.*, 2013) concluded the following concerning horizontal observation requirements:

"One important conclusion from the VHAMP study is that most of the observation requirements cannot be separated for an accumulating instrument like Aeolus. Changing the along track accumulation length (MR-50) will impact the precision (MR-110) and the representativeness error. The accumulation length also impacts the error correlation (MR-140), because accumulation over shorter distances yields more dense observations, with increased correlated errors (the representativeness error part). One way of tackling this coupling of requirements is to take radiosonde winds as a benchmark for Aeolus winds, because radiosondes are still a major component of the GOS and similar type of observations in data void areas over the Northern Hemisphere oceans, Tropics and Southern Hemisphere are likely to yield substantial additional value for NWP. Radiosonde innovation statistics, in the remainder denoted (o-b) statistics, combine instrument error, observation representativeness error and model error, see Figure 3 in section 8.3.5.1 below. An Aeolus instrument yielding similar (o-b) statistics as obtained from radiosondes is likely to be beneficial for NWP. The radiosonde instrument error is small and in the order of several decimetres per seconds. The (o-b) statistics for radiosondes is thus dominated by the representativeness error and model error. For Aeolus, a short accumulation length yields relatively large instrument errors (random photons noise) and representativeness errors, giving large (o-b) values. Increasing the accumulation length reduces both the instrument error and representativeness error, thus reducing (o-b). For large accumulation lengths, the instrument error further decreases, but the representativeness error increases because the observation is no longer representative for the model counterpart. Note also that radiosonde (o-b) bias may be used as reference for Aeolus zero wind bias, which is mainly constituted of sampling error (due to location and flow near radiosonde ascends) (MR-120). The VHAMP study aimed at finding optimal settings for Aeolus horizontal accumulation and vertical binning to yield maximum impact for NWP. An alternative formulation is to find settings that yield (o-b) statistics as closely as possible to those obtained from radiosondes. Energy density spectra from scatterometer winds (12.5 km OSI-SAF product) were compared with spectra from ECMWF model winds at the same location. In conclusion, assuming a baseline laser energy of 80 mJ, accumulation lengths smaller than 85 km are not favourable because (i) the HLOS wind instrument error standard deviation will exceed 2 ms^{-1}, (ii) the representativeness error will increase and hence also increase (o-b) statistics and (iii) global NWP analysis in the Aeolus timeframe are not expected to resolve spatial scales below 90 km in the free troposphere. In addition, longer accumulation lengths, i.e., more measurements per observation, enables better quality control in the level-2 processing."

However, in order to monitor and assess the atmospheric variability within an observation, it is important for the users to receive measurement data at the smallest horizontal resolution possible. It is therefore required that users have access to the measurements on a resolution of kilometres (Wergen, 2011).

The ECMWF impact study (Abdalla *et al.*, 2012 and Horanyi *et al.*, 2013) reported that the operational ECMWF model (2013) is able to resolve the atmosphere fully at scales larger than 6-8 times the grid resolution. Significant power spectra amplitude (approximately 50% of the observed energy) is still available down to 3-4 times of the grid resolution, and the model is able to represent frontal zones and other sharp meteorological features to the resolution of 3-4 times the grid resolution. Based on these results, it was concluded that if the Aeolus is able to provide radiosonde quality HLOS winds at 86 km (one Basic Repeat Cycle (BRC)) length scales, it is recommended not to average Aeolus data beyond one BRC. With the 40-80 km effective resolution of the operational model anticipated in 2017-2018 (when Aeolus is expected to be launched), it should even be considered to provide Aeolus data averaged over half-BRC (43km) length scales.

Based on the outcome of these investigations, the Aeolus horizontal sampling requirement is formulated as follows.

MR-50: Wind observation profiles shall be provided with a horizontal observation resolution of less than 100 km, with sub-sample information (measurements) on 3 km scale

8.3.2.2 Vertical

In the vertical, meteorological model levels are at roughly 500 to 1000 m separation with typical error correlation lengths around 1500-2000 m (Houchi *et al.*, 2010). Range integration over 1000 m is thus appropriate. The required resolution in the stratosphere is lower (2000 m), based on the fact that stratospheric observations are much less abundant and hence new good quality observations will yield a positive impact despite of a less good vertical resolution. In the planetary boundary layer (0 to about 2 km altitude), the required vertical resolution is higher (500 m) because of the particular vertical structure of the flow (high occurrence of turbulence especially in and near rough terrain and during thermic activity). On the other hand, observations in the lower troposphere region close to the surface are relatively abundant in the current GOS (e.g. AMV and scatterometer wind vectors and Special Sensor Microwave / Imager (SSM/I) winds), so new DWL wind observations are not expected to have as much impact here as in the free troposphere. To allow for the investigation of the impact of vertical sampling on the data quality, the vertical resolution of the measured wind profiles should be variable and allow to observe variability down to 250 m.

Horizontal and vertical aircraft data thinning experiments by Horanyi *et al.* (2013) confirmed the results above. Furthermore, it was argued that more information is needed at the planetary boundary layer in order to properly describe near-surface radiative processes and the small scale turbulence. Hence the following requirement for the vertical integration length can be formulated:

MR-60: Wind observation profiles shall be provided with a vertical resolution as follows: 250 m (ground echoes for calibration purposes), 500 m (PBL: 0-2 km altitude), 1 km (free Troposphere: 2-16 km altitude), 2 km (lower Stratosphere: above 16 km)

8.3.3 Coverage

8.3.3.1 Temporal

The required temporal coverage of the Aeolus observations is equal to the typical time-scale of the resolved atmospheric structures. This time scale is typically one day, and a sensible requirement is global sampling every **12 hours**. A space-based wind lidar system cannot sample the complete globe within 12 hours, but it can achieve evenly distributed sampling of the whole globe. In 12 hours, about 8 Aeolus orbits (90 minutes, 6am/pm local equatorial crossing times) will have moved along more than half of the globe in the longitudinal direction, covering the whole globe with ascending or descending orbit segments (see Figure 2).

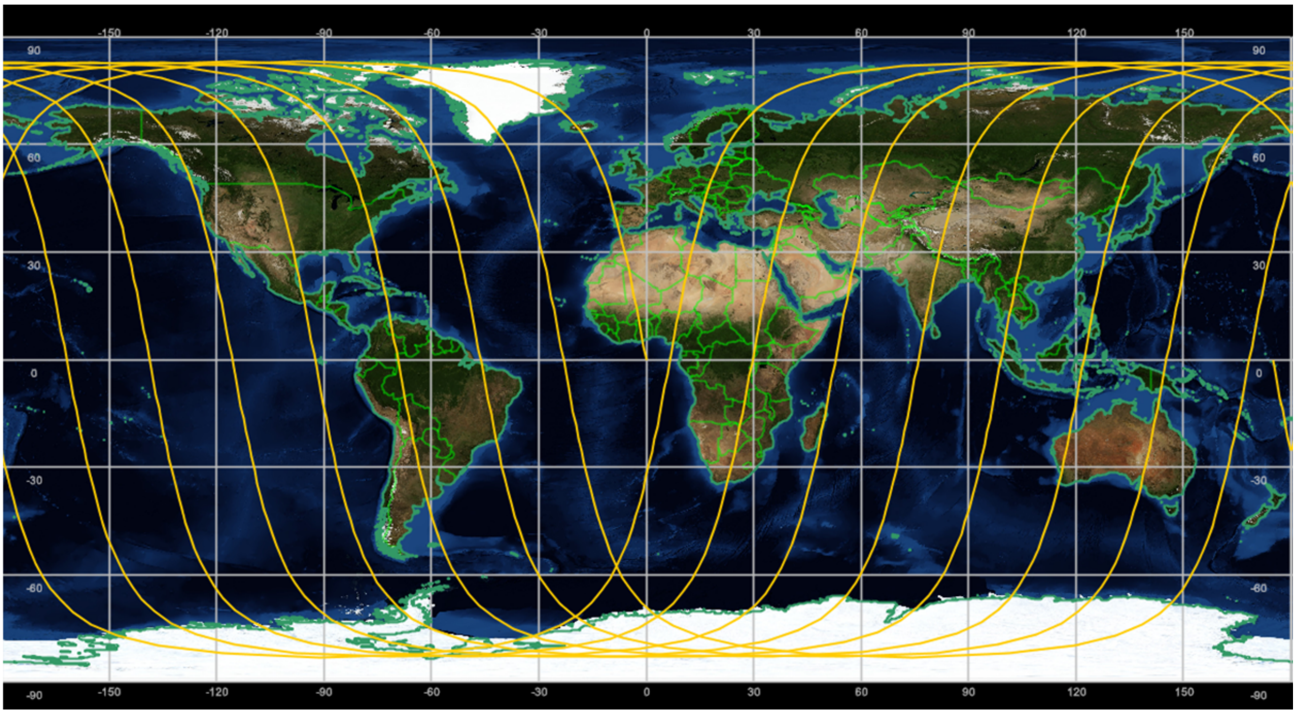

***Figure 2**: Example of Aeolus orbit tracks during 12 hours.*

Atmospheric structures in global NWP analyses have typical horizontal scales of 200 km. If each wind observation profile represents a box of 200 km by 200 km on the Earth's

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surface, then the total Earth surface contains 13,000 boxes. Therefore, 26,000 independent wind observation profiles every day would define the three-dimensional global wind vector completely, which corresponds to more than 1000 observation profiles per hour. This ideal requirement is clearly not achievable with a single wind lidar, but future operational wind missions could get closer to this ideal value.

However, any additional observation input of sufficient quality that can be assimilated generally leads to some improvement of weather prediction skill. For global observations, WMO (1996, 1998, 2004) has indicated a number of 100 independent wind observation profiles per hour as a threshold requirement. Anything better than this minimum requirement would lead to additional benefits.

MR-70: At least 100 independent wind observation profiles per hour shall be provided

MR-75: A collection of wind observation profiles, evenly distributed over the globe, shall be achieved every 12 hours

8.3.3.2 Horizontal and vertical coverage

The largest impact of additional wind observation profiles in the current GOS is expected in the Tropics, over oceans in the extra-Tropics, in polar areas, and in the upper troposphere and lower stratosphere, i.e. between 5 and 16 km (e.g. ESA 2008, Marseille *et al.*, 2013 and Horanyi *et al.*, 2013 and 2015a and references therein). Wind profile information is still required over the full tropospheric range (from the surface up to 16 km), in the lower stratosphere (16 - 30 km) and in all regions (globally).

The Aeolus mission is required to measure from the surface up to 20 km (lower stratosphere). In addition, as more forecast models are being extended into the upper stratosphere and mesosphere, wind profiles in the lower stratosphere (between 20 and 30 km) will be highly desirable, even at reduced accuracy and vertical resolution, as there are only very few direct wind measurements at these altitudes. Radiosondes rarely reach heights above 20 km (e.g. Houchi *et al.*, 2010).

MR-80: The mission shall provide global coverage

MR-85: The mission shall provide wind observation profiles from the surface up to 20 km (threshold). An extended sampling to 30 km is desirable (goal)

8.3.4 Dynamic Range

Statistics of wind speeds as measured by radiosonde data between 1995 and 1997 revealed maximum wind speeds of 125 m/s in the troposphere around the jet streams at mid latitudes and stratospheric wind speeds on the order of 140 m/s below 30 km (Håkansson, 2001). In order to cover the range of wind speeds encountered in the atmosphere, Aeolus shall be capable of delivering HLOS wind speeds over the range 0 to 150 m/s.

MR-90: The wind observation profiles shall have a dynamic range of +/-150 m/s along the HLOS direction

MR-95: The wind observation profile performances shall be applicable over a dynamic range of +/-100 m/s along the HLOS direction

8.3.5 Observation quality requirements

The quality of the observations shall be expressed in terms of their precision (random errors), bias (systematic error) and error correlation. As specified in section 3 and 7, the observation error requirements reported in Table 1 refers to the accuracy (total error), which is the square root of the sum of the squared bias and precision. Therefore, the precision and bias error requirements are interlinked and cannot be considered in isolation. Furthermore, the observation requirements given here are applicable to instrument and system related errors only. In an assimilation system, the attributed observation error is the sum of the instrument error, the so-called observation representativeness error and the model background error (e.g. Marseille *et al.*, 2013). The representativeness error compensates for the introduction of a point measurement in a discretized numerical representation of the atmosphere by the forecast models, and depends on the assimilation system model resolution. The instrument and system related and representativeness errors also depend on the observation averaging length. Model background errors are model dependent, and improve slowly with further model and observation improvements. Marseille *et al.* (2013) and Horanyi *et al.* (2013) concluded that the most appropriate Aeolus observation size, relative to the ECMWF operational model effective resolution in 2013 (T1279, ~16 km horizontal grid resolution at mid-latitude), is 80 – 100 km (see section 8.3.2.1). An observation size of 1 BRC will lead to negligible representativeness errors for this model version (Marseille *et al.*, 2013), which is also assumed to be a reasonable assumption for the ECMWF system at the time of the Aeolus launch. Therefore, the instrument error requirements given below are relative to an observation size of 1 BRC (~86 km).

8.3.5.1 Wind observation precision and bias requirements

Precision requirements:

Wind speed varies with height, leading to a height-dependent random (precision) and systematic (bias) error requirement, e.g. as listed in Table 1. The precision associated to radiosonde wind observations is considered by the forecast community as a key indicator for the requested wind observation quality in the GOS (see e.g. Marseille *et al.*, 2013). The reported observation error of radiosondes is less than 1 m/s, and for the best radiosonde tracking systems even below 0.2 m/s (Marseille *et al.*, 2010). When radiosonde observations are assimilated into numerical weather prediction models, the associated observation error is increased, including the above mentioned observation representativeness error and estimated model background error (Marseille *et al.*, 2013, Horanyi *et al.*, 2013). The total associated observation error is mostly defined through the use of statistics, comparing the observations with the model first guess and analysis. Figure 3 shows vertical profiles of the standard deviation and bias of the radiosonde observation minus first guess, together with the equivalent observation minus analysis profiles. This statistics indicate a height-dependent "effective" precision on the order of 2 m/s with a peak around the jet stream and in the stratosphere approaching 3 m/s.

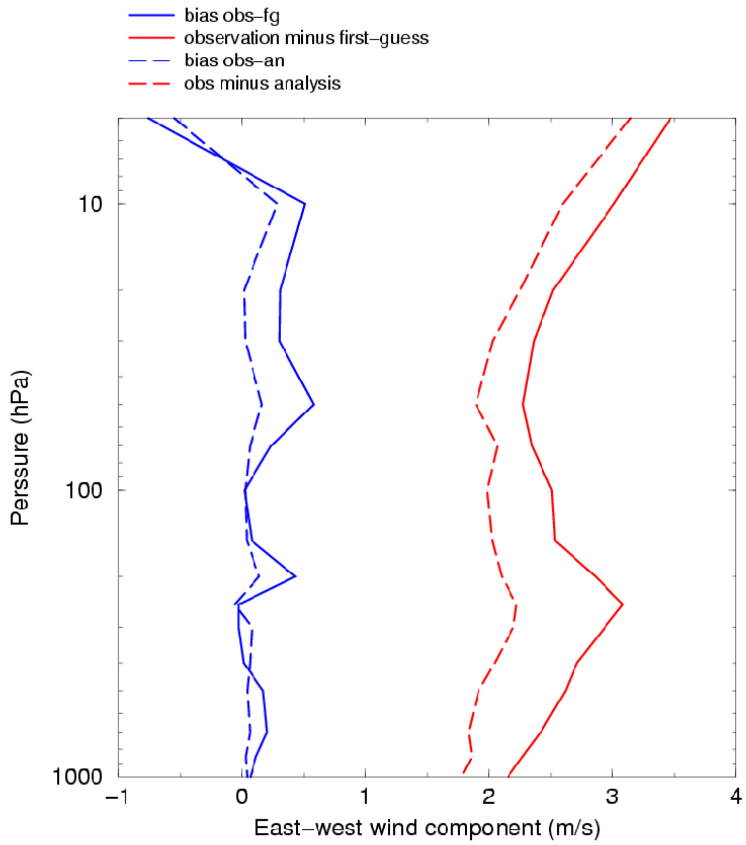

Figure 3: *Mean (blue) and standard deviation (red) of the difference between radiosonde wind observations (east-west component, m/s) and the first-guess (full lines) and analysis (dashed lines), for all stations in the Northern Hemisphere north of 20N, for one day in ECMWF's data assimilation system. The graph provides indication of the combined errors in first-guess and observations. Courtesy ECMWF.*

Marseille *et al.* related radiosonde error statistics to Aeolus observation errors, separating the various errors contributors mentioned above by the method of Desroziers *et al.* (2005). They also calculated the global mean background error in the ECMWF model and showed that the representativeness error of Aeolus observations of about 80 - 100 km horizontal resolution is negligible. When combining these results with the observation minus background (o-b) statistics from Figure 3, the required Aeolus observation error could be calculated, as shown in Table 2.

Height	Radiosonde σ_{o-b} (ms^{-1})	σ_b (ms^{-1})	Aeolus σ_o (ms^{-1})
Surface	2.2	1.05	1.93
700 hPa	2.3	1.48	1.76
500 hPa	2.5	1.64	1.88
250 hPa	3.0	1.87	2.35

Table 2: *Radiosonde (o-b) standard deviation from Figure 3 (2nd column), ECMWF model background errors derived from aircraft (o-b) statistics in Marseille et al (2013) (3rd column), and the corresponding estimated Aeolus instrument precision requirements in order to achieve an identical (o-b) statistics as radiosondes.*

Due to the high amount of available wind observations close to the surface in the current GOS (scatterometers and synop stations), it was recommended to require more accurate Aeolus observations in the PBL (0-2 km altitude) to ensure mission impact. In the lower stratosphere (16-30 km altitude), a further investigation of model background wind error statistics and high resolution radiosonde data showed that Aeolus precision of 3.3 ms^{-1} would yield impact comparable to radiosondes. Marseille *et al.* (2013) also investigated the impact of simulated Aeolus observations in an Ensemble Data Assimilation (EDA) experiment (Tan *et al.*, 2007). The Aeolus observations were simulated using the so-called LIPAS instrument simulation and retrieval software (Marseille *et al.*, 2003). Different EDA experiments were performed with varying simulated Aeolus observation precision. The main conclusion was that Aeolus observation precisions of 1 m/s in the PBL, 2-2.5 m/s in the free troposphere and 3-5 m/s in the stratosphere allows for a significant positive forecast impact, comparable to the impact of radiosondes. **In these investigations, the systematic observation errors (bias) were set to 0 m/s**.

Horanyi *et al.* (2013 and 2015b) performed a series of OSEs with direct wind measurement datasets from the current GOS. In the experiments, the zonal component of the measurements were assimilated, and different random errors were added. The random observation errors (including representativeness errors) were about 2 m/s in the control experiment. These were increased to 2.5 m/s (25% increase), 3 m/s (50% increase) and 4 m/s (100% increase). It was shown that a random error increase of 25% gave, on average, a small forecast impact deterioration as compared to the control experiment. A random error increase of 100% gave a large reduction of the forecast impact, but still did not lead to a significant forecast deterioration. This is consistent with the threshold value for wind observation accuracies given in Table 1, provided that the associated systematic (bias) error is very small. **In these experiments, the systematic errors (bias) were set to 0 m/s**.

As discussed in Bonavita *et al.* (2012), data assimilation systems can also deal with observations being quite noisy as long as the observation precision and bias errors are well known and specified in the assimilation process. Therefore, some NWP centres prefer to assimilate large-scale observations with high precision in their systems, while others believe that smaller-scale observations may be more beneficial even though the precision may be lower.

Marseille *et al.* (2013) and Horanyi *et al.* (2013) hence both concluded that a 1 m/s (PBL), 2-3 m/s (free troposphere) and 3-5 m/s (stratosphere) "effective" observation accuracy requirement is expected to be sufficient to provide a beneficial impact on meteorological analyses. **This requirement is valid provided that the observation systematic error (bias) is 0 m/s (see next paragraph).**

Bias requirements:

For satellite observations, observation errors may vary due to a varying thermal environment or satellite attitude and altitude over an orbit. In this case, the variability follows harmonic functions with frequency components given by multiples of the orbital frequency. Such biases must be minimized by suitable design and calibration procedures. Systematic errors in space-based DWL observations can hence come from undetected instrument misalignments, LOS mispointing and calibration errors. The biases can be divided into a component that stays independent of the observed wind speed ('zero wind bias') and a component that varies proportional to the observed wind speed ('slope error'). Both bias components can vary or remain constant with time. Constant biases can be significantly reduced or eliminated by suitable calibration by other co-located high-quality observations and/or NWP monitoring techniques.

Horanyi *et al.* (2013) and Horanyi (2014 and 2015b) investigated the effect of constant and varying systematic Aeolus observation errors in dedicated OSE experiments. In the first set of OSE experiments, constant biases of 0.5, 1 and 2 m/s were added to radiosonde, aircraft, PILOT and wind profiler data. The results showed that an unknown bias of 0.5 m/s (in addition to the corresponding data-specific observation random errors) still allowed for a significant forecast impact. A bias of 1 m/s still allowed for a global neutral forecast impact (no significant forecast deterioration w.r.t. an observation denial experiment) but a clearly reduced impact as compared to unbiased data. A 2 m/s bias lead to a significant forecast deterioration. Further OSE experiments were performed looking at wind-speed dependent biases (caused by detector response slope errors) and orbit-dependent errors caused by thermal effects or platform miss-pointing. Also, the effect of uncorrected satellite altitude variations was considered. The same observation dataset was used. (Horanyi, 2014). In conclusion it was found that negative biases at the Equator have larger negative impacts than positive ones. A wind speed dependent bias of ±0.7% did not cause major concerns in terms of global NWP impact. Latitudinal biases might lead to significantly reduced observation impact, especially if the highest bias values are at the Equator (and even more if they are negative). Altitude dependent biases are generally very detrimental and should be avoided in order not to counteract the general positive impacts at the jet level. In conclusion, the most detrimental type of bias variability is altitude-dependent variations. Secondly, biases should be avoided along the Equator by design or if unavoidable through characterization and bias correction. This is especially true for negative biases.

In chapter 7 of Marseille *et al.* (2013), a theoretical tool, developed by met.no, was used to assess analysis impact for different levels of constant systematic observation errors. The random error (precision) of the simulated Aeolus observations was 2.5 m/s. The analysis tool computes analysis error covariance matrices for a one-dimensional assimilation of HLOS winds along a horizontal satellite track to study the horizontal sampling. When inserting background error covariances extracted from operational NWP systems and an observation operator for a certain horizontal sampling and corresponding estimate of observation errors (in terms of an observation error covariance matrix), the analysis error covariance matrix can be calculated. The method follows standard data assimilation theory (identical to that behind variational and optimal interpolation schemes). The tool was used to assess the impact of constant biases of 0, 0.5, 1, 2, 4, 8 and 16 ms^{-1}. The analysis showed that Aeolus impact decreases substantially for biases of 0.5 ms^{-1} and larger, with even negative impact for biases exceeding 1.5 ms^{-1}. EDA experiments could not be used to investigate observation biases because the method estimates forecast spread and not the absolute forecast quality as compared to a control experiment.

Turbulence induced errors occur in the PBL, orographic waves, Clear Air Turbulence (CAT) and convective conditions may introduce large systematic errors (bias) in the Aeolus observations. It is assumed that the assimilation process will be able to detect such situations and add an additional error to the observations in such conditions (Wergen, 2011). It is therefore ignored in the further specifications of the required measurement precisions.

The analysis above were performed investigating either forecast impact of different random errors only, or a fixed random error for different systematic errors. It was concluded that a combination of the Aeolus systematic (bias) and random (precision) errors must fulfil WHO accuracy requirements. Unknown systematic errors must be kept low and at least below 1 m/s (threshold). **Based on this, the following bias and precision requirements have been defined for the Aeolus L2B product:**

MR-100: The bias of the HLOS wind observations shall not exceed 0.7 m/s over all mission time periods (1 minute to 3 years), over the required dynamic range (MR-95), and over the required vertical measurement domain (MR-85)

MR-110: The precision of the HLOS wind observations shall be better than 1 m/s in the PBL (0-2 km altitude) and 2.5 m/s in the free Troposphere (2 – 16 km altitude). Above 16 km, it is desirable to achieve a precision of 3 m/s between 16-20 km altitude and 3-5 m/s between 20 and 30 km

8.3.5.2 Error correlation

Spatially correlated errors are potentially very damaging in data assimilation, in particular when the error structure is not well known and when the general assumption is that the observation error covariance matrix is diagonal. For example, the spatial error structure in satellite temperature and humidity profiles has been a problem in meteorological data assimilation for more than a decade. In particular, when the precise spatial observation error correlation characteristics are poorly known, the analysis may have high-pass-filter characteristics and the resulting analysis can be noisy (Liu and Rabier, 2002).

Air-mass-dependent errors are the most damaging, since these potentially change the way in which air masses interact. In the case of wind observations, vertical error correlations concern the measured vertical wind-shear. The first-guess vertical error-correlation scale is small and any vertical correlation error structure may be potentially very damaging since wind-shear information may be lost. In the case of a wind shear of 2 m/s between two adjacent levels (common both in the boundary layer and around the jet stream) a correlated error of a few tenths of m/s may already significantly blur the detection of such shear. Horizontal error correlation between profiles also require attention, although these are possibly less damaging than vertical error correlation.

As described by Horanyi *et al.* (2013); "Correlated observation errors are typically instrument dependent, data processing dependent or atmospheric state dependent. Observation errors can be temporally (which can be the case e.g. for SYNOP surface observations), spectrally (e.g. for multi-spectral satellite data) or spatially (e.g. Aeolus) correlated. For example, if an observation has a given temporal random error, and neighbouring observations (in space) have the same (or partially correlated), the observation errors are correlated. Observations are biased if they have a systematic (not random) deviation from the true value. A bias may pose a more serious problem than random errors because it cannot be reduced by mere increase in sample size and averaging the outcomes. Observations can be biased with or without having correlated errors. In the case of Aeolus, spatial observation error correlations must be minimized. This can be done through careful instrument design, calibration and data processing and/or by observation thinning.

When doing observation thinning, an optimal compromise between the benefit of including more data and the harming effects of not accounting properly for observation error correlations in the assimilation system must be found. It is often very difficult, both technically and scientifically, to account explicitly for correlated observation errors. As shown e.g. by Desroziers, 2011 and Liu and Rabier, 2002, even in the case of a correct consideration of observation error correlations in the data assimilation process, the precision of the analysis will not improve below a certain limit (red line Figure 4). In case of uncorrelated observations, the quality of the analysis is monotonously increasing with the increase of the observation amount and density (black line Figure 4). In case of correlated errors, the analysis error is decreasing until the correlated effects of dense data kicks in (blue line in Figure 4). Because the observation error covariances don't account properly for the correlations, the dense data cause a degradation of the analysis. The optimal thinning corresponds to the inflexion point."

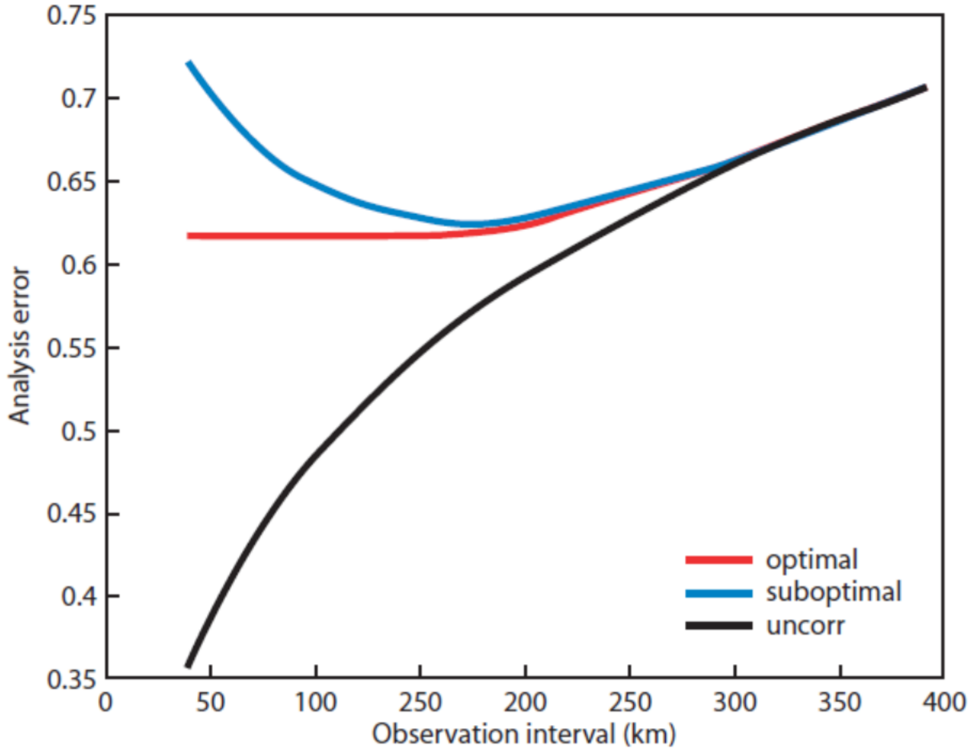

Figure 4: *The change in analysis error with respect to the increase of observation resolution for a data set that contains spatially correlated errors. The red line represents a data assimilation system where correlated errors are taken into account (in a perfect way); the blue line represents a data assimilation system not accounting for correlated observation errors and the black line represents assimilation of uncorrelated observations. (Desroziers, 2011).*

Further from Horanyi *et al.*, 2013; "In case of the Aeolus mission, possible spatial error correlations need to be considered. At the same time, the quantification of a threshold value, where the effect of the correlated errors balance the benefit of including the information provided by the observations, is a very difficult task. Continuously spaced horizontally averaged lidar observations are spatially correlated when observing large-scale geophysical features. The most extensive theoretical study on observation error correlations performed by Liu and Rabier (2002) provides a general recommendation for observation error correlations using a simple one-dimensional model. The authors concluded that thinning data to the level where neighbouring observations has a 0.15 spatial correlation value will lead to the optimal use of the data. Bormann *et al.* (2003) investigated horizontal correlations for AMV data and concluded that the large correlations (often larger than 0.35 over 200 km) caused detrimental impact of the data, so it was necessary to thin the data heavily and also assign large observations errors to account for correlation (in a suboptimal way). Bormann *et al.* (2011) found that for microwave imager radiances, the error correlation value of **0.2** is too high and thinning is needed to avoid detrimental effects on forecast quality. These results leads us to propose to keep Aeolus observation correlations below 0.15 per 100 km. On the other hand, one should notice that all these studies were considering point measurements and may therefore not be directly applicable to Aeolus observations. Therefore, M. Rennie at ECMWF made a simple "toy" model (1D grid of state variables with flexible boundaries and resolution) for the testing the

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impact of Aeolus observation error correlation. The study showed a damaging effect of observation error correlation, increasing rapidly for any value larger than 0.01. It was therefore concluded that observation error correlation for Aeolus data should therefore be kept to a minimum to get good impact, hence it is propose to reduce observation correlation to 0.01 per 100 km."

Marseille *et al.* (2013) concluded the following; "Given that global NWP models cannot well resolve scales below 180 km in 2016, errors from observations from profiles separated by less than 180 km are inherently correlated, violating the 0.01 requirement. Observation thinning or error inflation are effective methods to deal with correlated errors. In this report, error correlation was linked to horizontal distance by defining the observation error correlation function as a Gaussian with length scale L, with L being the value where the correlation function equals 1/e. A correlation of 0.01 then means that the correlation function has dropped to a value of 0.01 for the distance of two neighbouring observations. A theoretical tool was used to translate the impact of observation error correlation to the impact of random observation error. It was found that a correlation of 0.01 corresponds to an increase of the observation random errors (precision) of less than 0.1 m/s, a correlation of 0.1 corresponds to an increase of the observation precision of about 0.2 m/s and a correlation of 0.38 corresponds to an increase of the observation precision of about 0.7 m/s. Accepting impact reduction of 10% relative to the maximum achievable impact for observations without correlated errors implies that a correlation value between 0.1 and 0.15 seems reasonable for the error of neighbouring observations. A correlation value of 0.1 corresponds to a Gaussian observation error correlation function with L=66 km and observations separated by 100 km. Although not investigated explicitly in the vertical, it is anticipated that adjacent vertical observations should have similarly small correlations."

In the case of Aeolus, two examples of possible damaging instrument-related error correlations have been identified so far, namely excessive laser frequency jitter interacting with inhomogeneous cirrus or broken clouds within one measurement, or significant range-dependent biases. In the Aeolus design, the atmospheric direct backscatter signal from the outgoing laser pulses are accumulated on-board the spacecraft to measurements before data down-link. This means that a pulse-to-pulse normalization of the signal frequency with the internal reference is not possible. The frequency of the pulses averaged over one measurement will hence be affected by atmospheric heterogeneities within the measurement bin, and these errors will be vertically correlated below the bin for the Rayleigh channel. Uncorrected range-dependent biases will cause horizontal error correlation.

Given the consistent recommendation from the extensive study of Liu and Rabier (2002) and the theoretical investigations from Marseille *et al.* (2013), the following requirement on observation error correlation is defined:

MR-120: The observation error correlation shall be less than 0.1 per 100 km and between adjacent vertical bins

8.3.5.3 Probability of gross error

Routine data assimilation systems include quality-control procedures to prevent observations having large errors from affecting the atmospheric analysis (e.g. Lorenc and Hammon, 1988). This can be done e.g. by comparison of the observation with the model background and rejection in case the deviation between the two are above a defined threshold. When a gross error occurs as illustrated in Figure 1, the observation does not relate to the true atmospheric state and can therefore potentially damage the objective analysis, leading to an incorrect picture of the state of the atmosphere. For conventional systems, gross errors are usually caused by data transmission or instrument failure, or by spatially unrepresentative measurements. A classic example of the latter is the release of a radiosonde through a thunderstorm. Forecasts are known to be sensitive to gross-error elimination procedures in critical atmospheric conditions (ESA, 1996).

Many operational centres are using or developing variational analysis systems. The variational analysis system is quite flexible in dealing with observations with complex error characteristics. However, for the observations to be useful, their characteristics have to be known in detail *a priori*. Experience with conventional observation systems and associated instrument and retrieval quality control (QC), decisions in operational meteorological analysis indicate that the rate, or probability, of gross errors presented to the analysis (after QC) should not exceed a few percent (e.g. Lorenc and Hammon, 1988). All signal characteristics have to be used in the data processing to optimally specify the observation errors in order to reject measurements containing no information on the true atmospheric state. All this is necessary to prevent random wind estimates that are, by coincidence, close to the true wind, from influencing the analysis. For scientific applications not involving data assimilation, data quality control is even more important due to the lack of background information of the atmospheric state. For such applications, undetected gross errors in observations can be detrimental for the scientific analysis.

As explained by O. Reitebuch (DLR) in a theoretical analysis evaluating the ALADIN gross error requirement: "Gross errors are defined as errors beyond a defined threshold, representing large outliers in the wind estimate that have not been flagged invalid by the data processing algorithms. It is mainly applicable for observations with error characteristics as depicted in **Figure 1, where gross errors are represented by the shaded area. This is expected for the ALADIN Mie winds, and not the Rayleigh winds which will have an almost Gaussian error distribution only**. Gross error requirement are only applicable to non-Gaussian error sources because the Gaussian errors are covered by the random error requirement. A realistic range for consideration of a uniform distribution of outliers from a space-based Doppler wind lidar system would be a range of six times the standard deviation of a Gaussian error distribution ($6\sigma_{LOS}$). Quality Control (QC) algorithms on instrument level will not be able to flag uniformly distributed outliers within this range. For a random error (precision) σ_{LOS} in the range of 2-3 m/s, the gross-error standard deviation would be:

$$\sigma_{Gross} = \frac{Vs}{\sqrt{12}} \qquad \text{(Eq. 3)}$$

hence 3.5 – 5.2 m/s. If one assumes that the observations contain 5% gross errors (e.g. P_{ge}=0.05), this would increase the total random error by about 5% if the gross errors are limited to a range of $V_s=6\sigma_{LOS}$ (which is considered an acceptable increase). It will hence not be possible to distinguish between a uniformly distributed gross error within a given range, and a Gaussian distributed error, if the range of the uniform distribution is comparable to the width of the Gaussian.
When comparing ALADIN winds with other observations (or the model background), it will hence not be possible to distinguish both error sources. Both error distributions will be present in the instrument as Gaussian errors arising from Poisson-distributed photon noise and uniform distributed errors arising from outliers in the detection on the ACCD, transmission, or signal analysis.
Gross errors will occur also outside of the 6σLOS wind speed range. The total wind speed range V_s is determined by the HLOS dynamic range (±100 m/s and ±150 m/s capability). The standard deviation of the corresponding uniform distribution of gross errors over the total wind speed range corresponds to 58 m/s and 87 m/s. Thus, the Aeolus L1B and L2B Mie core algorithm QC schemes (**mainly the signal-to-noise threshold setting**) needs to eliminate all gross outliers (100%) outside of the range of V_s=6σLOS. Otherwise the random error would be dominated by the uniform gross error distribution, rather than the Gaussian distribution."

MR-130: The probability of gross errors shall be less than 5% within a wind speed range of 6 times the random error requirement. Outside this wind speed range the gross error shall be 0%

8.3.6 Data timeliness, track availability and mission duration

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 data cut-off times (allowing time for data preparation before the start of the assimilation) are applied. For numerical weather prediction, acceptable timeliness for short- (12-72 hours) and medium-range (72 to 240 hours) forecasting vary generally between 30 minutes and more than 6 hours (e.g. WMO, 2011), depending on the analysis time window and analysis cut-off delay. A timeliness requirement of 3 hours is usually specified in NWP for NRT space-borne observations. Recently, regional QRT delivery (within 30 minutes of sensing by polar-orbiting operational meteorological instrumentation) has been initiated. It is thus desirable to receive (parts of) the measurements as close to sensing as possible.

For regional modelling, the NRT requirement is valid for the model domain. This means that observations outside of the region of interest do not need to be NRT. Aeolus, being a European wind lidar mission, shall serve European weather forecasting both on short and medium range. A goal requirement is to have all measurement data available in NRT, and a threshold requirement is that a few orbits outside the region influencing European weather on the short range (12 – 72 hours) may be delivered with a few hours further delay (see discussion of track data availability in the following paragraph).

Data impact is dependent on the data meeting the required accuracy and temporal and spatial coverage. Many remote sensing instruments cannot operate in nominal measurement mode 100% of the time because some time is needed for regular instrument calibration. Also, anomalies can lead to occasional instrument down time. It is recommended to have a track data availability of 95%, meaning that the instrument is working nominally in measurement mode and be available NRT at least for areas impacting European weather on the short term (12-72 hours). Blind orbits, hence orbits not meeting the NRT requirements, are tolerated out-side this range.

It is recommended that the length of the observational dataset is at least three years in order to allow a demonstration of Aeolus for an operational mission. When a new instrument technology is launched into space, time is needed for instrument calibration, validation and operations and algorithm optimization. When the data quality has been established, the assimilation of the new data type over a couple of years is needed to optimize and demonstrate its impact.

MR-140: The mission shall ensure L1b data delivery (timeliness) within 3 hours of sensing, in particular for the areas influencing European weather on short range (12-72 hrs)

MR-150: The mission shall ensure a horizontal track wind observation data availability of at least 95% within a repeat cycle during routine operation in phase E2

MR-160: The mission dataset length shall be at least 3 years

8.4 Summary of Requirements

The above identified Aeolus mission requirements can be listed as follows:

MR-10	ESA shall implement NRT delivery of L1B data to users, delivery of a L2B processor and L2A, L2B, L2C, calibration and auxiliary products, relevant product and processing-related documentation, and a long-term archive of the mission L0, L1B, L2A, L2B, L2C, calibration and auxiliary data
MR-20	The measurement technique shall provide accurate wind observation profiles in clear atmosphere, within and below optically thin clouds, and at the top of optically thick clouds
MR-30	The orbit shall provide globally distributed measurements within one day allowing the necessary pointing and instrument stability to meet MR-75, MR-80, MR-100 and MR-110
MR-40	Profiles of horizontally projected line-of-sight wind observations shall be provided, preferably in the zonal direction

MR-50	Wind observation profiles shall be provided with a horizontal observation resolution of less than 100 km, with sub-sample information (measurements) on 3 km scale
MR-60	Wind observation profiles shall be provided with a vertical resolution as follows: 250 m (ground echoes for calibration purposes), 500 m (PBL: 0-2 km altitude), 1 km (free Troposphere: 2-16 km altitude), 2 km (lower Stratosphere: above 16 km)
MR-70	At least 100 independent wind observation profiles per hour shall be provided
MR-75	A collection of wind observation profiles, evenly distributed over the globe, shall be achieved every 12 hours
MR-80	The mission shall provide global coverage
MR-85	The mission shall provide wind observation profiles from the surface up to 20 km (threshold). An extended sampling to 30 km is desirable (goal)
MR-90	The wind observation profiles shall have a dynamic range of +/-150 m/s along the HLOS direction
MR-95	The wind observation profile performances shall be applicable over a dynamic range of +/-100 m/s along the HLOS direction
MR-100	The bias of the HLOS wind observations shall not exceed 0.7 m/s over all mission time periods (1 minute to 3 years), over the required dynamic range (MR-95), and over the required vertical measurement domain (MR-85)
MR-110	The precision of the HLOS wind observations shall be better than 1 m/s in the PBL (0-2 km altitude) and 2.5 m/s in the free Troposphere (2 – 16 km altitude). Above 16 km, it is desirable to achieve a precision of 3 m/s between 16-20 km altitude and 3-5 m/s between 20 and 30 km
MR-120	The observation error correlation shall be less than 0.1 per 100 km and between adjacent vertical bins
MR-130	The probability of gross errors shall be less than 5% within a wind speed range of 6 times the random error requirement. Outside this wind speed range the gross error shall be 0%
MR-140	The mission shall ensure L1B data delivery (timeliness) within 3 hours of sensing, in particular for the areas influencing European weather on short range (12-72 hrs)
MR-150	The mission shall ensure a horizontal track wind observation data availability of at least 95% within a repeat cycle during routine operation in phase E2
MR-160	The mission dataset length shall be at least 3 years

Table 3: *Overview of the Aeolus Mission Requirements*

Table 4 provides an overview of a subset of the observation requirements discussed in section 8.

Requirement ID	Observation Requirements		PBL	Troposphere	Stratosphere
MR-85	Vertical Domain	[km]	0-2	2-16	16-20 (30)*
MR-60	Vertical Resolution	[km]	0.5	1.0	2.0
MR-80	Horizontal Domain		Global		
MR-70	Number of Profiles (sampling)	[hour^{-1}]	>100		
MR-150	Minimum horizontal track data availability	[%]	95		
MR-75	Temporal sampling	[hour]	12		
MR-50	Horizontal observation size (L1 and L2)	[km]	15 (goal) – 100 (threshold)		
MR-50	Horizontal measurement size	[km]	3 km		
MR-110	Precision (HLOS Component, L2)	[m/s]	1	2.5	3* (3-5)*
MR-100	Systematic error (HLOS component, L2)	[m/s]	0.7		
MR-90&95	Dynamic Range, HLOS	[m/s]	±100 (150)**		
MR-120	Error Correlation (per 100 km and between adjacent vertical bins, L2)		< 0.1		
MR-130	Probability of Gross Error (L2)	[%]	5		
MR-140	Timeliness (L1)	[hour]	3		
MR-160	Length of Observation Dataset	[yr]	3		

Table 4 *Observational requirements of the Atmospheric Dynamics Mission Aeolus for a realistic (heterogeneous) atmosphere. ()*: Desirable, (i) atmospheric sampling from the surface up to 20 km altitude is required whereas sampling up to 30 km is highly desirable, (ii) above 16 km there is no formal requirement on the HLOS precision, but a precision of 3 m/s between 16 and 20 km and 3-5 m/s between 20 and 30 km is desirable. ()**: Wind observation performance requirements are linked to a dynamic range of +/-100 m/s, wind observations shall not saturate up to +/-150 m/s.*

For a mission intended to demonstrate the feasibility of a full-scale space-borne wind observing system to improve global atmospheric analyses, the requirements on accuracy and vertical resolution are the most stringent and most important to achieve. The derivation of the coverage specification is supported by weather-forecast-impact experiments, which included the inputs of the conventional wind-profile network that is sparse and irregular but of key importance (Horanyi *et al.*, 2013 and 2015a).

9 THE ADM-AEOLUS MISSION

9.1 Mission measurement concept and operation

A detailed instrument description is provided in the Aeolus Science Report (ESA, 2008). A short summary of the main instrument features is provided here. Please note that a few instrument concepts have changed since ESA (2008) was issued, such as the change from burst to continuous mode operation.

The Aeolus satellite carries a single instrument – a Doppler wind lidar called Aladin (Figure 5). Aladin is a pulsed UV lidar (355 nm, circularly polarized, 50 Hz), measuring continuously along the orbit (Figure 6, left panel). The laser system emits short powerful pulses of ultraviolet light down into the atmosphere. The telescope collects the light that is backscattered from air molecules, aerosols and hydrometeors. The receiver analyses the Doppler shift of the backscattered signal to determine the wind speed at various altitudes below the satellite (Figure 7). Its high spectral resolution concept allows for the detection of the parallel polarized molecular (Rayleigh) and particle (Mie) backscattered signals in two separate channels, each sampling the wind in 24 vertical height bins (Figure 6, right panel). This makes it possible to deliver winds both in clear and (partly) cloudy conditions down to optically thick clouds. The height of the wind measurement is detected by time-gating. A quasi-global coverage is achieved daily (~ 15 orbits per day) and the orbit repeat cycle is 7 days (109 orbits). The orbit is sun-synchronous with a local equatorial crossing-time of 6 am/pm. Comprising a powerful transmit laser, a large telescope and a very sensitive receiver (Figure 7), Aladin will be the first Doppler wind lidar in space.

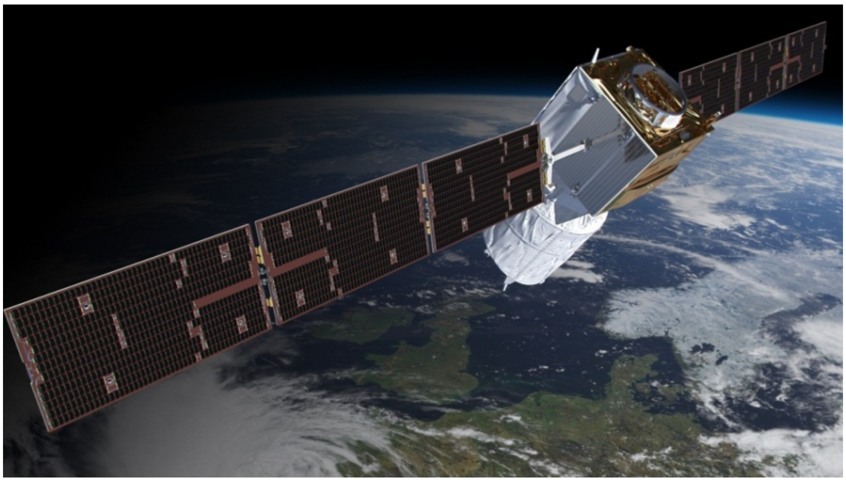

Figure 5: *An artists' view of Aeolus in-flight, illustrating its dusk-dawn orbit.*

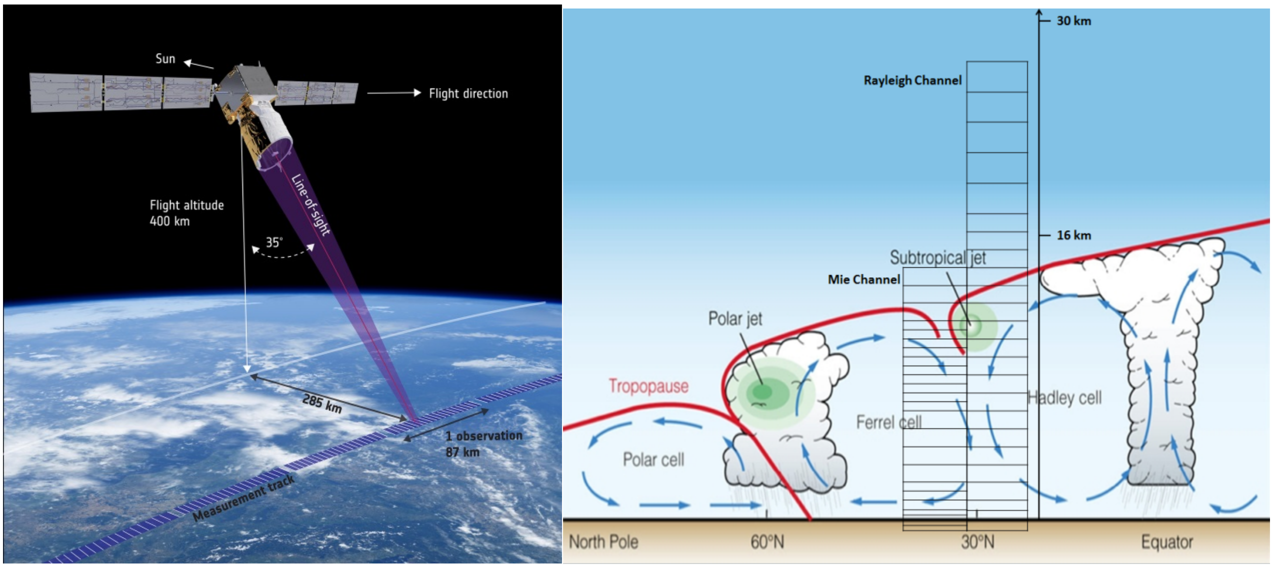

Figure 6: *Aeolus measurement geometry (left) and vertical sampling by its molecular (Rayleigh) and particle (Mie) channels (right).*

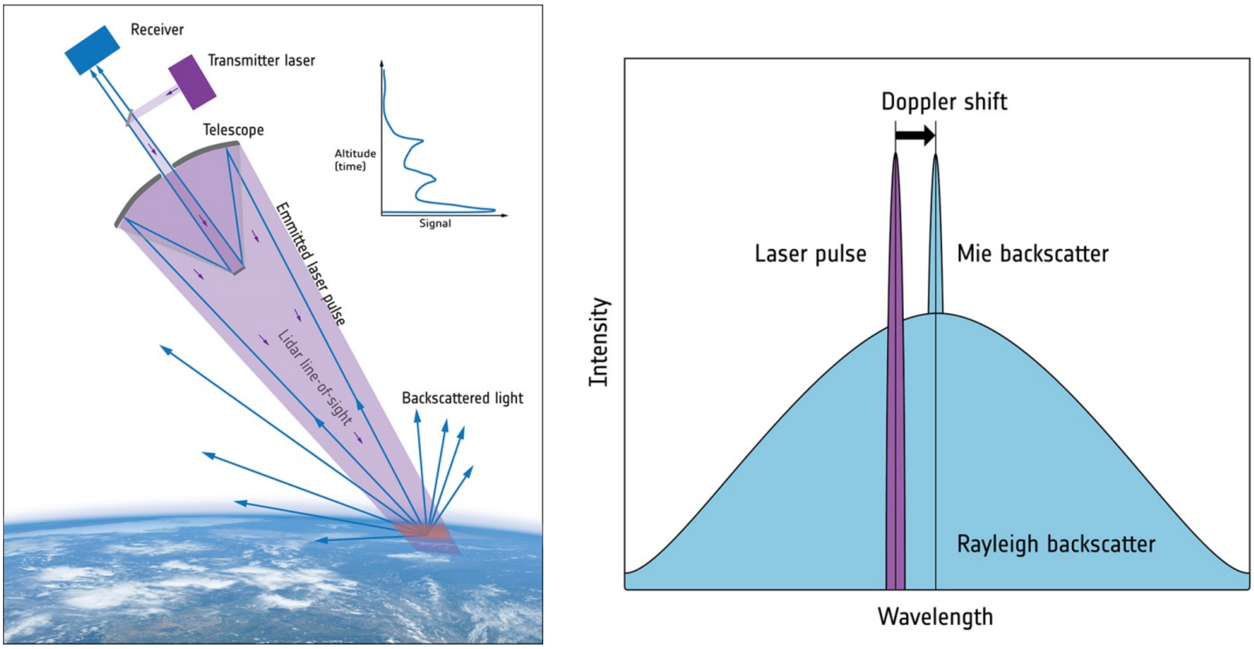

Figure 7: *The ALADIN measurement principle. Wind and atmospheric optical properties profile measurements are derived from the Doppler shifted signals that are back-scattered along the lidar line-of-sight (LOS).*

The Aladin instrument will be operated in six different modes, as summarized in Table 5. Besides the nominal Wind Velocity Measurement (WVM) mode, eight calibration, characterisation and health-check modes are implemented.

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Instrument Operation	Acronym	Occurrence	Purpose	Transmitter frequency (range/step)	Processed data
Instrument Spectral Registration	ISR	On-ground and Commissioning phase	To centre laser transmitter frequency and calibration for L2	[-5.5, +5.5 GHz] Step 25 MHz	Internal
Instrument Auto test	IAT	On-ground and/or in-orbit health check	To verify Mie/Rayleigh receiver (MSP/RSP) spectral transfer functions	[-5.0, -0.75 GHz] and [0.75, 5.0 GHz] with 250 MHz steps [-0.75, +0.75 GHz] with 25 MHz steps	Internal
Dark Current Calibration	DCC	On-ground In-orbit	To characterise detection chain in darkness	Fixed	Internal
Instrument Defocus Characterization	IDC	On-ground characterization, in-orbit, preparatory phase, every 100 orbits	To characterise defocus of optics by measuring Rayleigh spot size	Fixed	External on RSP
Instrument (Mie, Rayleigh) Response Calibration	IRC MRC RRC	On-ground functional testing, in-flight every 100 orbits	To measure MSP and RSP response with satellite in nadir, including centring of frequency	[-0.5, +0.5 GHz] Step 25 MHz	Internal and ground return on MSP and RSP, and atmosphere on RSP
Wind Velocity Measurement	WVM	On-ground characterization, nominal mode	Nominal wind measurement mode	Fixed	Internal, atmosphere and ground return on MSP and RSP

Table 5: *Aladin Instrument operation modes. RSP: Rayleigh spectrometer. MSP: Mie spectrometer.*

9.2 Aeolus data processing and product overview

The Aeolus products and how they are derived are described in the respective product Algorithm Theoretical Basis Documents (ATBDs) [Reitebuch *et al.*, 2014, Flamant *et al.*, 2015, Tan *et al.*, 2015]. The main data processing steps for the Aeolus wind and aerosol products is illustrated in Figure 8.

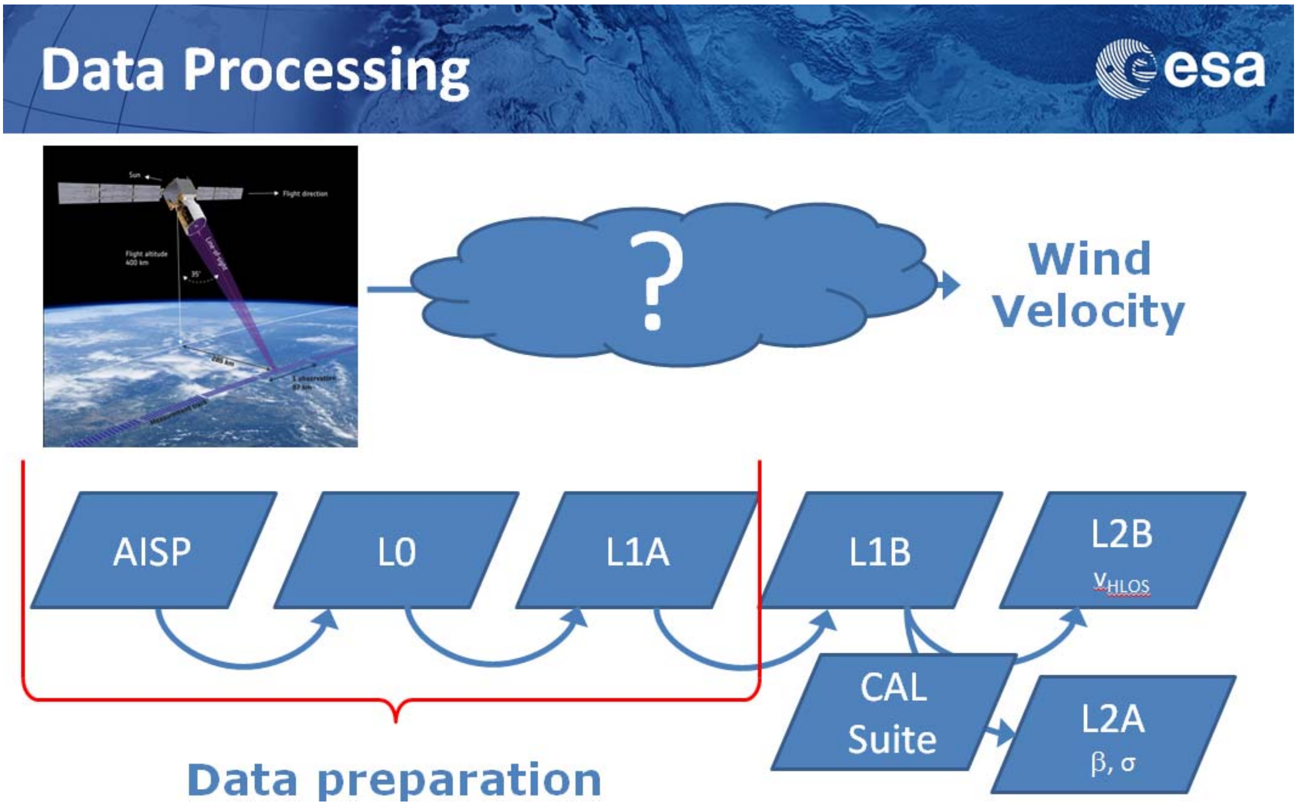

Figure 8: *Schematic overview of the Aeolus data processing steps. Courtesy: T. Kanitz.*

The main product from Aeolus will be horizontally projected line-of-sight (HLOS) wind observation profiles (approximately zonally oriented) from the surface up to about 30 km. The product levels and individual products are described in the product Input Output Data Definition documents (IODDs) (MDA *et al.*, 2016, Huber *et al.*, 2013, de Kloe *et al.*, 2015) and an overview is provided in Table 6.

Product/ Data Set	**Contents**	**Approx. Size [Mbytes/ orbit]**	**Remarks**
AISP ("Raw Data")	**<u>Header Data</u>** FH **<u>Measurement data</u>** Instrument source packet data with raw Aladin measurement data and platform housekeeping/AOCS data (CDMU)	50	Actual sensing period will typically cover 1 orbit but may vary in the range ~ 0.5 … 1.5 orbits, depending on actual X-band downlink scenario

Product/ Data Set	Contents	Approx. Size [Mbytes/ orbit]	Remarks
Level 0	**<u>Header Data</u>** FH, VH (MPH + SPH) **<u>Measurement data</u>** Instrument source packet (ISP) data with - Raw Aladin measurement data (DEU output) - Instrument housekeeping data (ACDM) - Aeolus platform housekeeping/AOCS data (CDMU) **<u>Annotation data</u>** - Vertical sampling grid information - Calibrated housekeeping data (ACDM + CDMU) - Instrument health parameters	55	
Level 1A	**<u>Header Data</u>** FH, VH (MPH + SPH) **<u>Measurement data</u>** - Reconstructed Aladin measurement data (DEU output data, no processing performed) - Pre-processed AOCS and orbit geometry data **<u>Annotation data</u>** - Vertical sampling grid information - Calibrated housekeeping data (ACDM + CDMU) - Instrument health parameters	70	
Level 1B	**<u>Header Data</u>** FH, VH (MPH + SPH) **<u>Measurement data</u>** - Processed ground echo data - Preliminary HLOS wind observations (calibrations applied (zero wind correction, receiver response calibration, harmonic and range dependent bias corrections) - Viewing geometry & scene geolocation data **<u>Annotation data</u>** - Processed calibration data - Product confidence data (PCD) - Calibrated housekeeping data (ACDM+CDMU)	90	Preliminary HLOS data for Rayleigh channel based on standard (default) atmospheric corrections

Product/ Data Set	Contents	Approx. Size [Mbytes/ orbit]	Remarks
Level 2A	**Header Data** FH, VH (MPH + SPH) **Measurement data** - Geo-located consolidated backscatter and extinction profiles, backscatter-to-extinction (BER) ratio per observation - Scene classified backscatter, extinction and BER profiles - Error information **Annotation data** - Product confidence data (PCD) - Others	20	
Level 2B	**Header Data** FH, VH (MPH + SPH) **Measurement data** - Geo-located consolidated HLOS wind observations, after applying actual atmospheric corrections to Rayleigh channel data - Error information **Annotation data** - Product confidence data (PCD) - Others	22	
Level 2C	**Header Data** FH, VH (MPH + SPH) **Measurement data** - Vertical profiles of wind vectors (horizontal components, u and v) - Supplementary geophysical parameters - Fully processed error information **Annotation data** - NWP model settings - Definition of non-Aeolus model input data - Product confidence data (PCD) - Others	25	Aeolus assisted wind fields, resulting from NWP assimilation processing. Data co-located in time and space with Aeolus wind observations
Higher level data products	No processing, dissemination of higher level data products by the PDGS envisaged	-/-	

Product/ Data Set	Contents	Approx. Size [Mbytes/ orbit]	Remarks
Auxiliary data	**Header Data** FH, VH (MPH + SPH) **Data blocks** - Instrument characterisation data (AUX_CHAR) - Miss-pointing / geometry correction data (AUX_HBE, AUX_RDB) - In-flight calibration data (AUX_RRC, AUX_MRC, AUX_HBE, AUX_CAL, AUX_RBC, …) - Algorithm configuration parameters, settings (AUX_PAR) - Information on atmospheric state (e.g. pressure, temperature, humidity etc. from a forecast model) (AUX_MET) and an atmospheric backscatter-to-extinction ratio climatology (AUX_CLM) - Validation thresholds / templates - Others	40	Examples of Aeolus auxiliary files: AUX_PAR_1B AUX_PAR_2A AUX_PAR_2B AUX_PAR_CL AUX_RRC_1B AUX_MRC_1B AUX_HBE_1B AUX_RDB_1B AUX_MET_12 AUX_RBC_L2 AUX_CAL_L2 AUX_CLM_L2 For further details, see section 9.2.6 below

Table 6: *Aeolus data products and product levels. For an explanation of acronyms and abbreviations, see chapter 4.*

9.2.1 Data down-link and data preparation (L0 and L2A)

The data that is sent from the satellite to the ground station in Svalbard is called Annotated Instrument Source Packets (AISP). These “raw data” contain instrument, platform, orbit and measurement related information. The scientific data contains the averaged detector signal from each altitude bin together with information on the frequency of the individual outgoing laser pulses. In addition, instrument calibration data (mainly spectral calibration) will be obtained from on-board calibration measurements. These calibration data will be used on ground for the L1B processing. As reported in section 9.1, the atmospheric returns from individual laser pulses (shots) are averaged on-board the spacecraft to a so-called measurement. The current instrument baseline is a measurement size of 3 km (average over 0.4 s or 20 shots). The instrument also measures the laser frequency for every laser shot via the so-called “instrument internal path” (internal reference). These measurements are not averaged on-board.

The AISP is further processed to Level 0 (L0) and to Level 1A (L1A) at the Aeolus Processing Facility (APF) in Tromsø, Norway. This processing is in preparation of the Level 1B (L1B) processing, and consists of “cleaning” and time-ordering of the raw data (L0), and measurement geo-location and full processing of satellite house-keeping data (L1A).

9.2.2 Data processing to Level 1B

At the APF the further L1B processing results in the L1B data product, which contains preliminary horizontally projected line-of-sight (HLOS) winds, processed calibration files (including instrument characterization, instrument settings and calibration processor output), product confidence data (e.g. random and systematic errors and product quality flags), and Mie and Rayleigh useful signal profiles. The Aeolus L1B product is calibrated using information on instrument offsets, atmospheric background and the instrument responses in both channels. The data are further corrected with information on the satellite pointing both from the satellite attitude information and through the use of a so-called Harmonic Bias Estimator. The Harmonic Bias Estimator collects valid ground returns over a number of orbits to characterize the instrument pointing, altitude and thermal effects as a function of orbit position. The output of the tool is used to correct the retrieved wind Doppler shifts for these effects. Also, range-dependent errors in the instrument responses are corrected by a range-dependent bias correction algorithm after a dedicated instrument characterization observation campaign.

9.2.3 Dedicated calibration for Level 2 retrieval (CAL Suite)

A dedicated chain of calibration processors for the further Level 2A (L2A) and Level 2B (L2B) processing (the so-called Calibration Suite) is run in the Aeolus Calibration and Monitoring Facility (ACMF) in ESA-ESRIN. The Calibration Suite produce auxiliary data files used in the L2 processing described in the sections below.

One of the files produced by the Calibration Suite allows for a Rayleigh-Brillouin scattering correction of the atmospheric backscatter. The monochromatic Aladin emitted laser light that is backscattered by molecules undergoes a frequency broadening which is both temperature (Rayleigh) and pressure (Brillouin) dependent. The atmospheric temperature and pressure along the lidar line-of-sight is in general unknown during the time of the L1B processing. Thus the output from the molecular channel will be given for a standard temperature and pressure profile. This simplification is corrected during the Level 2 processing, making use of NWP 6-h forecast information (AUX_MET, see section 9.2.6 below) on the local temperature and pressure throughout the measurement volume. The effectiveness of the correction is strongly dependent on the provision of a well-characterized instrument spectral response. The Calibration Suite prepares a look-up table for the instrument Rayleigh responses as a function of atmospheric temperature and pressure (AUX_RBC, see section 9.2.6 below).

The Calibration Suite further calculates instrument performance information (transmissions and calibration coefficients), which is used in the L2A processing. This information is stored in the AUX_CAL file (see section 9.2.6 below).

9.2.4 Data processing to Level 2B and Level 2C (wind products)

The L1B product is then further processed to Level 2B (pressure and temperature corrected HLOS wind profile product) and Level 2C (L2C, ECMWF forecast model wind profiles at the Aeolus observation location after assimilation of Aeolus Level 2B winds) at the European Centre for Medium-Range Weather Forecasts (ECMWF). The L2B and L2C are the primary data products from Aeolus.

The main L2B processing steps concern the correction of the Rayleigh wind processing for atmospheric temperature and pressure broadening effects (using the so-called AUX_RBC look-up table). This is done using a priori temperature and pressure information, collocated to the wind observations, from the weather forecast model (AUX_MET). Particle (aerosols or hydrometeors) detection is performed using the so-called scattering ratio provided by the L1B processing (called scene classification). The wind observations are then classified into cloudy and cloud free, as illustrated in Figure 9. Finally, the data are averaged to form a representation of the actual wind observation over the 87 km long pixels (illustrated for Rayleigh winds in Figure 10). The processor also performs L1B and L2B data quality control and estimates error quantifiers.

The Aeolus L2B wind observations are then assimilated in the ECMWF model. The output assimilated winds (zonal and meridional wind component profiles at the location of the L2B wind profiles) are then used to populate the L2C product.

The vertical resolution of the layer-average winds vary from 0.25 to 2 km, and can be adapted as a function of the under-laying topography and/or climate zone. An example of terrain following sampling is clearly visible in the upper panel of Figure 10. The required wind accuracies (a combination of bias and precision, as defined in section 3) are 2 m/s in the planetary boundary layer (PBL), 2-3 m/s in the free troposphere, and 3-5 m/s in the stratosphere. A detailed description of the Aeolus wind retrievals can be found in Tan *et al.* (2008).

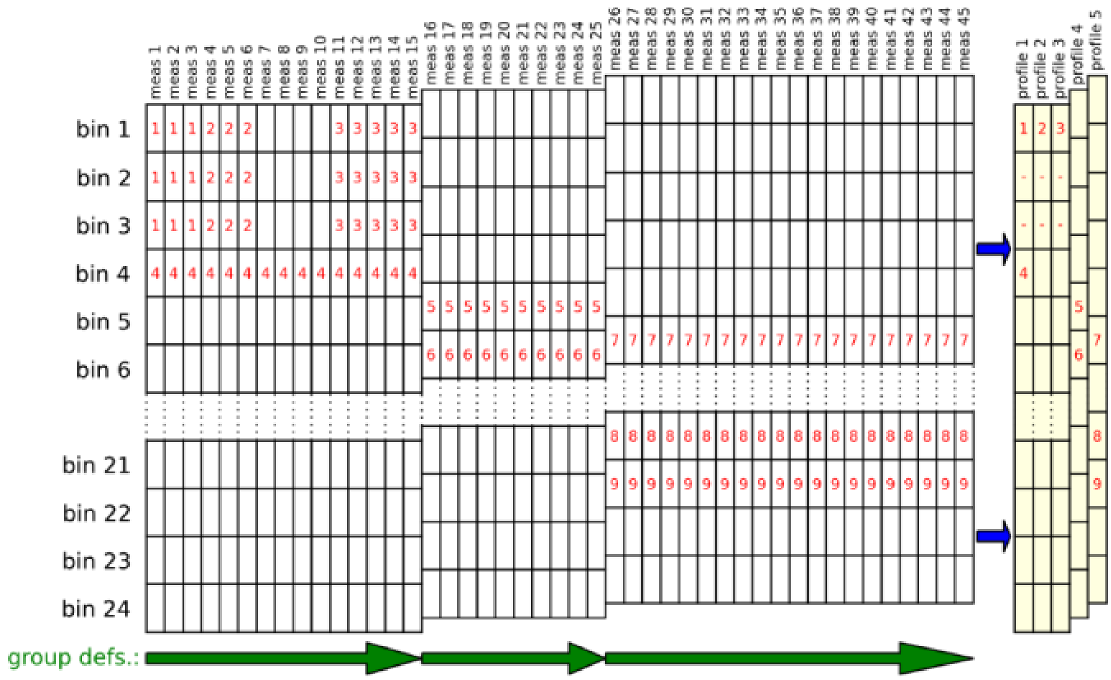

Figure 9: *Schematic view of the Aeolus L2B wind observation processing. The number indicate different scene classifications (clouds versus no clouds), resulting in a number of wind profiles for an observation. These are partial or full wind profiles for the Rayleigh (cloud free) and Mie (cloud or aerosol layer winds) channels. Courtesy: J. de Kloe (KNMI).*

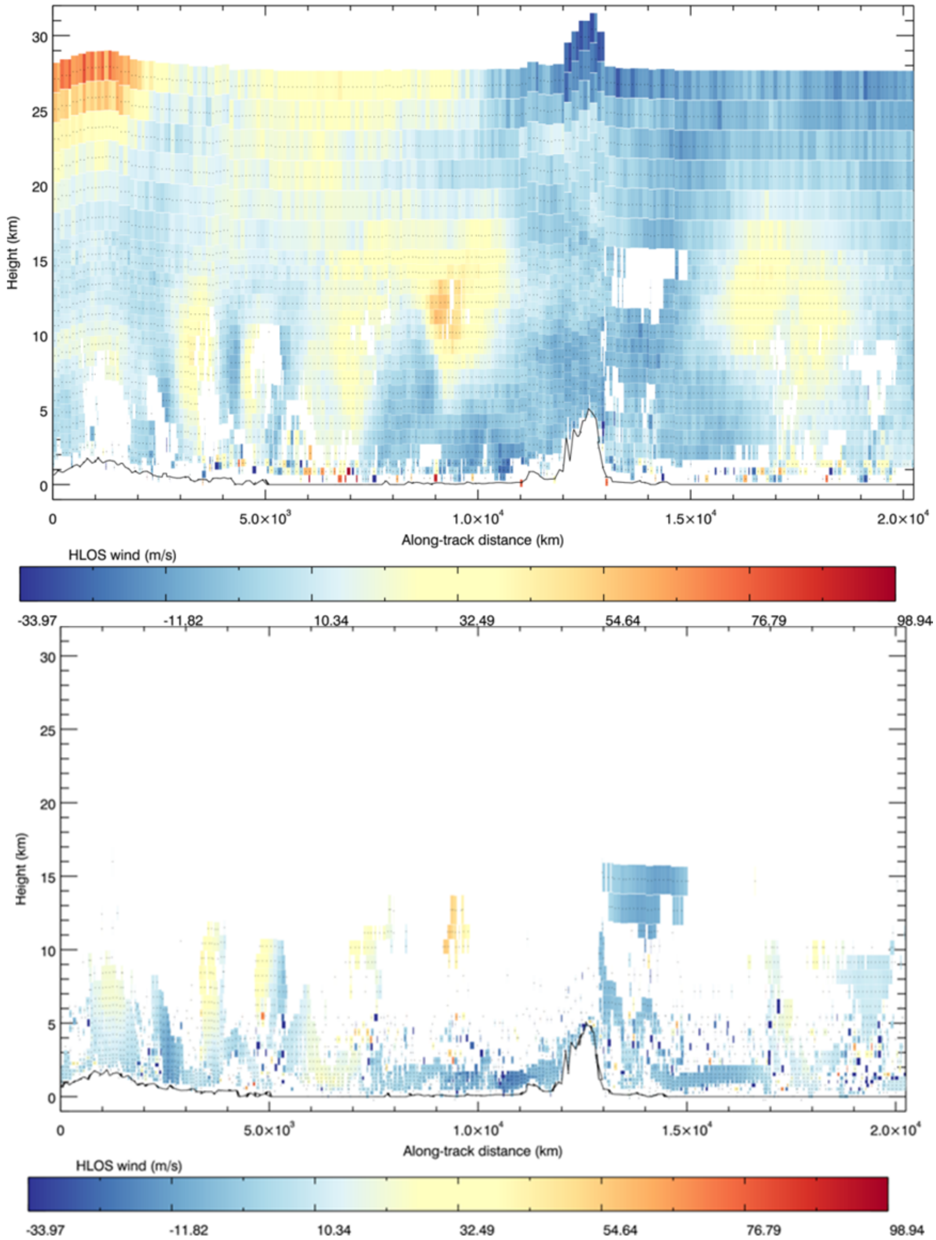

Figure 10: *Example of simulated Aeolus L2B Rayleigh clear air wind observations (ms^{-1}) (upper panel) and Mie cloud/aerosol wind observations (ms^{-1}) (lower panel). Courtesy: M. Rennie (ECMWF).*

9.2.5 Data processing to Level 2A (backscatter and extinction products)

At the APF, the L1B product is also further processed to Level 2A (atmospheric optical properties product). The Level 2A product is defined as an Aeolus spin-off product.
The L2A product contains height profiles of Mie and Rayleigh co-polarized backscatter and extinction coefficients, scattering ratios and lidar ratios (Flamant *et al.*, 2008, Flamant *et al.*, 2013) along the lidar line-of-sight. From these parameters it is possible to derive cloud and aerosol information such as layer height, multi-layer cloud and aerosol stratification,

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cloud and aerosol optical depths (integrated light-extinction profiles), and some information on cloud/aerosol type (lidar ratio).

The profiles will be provided both on observation scale (87 km averages) and on smaller scales after applying scene classification. An example of simulated Aeolus backscatter and extinction profiles on observation scale is given in Figure 11.

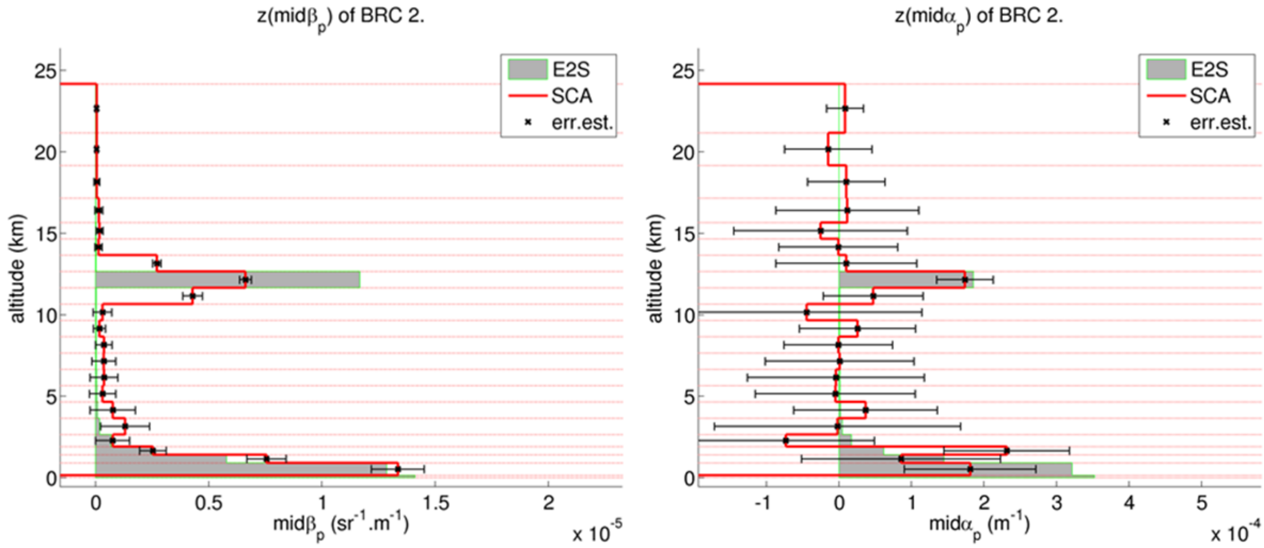

Figure 11: *Examples of simulated Aeolus L2A co-polar backscatter (left) and extinction profiles, retrieved from a scene measured by the NASA LITE mission. E2S: The original backscatter profile used to feed the end-to-end simulator, SCA: results from the so-called Standard Correct Algorithm (SCA), Err.est.: Retrieved error estimate. Courtesy: P. Martinet (MeteoFrance).*

9.2.6 Auxiliary files

As described in section 9.2.3, the L2A and L2B data processors make further corrections w.r.t. instrument transmission, responses and channel crosstalk (AUX_CAL), the Rayleigh-Brillouin scattering broadening of the backscattered signal (AUX_RBC) using a priori temperature and pressure information (AUX_MET) and a priori lidar ratio information (AUX_CLM). These corrections require a set of auxiliary files produced by the ECMWF NWP model, a dedicated calibration processor called the Calibration Suite running in the Aeolus Calibration and Monitoring Facility (ACMF) in ESA-ESRIN, and forward model simulations. The Aeolus auxiliary files used during the L2 processing listed in Table 7.

AUX file name	**Generated by**	**Content**
AUX_PAR_2A	PDGS	Generated with input from Aeolus Algorithm Core Team
AUX_PAR_2B	PDGS/ECMWF	Generated with input from Aeolus Algorithm Core Team
AUX_MET_12	Aeolus AUX_MET processor within the ECMWF Integrated Forecast System (IFT)	Forecasted temperature and pressure information at the (predicted) location of the Aeolus L1B observations. Predicted locations are used in the case of late L1B arrival at the Aeolus L2B processing facility at ECMWF
AUX_RBC_L2	Aeolus AUX_CSR	Look-up-table of Rayleigh responses corresponding

	processor at the ACMF	to atmospheric temperature and pressure combinations
AUX_CAL_L2	Aeolus AUX_CSR processor at the ACMF	Calibration coefficients defining the instrument transmissions for the Mie and Rayleigh channels (K_{Ray}, K_{Mie}) Calibration coefficients defining the atmospheric Mie and Rayleigh backscatter contributions to the measured Rayleigh and Mie signals (C_1, C_2, C_3, C_4) Spectral transmission characteristics of the Fabry-Perot and Fizeau interferometers (T_A, T_B)
AUX_CLM_L2	Forward model simulations performed by Aeolus L2B algorithm team, KNMI	Global map of extinction-to-backscatter ratios based on climatological information

***Table 7**: Auxiliary files used in the Aeolus L2A and L2B processing together with the L1B product.*

9.3 Data downlink, processing and distribution

The raw measurement data is received by the ground stations and submitted to the Aeolus data processing centres. These are located in Tromsø (Norway), Reading (United Kingdom) and Frascati (Italy). Data processing up to L1B is done in Tromsø. Processing up to L2B and L2c is done by ECMWF, and further data monitoring, calibration and the data distribution (all product levels) is done by ESA-ESRIN in Frascati (see Figure 12).

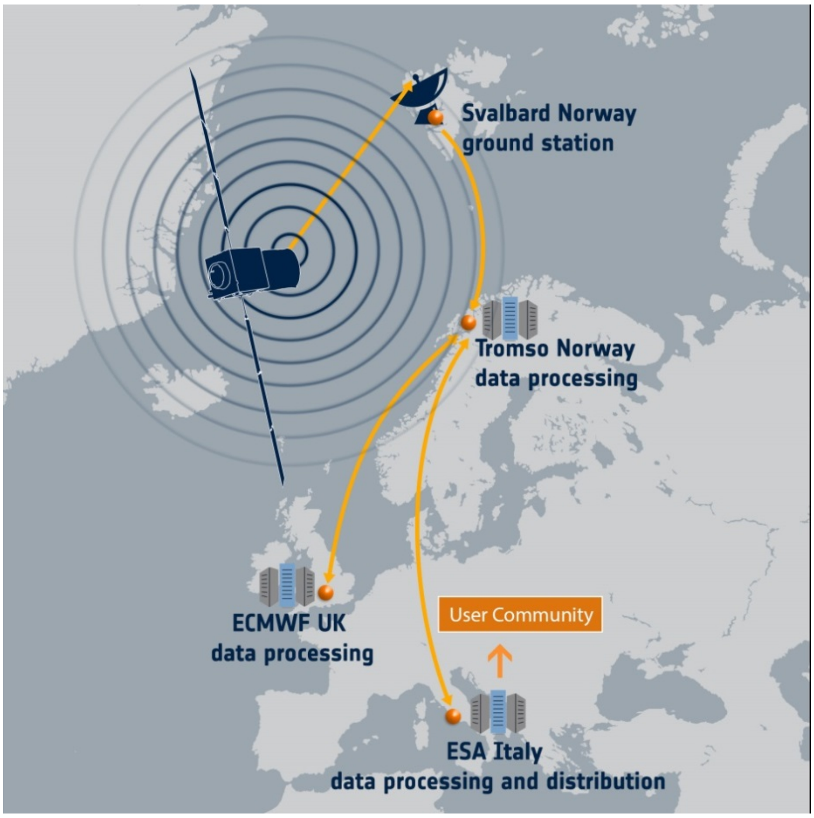

***Figure 12:** Illustration of the Aeolus data downlink and data processing facilities*

The data are made available to the users via the "ESA Earth Online" web site, http://aeolus-ds.eo.esa.int. The Aeolus data user interface is illustrated in Figure 13.

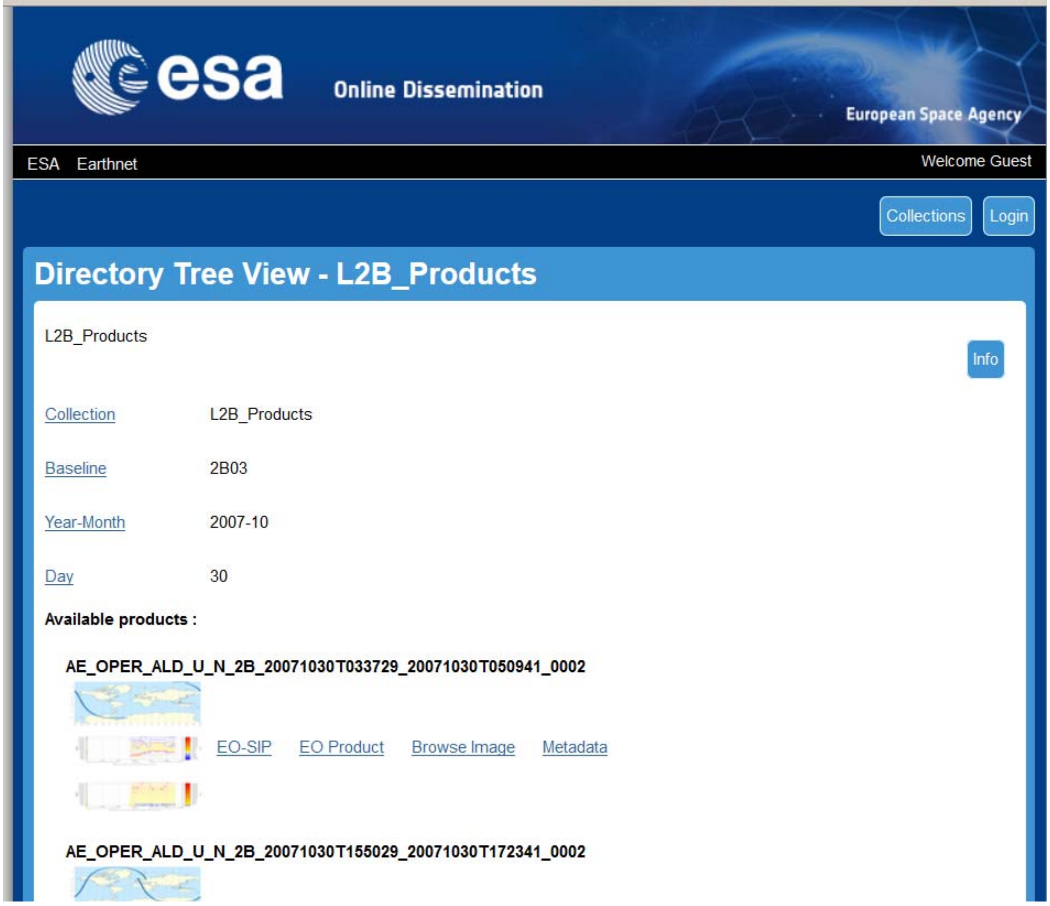

Figure 13: *Illustration of the ESA web site for the ordering of Aeolus data.*

10 DATA PRODUCT USE AND SYNERGIES WITH OTHER OBSERVING SYSTEMS

10.1 Data Product Use

The ADM-Aeolus L2A, L2B and L2C products will be used by different categories of users.

The first category of users will be NWP centres using the L2B single line-of-sight wind profile product as input to their weather forecasts. The globally distributed wind observations are expected to significantly improve weather analyses and forecasts due to its global coverage and information content (direct wind observations). The data will be assimilated in the models together with other available observations from the Global observing System (see also section 10.2 below), and the model 3-D wind field is expected to greatly improve due to the Aeolus 1-D zonal wind profile information (e.g. Marseille *et al.*, 2013, Horanyi *et al.*, 2013 and 2015a).

The second category of users are air quality forecast centres using the L2A optical properties products as input to their air quality models. Air quality forecasting models are expected to benefit from the Aeolus backscatter and extinction coefficient profile products to help with the vertical assignment of aerosol layers. Air quality forecast models are today mostly using satellite and ground-based Atmospheric Optical Depth (AOD) observations as input to their models, and have to rely on the model dynamics and physics for the vertical placement of aerosols. The use of lidar observations to improve on the vertical placement has been shown to be important (e.g. Sekiyama *et al.*, 2010). The synergistic use of Aeolus aerosol observations with other observations is also discussed in section 10.2.

The third category of users are scientific groups who will use the L2A and L2B products to perform studies to better understand atmospheric dynamics and its interaction with the atmospheric and surface radiation budget. Examples of such activities are

- investigations into atmospheric gravity waves and their impact on the atmospheric general circulation (investigating the vertically resolved zonal wind observations (Aeolus L2B product) in the troposphere and lower stratosphere),
- understanding of the impact of vertically propagating gravity waves on the Tropospheric ozone layer and it's meridional coupling with polar areas (Brewer-Dobson circulation),
- investigations into the coupling of dynamics and cloud formation in the lower troposphere (Aeolus L2A and L2B products),
- investigating the role of dynamics in the heat transfer between tropical oceans and the atmosphere,
- understanding the coupling between atmospheric dynamics and diabatic processes and their impact on forecast and climate change prediction skills (Aeolus L2A and L2B products).

These research topics are inter-related and are all recognized as challenges both for weather forecasting and for the prediction and understanding of climate change (WCRP grand challenges). Aeolus observations are expected to contribute to research in these areas.

A fourth category of users are expected to use Aeolus observations to cross-validate with other satellite, airborne and/or surface wind and aerosol observations (e.g. Atmospheric Motion Vectors (AMVs) height assignment, EarthCARE aerosol products, ground-based and airborne wind and aerosol observations with various instrumentation). Such activities are described in more detail in section 10.2.

A fifth category of users are expected to derive new data products from the Aeolus mission. Potential new products could be UV surface reflectivity in the direct backscatter direction over oceans and land, ocean state information etc.

10.2 Synergies with other observing systems

For users to fully exploit the data from the Aeolus space element (mainly for processing to level 2 and higher, and for validation of the Aeolus data), other observing systems providing complementary data are required. Table 8 lists the key data types that will be useful for these higher processing levels, and in particular, to validation campaigns. Further details on these observation types is given in section 10.2-5.

Mission Element	Instrument type / data source	Observations
Core Aeolus mission element	ALADIN	Wind profiles Co-polar backscatter and extinction profiles
Other relevant space-based observation types	AMVs	Cloud top winds
	SATEM	Profiles of temperature and humidity in the atmosphere
	Scatterometers	Ocean surface winds
	Radio occultation (e.g. GRAS on MetOp)	Profiles of temperature and humidity
Relevant airborne observation systems	AIREPS, radiosondes, airborne lidars, dropsondes, stratospheric balloons	Wind, temperature, pressure, humidity, aerosols/clouds Profiles / single level
Relevant ground-based observation systems	Weather stations, ship observations, buoys, lidars, wind profilers	Wind, temperature, pressure, humidity, aerosol Single level / profiles
Auxiliary data	NWP models Air quality forecast models	3-D wind, temperature, pressure, humidity, aerosol, chemistry

Table 8: *Aeolus mission elements and the observational data provided.*

10.2.1 Space-based observing systems

AMVs are wind observations obtained by tracking cloud or aerosol features from imaging satellite observations. These are currently obtained mainly from geostationary missions (e.g. SEVIRI on Meteosat Second Generation (MSG)) but also from polar orbiting instruments (e.g. MODIS on the NASA Terra and Aqua platforms). The accuracy of the retrieved wind product is sensitive to the altitude of the signal centre of gravity, which is retrieved with about 1 km accuracy. Whereas SATOB winds are provided 4 times an hour over the domain seen by the geostationary satellites, ALADIN will have a smaller horizontal and temporal coverage, but a better vertical coverage by providing wind information both in cloud-free air, in and below optically thin clouds and down to optically thick clouds. ALADIN is expected to provide more accurate height information with a resolution between 500 m (PBL), 1 km (free troposphere) and 2 km (stratosphere).

SATEM are temperature and humidity profiles derived from satellite radiance measurements (e.g. TOVS or ATOVS). These hence provide observations of the atmospheric mass fields. Using the geostrophic approximation, these allow for wind information on large scale at extratropical latitudes.

Scatterometers provides all-weather ocean surface wind information. The combination of these data with a Doppler wind lidar is potentially very powerful to resolve the turning of the wind direction from the surface (surface stress vector) to the height where the wind is in geostrophic balance (a so-called Ekman spiral) in the atmospheric boundary layer (e.g. Stull, 1991). The same effect also influence ocean currents just below the surface, causing surface drift to be at 45 degrees angle to the surface wind direction. This wind driven drift is turning further with depth. The determination of the impact of the surface on the general flow is important for detecting instabilities in the lower troposphere, and for a proper estimation of fluxes across the atmosphere-ocean interface.

Radio occultation instruments like the GNSS Receiver for Atmospheric Sounding (GRAS) on MetOp provides provide temperature and humidity information in the troposphere and lower stratosphere. This information is useful to define the geostrophic component of the flow, and complements the Earth Explorer Atmospheric Dynamics Mission Aeolus which also provides the ageostrophic flow component. The two missions also complement each other by providing additional data for monitoring, validation and quality control.

The largest impact of the Aeolus instrument is expected in the tropics where direct wind observations are of importance to correctly determining the flow. The contribution of wind profiles in clear air in the Tropics is currently not provided by other space-based systems.

10.2.2 Airborne observing systems

Airborne or balloon-borne systems play a large role in eth Global observing system today. In particular radiosonde observations and measurements by commercial aircrafts (AIREPS) have a significant impact on NWP. These provide very accurate observations, but the majority are located above continents in the Northern Hemisphere (radiosondes) or at cruise level along the main flight corridors (AIREPS). Aeolus would largely complement these observations by providing wind profile information uniformly distributed over all geographical regions.

Airborne wind and aerosol lidar systems fly during dedicated campaigns. The aircraft are often also equipped with dropsondes. This instrumentation is key to CAL/VAL since satellite underflights providing good spatial colocation and reasonable time collocation is achieved. For Aeolus validation, the ALADIN airborne demonstrator (A2D) instrument will be of particular importance for instrument calibration and validation.

Stratospheric balloons are released during dedicated campaigns, and can fly around the globe several times following the stratospheric tropical zonal flow. Their accurate tracking allows for good quality wind data. Data from stratospheric balloons are very important for NWP model validation due to the lack of other observations in this region constraining the models. Also, tropical model parameterizations benefit from high quality observation datasets. Stratospheric balloons are very useful for Aeolus data validation due to their quality, coverage and dataset duration.

In-situ observations from aircraft can be useful for classification of (mixed) aerosol layers such as desert dust, biomass burning, volcanic ash etc.

10.2.3 Ground-based observing systems

Ground based observing systems contributing to NWP are routine weather station observations and observations from buoys. Weather station observations give important observations in the PBL of importance especially for short-range forecasting (12 – 72 hours). Ship observations and buoys give much needed information over oceans which are sparsely sampled areas. Aeolus is expected to largely complement these due to is good horizontal and vertical coverage over the oceans.

Ground-based wind profilers give very accurate 3D wind profiles in the PBL and some systems also up to the stratosphere. These are assimilated in a number of NWP models and have shown to have good impact per observation. Wind profilers probing the whole troposphere are expected to be very useful for Aeolus validation in the case of good sampling collocation.

Most ground based wind lidar systems operate in the short-wave infrared and provide wind observations in the PBL. These are useful for airport forecasting, but are expected to be less useful for ADM-Aeolus due to their limited vertical range.

Ground based lidar networks, such as EARLINET, provide information on aerosol and cloud stratification. These networks have proven to be very useful for space-based lidar validation when looking at observations with good spatial and temporal collocation, time series and when used in combination with back-trajectory models. The ground-based systems are well calibrated and can provide detailed information on aerosol classification.

10.2.4 Auxiliary data

NWP background or short range forecast winds provide a globally consistent view of the atmospheric flow. NWP monitoring has been shown to be very effecting in quality monitoring of satellite-based data. Biases occurring after instrument anomalies or processing changes can be detected and quantified. ECMWF will monitor the Aeolus wind profile quality with the integrated forecast system. NWP monitoring can also allow for bias corrections.

Air quality forecasting models are expected to benefit from the Aeolus backscatter and extinction profile products. Aeolus can be used to help with the vertical assignment of aerosol layers. Such models could potentially also be used for Aeolus data monitoring.