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<tr>
<td><strong>Prepared by:</strong></td>
<td>Oliver Reitebuch (DLR, Oberpfaffenhofen, Germany, responsible)</td>
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<td>Ines Nikolaus (Physics Solution, Munich, Germany)</td>
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## Document Change Log

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1 Introduction and Purpose of Document

The Algorithm Theoretical Basis Document ATBD defines the theoretical basis for the ADM-Aeolus ground processing algorithms up to Level 1B (geolocated horizontal line-of-sight wind observations). It covers Task 1.5 of the SoW AE-SW-ESA-GS-011, Issue 01a (ESA 2004a), DLR Technical proposal Work-Package WP15000 (DLR 2004a) and WP 1200 from DLR (2014).

This ATBD will be updated regularly. A first issue of the ATBD (1.0 from 31.05.2005) was prepared by Oliver Reitebuch (DLR, responsible), Dorit Huber (DLR), and Ines Nikolaus (PSol). Ulrike Paffrath (DLR) contributed to the second issue from 10.05.2006. This third issue was updated after the final delivery of the TN for the L1B sensitivity analysis (DLR 2006, AE-TN-DLR-L1B-002). The 4th and 4.1th issue was updated by Reitebuch and Huber after the delivery of Issue 6 and 7 of the “Level 1B Master Algorithm Document” by EADS-Astrium (2013a) and the Version 6.03 from the operational L1B processor and Version 3.04 from the End-to-End Simulator (DoRIT and MDA 2014 a,b,c).

Chapter 2 describes the ADM-Aeolus mission and observational requirements, and chapter 3 gives a short introduction to atmospheric processes relevant to the lidar instrument for ADM-Aeolus. Chapter 4 describes the ADM-Aeolus instrument with emphasis on those functionalities and units with relevance to the algorithm development. Chapter 5 introduces the ADM-Aeolus data products up to Level 1B and chapter 6 gives an outline of geolocation processing. Chapter 7 describes the Level 0 to Level 1A processing and chapter 8 gives the theoretical basis for the processing steps from Level 1A to Level 1B.
2 ADM-Aeolus Mission Overview and Requirements

The Atmospheric Dynamics Mission ADM-Aeolus will provide global wind profile observations with the aim to demonstrate improvement in atmospheric wind analyses for the benefit of numerical weather prediction and climate studies. ADM-Aeolus is the first satellite wind lidar mission worldwide and the first lidar mission of the European Space Agency (ESA, lidar: light detection and ranging).

The concept of the mission is shown in Fig. 2-1. A Doppler wind lidar (DWL) called ALADIN (Atmospheric LAser Doppler INstrument) is accommodated on a satellite flying in a polar, sun-synchronous orbit at an altitude of about 400 km. The DWL will measure profiles of the projection of the wind vector on the line-of-sight (LOS) under a slant angle of 35° versus nadir perpendicular to the flight track. Thus the satellite ground track and the measurement ground track are separated by 285 km. The incidence angle between the LOS and the local normal direction at the measurement ground point is not 35 ° but about 37.6 ° due to the earth curvature (see also Fig. 6-1).

Profiles of the projection of the measured LOS wind speed on the horizontal plane HLOS (horizontal LOS) are obtained every 90 km, which corresponds to a travel time of the satellite of 12 s. The HLOS wind profile observations with an along-track horizontal integration length of 90 km are obtained from individual measurements with a horizontal sub-sample length of minimal 3 km. The 90 km wind observation consists of the return of 600 individual laser pulses during a period of 12 s. The wind profile is determined from the backscattered signals from aerosols and molecules separately and is thus contained in separate vertical layers spanning from below ground to up to 30 km altitude. The distance of the vertical layers is depending on the altitude referenced to the WGS84 (World Geodetic System of 1984) ellipsoid. The vertical resolution can be commanded separately for the aerosol and molecular layers with multiples of 250 m, such that the boundaries of the aerosol vertical layers will coincide with the boundaries of the molecular layers. The actual commanded vertical resolution will be typically in the range of 250 m to 2 km, with lower values chosen such as to enhance the sampling of large vertical gradients in the atmospheric and ground return signal.

Figure 2-1: Schematic view of the ADM-Aeolus measurement geometry (ESA 2008 and adapted afterwards).
The observational requirements for the ADM-Aeolus mission have been carefully chosen to be able to demonstrate the beneficial impact of DWL winds (ESA 1999, 2008, 2014, Stoffelen et al. 2005) and are listed in Tab. 2-1 for the new continuous mode operation baseline (ESA 2010, LeRille et al. 2012, Reitebuch 2012b). The vertical domain of the observations spans from the Planetary Boundary Layer (PBL) to the lower stratosphere with an altitude dependent vertical resolution from 0.5 km to 2 km of the observations. The requirement on the precision (random error given as root-mean-square rms value) of the HLOS component is related to the corresponding vertical resolutions in that altitude range and a horizontal integration length of 100 km below 14 km and 140 km above 14 km. It is worth to note, that the precision requirement on the measured LOS component is even more stringent by a factor of 0.61 for an incidence angle of 37.6°. The requirement on the unknown bias is composed of two parts with a wind speed dependent part of 0.7 % (wind speed slope error) and a constant part of 0.5 ms\(^{-1}\) (zero-wind bias); both bias requirements apply on the HLOS-component and should be considered as rms-values. The ADM-Aeolus L1B data products must be available latest 3 hours after the actual observation to the primary users as meteorological services, e.g. the European Centre for Medium-Range Weather Forecasts ECMWF.

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<td>PBL</td>
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<tr>
<td>vertical domain</td>
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</tr>
<tr>
<td>vertical resolution</td>
<td>0.5 km</td>
</tr>
<tr>
<td>horizontal domain</td>
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</tr>
<tr>
<td>Minimum horizontal track data</td>
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<td>availability (before QC)</td>
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</tr>
<tr>
<td>horizontal integration length per</td>
<td>90/100/140 km*</td>
</tr>
<tr>
<td>observation</td>
<td></td>
</tr>
<tr>
<td>horizontal subsample length per</td>
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<td>measurement</td>
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<tr>
<td>precision HLOS component</td>
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<tr>
<td>unknown bias (HLOS)</td>
<td>0.5 ms(^{-1})</td>
</tr>
<tr>
<td>unknown wind speed slope error</td>
<td>0.7 %</td>
</tr>
<tr>
<td>probability of gross errors</td>
<td>0.5 %</td>
</tr>
<tr>
<td>data availability, timeliness</td>
<td>3 hour</td>
</tr>
<tr>
<td>length of observational data set</td>
<td>3 years</td>
</tr>
</tbody>
</table>

Table 2-1: Observational requirements for ADM-Aeolus (from ESA 2014); *90 km horizontal length is used as observation length for L1B product; 100 km integration is applied to achieve wind accuracy requirement below 14 km, while 140 km is applicable for altitudes above 14 km (ESA 2010).

ADM-Aeolus satellite is operating in a polar, sun-synchronous orbit at an inclination of 97° and a mean altitude of 408 km with a variation between 395 and 425 km. The orbit period is 92.5 minutes with an orbital velocity of about 7700 ms\(^{-1}\) and a ground track velocity of about 7200 ms\(^{-1}\). Although the observation is performed perpendicular to the satellite velocity, which should result in a zero LOS component from the satellite, a residual velocity component from the Earth rotation is obtained. This is compensated by yaw steering of the satellite.
3 Lidar Principle and Atmospheric Processes

3.1 Lidar Principle

A lidar consists of three main subsystems: the laser transmitter, the receiver, and the detection system (Fig. 3-1). The laser transmitter is the source which generates laser pulses and directs them into the atmosphere. The optical receiver unit of a lidar collects the backscattered signal via a telescope and analyses the spectral content of the signal via filters and a detection unit. For the case of a Doppler wind lidar the backscatter signal is analysed to obtain the LOS wind speed by the properties of the wavelength of the backscatter light.

![Figure 3-1: Sketch of the principle of a lidar, where a transmitter laser sends out laser pulses, which are backscattered in the atmosphere by particles and molecules, collected by a receiving telescope, and analysed by an optical and electronic receiver unit; note that the actual implementation of the ALADIN instrument is not a bistatic configuration of transmitter and receiving telescope, as shown on this figure, but a transceiver configuration as shown in Figure 4-1.](image)

The lidar equation is used to determine the energy of the backscatter signal and takes into account both the instrumental parameters and the atmospheric variables. The backscatter laser energy at a distance \( r \) from the lidar is given by:

\[
E(\lambda, r) = \frac{E_L}{r^2} \cdot A_0 \cdot C(\lambda) \cdot \beta(\lambda, r) \cdot T^2(\lambda, r)
\]

where \( E_L \) is the energy and \( \lambda \) the wavelength of the transmitted laser pulse. \( A_0/r^2 \) is the acceptance solid angle of the receiving optics with \( A_0 \) the collecting area of the telescope (optical aperture). An atmospheric volume with a length of \( \Delta R \) (range resolution) is sampled by the lidar. The instrumental constant \( C(\lambda) \) takes into account the response of the receiver, such as the spectral transmission factors and the overlap function of the telescope. The transmission coefficient \( T^2(\lambda, r) \) describes the range-dependent transmission factor of the atmosphere due to extinction. The atmospheric backscatter coefficient \( \beta(\lambda, r) \) characterizes the illuminated atmospheric volume backscatter from aerosol, cloud particles and molecules. In case of a return from the earth surface the product of \( \beta(\lambda, r) \cdot \Delta R \) is replaced by the albedo value \( a \), which is the ratio of the radiation reflected by a surface to the incident energy. Mean albedo values \( a \) are 0.03 of soil, 0.5 of ice, 0.8 of dry...
snow, and 0.14 of water for a 355 nm source (Vaughan et al. 1998). For the case of inclined incidence of light at an angle $\phi$, the albedo of a Lambertian reflector is calculated by $a(\phi) = a / \pi \cos(\pi - \phi)$. In case of water surfaces the reflectance is strongly depending on incidence angle and is composed of several contributors, which are discussed in Li et al. (2010) for UV wavelengths. Airborne observations of surface reflectances in the UV spectral range from the ALADIN airborne demonstrator are discussed in Manninen (2012). Monthly climatological reflectance values from 300 nm to 4000 nm with high spatial resolution (10 km) based on different satellite observations are available through ESA’s ADAM project (http://adam.noveltis.fr).

Doppler wind lidar systems determine the LOS wind speed as a function of range using the change in wavelength or frequency of the emitted laser pulse. The atmospheric particles that are moving with the wind velocity cause a frequency shift of the backscatter signal due to the Doppler effect. The frequency shift is related directly to the wind velocity along the laser beam (see Chap. 3.4). A detailed and current introduction to lidar fundamentals is contained in Measures (1992), Weitkamp (2005), Paffrath (2006) and Reitebuch (2012a) focussing on wind lidars.

3.2 Beam Propagation and Range Equation

The lidar instrument uses a slant angle 35° off nadir from a 400 km orbit, which was chosen to optimise the accuracy of the instrument. The direction of the emitted laser signal is chosen perpendicular to the flight direction, to compensate for the Doppler shift due to spacecraft motion and the earth rotation.

The laser pulse duration $t_L$ limits the minimal vertical atmospheric resolution $\Delta R_{\text{min}} = t_L c / 2$, where $c$ is the speed of light. For the pulse duration of the ALADIN laser transmitter $t_L = 30$ ns, the minimal resolution is 4.5 m. The feasible vertical resolution depends on the integration time of detector and the slant angle. A minimum vertical resolution of 250 m is achieved for ALADIN due to the slant angle of 35° (mean incidence angle of 37.6°) and a minimum integration time of the electronic detection unit of 2.1 µs, which results in a range resolution $\Delta R$ of 315 m along the LOS. The overall vertical measurement range is limited by the detectors capability to store data for 25 range bins (see chapter 4.2.5).

3.3 Aerosol and Molecular Scattering

When light from a laser propagates through the atmosphere, it is scattered and absorbed by the atmospheric constituents, resulting in a change in intensity and spectral characteristics of the scattered light. Backscattered light from molecules, whose diameter is much smaller than the wavelength, results from a Rayleigh scattering process. Mie scattering occurs for aerosol and clouds particles, whose size is comparable or larger than the wavelength.

The intensity of the return signal from Mie scattering depends on the number density of aerosols, which varies largely over different geographical locations and altitude and increases strongly for clouds, fog, or haze. A convenient approach to estimate the Mie backscatter coefficient is the usage of climatological databases derived from measurements and applying scaling laws for the wavelength dependency. The ESA Reference Model Atmosphere (RMA) was obtained from airborne measurements over Atlantic regions during the period 1988-1990 (Vaughan et al. 1995 and 1998). The RMA comprises data of different aerosol backscatter (Fig. 3-2), cloud backscatter, extinction, background radiance, and ground albedo.
Figure 3-2: Aerosol backscatter coefficients of different aerosol models versus altitude for a wavelength of 355 nm used for ALADIN (adapted from Vaughan et al. 1998). The percentiles are those values of backscatter at which a given percentage of the data is greater or less than this value. Thus the upper/lower quartiles have 25% of data greater/less than, whilst the upper lower deciles have 10% of data greater/less than. The enhanced backscatter due to clouds is seen in the higher decile profile (light blue).

The cloud backscatter and extinction coefficients from the RMA model for different type of clouds and their typical altitude range are listed in Table 3-1.

<table>
<thead>
<tr>
<th>Types of cloud</th>
<th>Backscatter coefficient $\beta_{\text{cloud}}$ [m$^{-1}$ sr$^{-1}$]</th>
<th>Extinction coefficient $\alpha_{\text{cloud}}$ [m$^{-1}$]</th>
<th>Altitude [m]</th>
</tr>
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<tbody>
<tr>
<td>Stratus</td>
<td>5x10$^{-3}$</td>
<td>9x10$^{-2}$</td>
<td>200 - 700</td>
</tr>
<tr>
<td>Cumulus</td>
<td>6x10$^{-4}$</td>
<td>1.2x10$^{-2}$</td>
<td>750 - 1000</td>
</tr>
<tr>
<td>Cumulonimbus</td>
<td>1x10$^{-2}$</td>
<td>1.8x10$^{-1}$</td>
<td>2000 - 4000</td>
</tr>
<tr>
<td>Altostratus</td>
<td>1x10$^{-3}$</td>
<td>1.8x10$^{-2}$</td>
<td>4000 - 4500</td>
</tr>
<tr>
<td>Cirrus</td>
<td>1.4x10$^{-5}$</td>
<td>2x10$^{-4}$</td>
<td>8500 - 9500</td>
</tr>
<tr>
<td>Polar Stratospheric Cloud</td>
<td>3.0x10$^{-7}$</td>
<td>6x10$^{-6}$</td>
<td>16000 - 17000</td>
</tr>
</tbody>
</table>

Table 3-1: Backscatter and extinction coefficients for different type of clouds and their typical altitude range for a wavelength of 355 nm from the RMA model.

Rayleigh scattering from air molecules occurs in the case of a clear atmosphere. The intensity of the return signal depends on the number of molecules per m$^3$ (Eq. (3.3)) and the backscatter cross section per molecule (Eq. (3.2)), which indicates the theoretical effective area, where light is scattered back in a solid angle of $2\pi$ sr. The Rayleigh backscatter cross section (m$^2$ sr$^{-1}$) for a mixture of atmospheric gases of altitudes up to 100 km is calculated from (Measures 1992, p. 42):

$$\sigma_{\text{Mol}} = \left( \frac{0.55 \times 10^{-6} m}{\lambda} \right)^4 \cdot 5.45 \times 10^{-32} \text{ m}^2 \text{sr}^{-1}$$

(3.2)

and the number of molecules $N_{\text{Mol}}$ per m$^3$ depending on altitude $z$ is given by (Measures 1992 p. 42):
\[ N_{\text{Mol}}(z) = \left( \frac{273.15K}{T(z)} \right) \cdot \left( \frac{p(z)}{1.01325 \times 10^5 \text{Pa}} \right) \cdot N_L \] (3.3)

with temperature \( T \), pressure \( p \) and the Loschmidt’s number \( N_L = 2.68 \times 10^{25} \, \text{m}^{-3} \) for a temperature of 273.15 K and a pressure of 1.01325 \( \times 10^5 \) \, Pa. Hence, the backscatter coefficient per volume \( \beta_{\text{Mol}} \, (\text{m}^{-1} \, \text{sr}^{-1}) \) is found from:

\[ \beta_{\text{Mol}}(z) = N_{\text{Mol}}(z) \cdot \sigma_{\text{Mol}} \] (3.4)

Since the amount of backscatter energy is proportional to \( \lambda^{-4} \) (Eq. (3.2)), shorter wavelengths are scattered far more than longer wavelengths, illustrated in Fig. 3-3. Assuming a temperature and pressure profile from a reference atmosphere (U.S. standard atmosphere, Champion 1985) the resulting molecular backscatter coefficients are shown in Fig. 3-3 at 10 \( \mu \)m, 2 \( \mu \)m, and 0.355 \( \mu \)m wavelengths, which increase by three orders of magnitude with each transition to a shorter wavelength.

**Figure 3-3**: The molecular backscatter coefficients for the U.S. standard atmosphere temperature and pressure profiles at different wavelengths (355 nm, 2 \( \mu \)m, and 10 \( \mu \)m) versus altitude.

The 355 nm wavelength was selected for ALADIN to obtain high molecular backscatter even in regions of the atmosphere with low aerosol loading in the upper troposphere and lower stratosphere. Shorter wavelengths than 355 nm, e.g. the fourth-harmonic of a Nd:YAG laser transmitter at 255 nm was abandoned, because of absorption from ozone in the stratospheric ozone layer.

**Scattering ratio**

The scattering ratio \( B \) (also called backscatter ratio) describes the ratio of the total backscatter from aerosols (including clouds) \( \beta_A \) and molecules \( \beta_{\text{Mol}} \) to the backscatter from molecules \( \beta_{\text{Mol}} \).

\[ B = \frac{\beta_A + \beta_{\text{Mol}}}{\beta_{\text{Mol}}} \] (3.5)

In case of pure backscatter from molecules the scattering ratio is 1, whereas it is higher than 1 in case of aerosol and molecular backscatter. For the wavelength of 355 nm and the aerosol backscatter coefficients from the RMA model (Fig. 3-2), the scattering ratio can reach values up to 2 for the median aerosol model and up to 5 for the higher decile model in the boundary layer below 2 km. In case of clouds the scattering ratio can exceed a value of 10 and reach values up to several hundred.
Extinction and lidar ratio

The atmospheric two-way transmission $T^2(\lambda, r)$ depends on the aerosol, cloud, and molecular extinction coefficient $\alpha_A$ resp. $\alpha_{Mol}$ by the Lambert-Beer law:

$$T(\lambda, r) = e^{-\int_0^r a(\lambda, z)dz}$$  \hfill (3.6)

The extinction coefficients can be derived from the backscatter coefficients by use of the lidar ratio $L$. The lidar ratio for aerosols $L_a$ has been discussed by many authors (Doherty et al. 1999, Liu et al. 2002, Evans 1988, Spinahire et al. 1997). It was shown that a linear relationship applies for monodispersed spherical particles:

$$L_a = \frac{\alpha_A}{\beta_A}$$  \hfill (3.7)

Values of $L_a$ depend on the wavelength $\lambda$ and vary over a large range depending on the type and number concentration of the aerosol (Ansmann and Müller 2006).

The extinction coefficient for molecules $\alpha_{Mol}$ is derived from the molecular backscatter $\beta_{Mol}$ coefficient by using the constant molecular lidar ratio $L_m$ (Measures 1992):

$$L_m \frac{\alpha_{Mol}}{\beta_{Mol}} = \frac{8\pi}{3} \text{sr}$$  \hfill (3.8)

Depolarisation

Discussion of depolarisation needs to be included for next version.

Discussion of circular depolarization ratio from linear depolarization ratio according to Ansmann and Wandinger (2013).
3.4 Doppler-Shift and Spectral Lineshape of Aerosol and Molecular Return

The Doppler effect was first described by the Austrian physicist Christian Johann Doppler in 1842 (Doppler 1842). The Doppler effect is the change of a wave’s frequency or wavelength caused whenever there is a relative motion between a source of waves and the observer of the wave. The optical frequency of light is shifted by a factor of $v/c$, where $v$ is the speed at which the observer is approaching or receding from the source, and $c$ is the speed of light. Actually only the component of the wind along the line between the source and the observer is resulting in a Doppler effect. This wind component is obtained by projection of the three-dimensional wind vector onto this line, and is subsequently called line-of-sight LOS wind $v_{LOS}$.

The first shift in frequency occurs with the scattering air particles, which constitute a moving observer. The second shift arises because the particles in the air then act as moving sources. Since $v \ll c$, the Doppler frequency shift $\Delta f_D$ detected at the lidar is given by (Werner 2005, Reitebuch 2012a):

$$\Delta f_D = f_o - f_a = 2f_o \frac{v_{LOS}}{c}$$

with $f_0$ the frequency of the transmitted laser pulse and $f_a$ the frequency of the backscattered light from the atmosphere. The sign convention for the Doppler shift frequency $\Delta f_0$ is such, that a positive sign ($\Delta f_0 > 0$, $f_a > f_0$) is related to a LOS wind speed in the direction towards the instrument ("blue wavelength shift"), while a negative sign ($\Delta f_0 < 0$, $f_a < f_0$) indicates a LOS movement away from the instrument ("red wavelength shift"). Thus $v_{LOS}$ is positive for movements towards the lidar, while $v_{LOS}$ is negative for movements away from the lidar in this context. Using the same sign convention for the Doppler wavelength shift $\Delta \lambda_D$ and $v_{LOS}$ the equation contains a different sign:

$$\Delta \lambda_D = \lambda_a - \lambda_0 = -2\lambda_0 \frac{v_{LOS}}{c}$$

with the wavelength of the laser $\lambda_0$ and the backscattered atmospheric signal $\lambda_a$.

For the laser transmitter wavelength of 355 nm of ALADIN, which corresponds to a frequency of 845 THZ, the Doppler shift in frequency and wavelength is given in Table 3-2 for 1 ms$^{-1}$ LOS and 1 ms$^{-1}$ HLOS for an incidence angle of 37.6°.

<table>
<thead>
<tr>
<th></th>
<th>1 ms$^{-1}$ LOS</th>
<th>1 ms$^{-1}$ HLOS</th>
<th>1 fm</th>
<th>1 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ms$^{-1}$ LOS</td>
<td>1</td>
<td>1.638</td>
<td>2.37</td>
<td>5.639</td>
</tr>
<tr>
<td>1 ms$^{-1}$ HLOS</td>
<td>0.610</td>
<td>1.446</td>
<td>1.446</td>
<td>3.441</td>
</tr>
<tr>
<td>1 fm</td>
<td>0.423</td>
<td>1.446</td>
<td>1</td>
<td>2.380</td>
</tr>
<tr>
<td>1 MHz</td>
<td>0.1775</td>
<td>0.291</td>
<td>0.425</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3-2: Conversion table for a wavelength of 355 nm using EQ 3.9 and an incidence angle of 37.6° to convert from LOS to HLOS; e.g. a 1 ms$^{-1}$ LOS corresponds to 1.638 ms$^{-1}$ HLOS and a Doppler shift of 2.37 fm or 5.639 MHz (first line); these conversion values will change slightly for the actual laser wavelength (354.8 nm from the satellite characterisation test)

But not only is the mean movement of the molecules and the aerosol particles by the atmospheric wind is affected by a Doppler shift. Also the individual thermal movement of the molecules (Brownian motion) results in a Doppler shift and thus leads to a spectral broadening of the Rayleigh line. The most significant factor for the Rayleigh line shape is the Doppler broadening, which may be described by a Gaussian line profile function (Measures 1992 p. 99):
where $\sigma$ is the standard deviation of the Rayleigh spectrum which is given by:

$$\sigma = \frac{2\lambda}{c} \sqrt{\frac{k T N_A}{m_{air}}}$$  \hspace{1cm} (3.12)

where $m_{air}$ is the mean molecular air mass ($2.885 \times 10^{-2}$ kg mol$^{-1}$), $\lambda$ the wavelength of the laser, $k$ the Boltzmann constant ($1.38 \times 10^{-23}$ J K$^{-1}$), $c$ the speed of light, $T$ the atmospheric temperature and $N_A$ the Avogadro constant ($6.022 \times 10^{23}$ mol$^{-1}$). Thus, the broadening of the Rayleigh backscatter spectrum depends on atmospheric temperature $T$ (Eq. (3.11)). The wavelength spectra for backscatter from Mie and Rayleigh is shown in Fig. 3-4. Due to the much higher mass of aerosols no spectral broadening occurs due to the motion of the aerosols. Thus the spectral width of the Mie signal is the same as for the transmitted laser pulse.

![Figure 3-4](image-url) **Figure 3-4**: Wavelength spectra for the backscatter signals from aerosols (Mie spectrum, red) and from molecules (Rayleigh spectrum, green) illustrating the different spectral widths ($\sigma$, Full Width Half Maximum FWHM=$2\sqrt{2\ln 2}\sigma$) at a laser wavelength of 355 nm for 0 m s$^{-1}$ wind speed.

![Figure 3-5](image-url) **Figure 3-5**: Wavelength spectra for the backscattered Mie (red) and Rayleigh (green) signal for a 355 nm source at $\lambda_0$ (dotted lines) and a Doppler shift $\Delta\lambda_D$ (bold lines); the indicated Doppler shift of 0.5 pm corresponds to a LOS wind speed of $\sim 200$ m s$^{-1}$. 
It should be noted, that the vertical sampling grid for the Mie and the Rayleigh spectrometer can be different, which results in different vertical atmospheric volumes for each receiver. This may produce a different Doppler shift on the Mie and Rayleigh signal for the case the HLOS wind speed differs within each of the atmospheric volumes. It is assumed in Fig. 3-5, that the same volume is sensed for the Mie and the Rayleigh signal.

Even in the case of sampling the same atmospheric volume for the Mie and Rayleigh spectrometer, different HLOS wind speed could be obtained in the presence of a vertical gradient in the backscatter coefficients combined with a vertical gradient in wind speed (Sun et al. 2014). This is caused by the vertical weighting of the atmospheric signal with the backscatter profile. Only in case of assuming a constant backscatter profile or a constant wind speed within one vertical range bin, the mean wind speed of this range bin is sensed. In case of strong vertical gradients, e.g. in the presence of a cloud within the range bin, the wind speed from the Mie and Rayleigh spectrometer could be differ significantly.

The actual lineshape from molecular backscatter differs from a pure Gaussian lineshape due to Rayleigh-Brillouin scattering in the atmosphere (Witschas et al. 2010, Witschas 2011a, Witschas 2012, Witschas et al. 2012), which can be described by a model of Tenti et al. (1974). A parameterized version applicable for UV wavelengths and air was developed by Witschas (2011b). The Rayleigh-Brillouin lineshape model needs to be included for the wind retrieval from molecular backscatter (Dabas et al. 2008).

### 3.5 Earth Background Radiation

In addition to the backscatter from molecules and particles also the earth background radiation contributes to the signal received at the lidar telescope. The earth background radiant energy $E$ is due to the solar spectral radiance $S$, which is the radiance (Watt) per unit wavelength interval, per cm², and per steradian [W cm⁻² µm⁻¹ sr⁻¹]. The receiver system bandwidth is as small as compatible with the spectral width of the backscattered signal. Due to the sufficiently narrow spectral width of the receiver (1 nm, see Tab. 4-1) the energy may be assumed to be constant and the radiant energy per micron wavelength interval $E_{\text{micron}}$ [J µm⁻¹] may be written as (Measures 1997 p. 225):

$$E_{\text{micron}} = S \cdot \Omega_0 \cdot A_0 \cdot t_0 \cdot C(\lambda)$$  \hspace{1cm} (3.13)

where $\Omega_0$ is the acceptance solid angle, $A_0$ the effective aperture, $t_0$ the detection time, and $C(\lambda)$ is the instrument filter function.
4 ALADIN Instrument

4.1 Overview

The ADM-Aeolus lidar instrument ALADIN is based on a direct-detection Doppler lidar operating in the ultraviolet (UV) spectral region at 355 nm. The receiver consists of two interferometers (also called spectrometers), which sense the Doppler shift from particles (aerosol, cloud particles) as well as from molecules, yielding profiles of the LOS wind speed throughout the whole troposphere and part of the stratosphere with high vertical resolution (250-2000 m). The spectrometer, which is mainly sensitive to molecular backscatter, uses the double-edge technique using two Fabry-Perot interferometers (Chanin et al. 1989, Flesia et al. 2000, Gentry et al. 2000). The spectrometer, which is sensitive to aerosol and cloud returns, is based on a Fizeau interferometer (EADS-Astrium 2004b, Schillinger et al. 2003, Morancais et al. 2004). The instrument concept of ALADIN combines new techniques, like a novel combination of the molecular and aerosol receiver, and the use of an Accumulation Charge Coupled Device (ACCD) to improve detection sensitivity. Also the use of a sequential implementation of the two Fabry-Perot interferometers with different maximum transmissions and spectral widths for the two channels of the Fabry-Perot interferometer was never applied before. The use of novel technologies within this instrument in addition with the first deployment of a Doppler lidar on a satellite raises several topics for the ground processing algorithm theoretical basis.

An overview of the optical architecture is given in Fig. 4-1 and main instrument parameters are summarized in Tab. 4-1. The ADM-Aeolus satellite will be placed in a polar, sun-synchronous orbit at a mean altitude of 408 km, resulting in a mean orbital speed of 7664 ms⁻¹. The ALADIN instrument points perpendicular to the satellite ground speed vector with a slant angle 35 ° off nadir (Fig. 2-1). The satellite is steered in yaw angle to compensate for earth rotation and to compensate for systematic orbit height variations. Measurements are performed with an adjustable, in-flight commandable vertical resolution between 250 m and 2 km from ground up to 30 km. The maximum number of vertical range gates is 25, where 24 range gates are used for atmospheric return measurements and one range gate is used to characterize the background light contribution due to earth or cloud albedo. Atmospheric returns for each vertical range gate of subsequent measurements are horizontally integrated over 90 km to obtain one observation. The observations are obtained continuously without significant gaps (ESA 2010, LeRille et al. 2012, Reitbuch 2012b), in contrast to the earlier mission concept of burst-mode operation of the laser (ESA 2008).

The ALADIN instrument is equipped with two fully redundant Power Laser Heads (PLH nominal n and redundant r), where one PLH acts as a spare and a Flip-Flop Mechanism (FFM) switches between both PLH’s. The two PLH’s are coupled via an optical fibre to a Reference Laser Head (RLH n, RLH r) each, which provides the narrowband, continuous wave (cw) laser light as reference. The laser pulses are sent out via a half-wave plate (HWP), polarising beam splitter (Pol), quarter-wave plate (QWP), beam expander and the telescope to the atmosphere with circular polarisation. Small amounts of the outgoing laser pulse are reflected and directly transmitted via mirrors to the spectrometers to obtain a reference measurement. As the same telescope is used for transmitting the laser pulse and receiving the atmospheric backscatter signal it is used in a transceiver configuration. This allows to limit the Field-Of-View (FOV) for background light to very small values (18.1 μrad full angle) and no active co-alignment between transmit and receive optic is necessary. The backscattered light is received by the telescope, and directed through the beam expander. The circular polarized backscattered light changes its polarization to linear after the quarter-wave plate (QWP) and is therefore transmitted through the polarizer (Pol) towards the interference filter (IFF) and laser chopper mechanism (LCM). The depolarized component of the backscattered light is reflected at the polarizer (Pol) towards the laser and is considered as a signal loss for the ALADIN instrument. The LCM blocks stray light at the receiver input, while the laser pulse is sent out. An interference filter (IFF) is used to filter out background light with an equivalent bandwidth of 1 nm centred at 355 nm. The field stop limits the receiver FOV of the telescope to only 18.1 μrad and the aperture stop limits the beam diameter at the input of the spectrometers to 20 mm. A half-wave plate (HWP) at the output of the transmit/receive optics is used to obtain linearly polarized light of defined direction at the input of the spectrometers.

At the input of the Rayleigh spectrometer (RSP) the beam is reflected at a polarising beam splitter (Pol) towards the Mie spectrometer (MSP) and increased in diameter by a beam expander to 36 mm to reduce the divergence on the MSP. The MSP is composed of a Fizeau interferometers producing linear fringes at the output, which are imaged to an ACCD within the Detection Front-End Unit Mie (DFU-M). As the Fizeau interferometer transmits only a small spectral band around the laser wavelength, it acts mainly as a sensor for the Mie signal (chapter 4.2.3 and Fig. 4-3). The reflected part of the signal spectrum from the MSP is
directed towards the RSP on the same beam path and linearly polarised in such direction, that the beam is now transmitted through the polarising beam splitter within the RSP.

The RSP is composed of two Fabry-Perot interferometers, which act as a spectral filter for the backscattered signal from molecules. The beam is at first directed to one Fabry-Perot interferometer, which is called subsequently filter A. The transmitted signal of the filter A and B is of circular spatial shape (spot) and is directed towards the imaging zone of an ACCD within the DFU-R (DFU-Rayleigh). The reflected part of the signal of the filter A is rotated in polarisation in such a way that it is directed towards the other Fabry-Perot interferometer of the RSP, which is called subsequently filter B. It is composed of the same reflecting plates, but with a slightly decreased distance by a deposited step, which results in a small wavelength shift of the transmission maximum of filter A wrt. filter B. The signal of filter B is directed towards the same ACCD within DFU-R, but illuminating another half of the ACCD than filter A (section 4.2.4 and Fig. 4-2). One half of the imaging zone of the ACCD is illuminated by the signal of filter A, while the other half is illuminated in parallel by the signal of filter B. Thus a sequential, double-edge Fabry-Perot interferometer is realised for detecting the molecular return signal with two filters A and B. The Transmit-Receive Optics (TRO), both spectrometers MSP and RSP, and both detection units DFU-M and DFU-R are mounted on a common structure – the Optical Bench Assembly (OBA).

Figure 4-1: Optical architecture of ALADIN (from ESA (2008)).
<table>
<thead>
<tr>
<th>Unit</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>polar, sun-synchronous, dawn-dusk orbit, yaw-steering</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean altitude</td>
<td>408 km</td>
</tr>
<tr>
<td></td>
<td>mean orbital velocity</td>
<td>7664 ms⁻¹</td>
</tr>
<tr>
<td>ALADIN instrument</td>
<td>slant angle at satellite</td>
<td>35 ° off nadir</td>
</tr>
<tr>
<td></td>
<td>incidence angle at ground</td>
<td>37.6 ° wrt local zenith</td>
</tr>
<tr>
<td></td>
<td>vertical resolution</td>
<td>250 m – 2 km</td>
</tr>
<tr>
<td></td>
<td>number of range gates</td>
<td>24 atmosphere and 1 background light</td>
</tr>
<tr>
<td></td>
<td>range</td>
<td>ground to 30 km</td>
</tr>
<tr>
<td></td>
<td>horizontal averaging length</td>
<td>90 km per observation</td>
</tr>
<tr>
<td>Laser Transmitter</td>
<td>Nd:YAG, frequency-tripled, diode-pumped</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wavelength</td>
<td>354.8 nm</td>
</tr>
<tr>
<td></td>
<td>energy per pulse</td>
<td>80 - 110 mJ</td>
</tr>
<tr>
<td></td>
<td>repetition rate</td>
<td>50.5 Hz</td>
</tr>
<tr>
<td></td>
<td>linewidth</td>
<td>50 MHz FWHM</td>
</tr>
<tr>
<td></td>
<td>pulse-to-pulse frequency stability</td>
<td>4 MHz rms</td>
</tr>
<tr>
<td>Telescope/Front Optics</td>
<td>afocal Cassegrain, SiC structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>primary mirror diameter</td>
<td>1.5 m</td>
</tr>
<tr>
<td></td>
<td>background light filter bandwidth</td>
<td>1 nm</td>
</tr>
<tr>
<td></td>
<td>receive FOV</td>
<td>18.1 µrad</td>
</tr>
<tr>
<td></td>
<td>transmit beam divergence</td>
<td>12 µrad</td>
</tr>
<tr>
<td>Mie Spectrometer</td>
<td>fringe imaging Fizeau interferometer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fizeau Free Spectral Range</td>
<td>0.92 pm / 2190 MHz</td>
</tr>
<tr>
<td></td>
<td>Fizeau Useful Spectral Range</td>
<td>0.72 pm / 1687 MHz</td>
</tr>
<tr>
<td></td>
<td>Fizeau FWHM</td>
<td>0.067 pm / 159 MHz</td>
</tr>
<tr>
<td></td>
<td>total radiometric efficiency</td>
<td>0.64 % (BOL)</td>
</tr>
<tr>
<td>Rayleigh Spectrometer</td>
<td>double edge Fabry-Perot interferometer, 2 filters, sequential</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fabry-Perot Free Spectral Range</td>
<td>4.6 pm / 10938 MHz</td>
</tr>
<tr>
<td></td>
<td>filter separation</td>
<td>2.33 pm / 5547 MHz</td>
</tr>
<tr>
<td></td>
<td>filter FWHM (direct/reflected)</td>
<td>1523 MHz / 1594 MHz</td>
</tr>
<tr>
<td></td>
<td>total radiometric efficiency</td>
<td>5.5 % (BOL)</td>
</tr>
<tr>
<td>Detection Unit</td>
<td>Accumulation CCD for Mie and Rayleigh receiver</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantum efficiency</td>
<td>82 %</td>
</tr>
<tr>
<td></td>
<td>Detection chain noise</td>
<td>4-6 electrons per pixel</td>
</tr>
<tr>
<td></td>
<td>Number of used pixels</td>
<td>16 lines * 25 rows</td>
</tr>
</tbody>
</table>

Table 4-1: Main ALADIN instrument parameter (ESA 2008 and updates in EADS-Astrium (2012), BOL: begin of life).
4.2 ALADIN units

The following sub-chapters describe the units of ALADIN in more detail.

4.3 Laser Transmitter

A diode-pumped Neodymium doped Yttrium-Aluminium-Garnet (Nd:YAG) laser emitting at 1064.4 nm is used to generate the 354.8 nm pulses with a frequency-tripling stage by use of non-linear Lithium-Borate (LBO) crystals. Stringent requirements are set to the laser transmitter in terms of frequency stability of only 4 MHz root-mean-square (rms) pulse to pulse variation. This corresponds to a stability of $5 \times 10^{-9}$ relative to the laser frequency of 845.3 THz. The laser frequency must be tuneable over a large spectral range of 11 GHz for calibration purpose (see 4.3.3). In order to achieve these stringent requirements a Maser Oscillator Power Amplifier (MOPA) configuration (Cosentino 2004) was chosen with injection seeding of continuous-wave (cw) laser radiation of very high frequency stability from a tuneable Reference Laser Head (RLH). During calibration the laser has to be tuned over ± 5.5 GHz in steps of 250 MHz and 25 MHz with an accuracy of 1 MHz rms noise (UV) and a slow drift of below 1.7 MHz (UV) during the calibration time of 30 minutes. After calibration the laser transmitter frequency will be tuned to the centre of the useful spectral range of the MSP. The output beam diameter of the laser transmitter is 7.5 mm. The laser beam is expanded and transmitted via the ALADIN telescope of diameter of 1.5 m. An output divergence of 12 µrad (full angle, 99.7 encircled energy) is obtained in the atmosphere in order to obtain eye-safe operation.

The laser transmitter is used to generate laser pulses at a wavelength of 354.8 nm with a repetition rate of 50.5 Hz and average laser energy per pulse of 80-110 mJ with a length of 20-30 ns (FWHM). Because of the electrical power limitations on the satellite it was planned during earlier mission phases to operate the laser not continuously but in a burst mode, where 700 pulses are transmitted during 7 s with a higher pulse repetition frequency of 100 Hz (ESA 2008). After a period of 7 s, the PLH power amplifier’s would have been switched-off for a period of 21 s, because of the electrical power limitations. This concept was changed to a continuous mode operation of the laser (ESA 2010, LeRille et al. 2012) in order to achieve higher thermal-mechanical stability of the laser. In order to cope with the power limitations on the satellite the repetition rate had to be decreased from 100 Hz to 50.5 Hz. Thus the averaging length for one observation had to be increased to 90 km to obtain sufficient signal levels from a number 600 pulses (before 700 pulses), which are emitted during a period of 12 s (N.B. The observation period in the L1B product refers to a length of 600 pulses within 90 km, while the requirements for random error refer to a range of 100 km below 14 km and 140 km above 14 km). A similar laser concept with an injection-seeded, frequency-tripled power laser in MOPA configuration, frequency tuning capabilities and laser energies of 60 mJ at 354.9 nm was realized for the ALADIN airborne demonstrator (Schröder et al. 2007).

4.4 Telescope and Front Optics

The laser pulses are directed through a beam splitter, where small amounts of the outgoing laser pulse are directed to the spectrometers for internal laser frequency reference measurements. The linear-polarised beam from the laser transmitter is converted to circular polarised light with a quarter-wave plate and adapted to the telescope optics by a beam expander.

The telescope is a 1.5 m diameter afocal Cassegrain telescope with a focus adjustment by thermal control of the tripod holding the secondary mirror. The divergence of the output laser beam is only 12 µrad, as it is expanded to 1.5 m by the telescope. This results in a spot diameter on ground of 10 m in a distance of 500 km (400 km altitude with 35° off nadir angle). The backscattered signal from the atmosphere is collected by the primary mirror and send to the transmit/receive optics. The circular polarized light is converted to linear polarisation by a quarter-wave plate. The depolarised part of the backscattered light is not transmitted to the spectrometers, but reflected on the first polarising beam splitter (Pol). Thus this portion is discarded and results in a signal loss, depending on the circular depolarisation ratio. A laser chopper mechanism avoids stray-light entering the spectrometer, while the laser pulse is send out, and a narrow bandwidth filter of 1 nm with a peak transmission of 80 % limits the broadband earth and atmospheric radiometric background from ground or cloud albedo. The receive beam FOV is limited by the field stop to 18.1 µrad and the beam diameter is limited to 20 mm by the aperture stop. A half-wave plate rotates the linear polarised light in a direction that the beam is reflected by the polarising beam-splitter at the input of the RSP towards the MSP.
4.5 Mie Spectrometer MSP

The reflected beam from the polarising beam splitter of the RSP passes a beam expander, thus reducing the beam divergence and a quarter-wave plate before illuminating the Fizeau interferometer of the MSP. The Fizeau interferometer, which is composed of two reflecting plates with a wedge angle of 4.77 µrad, acts as a narrowband filter with a Full Width Half Maximum (FWHM) of 0.067 pm (159 MHz). It transmits the central part of the backscattered atmospheric spectrum including the narrow bandwidth aerosol return superimposed on the broadband molecular return, and constant background signal. Due to the wedge angle of the Fizeau interferometer, different wavelengths interfere on different lateral positions of the Fizeau interferometer along the wedge. Thus a wavelength shift results in a shift of the interference pattern (fringe), which is imaged on the ACCD detector within the DFU-M. The Fizeau interferometer is designed to have a Free Spectral Range (FSR) of 0.92 pm. Only a portion of 0.71 pm, which is called Useful Spectral Range (USR) is imaged onto the ACCD. Fig. 4-2 shows the principle of the MSP.

The peak transmission of the Mie spectrometer (MSP) including the Fizeau spectrometer is 31 %, whereas the overall Mie radiometric efficiency is predicted as 0.64 % (BOL: begin of life), defined by the ratio of photons at the input of the telescope divided by the mean number of photons at the output of the MSP multiplied with the transmission of the laser emission path (but excluding the quantum efficiency of the ACCD). This radiometric efficiency results from the transmission of all optics (transmit path 0.588, receive path 0.41, MSP peak transmission 0.31), the spectral efficiency of the Fizeau interferometer (0.135) and the pupil truncation from the circular Fizeau aperture to the square ACCD aperture (2/π).

![Figure 4-2: Principle of the MSP with Fizeau interferometer; the central part of the Rayleigh spectrum and the Mie spectrum (blue) is transmitted through the Fizeau interferometer for zero-Doppler shift (left) and non-zero Doppler shift (right); the Fizeau filter transmission curve (red) has its central transmission on different lateral positions of the Fizeau interferometer wedge, which results in a fringe located at different pixels on the ACCD (bottom); the fringe is laterally imaged onto 16 ACCD pixel columns.](image)

4.6 Rayleigh Spectrometer RSP

The beam from the transmit/receive optics is first reflected towards the MSP. The reflected light from the MSP is mainly composed from the broadband molecular return. Most of the broadband Rayleigh signal is reflected at the MSP with a mean reflection of about 0.9, which is shown in Fig. 4-3. The periodic structure is caused by the FSR of 0.92 pm of the MSP.
Figure 4-3: Broadband reflection coefficient of the MSP (solid line) with a FSR of 0.92 pm and the spectral shape of the Rayleigh signal (shaded area).

Not only the Rayleigh signal is reflected on the MSP, but also portions of the narrowband Mie return, which contaminates the signal within the RSP. This results in a cross-talk effect between MSP and RSP, which yields to an error in the Rayleigh wind speed estimate depending on the scattering ratio. This is caused by different response curves for the Mie and Rayleigh signal, because of a factor of 100 smaller bandwidth of the Mie signal compared to the Rayleigh signal. As the scattering ratio can be estimated from the measurements on the MSP, the cross-talk effect can be corrected (Dabas et al. 2008), which is performed for the L2B but not for the L1B products.

The RSP is based on the double-edge technique, where two spectral filters with a FWHM of 0.67 pm are separated by 2.33 pm centred on the transmitted wavelength. The two spectral filters are realised by two Fabry-Perot interferometers, where the two distinct spacing of the reflecting plates are realised by an additional deposited step for one filter. The two spectral filters are illuminated sequentially by using the reflection from one spectral filter to feed the other. The use of two filters within the RSP leads to a differential measurement of the backscattered signal, thus allowing to determine the frequency shift with the use of a response curve. The basic principle of the RSP is illustrated in Fig. 4-3.

This sequential implementation of the double-edge technique is a novel approach to gain higher radiometric efficiency for the Rayleigh spectrometer, which was not realised in other double-edge systems before. It results in different maximum transmissions for both filters, compared to a parallel implementation of the double-edge technique. The peak transmission of both filters are about 79 % and 65 % respectively, whereas the overall Rayleigh radiometric efficiency is 5.5 % (BOL), defined by the ratio of photons at the input of the telescope divided by the number of photons at the output of one Rayleigh filter multiplied with the transmission of the laser emission path (but excluding the quantum efficiency of the ACCD). This radiometric efficiency results from the transmission of the optics (transmit path 0.588, receive path 0.41, RSP peak transmission 0.72 as mean of both filters), and the spectral efficiency of both Fabry-Perot interferometers for a molecular signal (33%).

Thermally tuning of the RSP in the range of ±1.1 GHz, which corresponds to one FSR of the MSP, is used to centre the RSP on the centre of useful spectral range of the MSP.
Figure 4-3: Principle of the sequential, double edge RSP: Rayleigh spectrum (red) and transmission curves of RSP Filter A and B (green) for zero Doppler shift (left) and a significant Doppler shift (right); the transmitted signal intensity through the filters is shown in light-blue; for a non-zero Doppler shift (right) the transmitted signal on B is higher than on A; the spots on the ACCD image zone are shown in the two figures below.

### 4.7 Detection Front End Units DFU and ACCD

Two DFUs are used for detecting the output of the MSP and the RSP. Elements of the DFU are the ACCD and an electronic pre-amplifier stage. The ACCD is optimised for operation in the UV (thinned and back-side illuminated) to yield high quantum efficiency of 82% and cooled to -30 °C for low electronic noise. The beams of the spectrometers are imaged onto 16x16 pixels of an ACCD. This results in 16 spectral channels for the MSP. The two spots from the two filters of the RSP are imaged to 8 pixels of the ACCD each. A novelty of the ALADIN detection unit is the usage of an accumulation CCD, where the atmospheric backscattered signals from consecutive laser pulses are accumulated within a memory zone of the ACCD (see Fig. 4-4). The charges of the memory zone are read out with low frequency to minimise read-out noise after accumulation of P-1 laser pulse. The duration of 1 pulse is necessary for read out, thus reducing the number of on-chip accumulated pulses to P-1. As the memory zone contains 25 rows, a maximum number of 25 range gates can be acquired with the ACCD. The duration of the transfer from the image to the ACCD memory of 1 µs limits the minimum time for one range gate to 2.1 µs, which corresponds to a vertical resolution of 250 m. The charge transfer leads to a temporal and spatial overlap of consecutive range gates of 1 µs, corresponding to 120 m altitude, which was observed with the ALADIN airborne demonstrator (DLR 2012a, DLR 2012d, Marksteiner 2012). The timing sequence of both ACCD’s is programmable, giving flexibility in range gate resolution within one profile for both the Mie and Rayleigh return independently. Also the number of accumulated shots P on the ACCD is programmable as a parameter valid for both the Mie and Rayleigh ACCD.

The photons at the input of the ACCD are converted to electrons with a quantum efficiency of 82 %, and a total noise of about 4-6 electrons per pixel (mainly read-out noise and dark current) thus allowing quasiphoton counting. After pre-amplification the charges are digitised with 16 bit. The response linearity of the detection chain was characterised on ground for the Rayleigh channel to be better than 0.1% (EADS-Astrium 2012). Due to this high linearity, a correction of the RSP signals is considered negligible.

In addition to the range-gated lidar mode, the ACCD can be used in an imaging mode, where images of 16*16 pixels are acquired. The imaging mode is used for verifying the collimation of the optical path during the Instrument Defocus Characterisation IDC mode (see 4.3.3).
In addition to the 16 illuminated pixels per line (range gate), there are 4 additional read-out sequences per line ("virtual pixels", which are not illuminated (not shown in Fig. 4-4)). These additional read-out sequences are also digitized and stored leading to a total number of 20 pixels per line (range gate). Two of these 4 additional pixels are used for detection chain offset correction.

**Figure 4-4:** Illustration of the ACCD (left) illuminated image zone with 16*16 pixels, and the memory zone of 32*25 pixels, where the charges are accumulated on-chip and the register for read out of the pixel charges after accumulation; the principle of the signal detection, signal accumulation and signal readout is shown on the right (from ESA 2008).
4.8 Instrument Operation

4.8.1 Timing Sequence within one Observation

The backscattered signal of a number of P laser pulses is accumulated directly on the ACCD. The value of P is typically between 20 and 50, which results in a time for one measurement between 0.4 s and 1 s and an along-track distance of 3 km to 7 km. These on-board accumulated signals are called one measurement, and every measurement is included in the downlinked data packages. These measurements are processed on-ground to form one observation, which is then a result of N measurements. Each observation consists of a total number of 600 returns from laser pulses, resulting in a duration of 12 s and a horizontal averaging length of about 90 km. Thus the product of N and P equals to 600 and the nominal settings are N=30 and P=20. The actual number of backscattered returns is only N*(P-1), because of the loss of 1 pulse per measurement due to read-out duration. The timing sequence for a number of N*P pulses (nominal 600) is called basic repeat cycle (BRC) and is repeated every 12 s.

4.8.2 Timing Sequence within one Laser Pulse Acquisition

The sequence of detecting the signal of one transmitted laser pulse is called acquisition. A small amount of the transmitted laser pulse is directed towards both spectrometers and detected by the ACCD. This detected reference signal is read out from the ACCD for every single laser pulse without accumulation on the ACCD, as there is sufficient time (3 ms) between the detection of the laser pulse reference and the first atmospheric range gate.

A programmable time delay between the transmission of the laser pulse and the acquisition of the first atmospheric sample starts the acquisition of atmospheric range gates. This time delay takes into account the change of satellite altitude (395 km – 425 km) during the orbit with respect to the WGS84 ellipsoid. Within one observation a variable time delay for every measurement is adjusted such that all measurements are acquired at a constant altitude above WGS84.

In addition information from a digital elevation model (DEM) is included in the on-board satellite software to provide knowledge about the height of the ground (above the WGS 84 ellipsoid) along the expected track of the satellite within one week (orbit repeat cycle) in form of a Look-Up Table (LUT). This information is used to optimise the number of detectable ground echoes and minimize the number of lost range bins below the ground. Thus an additional time delay for the start of acquisition of the atmospheric bins could be introduced for every observation (and not measurement as for the satellite altitude compensation) depending on the ground altitude (Marksteiner 2009).

The time delay and therefore the start of the highest range gate could be set separately for the Mie and the Rayleigh spectrometer, as well as the resolutions for every single range gate. Thus the vertical sampling grid for the Mie and Rayleigh range gates could be set independently. After the acquisition of 24 atmospheric range gates, the acquisition of the background light is started after an additional time delay, which is sufficiently long after the ground return at zero altitude. All the timing parameters are programmable in-flight and 8 different timing sequences could be programmed for one orbit to allow climate zone dependent sampling.

4.8.3 Instrument Modes

The different ALADIN instrument operation modes are summarized in Tab. 4-2. Besides the nominal Wind Velocity Measurement (WVM) mode, nine calibration, characterisation and health-check modes are implemented (EADS-Astrium 2004a, EADS-Astrium 2013a). Some modes are planned to occur regularly as the Instrument Response Calibration consisting of the Mie Response Calibration (MRC) and Rayleigh Response Calibration (RRC). Also the Laser Diode Temperature Adjustment (LDTA), and Instrument Defocus Characterisation (IDC) occur regularly, whereas others are used on-ground or during commissioning phase, or for health check on specific user request (oR). For Instrument Spectral Registration (ISR) and Instrument Auto Test (IAT) the transmitter frequency is tuned over a spectral range of ±5500 MHz resp. ±5000 MHz in steps of 25 MHz and 250 MHz, for IRC over ±500 MHz in steps of 25 MHz. During Dark Current Calibration (DCC), LDTA, OCKA, IDC and the nominal Wind Velocity Measurement (WVM) mode the laser is operated at a fixed frequency. For ISR, IAT, DCC, and IDC only the internal laser reference signal is processed. The atmospheric range gate with the signal from ground return on the MSP and RSP
data is used for processing of data obtained during MRC and RRC, and several atmospheric range gates detected by the RSP are processed for RRC in addition to the internal reference signal. The calibration scheme for RRC using atmospheric signals could cause problems arising from atmospheric inhomogeneities (e.g. clouds) and a quality-control scheme was investigated (DLR 2011). The atmospheric signal and the internal reference signal detected by both spectrometers are used during nominal WVM.

<table>
<thead>
<tr>
<th>Instrument Operation</th>
<th>Acronym</th>
<th>Occurrence</th>
<th>Purpose</th>
<th>Transmitter frequency (range/step)</th>
<th>processed data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument Spectral Registration</td>
<td>ISR</td>
<td>on-ground and in-orbit</td>
<td>to centre laser transmitter frequency and calibration for L2</td>
<td>[-5.5, +5.5 GHz] step 25 MHz</td>
<td>internal</td>
</tr>
<tr>
<td>Instrument Auto Test</td>
<td>IAT</td>
<td>on-ground and/or in-orbit health check (oR)</td>
<td>to verify Mie/Rayleigh receiver spectral transfer functions</td>
<td>[-5.0, -0.75 GHz] and [0.75, 5.0 GHz] with 250 MHz steps</td>
<td>internal</td>
</tr>
<tr>
<td>Dark Current Calibration</td>
<td>DCC</td>
<td>on-ground, in-orbit</td>
<td>to characterise detection chain in darkness</td>
<td>fixed</td>
<td>internal</td>
</tr>
<tr>
<td>Instrument Defocus Characterisation</td>
<td>IDC</td>
<td>in-orbit, every 100 orbits</td>
<td>to characterize defocus of optics by measuring Rayleigh spot size</td>
<td>fixed</td>
<td>internal</td>
</tr>
<tr>
<td>Laser Diode Temperature Adjustment</td>
<td>LDTA</td>
<td>every 100 orbits</td>
<td>optimisation of laser energy and diode lifetime</td>
<td>fixed</td>
<td>laser house-keeping data</td>
</tr>
<tr>
<td>Instrument (Mie, Rayleigh) Response</td>
<td>IRC</td>
<td>every 100 orbits</td>
<td>to measure MSP and RSP response with satellite in nadir</td>
<td>[-0.5, +0.5 GHz] step 25 MHz</td>
<td>internal and ground return on MSP and atmosphere on RSP</td>
</tr>
<tr>
<td>Wind Velocity Measurement</td>
<td>WVM</td>
<td>nominal mode</td>
<td>nominal wind measurement mode</td>
<td>fixed</td>
<td>internal and atmosphere and ground return on MSP and RSP</td>
</tr>
</tbody>
</table>

Table 4-2: ALADIN instrument operation modes (oR: on request) according to EADS-Astrium (2013a).

The purpose and realisation of the different modes is as follow:

**Instrument Spectral Registration:** The laser transmitter is tuned in frequency over one FSR of the Fabry-Perot interferometer of the RSP including several FSR of the Fizeau interferometer of the MSP. Purpose is to obtain the spectral transmission of the two filters of the RSP, and the spectral response of the MSP. From that the frequency $f_1$ will be determined, where the two transmission curves of the RSP filters are crossing and the closest centre frequency $f_0$ of the MSP. This is used to tune the laser transmitter frequency to $f_0$ and to shift the crossing frequency $f_1$ of the RSP to $f_0$ by thermally tuning the RSP. The ISR mode is also used to characterize the instrument for L2A (aerosol) and L2B (wind) processing (Dabas et al. 2008, Flamant et al. 2013, ECMWF 2014b).

**Instrument Auto Test:** Similar as during ISR the laser transmitter will be tuned in frequency to obtain the spectral transmission of the RSP and the MSP. The transmission curves of the RSP will be used to
determine the spectral parameters as FWHM and spectral spacing for both RSP filters. The response curve of the MSP will be derived with the mean slope and the deviation from the best fit as well as the FWHM of the fringe of the MSP for different frequencies. These numbers are used to monitor the stability of the spectrometers and to determine the internal response calibration parameters for MSP and RSP.

**Dark Current Calibration:** The dark current of the detection chain is measured by blocking the receiver input with the laser chopper mechanism and using the imaging mode of the ACCD. The laser can be either operated to investigate stray-light or is switched off for pure detector dark current investigation. Thus the mean dark signals, the dark signal noise, and dark signal non-uniformity can be characterized.

**Instrument Defocus Characterisation:** The ACCD is used in imaging mode to obtain a two-dimensional image of the two spots from the two RSP filters and of the linear fringe of the MSP. The data from the RSP is used to determine the centroid position and the size of the two filter spots. These parameters allow to determine the collimation of the optical path of ALADIN and to thermally adjust the focus of the telescope in order to minimize the spot sizes on the RSP.

**Laser Diode Temperature Adjustment:** The laser diode efficiency will evolve slowly over lifetime. During this instrument mode the laser diode heating current level is changed and the laser UV output energy is monitored. This is used to determine the optimal laser diode temperature.

All the above instrument operation modes are used for characterising, tuning and health-check. Data from these modes will not be used for processing the raw instrument data to the L1B wind product, whereas the L2A (aerosol) and L2B (wind) processing is using the ISR mode data for calibration (Dabas et al. 2008, Flamant et al. 2013, ECMWF 2014b). In contrast the data from Mie and Rayleigh calibration during IRC will be used to obtain calibration data, which is used for L1B wind processing. IRC applies an end-to-end calibration of the instrument including signal from the atmosphere. For this mode the whole satellite is rolled by 35° so that the ALADIN is pointing near nadir (with an angular offset of a few mrad), in order to obtain a zero frequency shift from the horizontal wind velocity (see Fig. 4-5). A zero vertical wind speed for the horizontal length of the integration (over 1 observation of 90 km) has to be assumed for processing. During IRC the laser transmitter frequency is tuned over ±500 MHz with steps of 25 MHz, corresponding to a range of maximum detectable wind speeds of ±89 m s⁻¹ (LOS) and ± 145 m s⁻¹ (HLOS). It is planned to perform this calibration mode about every 100 orbits, which is once per week. The derived parameters from the calibration mode will be used for the wind velocity determination. The IRC mode is composed of the following two response calibration modes:

**Mie Response Calibration:** Only the range gate, where a signal from the earth surface – called ground return - is used for further processing. The frequency of the ground return range gate is assumed to be zero, which is a good approximation over land and also over the ocean in nadir-pointing. The response of the MSP for the range of transmitted frequencies is used to derive the linearity parameters (slope and offset) for the MSP as well as its non-linearity from pixel to pixel.

**Rayleigh Response Calibration:** The atmospheric range gates, where negligible cross-talk from the aerosol signal and negligible vertical velocity is expected (e.g. between 6 and 16 km) is used to determine the Rayleigh response for different transmitted frequencies. In addition the ground return range gate is analysed wrt the Rayleigh response, as the spectral response from the ground is different as from the atmosphere for the Rayleigh receiver. The ground return can be considered as a narrowband spectral signal. As for the MRC the linearity parameters (slope and offset) and the non-linearity of the RSP will be characterized for atmospheric and ground return range gates independently. The calibration scheme for RRC using atmospheric signals could cause problems arising from atmospheric inhomogeneities (e.g. clouds) and approaches were studied, including the use of the scattering ratio from the MSP signal for quality-control of the RSP signal (DLR 2011).

The nominal mode of the instrument, which is used permanently until a command for mode switch is received is:

**Wind Velocity Measurement:** The instrument is operated with a fixed laser frequency with the satellite pointing to 35° off nadir. The internal reference signal and the atmospheric and ground return signal are sampled with the programmed vertical sampling scheme for Mie and Rayleigh independently and the horizontal sampling scheme determined by the number of accumulated pulses P and the number of measurements per observation N.
Figure 4-5: ADM-Aeolus in nadir pointing mode during instrument response calibration IRC (from ESA 2008).
5 Data Product Content

According to the processing level, the ADM-Aeolus data products are grouped into Level 0, Level 1 and Level 2 data sets (Tab. 5-1). Starting point for the processing are the raw telemetry data, as transferred from the ground station to the Payload Data Segment (PDS).

<table>
<thead>
<tr>
<th>Data Product</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td>Time-ordered source packet streams which are reorganised into different measurement data sets according to the system and instrument mode.</td>
</tr>
<tr>
<td>Level 1A</td>
<td>Housekeeping source packet fully processed, AOCS source packets (geolocation) processed and assigned to measurement data, measurement data unprocessed.</td>
</tr>
<tr>
<td>Level 1B</td>
<td>Fully processed, calibrated and georeferenced measurement data including HLOS winds, viewing geometry, ground echo data and product confidence data (PCD)</td>
</tr>
<tr>
<td>Level 2A</td>
<td>Additional aerosol/cloud optical properties, as optical depth, extinction coefficient, backscatter coefficient, cloud boundaries and PCD.</td>
</tr>
<tr>
<td>Level 2B</td>
<td>L2B products represent “consolidated” HLOS wind data and include corrections using actual pressure and temperature information as obtained from numerical models from a NWP centre. Additional corrections are based on retrieved optical properties. Measurements are grouped after a scene classification.</td>
</tr>
<tr>
<td>Level 2C</td>
<td>L2C products contain two-component wind vector profiles on the location of the ADM-Aeolus ground track as obtained after the assimilation process of L2B products at a NWP centre. L2C products mainly contain information from the NWP model.</td>
</tr>
</tbody>
</table>

Table 5-1: Content of data products for ADM-Aeolus.

This document describes the algorithms for the Level 0 and Level 1 products. For further information on the Level 2 products refer to ESA (2004b), ECMWF (2014 a,b), and Flamant et al. (2013).

5.1 Raw Telemetry Data

Baseline for the processing is the raw telemetry data (AISP: Annotated Instrument Source Packet), which is then processed to L0 product.

Raw telemetry data is either lidar mode data or imaging mode data (see chapter 4.2.5). In both cases, the telemetry data contains 71 data packets, which may be basically divided into five different types:

- Attitude and Orbit Control System (AOCS) data
- Housekeeping data
- Auxiliary data – Mie
- Auxiliary data - Rayleigh
- Measurement data

The AOCS data contains information about the satellite orbital position. The time, position, velocity, and attitude information of the satellite is repeated every 125 ms starting at the begin of an observation.

Data of the on board ALADIN Control and Data Management Unit, as cavity lock status, instrument mode, laser frequency, or UV energy, is stored in the Housekeeping data packet. Furthermore this packet contains information about the number of measurements N and number of shots per measurement P.

The internal references of the Mie channel are stored in the Auxiliary data - Mie packet, the Rayleigh channel internal references in the Auxiliary data – Rayleigh packet. These two packets are only filled with data for the lidar mode.
The **Measurement data** packet is repeated **30 times for the lidar and the imaging mode**. These packets contain the ACCD readouts.

### 5.2 General Data Product Structure

ESA has developed a general Ground Segment File Format Standard (ESA 2003), which applies to all data files exchanged between ground segment systems within the Earth Explorer Missions.

This standard introduces the following logical file structure: A logical file is split into two main blocks, a header section followed by a data section. The header section comprises the fixed header (FH) and the variable header (VH), which in turn is split into two parts, the main product header (MPH) and the specific product header (SPH). For every file the FH contains information about the file itself (name, type, and version), validity time, and source information (tool, version, date). The MPH contains information that applies to every file of a certain type, and a SPH contains information which is only valid for a specific file of a certain type. The SPH is completed by the data set descriptors (DSDs), which give information about the data sets following the header. Figure 5-1 sketches the product structure.

There are three different types of data sets, the measurement data sets (MDSs), the annotation data sets (ADSs), and the global annotation data sets (GADS). Whereas the MDSs contain actual measurement data the ADSs will include data required for the full interpretation of the measurement data, as geolocation or product quality information. Calibration data will be contained in GADS.

For **small data volume**, the header section and the data section are stored in one file written in the Extensible Markup Language (XML) standard.

For **large data volume**, the header section is stored in a file written in the XML standard and the data section is written in a second file as binary data, preceded by a copy of the VH written in the Key Value Terminator (KVT) format (see ESA (2003) for further information).

**Figure 5-1**: General product structure.
In addition to this logical structure, there is a physical structure. To facilitate processing of files, which have very different contents and/or are processed by different software tools, a product may be split up into two separate physical files, one containing the header information, and one containing the scientific data.

The following sections briefly introduce the Level 0 and Level 1 products, detailed information may be found in MDA (2006a).

### 5.3 Level 0

<table>
<thead>
<tr>
<th>FH</th>
<th>MPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPH</td>
<td>DSD</td>
</tr>
</tbody>
</table>

The Level 0 MPH contains information about
- the product itself: what kind of product, a reference to the detailed formal description, the acquisition and processing facility
- satellite position and velocity, sensing start and stop time
- the number and size of data within this product

The Level 0 SPH contains information about
- latitude and longitude of nadir point at start and stop time
- the number of missing or erroneous source packets and thresholds

Due to the different instrument functions, a Level 0 product may contain one or more of the following MDS: Wind MDS, Instrument Spectral Registration MDS, Mie Response Calibration MDS, Rayleigh Response Calibration MDS, Instrument Auto Test MDS, Dark Current Calibration MDS, Instrument Defocus Calibration MDS, Laser Chopper Phase Adjustment MDS.

All of these MDSs are of the same structure. They start with some information on start time and the source packets themselves. Then 71 Aeolus source packets follow. If some source packets are missing in the raw data, then the space for this packet is padded with zeros. Thus every MDS has the same fixed size.

The Aeolus Level 0 product does not contain any ADS or GADS.

A Level 0 product is mainly the raw instrument data, which has been time ordered and cleaned, reorganised into different MDSs, and annotated with error information.

Table 5-2: Content of Level 0 data product for ADM-Aeolus (*LDTA has to be added and LCP has to be removed for next issue*).
The Level 1A MPH and SPH contains the same information as the Level 0 MPH and SPH.

The Level 1A product contains four different annotation data sets, one for geolocation information, one for the data quality information, one for the reference pulses information, and one for the housekeeping data. Every ADS starts with an start-of-observation-time field.

The **geolocation** ADS contains AOCS data and geolocation data.

The AOCS data lists the centroid time, the position, velocity and roll, pitch, and yaw angle for the satellite. This information is given once for the entire observation and **30 times for the 30 measurements**, which are contained in the MDSs.

The geolocation ADS lists the Mie geolocation, the Rayleigh geolocation, the intersection with the Digital Elevation Model (DEM), and the satellite line of sight velocity once for the entire observation and **30 times for the different measurements**, which are contained in the MDSs. On observation level **topocentric elevation and azimuth, satellite range**, and a sun visibility flag is reported for every height bin. In addition the separation of the geoid to the WGS84 ellipsoid is provided for the observation.

The **data quality** ADS gives a summary flag indicating that some source packets are not valid. It also lists for each of the **30 Mie and Rayleigh measurements**, if the measurement source packets are valid, the laser frequency was locked, and the spacecraft is in a stable state.

The **reference pulses** ADS lists the number of pulses per BRC, followed by a list of ACCD readouts for each reference pulse of a BRC.

Finally the **housekeeping data** ADS starts with information on the instrument mode, the number of pulses per measurement, and the number of measurements per BRC. The following fields provide information about the frequency offset, the UV-energy, some pulse delay constants, and integration time for every layer for every laser shot. Also some information about the ACCD temperatures is present.

The **Mie- and Rayleigh** MDSs contain the ACCD readouts for the Mie and Rayleigh measurements from the atmospheric range gates.

**Table 5-3:** Content of Level 1A data product for ADM-Aeolus.
The main step from L0 to L1A product is the processing of the housekeeping data and the geolocation of measurements.

5.5 Level 1B
The content of the L1B product shown in the Table 5-4:

Table 5-4: Content of Level 1B data product for ADM-Aeolus.

The Level 1B MPH is the same as Level 1A MPH.
In the first block of the SPH latitude and longitude of the satellite nadir point and the LOS intersection with earth ellipsoid at the sensing start and stop time of the MPH are listed. The second block gives information about the number of measurements per BRC, number of pulses per measurement, and the total number of observations, measurements, and reference pulses. The third block states the number of observations and measurements used to estimate wind velocity and the number of Mie/Rayleigh reference pulses used. The fourth block gives information about the number of observations, in which Mie/Rayleigh zero wind was detected and the number of Mie/Rayleigh ground bins detected. The last block reports on the number of measurements and pulses with a laser transmitter unlocked, measurements with satellite not on target and number of corrupted Mie/Rayleigh measurements and reference pulses.
The Level 1B product consists of four different ADS, two GADS, and two MDS. Again, every ADS, GADS and MDS starts with the start-of-observation-time field. The geolocation ADS is a copy of the Level 1A geolocation ADS.

The product confidence data ADS starts with a block reporting on the number of laser frequencies not locked, satellite not on target for measurements and pulses, the number of corrupted Mie/Rayleigh measurements and pulses, some error quantifiers, information about the laser frequency and energy, Mie/Rayleigh quality information for wind and signal, and the number of invalid measurements and reference pulses for Mie/Rayleigh. The information in this block refers to the entire observation. This block is followed by at most 30 structural identical blocks for the 30 measurements containing the product confidence information for each measurement. The various product confidence information comprises processor settings, statistical parameters on valid and corrupt data, standard deviation of typical laser characterization parameters, and signal quality information like signal to noise ratio, scattering ratio and Mie core fitting results.

The Mie Core Parameters GADS contains a copy of the Mie Core parameters as set in the AUX_PAR_1B file used for processing this data. These parameters are picked up by the L2B processor who runs an identical Mie Core algorithm.

The calibration & characterization GADS reports a copy of selected data of the L1bP auxiliary files ‘Satellite Characterisation’, ‘Mie Response Calibration’, and ‘Rayleigh Response Calibration’. It contains satellite error quantifiers for the Mie/Rayleigh channels, tripod obscuration correction data, and Mie/Rayleigh frequency step data statistics (see chapter 5.7 for a description of MRC and RRC GADS).

The ground wind detection ADS reports the ground correction weighting factors, the average ground bin altitudes and thicknesses above DEM for Mie/Rayleigh, the number of Mie/Rayleigh ground bins detected and for every measurement the detected ground bin number and bin thickness above DEM for Mie/Rayleigh.

The measurement ADS copies and pre-processes data from the L1A input product to the L1B product. It contains copies and pre-processed Mie/Rayleigh reference pulse data, Mie measurement data, Mie/Rayleigh time delay information, and validity indicators for the Mie measurement data.

The processed scientific measurement data is stored in two different MDS, the useful signal MDS and the wind velocity MDS.

The useful signal MDS reports on the useful signal strength for observations and each measurement for all 25 height bins in the Mie channel and Rayleigh channels A and B, whereas the wind velocity MDS reports the derived wind velocity for observations and each measurement for all the height bins in the Mie and Rayleigh channels. In both MDSs the values reported are annotated with quality bit flags.
5.6 Auxiliary Calibration Products

General Auxiliary Calibration Products Structure

The auxiliary calibration products are an output of the Level 1A to Level 1B processing. There are eight different products, suitable for the seven calibration MDS and the wind MDS of the Level 0 product. Except for the specific data sets, they share a common structure.

Their MPH is a copy of the Level 1B MPH. Their SPH is a subset of the Level 1B SPH reporting the second, third, and last block of the Level 1B SPH.

Every data set starts with the start of observation times for the first and last BRC of the measurement data used to generate the calibration output.

Every auxiliary calibration then contains exactly one global annotation data set. As an example the figure to the left represents the Instrument Spectral Registration Calibration product.

Table 5-6: Content of Auxiliary Calibration Products for ADM-Aeolus for the ISR.

The auxiliary calibration products are written as XML-structure files in a single physical file. The list of auxiliary output products matches the list of instrument modes (Tab. 4-2), except for the wind measurement mode and an additional GADS for the Zero-Wind Calibration ZWC.

The ISR GADS contains for each frequency step the ISR results, the laser frequency offset, the Mie/Rayleigh spectral response and some additional statistics data, as the number of used Mie/Rayleigh pulses, and number of corrupted pulses. Furthermore, it contains an overall result of the frequency offset of the Rayleigh filter centre and the frequency offset of the Mie Channel USR closest to the Rayleigh filter centre and the temperatures from the RSP and MSP.

The IAT GADS reports for each frequency step the Mie FWHM and Mie response, as well as the Rayleigh transmission of both filters A and B, and the Rayleigh spectral response. As a main result it reports the mean slope of the Mie and Rayleigh channel response and the Rayleigh filter FWHM and filter spectral spacing. In addition, it contains statistics information and RSP and MSP temperatures.

The DCC GADS contains all the measurement and reference pulses dark signals and noise, their average values and standard deviations (dark signal non uniformity) over measurements and observations. Additionally, it contains the ACCD temperatures during the data acquisition.

The IDC GADS gives a map of mean image pixel intensity values and information about the energetic centroid of channel 1 and 2, as row and column value closest to the energetic centroid, row and column values of image pixel intensities along the centroid, and the size (standard deviation) of the spots. Additionally, the temperatures of the telescope (struts, mirrors) are provided.

The MRC GADS first gives an overall flag, indicating the Mie response calibration validity, based on acceptable ranges of calibration results for measurement (ground-return) and reference pulse and the number of valid frequencies. Then it gives detailed information about the measurement and reference pulse calibration validity, the channel response, its mean sensitivity, zero frequency, and response non-linearity. In addition it contains statistics information.

The RRC GADS has the same structure as the MRC GADS and contains the equivalent Rayleigh values for the reference pulse, the atmospheric range gates and the ground returns.

Finally, the ZWC GADS contains in the first block geolocation and instrument angle information for the centre of the observation. The second block may contain Mie zero wind and/or Rayleigh zero wind results depending on the Mie/Rayleigh ground correction factor. The zero wind results comprise information about the
ground echo bin detection and the Mie and Rayleigh channel and the raw LOS wind velocity estimate for the ground bins.

LDTA has to be added for next issue.
6  Geolocation, Coordinate Systems, and AOCS Processing

Complex geometrical problems have to be solved, to geolocate satellite observations (see Kidder and Vonder Haar (1995) for an introduction). It is necessary to know the Earth coordinates (latitude and longitude) of the particular scene the instrument is viewing. In the ADM-Aeolus mission the sensed data are wind velocity along the direction of the laser beam line-of-sight (LOS). Therefore, it has to be determined in which direction with respect to an Earth fixed local coordinate system the laser beam was pointing during the observation. In addition to the atmospheric wind vector, the movement of the satellite itself and the Earth rotation contribute to the sensed LOS velocity, which has to be corrected. All these tasks require an accurate knowledge of the position of the satellite in its orbit, the orientation of the satellite (attitude) and the scanning geometry of the instrument.

Not only the location on the Earth’s surface is important for analysing the observations but also the local surface altitude. The surface altitude from a Digital Elevation Model (DEM) is used to determine the distance from the satellite to the Earth’s surface. This is important to identify the ground return bin of the lidar signal among the data. To solve these geometrical problems different coordinate systems, surface models and appropriate geometrical algorithms are needed.

Figure 6-1: Pointing geometry of Aeolus, indicating yaw $\gamma$, pitch $\beta$ and roll angle $\alpha$. The instrument is pointing towards the line-of-sight; note that the incidence angle between LOS and local normal (at wind position) is different from the roll angle, because of the earth curvature; thus the incidence angle is slightly altitude dependent.
6.1 Coordinate Systems

The following coordinate systems are used

- the **J2000** reference frame as an inertial coordinate system for orbit calculations.
- a Local Horizontal/Local Vertical (**LVLH**) reference frame for determination of LOS direction.
- The standard Euler angle sequence of satellite **yaw**, then **pitch**, then **roll** from a (0,0,0)- LVLH coordinate system for overall satellite-ground communications on attitudes.
- an Earth fixed local coordinate system for Earth locations of measurements. The standard Earth fixed local coordinate system is the Earth Centred Earth fixed (**ECEF**) coordinate system.
- The use of a reference ellipsoid allows for the conversion of the ECEF Cartesian coordinates to the more commonly used geodetic coordinates of latitude, longitude, and altitude.

6.1.1 J2000 Reference Frame

J2000 is an inertial right-handed Cartesian coordinate system centred in the Earth’s core (Fig. 6-2). The x-axis is at the intersection of the mean ecliptic plane with the mean equatorial plane and is directed towards the mean vernal equinox at noon on January 1, 2000. The z-axis points out the North pole along the Earth’s rotational axis and is orthogonal to the mean equatorial plane. The y-axis completes the right handed coordinate system.

The satellite on-board processor transforms the GPS position and velocity into the J2000 frame. These are contained in the satellite AOCS data for every 125 ms as a 3d vector for position and velocity (in the J2000 frame) and a 4d quaternion, which represents the transformation from inertial space (J2000) to satellite reference frame.

![Figure 6-2: J2000 reference frame.](image)

6.1.2 LVLH Frame

The origin of the LVHV coordinate system is located at the satellite. In the LVLH reference frame the z-axis is pointing to the centre of the Earth (nadir vector). The y-axis is parallel to the orbit momentum vector and the x-axis completes the right handed coordinate system. The **LVLH** reference frame is used for the satellite and the instrument.
6.1.3 Pitch, Roll and Yaw

Pitch, roll and yaw are angles of rotation about three axes that are perpendicular to each other. Here pitch, yaw and roll are related to the LVHV coordinate system to define the satellite attitude (Fig. 6-1). Roll is the angle of rotation about the x-axis (flight direction), pitch about the y-axis (perpendicular to the flight direction) and yaw about the z-axis (nadir). Note, that the rotations have to be performed in order yaw, pitch and roll. In nominal mode the spacecraft z-axis is rotated by -35° from nadir about the roll axis (x-axis). Additionally the AOCS system steers the satellite such, that there is no relative velocity along the LOS including the earth rotation. In nominal mode the satellite is steered around the yaw-axis (z-axis) depending on the satellite latitude with a maximum earth rotation of 465 m/s at the equator and 0 m/s at the poles. In nadir-pointing mode the satellite is steered around the pitch-axis.

6.1.4 ECEF Frame

The Earth Centred Earth Fixed (ECEF) reference frame is a right-handed Cartesian coordinate system (x, y, z) and is the most recently defined International Terrestrial Reference Frame (ITRF). It’s origin is the mass centre of gravity of the Earth (Fig. 6-4). The x-axis is directed towards the intersection of equator (0° latitude) and Greenwich meridian (0° longitude). The z-axis points out the North pole along the Earth’s mean rotational axis. The y-axis completes the right handed coordinate system and, therefore, intersects the equator at a longitude of 90° East.

Figure 6-3: LVHV reference frame; the spacecraft is located at the centre of the coordinate system.

Figure 6-4: ECEF System of coordinates with x-axis pointing to equator and 0° meridian, and z-axis towards the North pole along the rotation axis.
6.1.5 Geodetic Coordinates

The use of a reference ellipsoid allows for the conversion of the ECEF Cartesian coordinates to the more commonly used geodetic mapping coordinates of latitude, longitude, and altitude. The altitude is defined here as the perpendicular distance above the reference ellipsoid (WGS84 is used for Aeolus).

6.2 Orbit

The ADM-Aeolus satellite will fly in a polar, sun-synchronous, dawn-dusk orbit. For a sun-synchronous orbit the inclination is chosen such that the orbit normal makes a constant angle with the Sun-Earth direction. As a consequence the equator crossing time is constant. The reference orbit parameters are summarized in Tab. 6-1.

<table>
<thead>
<tr>
<th>Orbit parameter</th>
<th>Mean Value</th>
<th>Osculating Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference epoch</td>
<td>01/10/2008 00:00:00.000</td>
<td></td>
</tr>
<tr>
<td>Orbit repeat cycle</td>
<td>7 days and 109 orbits</td>
<td></td>
</tr>
<tr>
<td>Orbit altitude at equator</td>
<td>396 km</td>
<td></td>
</tr>
<tr>
<td>Orbital period</td>
<td>≈ 92.48 minutes</td>
<td></td>
</tr>
<tr>
<td>Local Time of Ascending Node (LTAN) crossing</td>
<td>18.00 h ± 4 minutes</td>
<td></td>
</tr>
<tr>
<td>Tolerance of ascending node crossing</td>
<td>± 25 km (cross-track)</td>
<td></td>
</tr>
<tr>
<td>Semi-major axis</td>
<td>6767.973 km</td>
<td>6777.587 km</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.0013009</td>
<td>0.0013910</td>
</tr>
<tr>
<td>Inclination</td>
<td>96.9655 °</td>
<td>96.9606 °</td>
</tr>
<tr>
<td>Right Ascension of ascending node (RAAN)</td>
<td>279.9823</td>
<td>279.9822</td>
</tr>
<tr>
<td>Argument of perigee</td>
<td>90.1003 °</td>
<td>69.2927 °</td>
</tr>
<tr>
<td>True anomaly</td>
<td>268.878</td>
<td>290.7004</td>
</tr>
</tbody>
</table>

Table 6-1: Parameters of the ADM-Aeolus reference orbit (from ESA 2010)

6.3 Surface Reference Systems

Because of the inhomogeneous mass density of the Earth, its shape does not form a regular body. The form of the Earth is denoted by the term geoid. For geolocation this geoid is approximated by a geometrical reference surface. Usually, a rotation ellipsoid is used as a reference surface. A worldwide accepted model is the World Geodetic System of 1984 (WGS84) ellipsoid.

A DEM is required to define the exact height of the Earth’s surface with respect to the reference ellipsoid. The ACE (Altimeter Corrected Elevation) model will be used as DEM for ADM-Aeolus.

6.3.1 WGS84 reference ellipsoid

The WGS84 reference ellipsoid approximates the Earth surface by a rotation ellipsoid with main axis of 6378.137 km and 6356.752 km. Geodetic coordinates (latitude, longitude and altitude) are given with respect to this reference ellipsoid.
6.3.2 Geoid Correction

The WGS84 reference ellipsoid is not referenced to sea level – thus the altitude of the oceans is not 0 m (ASL) for the ellipsoid. The geoid is referenced to sea level and the difference between the geoid and the ellipsoid can be derived from a model, e.g. the earth gravitational model from 1996 called EGM96. The deviations of the EGM96 geoid from the WGS 84 reference ellipsoid range from about −105 m to about +85 m. This model can be obtained from http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/egm96.html

Note that the Aeolus L1B data product is referenced to the WGS84 ellipsoid and not to the geoid, so no geoid correction is applied to the Aeolus L1B altitudes.

6.3.3 Digital Elevation Model

ACE is used as a global DEM for ADM-Aeolus (see Johnson et al. 2004 and ESA 2004c). It covers the whole Earth surface with a horizontal grid spacing of 30 arcseconds (approximately 1 km). The horizontal coordinate system is decimal degrees of latitude and longitude referenced to WGS84. Figure 6-5 shows the ACE altitude deviations from the WGS84 ellipsoid in colour scale.

![Figure 6-5: The ACE digital elevation model (from Johnson et al. 2004); colours indicate altitudes wrt WGS84 ellipsoid.](image)

6.4 Geometrical Processing

6.4.1 Attitude and Orbit Control System Data

Attitude and Orbit Control System (AOCS) data represent the position, velocity and attitude of the satellite within the J2000 frame for every 125 ms. Position and velocity are represented by three-dimensional vectors, whereas the attitude is given as a quaternion, which represents the transformation from inertial space to satellite axis. The AOCS data is used to determine the geolocation of the measurement data with respect to the Earth. The processing of the AOCS data with related coordinate transformations, geolocation, satellite LOS velocity and direction computation, and time-basis transformation is performed in a software library (called CFI Customer Furnished Item Version 4.6). used for all Earth Observation Missions (Elecnor Deimos Space and ESA (2013a, b, c)).
6.4.2 Satellite Attitude

In nominal mode the instrument axis is rotated by −35 degrees from nadir (i.e. from the z-axis in the LVHV frame) about the roll axis. The AOCS steers the yaw angle to compensate for the earth rotation and systematic orbital height variations such that nominally no relative velocity along the LOS occurs. For the calibration modes MRC and RRC, the instrument axis points to the nadir. Then, steering is applied around the pitch axis. The real relative velocity along the LOS is determined from the actual AOCS attitude data.

6.4.3 Earth Locations of Observations

The LOS target is defined as the intersection point between the instrument LOS (without taking into account refraction of the beam) and the WGS84 ellipsoid. These are given in latitudes/longitudes and height above the WGS84 ellipsoid for the atmospheric levels according to the range-bin settings for the centroid times (of a measurement or observation). The horizontal geolocation is slightly altitude dependent, because of the 35° off nadir angle for the LOS in nominal wind measurement mode. From this target the location vectors to the centres of the sensing volumes can be deduced, because the lower altitude of the range bin is provided in the L1b Product (except for the top-most bin, where the upper edge is reported). The incident angle is the angle between the local vertical at the measurement location and the LOS and is slightly altitude dependent due to the curvature of the earth ellipsoid.

The following table lists the requirement for geolocation knowledge for the ADM-Aeolus mission according to the System Requirements Document SRD (ESA 2010).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>System Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement range</td>
<td>50 m (+3-sigma)</td>
</tr>
<tr>
<td>horizontal geolocation error</td>
<td>2000 m (± 2-sigma)</td>
</tr>
<tr>
<td>vertical geolocation error</td>
<td>200 m (± 2-sigma)</td>
</tr>
</tbody>
</table>

Table 6-2: Requirements for geolocation of ADM-Aeolus (ESA 2010)

6.5 Time

All instrument data packets in the raw data are provided in GPS time difference to a reference epoch from 6th January 1980. GPS times do not contain leap seconds needed for the correction of the Earth rotation, which are contained in the UTC (Universal Time Coordinated) time basis, e.g. GPS time is 16 seconds ahead of UTC for July 2012 (the last leap second was inserted on June 30, 2012). The timestamps in the Aeolus data product are provided in UTC time and thus the GPS times are converted to UTC by subtracting of leap seconds (UTC=GPS-leap seconds).
7 Algorithm Theoretical Baseline L0 and L1A Products

7.1 Processing from raw data to L0

Input to the level 0 processing is a raw data file which contains the telemetry source packets AISP (Annotated Instrument Source Packets) downlinked from the satellite during one pass over the receiving ground station. This file may contain source packets from different system and instrument modes. Some system and instrument modes will produce more than the 34 packets of one BRC. At the beginning or end of a file a BRC may not be complete. Sometimes raw data files will be concatenated at the ground station. Then, the resulting raw data file may contain duplicates of packets.

So the first major task for a level 0 processor is to extract complete BRCs within a given time frame, and sort and reformat packets belonging to the same system and instrument mode. The second major task is the subsequent validation of each individual source packet such that only complete BRCs with valid packets will be recorded in the L0 products.

7.1.1 Pseudo-Algorithm for Extracting and Sorting

The downlinked telemetry data comprising an individual observation are organized in a set of data structures ("packets") each associated to a particular structure identifier (SID). The extracting and sorting is performed as follows:

Loop over AISP

- Find next SID No.1 within processing start & stop time, validate, and extract orbital information needed for the Level 0 MPH and the instrument function mode
- Read subsequent packets, skip duplicates and validate
- If all 34 packets belonging to that BRC where found and validated, write the BRC to the corresponding measurement data set of the Level 0 product

7.1.2 Pseudo-Algorithm for Validation

The validation checks the source packet header information which consists of two parts, the Telemetry (TM) source packet header and the Front-End Processor (FEP) annotations. This validation is a sequence of error and consistency checks. If one step in the check is not completed successfully, the packet is not valid.

- Check that packet has no Virtual Channel Data Unit (VCDU) error
- Check Cyclic Redundancy Check (CRC) count
- Verify packet Identification (ID) fields
- Check consistency of sequence control fields
- Verify packet length
- Validate source packet data field header
- Check source data

In a final step the FH, MPH, and SPH of the product are generated using information gathered during the extraction and validation of packets and the MDSs are appended.
7.2 Processing from L0 to L1A

Input to the level 1A processing is the previously generated Level 0 data product. The main purpose of the Level 1A data processor is the processing of the AOCS and housekeeping data and the separation of measurement data into different products according to the system and instrument mode.

Thus the Level 1A processor loops over the measurement data sets of the Level 0 product, processes the packets into annotation data sets and measurement data sets and writes the sets into system and instrument mode dependent L1A product files.

For further information on the processing of AOCS packet SID no.1 to generate the geolocation ADS see chapter 6. SID no. 2 is processed for the Housekeeping data ADS, whereas SIDs no. 3 and 4 are processed for the Reference Pulse ADS, and SIDs no. 5 to 34 are processed for the Mie Channel and Rayleigh Channel MDSs. For the Data Quality ADS information from the processing of all the 34 packets is gathered.

7.2.1 Housekeeping Processing

Processing of housekeeping involves three different processing steps. In a first one, the quality indicators are derived. For every measurement the various quality flags of the corresponding reference pulses are copied to the data quality ADS. In case the number of locked pulses is above a certain threshold read from the processing parameters file, the Measurement_Laser_Freq_Locked quality flag is set to true.

In a second step the housekeeping ADS is filled. Except for average and standard deviation values, housekeeping data are just copied from the Level 0 product. Average and standard deviation values are then calculated.

In a final third step, the total number of reference pulses per observation is calculated from the number of measurements per observation N and the number of laser pulses per measurement P as provided in the L0 product.

7.2.2 Reference Pulse Processing

The reference pulse processing checks the presence and validity of the reference pulse data. The overall quality flags Mie_Reference_Pulses_Present and Mie_Reference_Pulses_Sp_Valid are set to true in case not a single source packet for all the measurements in a BRC is missing or not valid. This information is already contained in the L0 product. The Mie_Measurement_Sp_Valid flag is set to true for a specific measurement, in case the measurement source packet is not missing.

The number of reference pulses is set while processing the housekeeping information. The reference pulse data itself is just copied from the Level 0 input product to the Level 1A output product.

7.2.3 MSP and RSP Data Processing

The measurement data processing is done in two steps. First the number of measurements, height bins, and ACCD columns are set. Then Level 0 measurement data input packets are subdivided into Mie and Rayleigh packets on the basis of their SID number, and written to the Level 1A output product.

7.2.4 Data Quality Processing

Data quality indicators are set while processing the housekeeping information, and the reference data.
8 Algorithm Theoretical Baseline L1B Products

The following subchapters describe the algorithm theoretical baseline for deriving the L1B product. The implementation of the algorithms in the processors is described in EADS-Astrium (2013y) and DoRIT and MDA (2011c). The general process of determination of the wind velocity, which applies to both Rayleigh and Mie data, is described in chapter 8.1. Chapter 8.2 and 8.3 describe the processing from the data from the Mie and Rayleigh spectrometer to a wind observation in wind mode. The processing of the data obtained during the calibration modes MRC and RRC is contained in chapter 8.4 and 8.5, and the ground return processing is given in chapter 8.6. The derivation of the signal amplitudes from Mie and Rayleigh spectrometers is included in chapter 8.7 and 8.8. The quality control, identification of corrupted data and derivation of error quantifiers is included in chapter 8.9.

8.1 Wind Velocity Determination

The wind velocity is derived from the data obtained during nominal Wind Velocity Measurement WVM mode. It is possible to derive a wind velocity for each of the 24 altitude range gates from the MSP and RSP, and for each measurement and for an observation.

**Measurement:** The atmospheric signals from each spectrometer for a number of P-1 emitted laser pulses are accumulated on-chip the ACCD to one measurement. A measurement is typically averaged over 20 to 50 laser pulses, which is equivalent to a horizontal length of 3 km to 7 km.

**Observation:** A number of N measurements are averaged on-ground to obtain one observation, which is the nominal L1B data product. An observation is typically averaged horizontally over 90 km.

The L1B wind product is derived for each measurement within one observation and for each observation applying the same algorithms.

In addition to the 24 altitude range gates containing signal from atmospheric targets, a measurement of the atmospheric background radiation is performed after the acquisition of the atmospheric range gates for every emitted pulse on the MSP and RSP. The background radiation measurement is accumulated on-chip the ACCD with the same number of P-1 pulses as for atmospheric measurements, but with a longer duration $t_b$. This background radiation can be assumed as a constant offset over frequency for the MSP and RSP measurements (see chapter 3.5).

In principle the following contributors to the frequency of the atmospheric range gate have to be considered when deriving the mean LOS velocity within the atmospheric range gate:

- frequency of the emitted laser pulse
- frequency shift due to the projection of the satellite velocity on the LOS

A small portion of the emitted laser pulse is directed to both spectrometers MSP and RSP and the signal on the ACCD is not accumulated for these laser internal reference measurements, but read out for every single pulse. Thus, for every single shot a laser internal reference signal can be analysed in frequency and used to correct for non-constant internal reference frequencies from measurement to measurement. Instead the laser internal reference ACCD signals are accumulated on-ground to form one measurement and one observation.

The derivation of the satellite velocity on the LOS is done with data from the AOCS system including several sensors (star tracker, Global Positioning System GPS, Inertial Measurement Unit IMU) and is described in chapter 6. The satellite contribution to the LOS velocity is computed for every measurement, from the AOCS data, which is available with a rate of 8 Hz (125 ms). The AOCS data will be interpolated to the centroid time of a measurement and observation.

The determination of the frequency of an atmospheric range gate with a zero mean LOS velocity, e.g. from the non-moving earth surface (ground return), can be used to correct residual errors. As the frequency of the emitted laser pulse is monitored for every single pulse, the errors can be attributed to the frequency shift of the receiver spectrometers or the satellite velocity on the LOS.

From the determined frequency of the atmospheric range gate the mean LOS velocity of this range gate is determined by the Doppler equation (see chapter 3.4). The altitude dependent incidence angle is used to

...
convert from LOS velocity to the horizontal projection, which results in the HLOS velocity. Vertical profiles of the HLOS velocity for every observation are included in the L1B wind measurement product. The algorithm to determine the wind velocity is justified and described in the next subchapters for both the output from the MSP and RSP. Algorithm baselines, which are specific to the MSP and RSP are justified and described in detail in chapter 8.2 and 8.3.

### 8.1.1 Quality Control and Averaging of Measurements to Observations

The raw output of the ACCD from the MSP and the RSP is signal intensity per ACCD pixel (20 pixels total with 4 offset pixels and 16 useful pixels) per atmospheric range gate (25 total including 1 background gate) per measurement, which is a result of an on-board accumulation of returns of P-1 laser pulses. To achieve the mission requirements for random, slope and unknown zero-wind bias errors, the measurements have to be averaged to one observation. There are in principle two possible approaches to determine a wind velocity per observation:

- Determination of a wind velocity per measurement and averaging of the wind velocities to one observation.
- Averaging of the signal levels from single pixels of the ACCD per measurement and determination of the wind velocity from the averaged pixels of the ACCD for one observation.

The second approach is preferred, because of the non-linear process of the determination of the wind velocity from the ACCD pixels, which is justified in chapter 8.2 for the MSP and 8.3 for the RSP. When averaging ACCD pixel signals it has to be assured that no measurements contribute to the observation, which result in gross errors (outliers), or increase the random and systematic errors significantly. Discarding measurements is a trade-off between improving the random error budget by the averaging process and the introduction of additional errors.

Thus a quality control is applied to each single measurement or single laser pulses to discard measurements or laser pulses corrupted by gross errors:

- Laser pulse validity status for every single laser pulse: This status word is a combination of several flags, containing the cavity lock status, RLH on/off, RLH cavity temperature in range, RLH tuned, RLH locked and seeder locked. The cavity lock status flag describes, if the master oscillator cavity of the pulsed laser head is locked to the reference laser frequency. If the laser is not locked, then the laser is not operating in seeded mode and the emitted laser frequency is out of range of the expected frequency range and the linewidth of the pulse is much higher than specified (some GHz instead of 50 MHz). This would result in a gross error. The other flags refer to the correct operation of the RLH. If the number of discarded laser pulses exceeds a certain threshold, then the whole measurement is considered as invalid.

- AOCS status flag: This flag provides the information, if the spacecraft points in the nominal direction. If the spacecraft is pointing not in the nominal direction, e.g. due to orbital control manoeuvres the measurement has to be discarded. The AOCS status flag is available for each measurement, derived from the AOCS raw data with a repetition rate of 8 Hz (125 ms).

- Corrupted data flag: This flag describes, if the measurement data itself is showing strong deviations from the “expected” spectral behaviour (see chapter 8.10). A corruption could occur due to signal spikes on the ACCD caused by particles or radiation striking the ACCD.

In principle the quality control of single measurements can be extended to other instrument parameters (not currently implemented in L1B), which influence the zero-wind bias, slope or random errors, e.g.

- other laser housekeeping parameters, e.g. temperatures, energy
- receiver housekeeping parameters, e.g. MSP temperature
- AOCS housekeeping parameters
- derived emitted laser frequency from the laser internal reference
- quality-checks when averaging MSP output
- quality-checks when averaging RSP output, e.g. on the signal strength of the MSP to avoid contamination of the RSP signal (see chapter 8.3)
Only ACCD measurements are averaged, which have not been discarded by the quality control. For the internal laser reference, which is obtained for every single pulse, all ACCD output of the corresponding atmospheric measurement has to be discarded, when the number of flagged reference pulses exceeds a predefined threshold.

8.1.2 Correction of Detection Chain Offset

The wind velocity determination from the MSP and RSP are both sensitive to constant offsets. A constant offset on the signals of the ACCD would introduce a bias error for the Rayleigh signals. Therefore, this constant offset has to be determined and subtracted.

One source of constant offset for both MSP and RSP is the detection chain offset (DCO). This can be determined by the signal from pixels of the ACCD, which are not illuminated. A total of 20 pixels is read-out per ACCD line (range gate) with 16 useful, illuminated pixels and 4 non-illuminated offset pixels ("virtual pixels, see ch. 4.2.5"). The mean of two pixel intensities is determined for Mie (pixel no. 19 and 20), while only the signal level of pixel 20 is used for Rayleigh and subtracted from each of the 16 illuminated ACCD pixels. On the Rayleigh ACCD pixel no. 19 is not representative of the offset, due to spurious charges, and thus, averaging over 2 pixels cannot be performed. The averaging process for the determination of the detection chain offset (mean of the offset pixels over 1 ACCD line or over all ACCD lines, mean over one measurement or one observation) needs to be investigated, once real measurements are available. As a current baseline (L1bP Version 6) the mean is determined for every measurement and for every single line (range gate) and used for correction of the output of the ACCD from the RSP and MSP.

The other sources of constant offset differ for the RSP and MSP and their origin and determination will be discussed in chapter 8.2 and 8.3.

8.1.3 Determination of Mean Frequency of Atmospheric signal and Internal Reference

The determination of the mean frequency of the atmospheric signal from the averaged and corrected ACCD output differs for the MSP and RSP due to the different spectrometer principle (see chapter 4.2). In contrast to the frequency determination from a coherent Doppler lidar, which does not require a frequency calibration, this is required for the direct detection Doppler lidar. The frequency calibration gives the relationship between a derived response from the MSP and RSP and a reference frequency. The response from the MSP is the centroid from the ACCD pixel output in units of pixel index, which has to be converted to a frequency in units of MHz. The response from the RSP is a normalised differential measure of the intensity from the filter A and B, which has to be converted to a frequency in units of MHz.

The calibration constants will be determined during the Instrument Response Calibration IRC consisting of the Mie Response Calibration MRC and Rayleigh Response Calibration RRC, which is an end-to-end calibration using atmospheric returns (chapter 4.3.3). It is foreseen to perform these calibrations once per week. The algorithms deriving the calibration constants from MRC and RRC are described in chapter 8.4 and 8.5. These constants are used for determination of the mean frequency of the atmospheric signal and updated after each MRC and RRC.

Also the averaged and corrected ACCD outputs from the measurement of the internal laser reference will be used to determine a response and to convert this to a mean frequency by means of calibration constants. It has to be noted that the calibration constants for an atmospheric signal differs from the calibration constant for the internal laser reference due to the different spectral shape and width of both signals. In addition, the calibration constants differ due to the different divergence and incidence angles on the spectrometers for the atmospheric path and the internal reference path (see Fig. 4-1).

8.1.4 Determination of the Frequency Shift from the Atmospheric Wind Velocity

The determined mean frequency of the atmospheric signal and internal reference is a measurement of a frequency difference (in MHz) and not an absolute frequency measurement (in THz). The frequency difference is measured relative to a zero frequency $f_0$, where the laser transmitter is set during the Instrument Spectral Registration ISR (e.g. $f_0=844.962$ THz for a laser wavelength of 354.8 nm). The mean frequency of the internal reference is thus the difference between the frequency of the emitted laser pulse and $f_0$. 
The mean frequency of the atmospheric signal determined from the spectrometers output of RSP and MSP contains several components:

- the frequency of the emitted laser pulse, which is determined by the internal reference measurement
- the Doppler frequency shift due to the atmospheric wind velocity in direction of LOS, which is the projection of the three-dimensional wind vector on the LOS
- the Doppler frequency shift due to the moving satellite, which is determined from AOCS data
- the frequency drift of the spectrometers RSP and MSP with respect to the latest determination of the zero frequency response, which is performed during the calibration modes MRC and RRC

Thus the Doppler shift due to the atmospheric wind velocity in LOS can be determined by subtracting the frequency of the emitted laser pulse and the Doppler shift due to the moving platform from the determined mean frequency of the atmospheric signal. As the frequency of the emitted laser pulse can vary from pulse to pulse, and the Doppler shift of the satellite platform can vary from pulse to pulse, the determination of the atmospheric Doppler shift should be performed for every single pulse. Due to the on-board accumulation of atmospheric signals this cannot be performed and some assumptions have to be made, which are discussed for every component.

Influence of variation of laser frequency, satellite ground speed and receiver drift

The frequency of the emitted laser pulse can be determined for every single pulse, but the frequency of the atmospheric signal is determined from an accumulated signal over one measurement (accumulation of P-1 pulses). A variation of the emitted laser pulse frequency can be described in principle by a drift, a random component, and gross outliers, e.g. if the laser is not locked. An accumulation of atmospheric signals over one measurement from emitted laser pulses with varying frequency results in broadening of the frequency spectrum. If the variation of the laser frequency is small (specification is 4 MHz rms over 7 s) compared to the spectral width of the signal on the MSP and RSP, than the averaging process results in a negligible additional broadening. The spectral width of the signal on the MSP is the convolution of the spectral width of the aerosol backscatter signal (50 MHz FWHM laser linewidth) and the spectral transfer function of the Fizeau (159 MHz FWHM). In contrast, the spectral width of the signal on the RSP is much broader because it is determined by the spectral width of the molecular return (FWHM = 1.6 pm = 3.8 GHz, see chapter 3.4). Thus, the influence of laser emitter frequency variations is different for the RSP and the MSP. The quality-control routine on measurements (see chapter 8.1.1) should therefore discard measurements, where single laser pulses have gross outliers in frequency.

This argument is only valid, if the weighting of the frequency of a single pulse is equal for the laser internal reference and the atmosphere. The weighting for the internal reference is determined by the laser pulse energy, where the variations from pulse-to-pulse should be in the percentage range. In contrast, the weighting for the atmospheric signal is determined by the atmospheric backscatter. The atmospheric backscatter could vary from pulse to pulse with a horizontal separation of 140 m significantly in case of clouds (e.g. 1 pulse hitting a cloud and the next pulse without a cloud) or varying ground-returns. The influence of laser frequency jitter form pulse-to-pulse in combination with heterogeneity in the atmospheric backscatter is currently studied.

The same arguments on spectral broadening are applicable for the Doppler shift component of the satellite. The pointing accuracy of the AOCS can show variations due to a drift, random errors or gross outliers. Also infrequent orbital control manoeuvres occur, where the instrument is not pointing in the correct LOS direction. Thus, measurements must be discarded, where the AOCS system reports a non-nominal pointing.

The frequency drifts of the spectrometers RSP and MSP with respect to the latest determination of the zero frequency response during RRC and MRC cannot be detected directly with the ALADIN instrument. This requires locking the spectrometers or the emitted laser frequency to an absolute frequency standard, e.g. an atomic or molecular absorption line. Thus, a frequency drift can only be detected indirectly through monitoring of instrumental parameters, which influence the spectral response, e.g. temperatures. A correction could be applied, if an accurate knowledge of the relation of the spectral response on instrumental parameters is known (not implemented in L1bP V6.0). Nevertheless it is foreseen to perform an instrument response calibration on a weekly basis. Thus only drifts between the periods of 2 calibrations would be relevant.

Another approach is taken to handle the frequency drift of the two spectrometers:
parallel processing of the internal reference on both spectrometers, in contrast of using the frequency of the internal reference of the MSP also for wind velocity determination with the RSP. Thus a frequency drift of the RSP with respect to the MSP does not influence the determined mean frequency of both RSP and MSP. The parallel processing of MSP and RSP internal reference measurements is used as the current baseline for L1B processing.

- usage of mean velocity of the return from a non-moving target (e.g. earth surface) for correction of a residual error. This will cancel out drifts of the spectrometers as well as unknown drifts of the AOCS system (see chapter 8.6). The velocity of the ground return is used in case a ground return is detected for an observation, which leads to discontinuous corrections. If a known drift of the residual error can be assumed then the correction terms in case of a detected ground return can also be interpolated between observations with no ground return. It is assumed that the AOCS errors are composed of harmonic components over one orbit with sinusoidal variations. Thus, the ground return frequencies over several orbits are used for determination the residual satellite ground velocity (chapter 8.6).

Influence of averaging measurements to observations

The subtraction of the frequency of the emitted laser pulse and the frequency due to the moving platform is performed for single measurements to obtain an atmospheric velocity for every single measurement, but also on observation level. First an averaged signal of the ACCD is determined for the atmospheric signal and the laser internal reference, then the mean frequency of both is determined (see chapter 8.1.3). The mean Doppler shift frequency for the atmospheric wind velocity is determined from the subtraction of the mean frequency of the laser internal reference and the residual contribution of the satellite moving platform from the atmospheric signal.

This approach introduces an additional spectral broadening of the spectrometer signal and thus an additional random error compared to the case of averaging several laser pulses to one measurement (0.4-1 s). For an observation variation within 12 s or a horizontal averaging length in the atmosphere of 90 km are relevant. It is assumed that the additional random error is negligible, because the laser frequency variation and the frequency variation from the AOCS is small compared to the spectral width of the signal on the MSP (FWHM = 159 MHz = 28 ms\(^{-1}\) LOS) and thus for the RSP (FWHM = 3.8 GHz = 674 ms\(^{-1}\) LOS).

8.1.5 Determination of LOS and HLOS Velocity

The LOS velocity is determined from the frequency shift by use of the Doppler equation (see chapter 3) using a constant laser emitter wavelength \(\lambda_0\) of 354.8 nm, whose exact value is determined on ground and contained in the satellite characterisation file.

The actual emitted laser wavelength might differ from the on-ground determined laser wavelength, because the laser emitter frequency is tuned in orbit in over a range of ±5.5 GHz equivalent to ±2.3 pm. As the LOS velocity is proportional to the emitted laser wavelength, this would only introduce an error of 2.3 pm/355 nm = 6.5*10\(^{-6}\), which is negligible.

The HLOS velocity is the projection of the LOS velocity to the horizontal plane, by dividing the LOS velocity with the sinus of the incidence angle \(\varphi\). Due to the slant geometry of the beam propagation and the earth geoid curvature the incidence angle is depending on the altitude. Thus, an incidence angle depending on the atmospheric range gate has to be used. A fraction of 0.61 from the horizontal wind speed in LOS direction is projected onto the LOS for a mean incidence angle of 37.6° (resulting from a slant angle at the satellite of 35°, the mean satellite altitude of 408 km, and the Earth curvature). Thus a random error requirement of 1 m/s on the HLOS component is transferring to an even stricter requirement of 0.61 m/s on the measured LOS component.

As already stated in chapter 8.1.3 the measured LOS velocity is the projection of the three-dimensional wind vector onto the LOS. The three-dimensional wind vector can be described by its 2 horizontal components \(u\), \(v\), and the vertical component \(w\). When converting from LOS to HLOS it has to be assumed that the vertical component \(w\) is negligible; a fraction of \(\cos(37.6°) = 0.79\) from the vertical wind is projected onto the LOS direction. This can be assumed for the horizontal averaging length of 90 km for an observation for most conditions.
The vertical component is not negligible under the following conditions:

- horizontal averaging lengths of a measurement, which is between 3 km to 7 km
- strong up- und downdrafts, e.g. in convective situations in the planetary boundary layer (PBL) or above in high convective clouds, e.g. cumulonimbus
- during occurrence of atmospheric waves, e.g. gravity waves
- during occurrence of atmospheric turbulence in the PBL or in the higher troposphere, referred as clear-air turbulence (CAT)
8.2 Wind Measurement Processing Rayleigh

8.2.1 General description of double-edge wind retrieval method

The principles of the wind retrieval from the Rayleigh Spectrometer RSP is discussed shortly in chapter 4.2.4. It is based on the widely used double-edge technique, which was pioneered by Chanin et al. (1989) and Garnier and Chanin (1992) for stratospheric winds using the broadband molecular return with a laser wavelength of 532 nm, and by Korb and Gentry (Korb et al. 1992, 1998; Gentry et al. 2000) for tropospheric winds using laser wavelengths of 1064 nm and 532 nm for the narrowband aerosol return and 355 nm for the molecular return. The double-edge technique relies on the measurement of signal intensities, which are obtained after transmission through two narrowband filters. If the narrowband filters are placed at about the steepest slope of the atmospheric spectral lineshape (“turning point” or “edge”) then a Doppler frequency shift results in a maximum change in filter transmission. Each narrowband filter is usually realized by a Fabry-Perot interferometer, but also molecular absorption lines are used as filters for a single-edge technique (Liu et al. 2007, Baumgarten 2010, Hildebrand et al. 2012).

Doppler shift equation

First the basic equations for the wind retrieval of a Doppler frequency measurement, then the specific approach using the double-edge technique are described, before the step-by-step algorithms from the digitized raw signals of the ACCD to the LOS wind speed are discussed. The Doppler frequency shift Δf is defined as the difference between the frequency of the received atmospheric return \( f_a \) and the emitted laser frequency \( f_I \). It is derived from the Doppler frequency shift equation (Eq. (3.9)) using the frequency \( f_0 \) or wavelength \( \lambda_0 \) of the laser.

\[
\Delta f = f_a - f_I = 2 \cdot \frac{V_{\text{LOS}}}{c} = 2 \cdot \frac{V_{\text{LOS}}}{\lambda_0}
\]

The measured Doppler frequency shift of the atmospheric range gate \( \Delta f \) is composed of a contribution of the atmospheric LOS wind \( \Delta f_{\text{LOS,wind}} \) and the component of the satellite movement \( \Delta f_{\text{LOS,S}} \), which is projected onto the LOS (chapter 8.1.4). The sign convention for the Doppler frequency shift \( \Delta f \) is such, that a positive sign \((\Delta f>0, f_a>f_I)\) is related to a LOS wind speed in the direction towards the instrument (“blue wavelength shift”), while a negative sign \((\Delta f<0, f_a<f_I)\) indicates a movement in LOS direction away from the instrument (“red wavelength shift”). Thus, \( V_{\text{LOS}} \) is positive for movements towards the lidar, while \( V_{\text{LOS}} \) is negative for movements away from the lidar in this context (N. B. Here the usual definition of the Doppler shift \( \Delta f_{\text{received}}=f_{\text{emitted}}-f_{\text{received}}=2f_0*V_{\text{LOS}}/c \) is used, but this equation is used differently (but consistent) in the Master Algorithm Document MAD (EADS-Astrium (2013a)) and the L1b processor (DoRIT and MDA 2014c) with \( \Delta f_{\text{MAD}}=f_{\text{emitted}}-f_{\text{received}}=2f_0*V_{\text{LOS,MAD}}/c \). This means that \( \Delta f_{\text{MAD}}=\Delta f \) and consistently the sign of the LOS velocity is inverted between the text here and the MAD definition: \( V_{\text{LOS}}=-V_{\text{LOS,MAD}} \). This implies also that the definition of the satellite-induced speed on the LOS direction is inverted from the definition here and the definition provided in the MAD: \( V_{\text{LOS,S}}=\text{sign}(V_{\text{LOS,S,MAD}}) \). Both definitions will lead to correct results in case that the sign definition for the satellite induced speed \( V_{\text{LOS,S,MAD}} \) is used correctly).

Thus, the atmospheric LOS frequency shift \( \Delta f_{\text{LOS,wind}}=\Delta f_{\text{LOS,i}} \) (in MHz) and the related LOS wind speed (in ms\(^{-1}\)) can be obtained for each atmospheric range gate (subscript i):
The LOS wind speed is projected onto the horizontal plane by using the local incidence angle $\phi$ to obtain the HLOS component. This incidence angle is slightly different for each range gate, because it is referenced to the local nadir axis and thus depending on the Earth curvature. Then the HLOS wind speed component can be written as:

$$v_{\text{HLOS},i} = \frac{1}{\sin(\phi_i)} v_{\text{LOS},ij} = \frac{1}{\sin(\phi_i)} \left[ \frac{\lambda_0}{2} \left( f_{a,i} - f_I - \Delta f_{\text{LOS},ij} \right) \right]$$  \hspace{1cm} (8.3)

The incidence angle $\phi$, the frequency of the atmospheric range gate $f_{a,i}$, and the contribution of the satellite movement to the LOS-direction $v_{\text{LOS},ij}$ are all derived for each range gate $i$. The incidence angle $\phi$ and the satellite LOS speed are obtained from the AOCS sensors (see chapter 6). The average values for the incidence angle is $37.6^\circ$, and thus different from the $35^\circ$ slant angle at the satellite due to the Earth curvature. The wavelength of the laser $\lambda_0$ was determined on ground with a value of 354.8 nm.

Double-edge Doppler wind lidar

The Doppler frequency for the atmospheric range gates $f_{a,i}$ and internal laser reference $f_I$ is derived from the signal $I_A(f)$ and $I_B(f)$ transmitted through both filters via a so-called response function $R(f)$. The transmitted signal $I_A$ and $I_B$ through both filters ("transmissivity") is resulting from the convolution of the filter transmission functions $T_A$ and $T_B$ and the lineshape of the atmospheric return $S_a$ (Fig. 3-4 and Fig. 4-3) or internal laser reference $S_i$.

$$I_{A,B,i}(f) = \int_{-\infty}^{\infty} T_{A,B,i}(f') \cdot S_a(f') \cdot df'$$

$$I_{A,B,a}(f) = \int_{-\infty}^{\infty} T_{A,B,a}(f') \cdot S_i(f') \cdot df'$$  \hspace{1cm} (8.4)

The transmission function of both filters $T_A(f)$ and $T_B(f)$ can be described by Airy-functions with a period of the Free Spectral Range FSR, the frequency and amplitude of the maximum transmission, and the FWHM or finesse of the filter. Additionally, it was shown by Witschas (2011b) that the Airy-function needs to be convoluted with a Gaussian function, which accounts for filter defects using a defect parameter. Due to the slightly different implementation of both filters, the filter parameters for $T_A$ and $T_B$ differ and due to the sequential implementation the function $T_B$ must take into account the reflection on filter $A$. This mainly results in a lower maximum transmission for filter $B$ compared to filter $A$. It should be noted that the atmospheric signal and the internal reference use different optical paths through the instrument (Fig 4-1), which results in a slightly different illumination of both Fabry-Perot interferometers. Thus, the transmission functions $T_A$ and $T_B$ could be different for the atmospheric and internal path, which is denoted by the subscript $I$ and $a$.

The signal of the internal reference $S_i(f)$ can be approximated by a Gaussian function for the laser pulse lineshape with its laser linewidth parameter (FWHM laser or $\sigma_{\text{laser}}$) and frequency of the emitted laser $f_0$. The signal from the atmosphere $S_a(f)$ with its Doppler shifted frequency $f_a$ is composed of the broadband Rayleigh-Brillouin lineshape (Witschas et al. 2010), a narrowband Mie backscatter return and a constant offset from the background light. The Rayleigh-Brillouin lineshape depends on atmospheric temperature and pressure, while the narrowband Mie backscatter return can be approximated by the same lineshape as for the internal reference $S_i(f)$, neglecting atmospheric broadening by turbulent wind velocity variations. Thus the
measured signal on the atmospheric path is depending not only on the filter transmission $T_A$ and $T_B$, but also on the atmospheric temperature, pressure and scattering ratio (see Eq. (3.5)), which are all strongly altitude dependent. It can be shown (e.g. Flesia and Korb 1999), that the parameters for filter A and B can be optimized such, that the influence of a narrowband Mie return is almost equal to the influence of the broadband Rayleigh return.

Furthermore the signal of the atmospheric range gates contains a contribution not arising from the backscatter of the emitted laser light on molecules, aerosol and cloud particles but also from the background light in the UV spectral region. This extremely broadband signal is arising from reflections of the sunlight on the ground or clouds. Although this background signal is reduced by an interference filter in the front optics (Fig. 4-1) of 1 nm bandwidth, it needs to be measured and corrected during processing, because it acts as a constant signal contribution to $I_A$ and $I_B$. Additional offsets to the signal, which need to be corrected for the double-edge technique could arise within the detection chain from electronic offset voltages, which are applied before digitization (e.g. detection chain offset DCO for ALADIN).

**Definition of Rayleigh response**

The signal measured after transmission through filter A and B is depending on the actual frequency $f$ ($f$ is used here for both atmospheric $f_A$ and internal reference $f_I$). The response function can be either defined as the ratio of both filter signals $R=I_A/I_B$ or by the contrast-function, which is used here:

$$R(f) = \frac{I_A(f) - I_B(f)}{I_A(f) + I_B(f)}$$

The ratio-function was used by Korb et al. (1998) Flesia and Korb (1999), Gentry et al. (2000), while the above contrast-function was introduced by Chanin et al. (1989), Garnier et al. (1992) or Souprayen et al. (1999), because it is less sensitive to constant offsets and background light and the contrast function is more linear than the ratio around the frequency of the filter cross point $I_A=I_B$ (N. B. a thorough investigation of the influence of different error sources on the derived winds using a ratio or contrast is still outstanding, because it is anticipated that the differences in the errors is not significant). The response $R$ is a function of the Doppler frequency shift $f$. While the signals $I_A$ and $I_B$ are in units of digitizer counts LSB (Least Significant Bit), the response function $R$ is dimensionless (a.u. arbitrary units) with typical values between $\pm 0.3$ for a LOS wind speed range of $\pm 90$ m$^{-1}$ (or HLOS range of $\pm 145$ m$^{-1}$). The response functions $R(f)$ are different for the internal reference path and the atmospheric path, because the transmission through both filters $I_A$, $I_B$ is different mainly due to the difference of $S(f)$ and $S_0(f)$ (eq. 8.4).

The frequency of the filter crossing point $f_c$ is defined for equal transmission through filter A and B with $T_A(f_c)=T_B(f_c)$. Here the Rayleigh response $R(f_c)=0$ gets zero. The response function $R(f)$ is almost linearly depending on frequency $f$ around the crossing point $f_c$ for the used filter parameters of ALADIN. The response $R(f)$ can be linearized around the laser frequency $f_0$ in a Taylor series, which is close to the filter crosspoint $f_0=f_c$ (N.B. there is no need to be exactly with the laser frequency $f_0$ at the filter crosspoint $f_c$) and the filter crosspoint $f_c$ with $\Delta f_c=f_c$:

$$R(f) = \alpha + \beta \cdot (f - f_0) + \gamma (f - f_0)$$

$$R(\Delta f_c) = \alpha + \beta \cdot \Delta f_c + \gamma (\Delta f_c)$$

$$\Delta f_c = f - f_0$$

with the intercept (or offset) $\alpha$ and slope (or sensitivity) $\beta$ and a term describing the deviation from a straight line, called non-linearity (or residual) $\gamma$ as a function of the differential frequency $\Delta f_0=f_0$ (N. B. The non-linearity $\gamma$ is depending on $f$ and $f_0$). While the frequencies $f$ or $f_0$ are absolute frequencies (e.g. $f_0=844.962$ THz for a laser wavelength of 354.8 nm), the delta symbol $\Delta f$ indicates here, that a frequency difference is used. The slope parameter $\beta$ is called sensitivity, because it describes the change of the response for a change in frequency:
Typical values for the sensitivity are $4.5 \times 10^{-4} \text{ MHz}^{-1}$ to $6 \times 10^{-4} \text{ MHz}^{-1}$, depending on the spectral width of the internal reference signal and the atmospheric lineshape. Thus, for a LOS wind speed of 1 m/s, corresponding to 5.639 MHz, the response changes by only 0.3%, which illustrates the high sensitivity on the measurement of the response $R(f)$ and the related signal intensities $I_A(f)$ and $I_B(f)$. In order to achieve a random error (precision) for the wind of 1 m/s (LOS), the response needs to be determined with a precision of 0.3%. The intercept $\alpha$ is related to the response value at the offset frequency $f_0$ (neglecting the non-linearity):

$$\alpha = R(f_0 = 0) = R(f = f_0)$$

The intercept $\alpha$ is given in units of the response (a.u.). The frequency of the crosspoint $f_c$ of both filter A and B transmission curves can be derived from the sensitivity $\beta$ and intercept $\alpha$ (neglecting the non-linearity) using $R(\Delta f_0)=0$:

$$\Delta f_c = f_c - f_0 = \frac{\alpha}{\beta}$$

In case the offset frequency $f_0$ is chosen such, that it is exactly at the filter crossing point $f_0=f_c$, then the intercept $\alpha$ gets zero. Due to the difference in response function for the internal reference and atmospheric signal, also the filter crossing point $f_c$ is different for the atmospheric $f_{c,a}$ and internal path $f_{c,I}$. Thus, the laser frequency offset $f_0$ is set to the crossing point of the internal reference, which results in a non-zero offset $\alpha$ for the atmospheric path.

The Rayleigh response $R(\Delta f_0)$ is measured during a response calibration mode (RRC) as a function of laser frequency offset $\Delta f_0$ and the parameters intercept $\alpha$ and slope $\beta$ are determined from a straight line fit (see chapter 8.5) for both the atmospheric path and the laser internal reference. The nonlinearity of the response $\gamma(\Delta f_0)$ is determined as the residual between the measured response $R(\Delta f_0)$ and the linear fit by:

$$\gamma(\Delta f_0) = R(\Delta f_0) - [\alpha + \beta \cdot \Delta f_0]$$

As noted above the signals $I_A$ and $I_B$ are depending on the filter transmission function and the lineshape of the atmospheric return or the laser internal reference. Thus the response function $R(f)$ is different for the atmospheric returns and the laser internal reference. The derived parameters intercept $\alpha$, sensitivity $\beta$ and non-linearity $\gamma$ are therefore different for the atmospheric range gates and laser internal reference and determined independently during the response calibration with the signal from the atmospheric range gates and the laser internal reference. As the lineshape of the atmospheric return is depending on the atmospheric temperature $T$ (see ch. 3.4) and to a smaller extent on atmospheric pressure $p$ due to the Rayleigh-Brillouin lineshape (Witschas et al. 2010, Witschas 2011a), the derived quantities $\alpha_a$, $\beta_a$ and non-linearity $\gamma_a$ are valid only for the atmospheric conditions during the response calibration and thus only valid for a specific combination of the temperature and pressure profile. The dependency of the retrieved LOS wind speed on atmospheric temperature $T$ and pressure $p$ is not taken into account for processing of the L1B data product, because auxiliary information about the altitude profile for $T$ and $p$ is needed. These corrections are performed for L2B data products, which use $T$- and $p$-profiles from numerical weather prediction NWP models at the location of the observation (Dabas et al. 2008).

For retrieving the frequency offset $\Delta f_0$ from a response measurement $R$ and the absolute frequency $f$, the parameters $\alpha$, $\beta$ and non-linearity $\gamma$ need to be known from a previous response calibration:
During wind measurement the frequency Doppler shift is derived from the difference of the measured frequency of the atmospheric range gate \( f_a \) minus the frequency of the internal reference \( f_I \):

\[
\Delta f = \frac{R - \gamma (\Delta f_a) - \alpha}{\beta} = f - f_0
\]

\[
f = \frac{R - \gamma (\Delta f_I) - \alpha}{\beta} + f_0
\]

(8.11)

It is worth noting here that the offset frequency \( f_0 \) is not needed for the wind retrieval, because only the difference between the filter crosspoint frequencies \( f_{c,a} - f_{c,I} \) from the atmospheric range gate and the internal reference is relevant. For simplicity, the contribution from the satellite movement, which is corrected in a later stage is neglected here. Also it should be noted that the above equation is applied for each atmospheric range gate.

The equation 8.12 (third line) shows that the non-linearity correction

\[
\Delta f_{\text{non-linearity}} = \gamma_a (\Delta f_a) - \gamma_I (\Delta f_I)
\]

(8.13)

is depending on the difference between the non-linearity of the atmospheric path at the Doppler shifted frequency \( f_a \) (relative to the offset frequency \( f_0 \)) minus the non-linearity of the internal path at the transmitted frequency \( f_I \) (relative to the offset frequency \( f_0 \)). Thus, the non-linearity correction is depending on the knowledge of the offset-frequency \( f_0 \). Also the non-linearity function \( \gamma(\Delta f) \) is characterized during the response calibration mode RRC and used in the subsequent wind retrieval. As the non-linearity function \( \gamma(\Delta f) \) is actually depending on the absolute laser frequency \( f_0 \), a difference in \( f_0 \) between response calibration RRC and wind measurement will introduce an error, as different parts of the non-linearity function are used. As the non-linearity function is only a small correction to the response and only slowly varying with frequency, a small frequency difference in absolute laser frequencies will only result in small errors. It was shown, that the non-linearity function for the Rayleigh response can be approximated by a 5th order polynomial (DLR 2012a, DLR 2012f, Marksteiner 2012). Thus the coefficients from a 5th order polynomial are used to describe the non-linearity function \( \gamma(\Delta f) \) and used in the wind retrieval. These polynomial coefficients are derived from a least-square fit procedure, obtained from the calibration mode data.

If the non-linearity correction is not performed, it is assumed that the non-linearity for atmospheric and internal path is almost equal and constant with frequency. It should be noted here, that the non-linearity part is strongly depending on the applied frequency range for the response calibration around the filter crosspoint, and thus the required wind speed measurement range. The non-linearity is furthermore different for narrowband Mie type signals (internal reference) and broadband Rayleigh type signal, especially when derived from a large frequency range around the crosspoint. Thus also the non-linearity function is different for the laser internal reference (narrowband Mie signal), a ground return (narrowband Mie signal) and
atmospheric returns (broad bandwidth Rayleigh signal). Thus 3 different calibration parameters (internal, ground-return, atmospheric range gate) are used for the wind retrieval.

Discussion of error sources for Rayleigh response

The influence of constant offsets and signal variations on the signals $I_A$ and $I_B$ will result in errors in the determination of the Rayleigh Response $R = (I_A - I_B) / (I_A + I_B)$. These errors can be categorized in 3 cases:

Case 1: Constant offset $C$

Both signals $I_A$ and $I_B$ are affected by a constant offset $C$, e.g. background light or detection chain offset. Then the derived Response $R_c$ becomes:

$$R_c = \frac{(I_A + C) - (I_B + C)}{(I_A + C) + (I_B + C)} = \frac{I_A - I_B}{I_A + I_B + 2C} \neq R$$

(8.14)

Thus, a constant offset $C$ is resulting in an erroneous determination of the Rayleigh response $R_c$. The influence of the offset $C$ is depending on the signal level of $I_A + I_B$ and the response, which determines the signal difference $I_A - I_B$. A numerical example with typical values of $I_A=1000$ LSB, $I_B=900$ LSB results in a correct response of $R=0.05263$. A constant offset of only $C=10$ LSB ($=1\% I_A$) will give $R_c=0.05208$, which differs by $5.5 \times 10^{-4}$ from $R$, corresponding to an error of 1 MHz = 0.18 ms$^{-1}$ for a typical response slope. This shows that the offset $C$ has to be determined with high accuracy and subtracted before calculation of the Rayleigh response.

Case 2: Constant factor $k$ for both filters

Both signals $I_A$ and $I_B$ are affected by a constant factor $k$, which is related to a variation of signal level. This could be due to variation in atmospheric backscatter or emitted laser energy and the resulting response $R_k$ is:

$$R_k = \frac{k \cdot I_A - k \cdot I_B}{k \cdot I_A + k \cdot I_B} = \frac{I_A - I_B}{I_A + I_B} = R$$

(8.15)

Thus a factor $k$, affecting both filter signals equally is not resulting in an error of the determined Rayleigh response $R$, which enables wind measurements under varying atmospheric conditions without further corrections.

Case 3: Different factor $k_A$ and $k_B$ for both filters

Signals $I_A$ is affected by a factor $k_A$, while signal $I_B$ is affected by a different factor $k_B$. The resulting response $R_{k_A,k_B}$ is:

$$R_{k_A,k_B} = \frac{k_A \cdot I_A - k_B \cdot I_B}{k_A \cdot I_A + k_B \cdot I_B} = \frac{k_A I_A - k_B I_B}{k_A I_A + k_B I_B} \neq R$$

(8.16)

Thus a different factor $k_A$ and $k_B$ for both filter signals is resulting in an error of the determined Rayleigh response $R$. Actually the optical path and detection chain is different for filter A and B by design, due to the sequential implementation of the Fabry-Perot Interferometer, resulting in different filter transmission functions $T_A$ and $T_B$. But these differences are inherently calibrated, when using the derived parameters from the Rayleigh response calibrations. On the other hand any difference in the optical path or detection chain between calibration and wind measurement, which affects both filters differently will result in an error of the retrieved wind. This is the case for a non-uniformity and tilt of the Rayleigh spots on the ACCD in combination with the detection of a ground-return signal during the period of charge transfer from imaging to memory zone of the ACCD (DLR 2010). The influence is mainly depending on the ratio between $k_A$ and $k_B$. A numerical example with typical values of $I_A=1000$ LSB, $I_B=900$ LSB results in a correct response $R=0.05263$. A ratio of only 0.9 will result in $R_{k_A,k_B}=0$, which results in an error of 0.05263, corresponding to 100 MHz = 18 ms$^{-1}$. For other double-edge systems a corrective factor is used to account for differences in the optical
path or detection chain sensitivity of both edge filters (Chanin et al. 1989, Garnier and Chanin 1992), which needs to be determined separately by a calibration. For ALADIN the differences are inherently calibrated in the response calibration mode RRC, so only differences in the ratio $k_A/k_B$ between RRC and wind measurement mode would result in an error.

8.2.2 Specific implementation for ALADIN Rayleigh wind retrieval

Now the implemented processing steps for the retrieval of the wind speed from the Rayleigh spectrometer RSP are described. Table 8-1 summarizes the input data, the source, and description for the processing of the measurements for the Rayleigh wind retrieval. The following processing steps are applied both on measurement level, consisting of $P-1$ accumulated laser pulses on the ACCD, and on observation level, which is obtained after averaging a number of $N$ measurements in the on-ground processing (ch. 8.1.1). The signal output consists of digitized signal levels (in units of LSB: least significant bit) from 20 ACCD pixels per measurement $k$ and per atmospheric range gate $i$. The 20 pixels are composed of 8 pixels from the Rayleigh filter A (direct path), 8 pixels for filter B (reflected path) and 4 pixels, which are not illuminated. The optical output of each filter A and B is imaged onto a circular spot in the ACCD imaging zone (Fig. 4-3) and combined in the ACCD memory zone in 8 pixels per filter (Fig. 4-4). For the internal reference each laser pulse $n$ is acquired by the ACCD and digitized, and not accumulated as for the atmospheric range gates. Thus, the signals from each laser pulse have to be summed up to be equivalent to the accumulation period for 1 atmospheric measurement and one observation. A quality control is applied before averaging to measurements and observations to discard measurements with corrupted data or laser problems (chapter 8.1.1.) for both the internal reference and the atmospheric range gates.

On the ACCD each detected photon is converted to a signal electron (charges) with certain quantum efficiency. The electronic charges are sequentially transferred and read out from the ACCD after the accumulation period. These ACCD electronic signals are amplified by the Detection Front-End Unit (DFU) and digitized by a 16-bit Analog-Digital-Converter (ADC). The digitized signals for the atmospheric range gates are described as $S_{\text{at}}(i,j,k)$, where $i$ denotes the number of the atmospheric range gate ($i=1$ to 25), $j$ the number of the ACCD pixel ($j=1$ to 20) and $k$ the number of the measurement ($k=1$ to $N$, $N$: number of measurements per observation).

The situation for the internal reference is different, because it is acquired for each laser pulse $n$ and not accumulated on the ACCD. A maximum number of $n_{\text{max}}$ laser pulses are acquired with $n_{\text{max}}=N*(P-1)$ (P: number of laser pulses per measurement) per observation. The digitized signal from the internal reference is called $S_{\text{int}}(i=1,j,n)=S(i,n)$.

In addition, the background light through both Rayleigh filters A and B is measured via the atmospheric optical path, after a time period, which is significantly larger than the round-trip time to the ground. This is to ensure, that pure atmospheric background light is acquired, which should not contain any atmospheric backscatter signals from the emitted laser pulse. The background signal is contained in the last atmospheric range gate with $i=25$ and thus stored in $S_{\text{at}}(i=25,j,k)$.

1) Correction of Rayleigh detection chain non-linearity

The efficiency of the conversion from photons to signal electrons and the pre-amplification could be varying depending on the signal strength, e.g. a number of 10 photons could lead to a digitized signal of 5 LSB, while a number of 100 photons could only lead to a number of 49 LSB. As the principle of the Rayleigh receiver is based on a very accurate intensity measurement, the non-linearity in the detection chain for different signal levels needs to be characterized on-ground. Here the difference $E_{\text{RLC}}(S)$ between an ideal linear relationship between the input signal to the detection chain and the measured output signal $S$ for a range of signal levels is obtained (RLC: Rayleigh linearity correction). For a perfectly linear signal response $E_{\text{RLC}}(S) = 0$ over the whole signal dynamic range of $S$.

The first step is to apply non-linearity correction using a priori-knowledge $E_{\text{RLC}}(S)$ for both the atmospheric range gates and internal reference for each pixel:
This detection chain non-linearity correction is similar than applied for other detectors, e.g. Photo-Multiplier Tubes PMT, or corrections needed for high signal levels, when using a photon-counting method (e.g. McGill 1997. Souprayen et al. 1999).

It was shown by on-ground measurements that the non-linearity of the Rayleigh detection chain is better than 0.1% (EADS-Astrium 2012). It seems that the value of 0.1% is also the accuracy of the characterisation of the non-linearity in the Rayleigh detection chain. A 0.1% non-linearity means that a signal level of 1000 LSB can be determined with an accuracy of 1 LSB. Thus, no non-linearity correction is applied to the Rayleigh signal levels ($E_{RLC}=0$), leading to errors in the order of 1 MHz = 0.18 m/s for a maximum, uncorrected non-linearity of 0.1% (using eq. 8.16 with $k_A/k_B=0.999$).

2) Correction for detection chain offset DCO and dark charges

A detection chain offset (DCO) is present on the digitized signals $S_a$ and $S_i$ due to an electronic voltage offset within the detection chain from the ACCD to the ADC. This detection chain offset $E_{DCO}(i,k)$ is constant for all 20 pixel of one row on the ACCD (corresponding to the range gates $i$), but could vary from row-to-row and from measurement to measurement. As a constant offset to the signal is detrimental for the determination of the Rayleigh response, it needs to be measured and corrected. The DCO value $E_{DCO}(i,k)$ is determined from the signal level for pixels $j_{DCO}$ on the ACCD, which are not illuminated by photons and the following corrections are applied for each range gate $i$ and measurement $k$ or laser pulse $n$:

$$S_{a,DCO}(i,j,k) = S_{a,RLC}(i,j,k) - E_{a,DCO}(i,j,k) - E_{DC}(DCR,P)$$
$$S_{i,DCO}(j,n) = S_{i,RLC}(j,n) - E_{i,DCO}(j_{DCO},n)$$

(8.18)

Actually 2 pixels are foreseen for measurement of the DCO offset (pixel number 19 and 20) and $E_{DCO}(i,k)$ would be determined from the average signal of both pixels. But only pixel number 20 could be used for the Rayleigh detection chain, because pixel number 19 is contaminated with spurious charges ($j_{DCO}=20$). The accuracy of the DCO correction is directly influencing the derived Rayleigh response, because it acts as a constant offset. The offset pixels (“virtual pixels”, see ch. 4.2.5) on the ACCD are not influenced by photon noise, but contain read-out noise of the ACCD with a Gaussian distribution with zero mean. Thus, in case the DCO value of the offset pixels $j_{DCO}$ is not varying for different range gates $i$, and average value $E_{DCO}(k)$ for all range gates could be used for correction (DLR 2010, 2011).

An additional correction is applied to the Rayleigh signals arising from the dark current charge offset in the memory zone of the ACCD for the atmospheric signals $E_{DC}(DCR,P)$. Dark charges are accumulated on all pixels in the ACCD, leading to a constant offset, which is proportional to the dark current rate DCR (in units of electrons or LSB per pixel per second) and the duration of the charges in the respective zone of the ACCD. Only the dark charges in the memory zone of the ACCD are relevant, because the duration is in the order of 0.4 s for a number of 20 accumulated pulses (and PRF = 50.5 Hz), while the charges stay in the imaging zone of the ACCD only between 2.1-8.4 µs. Thus an additional offset $E_{DC}$ needs to be subtracted from the signal of the atmospheric range gates, depending on the dark current rate DCR and the number of accumulated pulses $P$. This offset is obviously constant for each pixel, each range gate and each measurement of one observation. The dark current rate DCR is characterized on-ground and monitored in orbit. No significant amount of dark charges is accumulated for the internal reference, because it is read-out for every single pulse. The detection chain offset pixels do not contain the accumulated dark charges, because they should be considered not as real pixels on the ACCD, but as additional read-out sequences of the ACCD (“virtual pixels”). Thus the dark current offset is not corrected by the DCO offset correction.

3) Correction for background light

The background light is measured via the atmospheric path and stored in the last row of the ACCD memory zone with $i=25$ for both filter A and B. In order to achieve sufficiently high signal levels for the background range gate, the integration times for the background light $t_b$ is significantly larger than the integration times...
for the atmospheric range gates $t_i$, e.g. the highest background integration times $t_b$ is 3750 µs, while the lowest integration time for atmospheric range gates is 2.1 µs. Thus, the contribution of the background light on the atmospheric range gates is a factor of $t_i/t_b$ smaller than measured during the acquisition of the background light. The following correction is applied for each atmospheric range gate and for each pixel to obtain the background (BCK) corrected signals $S_{a,bck}$:

$$S_{a,bck}(i,j,k) = S_{a,DCO}(i,j,k) - \frac{t_i}{t_b} S_{a,DCO}(i=25,j,k)$$  \hspace{1cm} (8.19)

A background correction is not applied to the internal reference signal $S_{i,DCO}$, because the internal optical path is not influenced by background light.

4) Summation of filter A and B signal

As stated above the filter A and B signal are contained in different pixels of the ACCD. In order to obtain the total number of signal of filter A and B, the corresponding pixels have to be summed up. While the filter B signal is contained in pixel with $j_{min}=3$ to $j_{max}=10$, the filter A signal is contained in pixel $j_{min}=11$ to $j_{max}=18$. The useful signal is contained in 16 pixels (8 for each filter), while the remaining 4 pixels are used as offset pixels. Thus the filter A and B signal for the internal reference is obtained from:

$$I_{A,I}(n) = \sum_{j=11}^{j=18} S_{i,DCO}(j,n)$$  \hspace{1cm} (8.20)

$$I_{B,I}(n) = \sum_{j=3}^{j=10} S_{i,DCO}(j,n)$$

and correspondingly for the atmospheric range gates:

$$I_{A,a}(i,k) = \sum_{j=11}^{j=18} S_{a,bck}(i,j,k)$$  \hspace{1cm} (8.21)

$$I_{B,a}(i,k) = \sum_{j=3}^{j=10} S_{a,bck}(i,j,k)$$

The major part of the filter A and B signal is contained in the 4-5 centre pixels per filter, due to the circular spots on the ACCD. In case that signal is present on the ACCD, which is not arising from the filter A and B transmission, e.g. straylight, parasitic reflections, the summation of the signal pixels could be limited to the 6 or 4 central pixels per filter (DLR 2010).

5) Summation of signals from measurements to observations

As the laser internal reference signal is acquired for each laser pulse, the corresponding signals from the internal reference for the duration of an atmospheric measurement with index $k$ have to be summed up:

$$I_{A,I}(k) = \sum_{n_{ref,l}}^{n_{ref,u}} I_{A,I}(n)$$  \hspace{1cm} (8.22)

$$I_{B,I}(k) = \sum_{n_{ref,l}}^{n_{ref,u}} I_{B,I}(n)$$

Thus, for each atmospheric measurement with index $k$ a corresponding internal reference measurement with index $k$ is determined. The wind retrieval is applied to signals on measurement level and after summation of a number of $N$ measurements to one observation. Thus, both the atmospheric signals and the internal reference signals have to be summed up to obtain the signals A and B per observation.
The following processing steps are applied in the same manner for a number of \( N \) measurements per observation and for each observation. For simplicity only the processing of the observations is described below (and the index \( k \) for each measurement is suppressed).

6) Determination of the Rayleigh response

The Rayleigh response for the internal reference \( R_I \) and for each atmospheric range gate \( R_a(i) \) is determined.

\[
I_{A,I} = \sum_{k=1}^{k=N} I_{A,e}(k)
\]

\[
I_{B,I} = \sum_{k=1}^{k=N} I_{B,e}(k)
\]

\[
I_{A,a}(i) = \sum_{k=1}^{k=N} I_{A,a}(i,k)
\]

\[
I_{B,a}(i) = \sum_{k=1}^{k=N} I_{B,a}(i,k)
\]

\[ (8.23) \]

7) Correction of the Rayleigh response non-linearity

As explained above, the Rayleigh response \( R \) can be linearized around the filter A and B crosspoint, and the intercept (offset) \( \alpha \) and slope (sensitivity) \( \beta \) is used to derive the frequency of the observation. This approach is acceptable for low wind speeds and thus low Doppler frequency shifts. For the required wind speed range of \( \pm 145 \text{ m s}^{-1} \) (HLOS, equivalent to \( \pm 500 \text{ MHz} \)) the Rayleigh response shows a non-linear behaviour, which cannot be neglected. In principle, this Rayleigh non-linearity can be described by a polynomial function, and it was shown that a 5th order polynomial is sufficient (DLR 2011f, Marksteiner 2012). In principle the frequency \( f \) could be determined by an inversion of the non-linear response function \( R(f) \) (Marksteiner 2012), but a different approach is used here. The analysis of the Rayleigh response calibration (ch. 8.5) is based on a decomposition of the non-linear response function \( R(f) \) in a linear part with parameters \( \alpha \) and \( \beta \) and a residual, describing the non-linearity \( \gamma(\Delta f_0) \). The measured nonlinearity of the response \( \gamma_m \) (m: measured) is determined for discrete frequency steps \( \Delta f_m \) as the residual between the measured response \( R_m(f_m) \) and the linear fit parameters by:

\[
\gamma_m = R_m(\Delta f_m) - [\alpha + \beta \cdot \Delta f_m]
\]

\[ (8.25) \]

The non-linearity \( \gamma_m \) can be described as a function of the frequency step \( \Delta f_m \) or as function of the measured response \( R_m \) at that frequency step \( \Delta f_m \). In principle the correction of the non-linearity can be performed using both descriptions of the non-linearity \( \gamma_m(\Delta f_m) \) and \( \gamma_m(R_m) \). The use of the function \( \gamma_m(\Delta f_m) \) would need an inversion procedure, because the frequency \( \Delta f_m \) is not known at the stage of the non-linearity correction. But the measured responses \( R_I \) and \( R_a(i) \) are known, and thus, the correction is applied using the \( \gamma_m(R_m) \) approach with:
\[ R_{I,\text{cor}} = R_I - \gamma_I (R_I) \]  \hfill (8.26)

\[ R_{a,\text{cor}}(i) = R_a(i) - \gamma_a (R_a(i)) \]

Alternatively the measured non-linearity \( \gamma_m(R_m) \) could be fitted by a 5th order polynomial function and the polynomial function could be used for correction.

Now the corrected responses \( R_{I,\text{cor}} \) and \( R_{a,\text{cor}} \) are only linearly depending on the frequency difference \( \Delta f \):

\[ R_{I,\text{cor}} = \alpha_I + \beta_I \cdot \Delta f \]
\[ R_{a,\text{cor}}(i) = \alpha_a + \beta_a \cdot \Delta f_a(i) \]  \hfill (8.27)

It should be noted that the parameters \( \alpha, \beta \) and \( \gamma \) are derived from the observations during Rayleigh response calibration RRC (ch. 8.5) for the internal reference and the atmospheric range gates and are input parameters to the Rayleigh wind retrieval here. The parameters \( \alpha_a, \beta_a \) and \( \gamma_a \) are derived for the sum of several atmospheric range gates, and not as an altitude dependent profile. All parameters are in principle depending on the lineshape of the atmospheric return and depending on atmospheric temperature, pressure and scattering ratio. The intercept \( \alpha_a \) and non-linearity \( \gamma_a \) are strongly depending on the Rayleigh filter functions \( T_{A,a}(f) \) and \( T_{B,a}(f) \), while the dependency on the atmospheric parameters is most pronounced for the sensitivity \( \beta_a \) (Paffrath 2006, DLR 2011a, DLR 2011b). This dependency on atmospheric profiles is corrected for the L2B products (Dabas et al. 2008).

A correction for the non-linearity of the Rayleigh response is typically not needed for double-edge Doppler wind lidars operated on ground (DLR 2006), because the wind speed measurement range is significantly smaller (\( \pm 50 \text{ m s}^{-1} \) compared to \( \pm 150 \text{ m s}^{-1} \)). Here, the considered frequency range around the filter crosspoint can be smaller and a linear dependency of the Rayleigh response on frequency can be used.

7) Determination of the Doppler frequency shift

Now the determination of the frequency of the internal reference and the atmospheric range gates is straightforward:

\[ f_i = \frac{R_{I,\text{cor}} - \alpha_I}{\beta_I} + f_0 = \frac{R_I - \alpha_I - \gamma_I(R_I)}{\beta_I} + f_0 \]  \hfill (8.28)

\[ f_a(i) = \frac{R_{a,\text{cor}}(i) - \alpha_a}{\beta_a} + f_0 = \frac{R_a(i) - \alpha_a - \gamma_a(R_a(i))}{\beta_a} + f_0 \]

The offset frequency \( f_0 \) is equal for both the internal reference and atmospheric range gates and is therefore eliminated, when calculating the Doppler frequency shift \( \Delta f(i) \) per range gate \( i \):

\[ \Delta f(i) = f_a(i) - f_i = \frac{R_a(i) - \alpha_a - \gamma_a(R_a(i)) - R_I - \alpha_I - \gamma_I(R_I)}{\beta_a} \]  \hfill (8.29)

8) Determination of LOS and HLOS wind speed

The LOS wind speed and the HLOS wind speed, which is the projection to the horizontal plane with the altitude dependent incidence angle \( \varphi(i) \), is derived using the Doppler shift equation:
\[
v_{\text{LOS}}(i) = \frac{\lambda_0}{2} \left( f_a(i) - f_j - v_{\text{LOS},S}(i) \right)
\]
\[
= \frac{\lambda_0}{2} \left[ \frac{R_a(i) - \alpha_a - \gamma_a (R_a(i))}{\beta_a} - \frac{R_j - \alpha_j - \gamma_j (R_j)}{\beta_j} \right] - v_{\text{LOS},S}
\]
\[
v_{\text{HLOS}}(i) = \frac{1}{\sin(\phi(i))} v_{\text{LOS}}(i)
\]
\[
= \frac{1}{\sin(\phi(i))} \left[ \frac{\lambda_0}{2} \left[ \frac{R_a(i) - \alpha_a - \gamma_a (R_a(i))}{\beta_a} - \frac{R_j - \alpha_j - \gamma_j (R_j)}{\beta_j} \right] - v_{\text{LOS},S} \right]
\]

with the correction of the satellite-induced Doppler shift velocity \(v_{\text{LOS},S}\) (in m/s), which is constant for all altitudes (in contrast to the incidence angle \(\phi(i)\)). The incidence angle \(\phi(i)\) and the satellite-induced Doppler shift velocity \(v_{\text{LOS},S}\) is obtained using the AOCS sensors and algorithms.

To our knowledge all other direct-detection Doppler Wind Lidar’s (DWL’s) using the single or double-edge technique with Fabry-Perot Interferometers or molecular absorption lines as filters do not determine the LOS wind speed \(v_{\text{LOS}}\) directly from the measurement in only one LOS pointing direction (Chanin et al. 1989, Garnier and Chanin 1992, Gentry et al. 2000, Flesia et al. 2000, Liu et al. 2007, Wang et al. 2010). The typical approach is to point alternately to several LOS directions (off-zenith, perpendicular and parallel, but opposite azimuth angles, or zenith and off-zenith pointing) in order to retrieve the LOS wind from differences of the LOS winds from different pointing directions. These methods are applied to eliminate possible influences of laser frequency drifts, spectrometer drifts, alignment drifts and other error sources. Thus, the offset parameters \(\alpha_A\) and \(\alpha_I\) in the above equation are eliminated by using different LOS pointing directions.

The challenge for ALADIN is that only one LOS pointing direction is used, and the instrument needs to be very stable between response calibrations, where the calibration parameters \(\alpha, \beta,\) and \(\gamma\) are determined and the wind measurement. It is foreseen to perform a response calibration once per week in-orbit. Thus the single LOS approach by ALADIN is unique and challenging for a direct-detection DWL. In contrast to DWL’s operated on the ground, the airborne A2D and satellite ALADIN operations allow the use of the reflection from the non-moving land surface for correction purpose (DLR 2011b), which is described in the next step.

9) Correction for residual ground speed

Although the correction with the satellite-induced LOS speed \(v_{\text{LOS},S}\) is applied, there could be a remaining LOS wind, which is not related to an atmospheric wind. This could be due to random or systematic errors in the knowledge of the AOCS parameters (e.g. pitch, roll, heading, LOS pointing direction, satellite ground speed), which result in random or systematic errors of \(v_{\text{LOS},S}\). Another reason for a residual LOS wind speed, could be erroneous calibration parameters \((\alpha, \beta\) and \(\gamma)\) or differences between the optical paths during response calibration and wind measurement. This could be induced by thermo-mechanical drifts of the optics, which result in different illumination of the Fabry-Perot interferometers, and thus, differences in Rayleigh response (see further discussion in DLR 2012b).

A residual, noncorrected LOS wind speed should be present on the atmospheric range gates, which contain the return from the non-moving Earth surface (ground return). For land surfaces this LOS wind speed should be zero m/s, while for ocean surfaces this cannot be assumed due to the wind-induced movement of the ocean surface and currents (KNMI 2008). While for nadir-pointing of the ALADIN instrument during response calibration, the LOS wind speed of the ocean surface can be assumed to be almost zero m/s, this cannot be assumed for off-nadir pointing during wind measurements with an average incidence angle of 37.6°. Thus, the usage of the ground return is limited to land surfaces.

The detection of atmospheric range gates, which contain a ground return signal is described in detail in chapter 8.6. The processing of the raw ACCD output \(S_d(i=g,j,k)\) from the range gates containing ground signal \((i=g)\) is applied up to step 6 to obtain the Rayleigh response \(R_a(i=g)\). No averaging of the measurements to observations is applied for ground return signal, because the ground return signal should be sufficiently high already on measurement level. The main reasons is that the ground return signal could be located in several atmospheric range gates, because of the surface terrain variation and the ground speed of the satellite, and due to a vertical movement of the satellite. Thus an averaging of signals in step 5 from
measurements to observations would increase the spread of the range gates, which contain ground return. Actually it will be the case already on measurement level, that the ground return signal will be contained in several range gates $g_i$, also due to the range gate overlap induced by the ACCD (DLR 2012a, Marksteiner 2012). The detection and processing of the signals from several range gates $g_i$ is described in chapter 8.6, while here the index $g$ is used for indicating one to several range gates.

The reflection on the non-moving land surface will result in a spectral lineshape, which is similar to the outgoing laser pulse. Thus, the frequency dependency of the Rayleigh response of the ground return is similar to the frequency dependency of the laser internal reference. Nevertheless there are differences in optical illumination through the laser internal path and the atmospheric path. Thus, the calibration parameters for a ground return signal (via the atmospheric optical path) are independently determined during the Rayleigh response calibration RRC. Those parameters $\alpha_g$, $\beta_g$ and $\gamma_g$ are used for determination of the frequency of the ground return:

$$f_a(g) = \frac{R_{a,\text{ps}}(g) - \alpha_g}{\beta_g} + f_0 = \frac{R_a(g) - \alpha_g - \gamma_g(R_a(g))}{\beta_g} + f_0$$  \hspace{1cm} (8.31)

The frequency shift of the ground return is obtained from

$$\Delta f(g) = f_a(g) - f_I = \frac{R_a(g) - \alpha_g - \gamma_g(R_a(g)) - R_I - \alpha_I - \gamma_I(R_I)}{\beta_I}$$  \hspace{1cm} (8.32)

In the next step the residual velocity of the ground return measurement is derived. As the ground-return velocity is derived for each measurement (and not for each observation), it must be noted here, that the internal reference response $R_I$ and the satellite component for the corresponding measurement $k$ has to be used here.

$$v_{\text{LOS,}\text{G}}(g) = \frac{\lambda_0}{2} \cdot \Delta f(g) - v_{\text{LOS,}\text{S}}(g) = \frac{\lambda_0}{2} \left[ \frac{R_a(g) - \alpha_g - \gamma_g(R_a(g)) - R_I - \alpha_I - \gamma_I(R_I)}{\beta_I} \right] - v_{\text{LOS,}\text{S}}$$  \hspace{1cm} (8.33)

For a perfect instrument, perfect knowledge of the satellite induced LOS wind speed and perfect measurement of the ground-return LOS speed the retrieved value for $v_{\text{LOS,}g}$ should be zero ms$^{-1}$. Any non-zero value is due to non-perfections of the instrument and or errors in satellite velocity $v_{\text{LOS,}S}$ and random errors in the retrieval of the ground-return LOS speed $v_{\text{LOS,}G}$ due to signal noise. Another source of significant errors in the ground-return speed is due to the sampling of atmospheric backscatter signal within the range gate of typical heights of 250 m or 500 m, which contains the ground return signal (DLR 2006, DLR 2012b, Marksteiner 2012). The atmospheric backscattering particles move with the surface wind and contribute to the total signal, depending on the relative location of the ground within the range gate.

The residual LOS wind speed from the ground return is derived per measurement and the averaging is performed using the retrieved LOS wind speeds (and not the signals as for atmospheric range gates):

$$v_{\text{LOS,}G} = \frac{1}{N} \sum_{k=1}^{N} v_{\text{LOS,}G}(k)$$  \hspace{1cm} (8.34)

It could be the case that no valid ground return is detected for a measurement (see ch. 8.6 for a discussion of the ground-return detection), which could be due to low SNR (over ocean surfaces or high extinction of atmospheric layers above) or due to a total blocking of the ground return layer by optically thick clouds. A valid ground return value for an observation is derived, if the number of ground returns per observation is above a threshold. If the number of ground-return measurements is too low or even zero, then no valid value for the observation can be derived. In this case the latest valid value for a ground-return velocity is used for the subsequent correction.

This residual LOS wind speed $v_{\text{LOS,}G}$ is used as additional term in the wind retrieval to correct for any offsets:
Further corrections using the residual ground return LOS wind speed from a number of observations, which could span several orbits, are applied to the retrieved wind speeds. This will introduce a correction similar to \( v_{LOS,G} \), which is dependent on the latitude of the observations to account for orbital variations (called Harmonic Bias Estimator HBE, see ch. 8.6). These correction values have to be determined from a number of observations from previous orbits and are treated as additional input values to the wind retrieval, similar as the parameters for the response calibration. So the correction with the ground return \( v_{LOS,G} \) could be either performed using the ground-return velocity from the current (or latest valid) observation (or measurement) or a function depending on the latitude of the orbit and derived from the Harmonic Bias Estimator HBE (EADS-Astrium 2013 b). Optional corrections could be applied using the Mie ground return velocity from the current observation and a term accounting for known differences between the Mie and Rayleigh ground return.
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<td>ZWC auxiliary file</td>
<td>residual LOS velocity from ground return</td>
<td>1 value per measurement, 1 value per observation</td>
</tr>
<tr>
<td>$N, P$</td>
<td>L1A housekeeping</td>
<td>instrument settings for number of laser shots per measurement P, number of measurements per observation N</td>
<td>1 value per observation for N and P</td>
</tr>
<tr>
<td>$t, t_{b}$</td>
<td>L1A housekeeping</td>
<td>range bin time $t$, for Rayleigh atmospheric range bins and for background measurement $t_{b}$</td>
<td>24 values for atmospheric range bins per measurement and 1 value for background bin per measurement</td>
</tr>
</tbody>
</table>

**Table 8-1:** Input data, source and description for processing of Rayleigh spectrometer data to wind observations; for a detailed description see DPM (DoRIT and MDA 2014 c)
### Input Variable

<table>
<thead>
<tr>
<th>Input Variable</th>
<th>Source</th>
<th>Description</th>
<th>Number of Values and Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validity Flags</td>
<td>L1A data quality</td>
<td>AOCS status flag, data corrupted flag, laser pulse validity flag</td>
<td>1 value per measurement for AOCS status data corrupted flag, 1 value per laser pulse for validity</td>
</tr>
<tr>
<td>$E_{RLC}(S)$</td>
<td>satellite characterisation file</td>
<td>Rayleigh Linearity Correction per signal level $S$</td>
<td>array of values</td>
</tr>
<tr>
<td>DCR</td>
<td>tbd</td>
<td>Dark Current Rate in LSB per pixel per second for Rayleigh</td>
<td>1 value</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>satellite characterisation file</td>
<td>nominal laser wavelength</td>
<td>1 value</td>
</tr>
<tr>
<td>processor flag</td>
<td>processor settings</td>
<td>flag indicating, whether LOS or HLOS should be derived</td>
<td>1 value</td>
</tr>
</tbody>
</table>

**Table 8-1 (continued):** Input data, source and description for processing of Rayleigh spectrometer data to wind observations; for a detailed description see DPM (DoRIT and MDA 2014 c)

### Output Variable

<table>
<thead>
<tr>
<th>Output Variable</th>
<th>Source</th>
<th>Description</th>
<th>Number of Values and Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{LOS,corr}(i)$ or $v_{HLOS,corr}(i)$</td>
<td>L1B</td>
<td>LOS or HLOS wind speed in ms$^{-1}$ per atmospheric range gate per observation</td>
<td>24 values per observation</td>
</tr>
<tr>
<td>$v_{LOS,corr}(i,k)$ or $v_{HLOS,corr}(i,k)$</td>
<td>L1B</td>
<td>LOS or HLOS wind speed in ms$^{-1}$ per atmospheric range gate per measurement $k$</td>
<td>24 values per measurement for a total of $N$ measurements</td>
</tr>
<tr>
<td>PCD flag</td>
<td>L1B</td>
<td>flag indicating quality of the retrieved wind</td>
<td>24 values per observation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 values per measurement for a total of $N$ measurements</td>
<td></td>
</tr>
<tr>
<td>$v_{LOS,G}$</td>
<td>L1B</td>
<td>residual LOS wind speed in ms$^{-1}$ per observation from ground return bin</td>
<td>1 value per observation</td>
</tr>
<tr>
<td>$v_{LOS,G}(k)$</td>
<td>L1B</td>
<td>residual LOS wind speed in ms$^{-1}$ per measurement $k$ from ground return bin</td>
<td>1 value per measurement for a total of $N$ measurements</td>
</tr>
</tbody>
</table>

**Table 8-2:** Output data, source and description for processed Rayleigh spectrometer data; for a detailed description see DPM (DoRIT and MDA 2014 c)
8.3 Wind Measurement Processing Mie

The basic algorithm for processing the data from the MSP is the determination of the centroid of the signal intensities from the 16 pixels of the ACCD, which can be interpreted as 16 frequency bins in case of the MSP. Therefore, the relation between the frequency and the output of 16 bins from the ACCD has to be used to convert from bin number to frequency. This relation is measured during the Mie Response Calibration MRC regularly, to cancel out drifts of the laser transmitter frequency and the Mie spectrometer with respect to each other. The output of the ACCD from the MSP can be considered as a frequency spectra, comparable to a frequency spectra obtained after a Fourier transformation of the signal from a coherent Doppler lidar. Thus, algorithms used for processing of frequency spectra of coherent Doppler lidar, radar or sodar (an overview is given by Reitebuch 1999) can be adapted to the algorithms of the MSP.

The experience from processing of frequency spectra from coherent Doppler lidar, radar and sodar can be adapted to obtain main baselines for processing the data from the MSP:

- Determination of centroid frequency from averaged frequency spectra gives lower random errors than the determination of mean frequency from centroid frequencies which are derived from a single frequency spectrum (coherent integration of spectra vs. incoherent averaging of frequencies)
  - The centroid determined from an averaged MSP frequency spectrum from one observation yields lower random errors than averaging of centroid frequencies from single measurement frequency spectra.

- Centroid determinations results in bias errors in case of non-constant, linear, or higher order offsets
  - Offsets from the Rayleigh signal on the MSP and from the background radiation on the MSP have to be subtracted before determination of the centroid; the detection chain offset is constant for each spectrum, but it needs to be subtracted to obtain a reliable signal and signal-to-noise estimate.

- Discretisation of a continuous frequency spectra into frequency bins results in artefacts (truncation and window effects)
  - Minimisation of discretisation artefacts necessary. This is mainly determined by the implementation and the characteristics of the MSP hardware, e.g. 16 pixels are used to represent the imaged frequency range of 1 USR (1 pixel ≈ 105 MHz = 18.6 ms⁻¹), or effects as pixel response non-uniformity and change in FWHM of the response depending on pixel position. Different centroid estimators show different behaviour for these discretisation effects, and thus were studied and compared (DLR 2006, Paffrath 2006, DLR 2012g).

- Determination of centroid frequency from a frequency spectrum shows a strong non-linear behaviour with respect to the determination of a peak above the noise level
  - Non-linear relationship between signal-to-noise ratio SNR and random error and probability of gross errors. Thus, SNR thresholds and Quality-Control QC methods need to be applied for reliable wind estimates.

- Averaging of frequency spectra can be performed without introducing errors, if the boundaries of each frequency bin stay constant, mainly the boundary of the bin representing a zero-frequency are constant. The zero-frequency can vary from spectrum to spectrum due to a change in outgoing laser frequency, a change in spectral response of the MSP, or a change in the LOS velocity contribution from the satellite.
  - Either frequency spectra are normalised in the frequency axis before averaging, or frequency spectra are discarded, where a change in zero-frequency exhibits a defined threshold (current baseline for L1B processing). Averaging of frequency spectra from several laser pulses will result in spectral broadening of the averaged spectrum. The broadening can be introduced by laser frequency variations of the emitted pulse and of variations in the Doppler frequency shift induced by LOS wind variations due to turbulence effects (turbulent broadening).

- A centroid determination can be performed with several algorithms, all having different performance with respect to random and systematic error, quality-control possibilities, complexity or behaviour in case of outliers (Reitebuch 1999, Flamant et al. 2002, DLR 2006, Paffrath 2006, DLR 2012g). Therefore different algorithms could be considered.
Determination of first moment of spectra

Determination of weighted first moment of spectra with different weights

Maximising correlation with different correlation functions like Gaussian or Lorentzian (current baseline for L1B processing using Gaussian function in EADS-Astrium (2013))

Maximum likelihood estimators

Levenberg-Marquardt non-linear curve fitting algorithms using different fit functions like Gaussian or Lorentzian

Downhill simplex optimisation algorithm using different fit functions like Gaussian or Lorentzian (current baseline for L1B processing using Lorentzian function in EADS-Astrium (2013))

Centroid determination and averaging of spectra is dependent on signal normalisation of spectra

- no normalisation of spectra is performed => frequency spectra with high signal intensities dominate the signal contribution within an averaged spectrum, and frequency spectra with high noise dominate the noise contribution within an averaged spectrum (current baseline for L1B processing)

- normalisation of spectra to the maximum value => the signal contribution from each spectrum is weighted equally, but frequency spectra with high noise dominate the averaged spectrum

From the above list, it is obvious that the selection and optimisation of a baseline algorithm for the MSP data is a complex task and includes several decisions and trade-offs between possible algorithmic steps. This was done by DLR (2006), Paffrath (2006), and DLR (2012g) with sensitivity analysis of different algorithms implemented in an end-to-end simulator of the instrument and atmosphere. The systematic error of different algorithms as well as the random error for different signal-to-noise-ratios (SNRs) was compared and used for further optimisation of the algorithm implementation.

In principle a centroid computation can be performed from data of one measurement and from the averaged frequency spectrum from one observation. The following subchapters describe the processing steps for each altitude range gate of the MSP. These processing steps have to be applied for each altitude range gate. The input data, source, and description for the processing of the measurements from the MSP is contained in Table 8-3 and the output products in Table 8.4. The symbols for the Mie signal processing are used equivalent as for the Rayleigh signal processing (range gate i, pixel index j, measurement index k, pulse index n, atmospheric index a, internal reference index I): It has to be noted, that actually the signals are arising from 2 different ACCD detectors.

1) Quality Control QC and Averaging of Mie Frequency Spectra (similar to Rayleigh QC)

Due to the non-linear process of determination of a frequency spectral centroid, it is preferred to average frequency spectra from each measurement to one frequency spectrum of one observation. The algorithms and flags described in chapter 8.1.1 are used for that task.

No correction of the detection chain non-linearity is performed for the Mie signals, because the non-linearity in detection chain introduces only small errors for the centroid computation, because the non-linearity as measured for the Rayleigh chain is below 0.1%.

2) Summation of signals from measurements to observations (similar to Rayleigh signals)

The summation of laser internal reference signal to measurements and for both the internal and atmospheric signal to observations is performed for Mie signals before correction of offsets and background and before summation of the pixels from each range gate. As a result the frequency spectra for each range gate are summed up to measurements and observations. As the laser internal reference signal is acquired for each laser pulse, the corresponding signals from the internal reference for the duration of an atmospheric measurement with index k have to be summed up:
Thus, for each atmospheric measurement with index $k$ a corresponding internal reference spectrum (with pixel index $j$) with index $k$ is determined. The wind retrieval is applied to signals on measurement level and after summation of a number of $N$ measurements to one observation. Thus, both the atmospheric signals and the internal reference signals have to be summed up to obtain the Mie signal spectra (with pixel index $j$) per observation.

$$S_i(j, k) = \sum_{n=1}^{\text{max}_i} S_i(j, n)$$  (8.36)

$$S_i(j) = \sum_{k=1}^{N} S_i(j, k)$$  (8.37)

$$S_a(i, j) = \sum_{k=1}^{N} S_a(i, j, k)$$

The following processing steps are applied in the same manner for a number of $N$ measurements per observation and for each observation. For simplicity only the processing of the observations is described below (and the index $k$ for each measurement is suppressed).

3) Correction of Detection Chain Offset

The centroid computation is sensitive to non-constant offsets of the signal. For the MSP the offset consists of the detection chain offset DCO and a signal contribution from the Rayleigh signal and the atmospheric background radiation. Although the DCO can be considered is constant for all pixels, and would therefore not influence the centroid computation, it is subtracted, because the determination of the signal amplitude and SNR needs offset corrected signals. The detection chain offset is measured using “virtual” pixels of the ACCD, which are not illuminated. The mean of these pixel intensities can be used as a constant offset, which is subtracted from each spectral frequency bin. Thus a similar DCO offset correction as described for the Rayleigh signals in ch. 8.2 (step 2 without dark-current offset correction) is performed for the Mie signals. As the pixels number 19 and 20 can be used for each range gate ($j_{\text{DCO1}}=19, j_{\text{DCO2}}=20$) the average of both pixels is used for DCO offset correction for Mie signals.

$$S_{a, \text{DCO}}(i, j) = S_a(i, j) - \frac{1}{2} \left[ E_{a, \text{DCO}}(i, j_{\text{DCO1}}) + E_{a, \text{DCO}}(i, j_{\text{DCO2}}) \right]$$  (8.38)

$$S_{i, \text{DCO}}(j) = S_i(j) - \frac{1}{2} \left[ E_{i, \text{DCO}}(j_{\text{DCO1}}) + E_{i, \text{DCO}}(j_{\text{DCO2}}) \right]$$

4) Correction of Tripod Obscuration for Mie spectra

The Fizeau interferometer is used as an imaging spectrometer. An optical element within the beam path will be imaged onto the ACCD of the MSP. The tripod of the telescope and the secondary mirror obscure part of the telescope optical aperture and are imaged onto the ACCD. This geometrical obscuration leads to a transmission loss, which is depending on the pixel position. As the orientation of the telescope tripod is known wrt to the ACCD image zone, the obscuration of every single pixel can be characterised on ground. The signal intensity of every pixel is divided by a correction factor, which is contained in the Tripod Obscuration $C_{\text{TOBS}}(j)$ array containing 16 values for each pixel ranging from 0.88 to 1.0. A value of 0.88 is applied to the pixel in the centre of the frequency range USR ($j=8$), because this pixel is blocked by the telescope secondary mirror. As the internal reference measurement is not affected by obscurations, this correction is only applied to atmospheric range gate measurements.

$$S_{a, \text{TOBS}}(i, j) = \frac{S_{a, \text{DCO}}(i, j)}{C_{\text{TOBS}}(j)}$$  (8.39)
5) Determination of Mie Spectra centroid

Several algorithms to determine the spectral centroid for the Mie signal were investigated by Paffrath (2006), DLR (2006) and DLR (2012g), e.g. simple centroid algorithms, Downhill Simplex Algorithm (DSA) with and without weights, Maximum Likelihood methods, or the “Levenberg-Marquardt” nonlinear data modelling algorithm. An algorithm using a downhill simplex optimisation procedure assuming a Lorentzian spectrum from the MSP was chosen to provide the optimum estimate wrt. random and systematic errors. Not only the spectra centroid is obtained with the algorithm, but also the signal amplitude, the spectral width FWHM, the constant offset and the residual fit error. In addition a faster correlation algorithm can be used alternatively. Both algorithms are implemented in the L1B Processor and are described below. It was shown that the DSA (without weights) has better performance in terms of errors than the correlation algorithm (DLR 2012g). Thus the DSA is used as a baseline. It should be noted here, that both the processing of the Mie spectral data from the calibration mode MRC as well as the data from the wind mode have to be performed with the same algorithm and settings to avoid systematic errors.

The atmospheric signal after the TOBS-correction \( S_{a,TOBS} \) is composed of the narrowband Mie signal – a peak with significant signal over 3-4 pixels (FWHM is about 1.6 pixel) and the broadband Rayleigh signal, which can be assumed constant for all pixels. The signal contribution from the Rayleigh signal is the dominant offset contribution on the Mie frequency spectrum within the USR, assuming the Rayleigh signal is stronger than the background radiation. Therefore the background radiation measurement from the MSP is not used for offset correction. As the useful spectral range of the Mie spectrometer spans only ±0.36 pm around the emitted laser wavelength \( \lambda_0 \), the Rayleigh signal within this bandwidth can be assumed as a constant (1.6 pm FWHM, see. Fig.3-4 and 4-3; a Gaussian function with FWHM of 1.6 pm (\( \sigma = 0.68 \) pm) is decreasing to 0.87*peak intensity at the spectral positions of ±0.36 pm). As both the broad bandwidth Rayleigh spectrum and the narrow bandwidth Mie spectrum are shifted by the same Doppler frequency, the centroids of both spectra are equal. Thus no systematic error arises from the broad bandwidth Rayleigh spectrum.

5a) Determination of Mie spectra centroid with correlation algorithm

This algorithm determines the correlation function between the measured Mie frequency spectra and a model function, which approximates the Mie frequency spectra. A Gaussian model function \( M(x) \) (as an approximation to the Lorentzian function with pixel position \( x=j \)) is used for simplicity with an unknown centroid pixel position \( x_0 \) on the ACCD. The determination of the centroid is performed with a fixed value for the spectral width \( \sigma \) of the Gaussian model function (e.g. \( \sigma = 1.27 \) pixel, FWHM=3 Pixel, which is larger than the actual width of the Mie spectrum on the ACCD with FWHM = 1.6 pixel), which is not varied through the correlation algorithm.

\[
M(x) = \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} \tag{8.40}
\]

As a constant offset is not included in the model function and determined with the correlation algorithm, it needs to be subtracted, before deriving the correlation function and the centroid computation. Thus a constant offset is estimated by determination the pixel \( j_{\text{min}} \) where the signal intensity \( S_{a,TOBS} \) and \( S_{a,DCO} \) shows a minimum value (N.B. The minimum is also subtracted for the laser internal reference measurement, although the offset is not composed from a Rayleigh or background signal). This minimum signal is subtracted from each frequency pixel.

\[
S_{a,\text{min}}(i,j) = S_{a,TOBS}(i,j) - S_{a,TOBS}(i,j_{\text{min}})
\]

\[
S_{a,\text{min}}(j) = S_{a,DCO}(j) - S_{a,DCO}(j_{\text{min}}) \tag{8.41}
\]

For simplicity the next equations are shown for the signal \( S(x) \) depending on pixel position \( x=j \), for both the internal reference signal \( S(x)=S_{i,\text{min}}(j) \) and for the atmospheric signal per range gate \( i \) with \( S(x)=S_{a,\text{min}}(i,j) \). The cross-correlation function of signal \( S(x) \) with the model function \( M(x) \) is:
The centroid of the Mie spectra is obtained at the pixel position, where the correlation function is maximized, thus its derivative is zero:

\[
\frac{dC(x)}{dx} = -\frac{1}{\sqrt{2\pi}\sigma_x} \int S(x) \cdot (x - x_0) \cdot e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} \, dx = 0
\]  

(8.43)

This leads to an equation to derive \( x_0 \), which could be perceived as an equation for the first moment of the function \( S(x) \) weighted with the model function \( M(x) \):

\[
x_0 = \frac{\int x \cdot S(x) \cdot e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} \, dx}{\int S(x) \cdot e^{-\frac{(x-x_0)^2}{2\sigma_x^2}} \, dx}
\]  

(8.44)

The integral representation of the functions is now replaced with the discrete approximation, because the function \( S(x) \) is only measured for a number of 16 pixels ranging from \( x_{\text{min}}=1 \) to \( x_{\text{max}}=16 \).

\[
x_0 = \frac{\sum_{x=x_{\text{min}}}^{x_{\text{max}}} x \cdot S(x) \cdot e^{-\frac{(x-x_0)^2}{2\sigma_x^2}}}{\sum_{x=x_{\text{min}}}^{x_{\text{max}}} S(x) \cdot e^{-\frac{(x-x_0)^2}{2\sigma_x^2}}}
\]  

(8.45)

An iterative approach is needed to solve the above equation, because the parameter \( x_0 \) is still contained in the exponent of the model function. In order to provide a good estimate for the initial value \( x_{0,\text{start}} \), the first moment of the function \( S(x) \) is computed as a “centre of gravity” over the 16 pixels.

\[
x_{0,\text{start}} = \frac{\sum_{x=x_{\text{min}}}^{x_{\text{max}}} x \cdot S(x)}{\sum_{x=x_{\text{min}}}^{x_{\text{max}}} S(x)}
\]  

(8.46)

The equation (8.45) is used with \( x_{0,\text{start}}=x_n \) to compute a new value for \( x_n=x_{n+1} \). The iteration is stopped, if the absolute difference between \( |x_{n+1}-x_n| \) is below a threshold (e.g. \( 10^{-5} \)) or after a maximum number of iterations (e.g. 30).
5b) Determination of Mie spectra centroid with Downhill-Simplex Algorithm

A second algorithm was developed, tested and optimized based on a Downhill-Simplex nonlinear optimisation algorithm DSA (also called Nelder-Mead algorithm after Nelder and Mead 1965, Press et al. 1992) to derive the centroid of the Mie spectrum. In addition this algorithm determines the spectral width of the Mie peak, the peak height, and the Rayleigh offset, which is used for the determination of the scattering ratio and SNR, and quality flags. The Mie spectrum on the ACCD is approximated by a Lorentzian function with peak position \( x_0 \), peak width \( \Delta x \) (as FWHM value), peak height \( A \) and a constant offset \( C \).

\[
M(x) = A \cdot \frac{\Delta x^2}{4 \cdot (x-x_0)^2 + \Delta x^2} + C \tag{8.48}
\]

As the parameters peak height \( A \) and the constant offset \( C \) are only linearly included in the model function \( M(x) \), these are determined by solving a linear equation first. Within the downhill simplex optimisation algorithm only the peak position \( x_0 \) and peak width \( \Delta x \) are determined, with fixed peak height and offset \( C \). This has the advantage that only 2 parameters need to be varied during the non-linear optimisation process rather than 4.

First the minimum value is subtracted from the TOBS and DCO corrected signals as in eq. (8.41).

\[
S_{a,min}(i,j) = S_{a,TOBS}(i,j) - S_{a,TOBS}(i,j_{min})
S_{I,min}(j) = S_{I,DCO}(j) - S_{I,DCO}(j_{min}) \tag{8.49}
\]

For simplicity here also the signal from both the atmospheric range gates \( S_{a,min} \) and the internal reference \( S_{I,min} \) is called \( S(x) \) after minimum subtraction \( S_{min}(x_{min}) \) with 16 discrete values for the pixel position \( x \). The spectrum is now normalized to its maximum value \( S(x_{max}) \) with the pixel position \( x_{max} \):

\[
S_{norm}(x) = \frac{S(x)}{S(x_{max})} \tag{8.50}
\]

As a starting value for the peak position \( x_{0,start} \) is needed, the centroid is computed using the two adjacent pixel values around the maximum \( S(x_{max}-1), S(x_{max}), S(x_{max}+1) \):
As the spectral width $\Delta x$ of the signal is only slightly varying for internal and atmospheric signal, a predefined value $\Delta x_{\text{start}}$ can be used.

The measured Mie spectrum $S(x)$ is only obtained for 16 discrete pixels $x_j$. Nevertheless the imaged fringe from the Fizeau interferometer and the Lorentzian model function $M(x)$ is a continuous and can be computed for a number of $N$ discrete pixel positions ($N=16*ns$ with $ns$ number of subsamples $s$ per pixel, typically $ns=5$), in order to take into account the discretization of a continuous Mie fringe (Lorentzian) on discrete ACCD pixels (“aperture broadening” or “pixel broadening”). Thus the continuous model function $M(x)$ is now derived for a number of $n_s$ discrete subsamples per pixel and the resulting values of $M(x)$ from 1 pixel are averaged to obtain a “pixelated” or discrete Model function $M_{p}(x_j)$:

$$M_{p}(x_j) = \frac{1}{n_s} \sum_{k=1}^{n_s} \left( \frac{\Delta x^2}{4} \cdot (x_j - 0.5 + \frac{k}{n_s} - x_0)^2 + \Delta x^2 \right)$$ (8.52)

The model function is calculated for each pixel $x_j$ ($j=1$ to 16) for a number of subpixels $n_s$ (from $k=1$ to $n_s$); for the first pixel $x_1=1$ and $n_s=5$ the Model function is derived at positions 0.6, 0.8, 1.0, 1.2, and 1.4. Thus $M_{p}(x_1=1)$ is the average Lorentzian function $M(x)$ for pixel positions 0.5 to 1.5 and accordingly for $x_j$ up to 16. The function $M_{p}(x_j)$ is valid for a peak height of $A=1$ and an offset $C=0$. The model function including the parameters $A$ and $C$ can be written as

$$M_{p,A,C}(x_j) = A \cdot M_{p}(x_j) + C$$ (8.53)

Now the 4 parameters describing the pixelated Lorentzian model function $M_{p,A,C}(x)$ are determined within an iterative algorithm (iteration number $n$) and $x_{n=1}=x_{0,\text{start}}$ and $\Delta x_{n=1}=\Delta x_{\text{start}}$ (a value of $\Delta x_{\text{start}}=1.6$ pixel is chosen, which should equal the Mie fringe on the ACCD of 159 MHz; it should be noted here that the performance of the DSA to derive the width $\Delta x$ depends on the start value for the width $\Delta x_{\text{start}}$ of the spectrum, see e.g. DLR 2012g).

1. Determination of the peak height $A_n$ and offset $C_n$ by solving a linear system of equations using the pixelated model function $M_{p,A,C}(x_j)$ with the start values for $x_{0,\text{start}}$, $\Delta x_{\text{start}}$ (for the first iteration) and $x_n$, $\Delta x_n$ from the previous iteration. The solution for the squared difference $\chi^2$ (chi-square) between the model function $M_{p,A,C}(x_j)$ and the normalized spectrum $S_{\text{norm}}(x_j)$ can be determined analytically for fixed values of $x_0$ and $\Delta x$:

$$\chi^2(A_n,C_n) = \sum_{x_j=1}^{16} \left[ A_n \cdot M_{p}(x_j) + C_n - S_{\text{norm}}(x_j) \right]^2$$ (8.54)

This is equivalent to find the linear fit parameters (slope $A_n$ and intercept $C_n$) and can be obtained with the following set of equations (linear regression analysis):

$$\begin{pmatrix} \sum_{j=1}^{16} M_{p}^2(x_j) & \sum_{j=1}^{16} M_{p}(x_j) \\ \sum_{j=1}^{16} M_{p}(x_j) & 16 \end{pmatrix} \begin{pmatrix} A_n \\ C_n \end{pmatrix} = \begin{pmatrix} \sum_{j=1}^{16} S_{\text{norm}}(x_j) \cdot M_{p}(x_j) \\ \sum_{j=1}^{16} S_{\text{norm}}(x_j) \end{pmatrix}$$ (8.55)

Thus, $A_n$ and $C_n$ are obtained after solving these equations.
2. Applying the DSA with fixed $A_n$ and $C_n$, and using $x_{0,\text{start}}, \Delta x_{\text{start}}$ (for the first iteration) and $x_n, \Delta x_n$ from the previous iteration and determine the values for $x_{n+1}, \Delta x_{n+1}$. The DSA searches for the values of $x_n, \Delta x_n$ which minimize the squared difference $\chi^2$ between the pixelated Lorentzian $M_p,A,C (x_j)$ and the measured normalized signal $S_{\text{norm}}(x_j)$. This is similar to a least-square fitting algorithm, but rather an optimization algorithm is used for this purpose. The minimum of the chi-square function $\chi^2$ is determined by the DSA for the parameters $x_n$ and $\Delta x_n$:

$$
\chi^2(x_0, \Delta x) = \sum_{j=1}^{16} \left[ A_n \cdot M_p(x_j, x_0, \Delta x) + C_n - S_{\text{norm}}(x_j) \right]^2
$$

The DSA is a type of optimization algorithms, which searches for the optimal values of peak position $x_0$, peak width $\Delta x$, for the squared difference between a model function ("pixelated Lorentzian") and the measured signal on the Mie ACCD. The term simplex refers to a geometrical body with $n+1$ vertices in an $n$-dimensional space. Hence in our case of only 2 unknowns (2-dimensional space) a body with 3 vertices ("triangle") is used. The simplex ("triangle") encloses the optimum solution (for centroid $x_0$ and peak width $\Delta x$). For each calculation step the corners of the simplex are analysed and the worst one is replaced by another, by applying a series of operations on the simplex (called "reflection", "expansion", "contradiction", "reduction") to find the optimal solution. The control parameters as reported by Nelder and Mead (1965) are used in our implementation. In contrast to other non-linear least-square fitting procedures (e.g. Levenberg-Marquard) there is no need to derive the derivative of the fitting function for the DSA. This is an advantage of the method asserting safer convergence.

The optimum search in the Downhill Simplex algorithm is terminated, if the minimum decrease in the residual error $\chi^2(x_{0,n+1}, \Delta x_{n+1})$ between 2 iterations is below a threshold (e.g. $10^{-3}$) or the number of iterations are higher than a threshold (e.g. 50). As a result new values for $x_{n+1}, \Delta x_{n+1}$ are obtained from the DSA.

3. The iterations with step 1 (linear fit) and 2 (nonlinear fit) are continued until function $\chi^2(x_{0,n+1}, \Delta x_{n+1}, A_n, C_n)$ is below a certain threshold (e.g. $10^{-3}$), or the number of iterations are higher than a pre-defined threshold for the maximum number of iteration (e.g. 30), or the residual error $\chi^2$ does not change between subsequent iterations (e.g. difference below $10^{-8}$).

The results from the iterative approach are values for peak position $x_{n+1}$, width $\Delta x_{n+1}$, peak height $A_n$ and $C_n$: As the iterative algorithm was performed using normalized signals $S_{\text{norm}}(x)$ to the maximum, and the minimum value was subtracted, this has to be re-normalized:

$$
A = A_n \cdot S_{\text{max}}(x_{\text{max}})
$$

$$
C = C_n + S_{\text{min}}(x_{\text{min}})
$$

The centroid position $x_{n+1}$ from both the Mie algorithms (correlation and DSA) are called subsequently Mie response $R_i$ for the internal reference signal and $R_a(i)$ for the atmospheric signal of range gate $i$ to use the same terminology as for the Rayleigh channel processing.

$$
R_i = x_{n+1} \text{ for internal reference signal}
$$

$$
R_a(i) = x_{n+1} \text{ for atmospheric range gates i}
$$

Nevertheless it should be noted that a Mie response is in units of pixel position, while the Rayleigh response is unitless. The determined centroid is in units of pixel index, which has to be converted to frequency using the response curves obtained during the instrument calibration mode MRC.
6) Correction for Response Non-Linearity

The result of the centroid computation from step 5) is a value in units of pixels on the ACCD, called Mie response (equivalent to the Rayleigh response). This centroid in units of pixels needs to be converted in a centroid in units of frequency. This is performed by using the parameters derived from the Mie response calibration MRC, which is establishing a relationship between centroid frequency and centroid pixel position for a narrowband Mie signal observed on the Mie ACCD. The almost linear relationship between pixel position and frequency is approximated by a linear function with slope $\alpha$ (in units of MHz/pixel) and intercept $\beta$ (in units of pixel). The deviation of the observed pixel position from the linear fit function is called non-linearity $\gamma$ (in units of pixel).

This is an equivalent approach as for the Rayleigh channel. The MRC parameters are derived for the internal reference signal and the atmospheric signal separately; the signal return from the ground is used as a representative signal for the atmospheric optical path. Although both the internal and the atmospheric path are illuminated by narrowband Mie signals, both parameter sets are derived independently for internal and atmospheric path, because of small differences in the optical paths in front of the MSP. In contrast to the Rayleigh channel, where the non-linearity function can be approximated by a polynomial function, this approach is not chosen for the Mie channel. The slowly varying variations of the Mie response could be approximated by a polynomial, because this is mainly caused by edge effects for large frequency offsets, where the Mie signal fringe is only partly visible on the ACCD. But in addition a higher-frequency variation is present on the Mie response signal with a variation from pixel-to-pixel due to the coarse frequency resolution of the ACCD (1 pixel about 105 MHz); thus each pixel acts as an aperture, as the Mie signal is not constant over 1 pixel. This would cause a sinusoidal variation of the response with a periodicity of 1 pixel, which could be also modelled. But the response of each pixel to the incoming photon flux is not equal (expressed in a quantity called pixel-response non-uniformity, which is in the order of several %). Thus the sinusoidal variation is varying with each pixel and no model function was derived up to now, which would be sufficiently determined to model the Mie response non-linearity.

Thus a different approach is used for correcting the Mie response non-linearity, which does not use a model function to decrease the random noise from the measurements during MRC. The derived non-linearity $\gamma(R)$ from the observation is used directly for correction in the wind retrieval:

$$ R_{I,\text{cor}} = R_I - \gamma_I(R_I) $$

$$ R_{a,\text{cor}}(i) = R_a(i) - \gamma_a(R_a(i)) $$

The function $\gamma_I$ and $\gamma_a$ are available for values $R_I$ and $R_a$ obtained during the MRC mode. The MRC mode responses are available for 40 discrete frequency steps (and response values) with a frequency step of 25 MHz (about 4 frequencies per pixel, about 0.25 pixel units) over the frequency range of $f_0 \pm 500$ MHz. Thus also the functions $\gamma_I(R_I)$ and $\gamma_a(R_a)$ are only available at discrete steps. During wind measurement mode the values of $R_I$ or $R_a$ are not discrete. Thus a linear interpolation from the two next discrete values (from MRC) is used to obtain the non-linearity correction function $\gamma_I(R_I)$ and $\gamma_a(R_a)$ during wind mode.

Now the corrected responses $R_{I,\text{cor}}$ and $R_{a,\text{cor}}$ are only linearly depending on the frequency difference $\Delta f$:

$$ R_{I,\text{cor}} = \alpha_I + \beta_I \cdot \Delta f_I $$

$$ R_{a,\text{cor}}(i) = \alpha_a + \beta_a \cdot \Delta f_a(i) $$

Thus it is obvious that the same approach and equations are used for correction of the response non-linearity and deriving the frequency from the Mie response signal (in units of pixel) as applied for the Rayleigh response signals (in arbitrary units). The difference here is that the non-linearity is used directly from the MRC observations without applying a polynomial fit function.
7) Determination of the Doppler frequency shift

Now the determination of the frequency of the internal reference and the atmospheric range gates is straightforward (and equal as for the Rayleigh derivations):

\[ f_i = \frac{R_{i,\text{cor}} - \alpha_i}{\beta_i} + f_0 = \frac{R_i - \alpha_i - \gamma_i (R_i)}{\beta_i} + f_0 \]  \hspace{1cm} (8.61)

\[ f_a(i) = \frac{R_{a,\text{cor}} (i) - \alpha_a}{\beta_a} + f_0 = \frac{R_a(i) - \alpha_a - \gamma_a (R_a(i))}{\beta_a} + f_0 \]

The offset frequency \( f_0 \) is equal for both the internal reference and atmospheric range gates and is therefore eliminated, when calculating the Doppler frequency shift \( \Delta f(i) \) per range gate \( i \):

\[ \Delta f(i) = f_a(i) - f_i = \frac{R_a(i) - \alpha_a - \gamma_a (R_a(i))}{\beta_a} - \frac{R_i - \alpha_i - \gamma_i (R_i)}{\beta_i} \]  \hspace{1cm} (8.62)

8) Determination of LOS and HLOS wind speed

The LOS wind speed and the HLOS wind speed, which is the projection to the horizontal plane with the altitude dependent incidence angle \( \phi(i) \), is derived using the Doppler shift equation:

\[ v_{\text{LOS}}(i) = \frac{\lambda_0}{2} \cdot \left( f_a(i) - f_i \right) - v_{\text{LOS,S}}(i) \]

\[ = \frac{\lambda_0}{2} \left[ \frac{R_a(i) - \alpha_a - \gamma_a (R_a(i))}{\beta_a} - \frac{R_i - \alpha_i - \gamma_i (R_i)}{\beta_i} \right] - v_{\text{LOS,S}} \]  \hspace{1cm} (8.63)

\[ v_{\text{HLOS}}(i) = \frac{1}{\sin(\phi(i))} v_{\text{LOS}}(i) \]

\[ = \frac{1}{\sin(\phi(i))} \left[ \frac{\lambda_0}{2} \left[ \frac{R_a(i) - \alpha_a - \gamma_a (R_a(i))}{\beta_a} - \frac{R_i - \alpha_i - \gamma_i (R_i)}{\beta_i} \right] - v_{\text{LOS,S}} \right] \]

with the correction of the satellite-induced Doppler shift velocity \( v_{\text{LOS,S}} \) (in m s\(^{-1}\)). The incidence angle \( \phi(i) \) and the satellite induced Doppler shift velocity \( v_{\text{LOS,S}} \) is obtained using the AOCS sensors and algorithms.

9) Correction for residual ground speed

The derivation of the residual ground return wind frequency \( \Delta f(g) \) and wind speed \( v_{\text{LOS}}(g) \) is very similar as for the Rayleigh channel (for a more detailed discussion see Chapter 8.2, step 9). Thus here only the differences in both derivations are discussed and the equations are presented.

The detection of atmospheric range gates, which contain a ground return signal is described in detail in chapter 8.6. The processing of the raw ACCD output \( S_{a}(i=g,j,k) \) from the range gates containing ground signal \( (i=g) \) is applied up to step 6 to obtain the Mie response \( R_a(i=g) \). The parameters from the MRC mode for an atmospheric signal are obtained from the ground returns. Thus these parameters \( \alpha_a, \beta_a \) and \( \gamma_a \) can be used also for the retrieval of the ground return frequency, and no distinction between atmospheric signal and ground needs to be made for these parameters as done for the Rayleigh channel processing. The frequency shift of the ground return is obtained from
\[ \Delta f(g) = f_a(g) - f_j = \frac{R_a(g) - \alpha_a - \gamma_a(R_a(g))}{\beta_a} - \frac{R_j - \alpha_j - \gamma_j(R_j)}{\beta_j} \]  (8.64)

In the next step the residual velocity of the ground return measurement is derived. As the ground-return velocity is derived for each measurement (and not for each observation), it must be noted here, that the internal reference response \( R_I \) and the satellite component for the corresponding measurement \( k \) has to be used here.

\[ v_{LOS}(g) = \frac{\lambda_0}{2} \cdot \Delta f(g) - v_{LOS,S}(g) = \frac{\lambda_0}{2} \left[ \frac{R_a(g) - \alpha_a - \gamma_a(R_a(g))}{\beta_a} \right] - v_{LOS,S}(g) \]  (8.65)

The residual LOS wind speed from the ground return is derived per measurement and the averaging is performed using the retrieved LOS wind speeds (and not the signals as for atmospheric range gates):

\[ v_{LOS,G} = \frac{1}{N} \sum_{k=1}^{N} v_{LOS,G}(k) \]  (8.66)

If the number of ground-return measurements is too low or even zero, then no valid value for the observation can be derived. In this case the latest valid value for a ground-return velocity is used for the subsequent correction. This residual LOS wind speed \( v_{LOS,G} \) is used as an additional term in the wind retrieval to correct for any offsets:

\[ v_{LOS,corr}(i) = v_{LOS}(i) - v_{LOS,G} \]

\[ v_{LOS,corr}(i) = \frac{\lambda_0}{2} \left[ \frac{R_a(i) - \alpha_a - \gamma_a(R_a(i))}{\beta_a} \right] - v_{LOS,S}(i) - v_{LOS,G} \]  (8.67)

Similar as for the Rayleigh wind processing the value of \( v_{LOS,G} \) could be used from the current (or latest valid) observation or from a function depending on the latitude of the observation, which is derived from the HBE. It must be noted here that the values for \( v_{LOS,G} \) or the model function from the HBE is different for the Rayleigh and Mie ground returns. If the reason for a non-zero ground-return would be caused by satellite mispointing or AOCS errors (leading to wrong values of \( v_{LOS,S} \)) then the residual of \( v_{LOS,G} \) would be equal for Rayleigh and Mie. But the reason for non-zero ground returns could be also specific to the optical paths in the MSP and RSP and the derived parameters from the RRC and MRC and the response from the wind mode. Thus the residual ground-return values are different for Mie and Rayleigh winds (see also DLR (2012a) and Marksteiner (2012)).
<table>
<thead>
<tr>
<th>Input Variable</th>
<th>Source</th>
<th>Description</th>
<th>Number of Values and Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{a}(i,j,k)$</td>
<td>L1A Mie MDS</td>
<td>16-bit digitized raw ACCD output from MSP per atmospheric range bin $i$, pixel $j$, and measurement $k$</td>
<td>20 pixel values per atmospheric range gate per measurement, 16 signal pixels and 4 offset pixels; background light in $i$=25</td>
</tr>
<tr>
<td>$S_{r}(j,n)$</td>
<td>L1A Reference Pulse MDS</td>
<td>16-bit digitized raw ACCD output from MSP for laser internal reference per pixel $j$, and for each laser pulse $n$</td>
<td>20 pixel values per laser pulse</td>
</tr>
<tr>
<td>$\alpha_{a}, \beta_{a}, \gamma_{a}(R)$</td>
<td>MRC auxiliary file</td>
<td>Mie response slope, zero frequency, non-linearity for atmospheric signal (ground) from MSP</td>
<td>1 value obtained during MRC for slope and zero frequency, 1 value per frequency bin of MSP obtained during MRC</td>
</tr>
<tr>
<td>$\alpha_{r}, \beta_{r}, \gamma_{r}(R)$</td>
<td>MRC auxiliary file</td>
<td>Mie response slope, zero frequency, non-linearity for laser internal signal from MSP</td>
<td>1 value obtained during MRC for slope and zero frequency, 1 value per frequency bin of MSP obtained during MRC</td>
</tr>
<tr>
<td>$v_{\text{Los}, s}$</td>
<td>L1A geolocation</td>
<td>LOS velocity from satellite</td>
<td>1 value per measurement</td>
</tr>
<tr>
<td>$\varphi(i)$</td>
<td>L1A geolocation</td>
<td>incidence angle per range bin $i$</td>
<td>1 value per atmospheric bin per observation and measurement</td>
</tr>
<tr>
<td>$v_{\text{Los}, \text{Gro}}$</td>
<td>ZWC auxiliary file</td>
<td>residual LOS velocity from ground return</td>
<td>1 value per measurement</td>
</tr>
<tr>
<td>$N, P$</td>
<td>L1A housekeeping</td>
<td>instrument settings for number of laser shots per measurement $P$, number of measurements per observation $N$</td>
<td>1 value per observation for $N$ and $P$</td>
</tr>
<tr>
<td>$t_{i}, t_{b}$</td>
<td>L1A housekeeping</td>
<td>range bin time $t_{i}$ for atmospheric range bins Mie and for background measurement $t_{b}$</td>
<td>24 values for atmospheric range bins per measurement and 1 value for background bin per measurement</td>
</tr>
<tr>
<td>validity flags</td>
<td>L1A data quality</td>
<td>spacecraft on target flag data corrupted flag laser lock status flag</td>
<td>1 value per measurement for spacecraft on target and data corrupted flag</td>
</tr>
<tr>
<td>TOBS</td>
<td>Satellite characterisation file</td>
<td>Mie Tripod Obscuration Data</td>
<td>1 value for Mie frequency pixel with a total of 16</td>
</tr>
<tr>
<td>$\lambda_{0}$</td>
<td>Satellite characterisation file</td>
<td>nominal laser wavelength</td>
<td>1 value</td>
</tr>
<tr>
<td>processor flag</td>
<td>processor settings</td>
<td>flag indicating, whether LOS or HLOS should be derived</td>
<td>1 value</td>
</tr>
</tbody>
</table>

**Table 8-3:** Input data, source and description for processing of Mie spectrometer data to wind observations; for a detailed description see DPM (DoRIT and MDA 2014 c)
<table>
<thead>
<tr>
<th>Output Variable</th>
<th>Source</th>
<th>Description</th>
<th>Number of Values and Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{LOS,corr}(i)$ or $v_{HLOS,corr}(i)$</td>
<td>L1B</td>
<td>LOS or HLOS wind speed in ms$^{-1}$ per atmospheric range gate per observation</td>
<td>24 values per observation</td>
</tr>
<tr>
<td>$v_{LOS,corr}(i,k)$ or $v_{HLOS,corr}(i,k)$</td>
<td>L1B</td>
<td>LOS or HLOS wind speed in ms$^{-1}$ per atmospheric range gate per measurement k</td>
<td>24 values per measurement for a total of N measurements</td>
</tr>
<tr>
<td>PCD flag</td>
<td>L1B</td>
<td>flag indicating quality of the retrieved wind</td>
<td>24 values per observation 24 values per measurement for a total of N measurements</td>
</tr>
<tr>
<td>$v_{LOS,G}$</td>
<td>L1B</td>
<td>residual LOS wind speed in ms$^{-1}$ per observation from ground return bin</td>
<td>1 value per observation</td>
</tr>
<tr>
<td>$v_{LOS,G}(k)$</td>
<td>L1B</td>
<td>residual LOS wind speed in ms$^{-1}$ per measurement k from ground return bin</td>
<td>1 value per measurement for a total of N measurements</td>
</tr>
</tbody>
</table>

Table 8-4: Output data, source and description for processed Mie spectrometer data; for a detailed description see DPM (DoRIT and MDA 2014 c)
8.4 Calibration Mode Processing Mie
TBD for next issues

8.5 Calibration Mode Processing Rayleigh
TBD for next issues

8.6 Ground Return Detection and Processing
TBD for next issues

8.7 Signal Amplitude and SNR Processing for Mie
TBD for next issues

8.8 Signal Amplitude and SNR Processing for Rayleigh
TBD for next issues

8.9 Quality Control and Quality Flags, Corrupted Data, Error Quantifiers
TBD for next issues
## 9 Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2D</td>
<td>ALADIN Airborne Demonstrator</td>
</tr>
<tr>
<td>ACCD</td>
<td>Accumulation CCD</td>
</tr>
<tr>
<td>ACE</td>
<td>Altimeter Corrected Elevation</td>
</tr>
<tr>
<td>ADAM</td>
<td>A surface reflectance Database for ESA’s Earth Observation Missions</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-Digital-Converter</td>
</tr>
<tr>
<td>ADM</td>
<td>Atmospheric Dynamics Mission</td>
</tr>
<tr>
<td>ADS</td>
<td>Annotation Data Set</td>
</tr>
<tr>
<td>AISP</td>
<td>Annotated Instrument Source Packets</td>
</tr>
<tr>
<td>ALADIN</td>
<td>Atmospheric Laser Doppler Instrument</td>
</tr>
<tr>
<td>AOCS</td>
<td>Attitude and Orbit Control System</td>
</tr>
<tr>
<td>APF</td>
<td>Aeolus Processing Facility</td>
</tr>
<tr>
<td>ATBD</td>
<td>Algorithm Theoretical Basis Document</td>
</tr>
<tr>
<td>a.u.</td>
<td>arbitrary unit</td>
</tr>
<tr>
<td>BOL</td>
<td>Begin of Life</td>
</tr>
<tr>
<td>BRC</td>
<td>Basic Repeat Cycle</td>
</tr>
<tr>
<td>CAT</td>
<td>Clear-Air Turbulence</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CFI</td>
<td>Customer Furnished Item</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
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<tr>
<td>cw</td>
<td>continuous wave</td>
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<tr>
<td>DCC</td>
<td>Dark Current Calibration</td>
</tr>
<tr>
<td>DCO</td>
<td>Detection Chain Offset</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DFU</td>
<td>Detection Front-End Unit</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt</td>
</tr>
<tr>
<td>DPM</td>
<td>Detailed Processing Model</td>
</tr>
<tr>
<td>DSD</td>
<td>Data Set Descriptor</td>
</tr>
<tr>
<td>DWL</td>
<td>Doppler Wind Lidar</td>
</tr>
<tr>
<td>E2S</td>
<td>End-to-End Simulator</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth Centred Earth Fixed</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
</tr>
<tr>
<td>EGM96</td>
<td>Earth Gravitational Model from 1996</td>
</tr>
<tr>
<td>EOL</td>
<td>End of Life</td>
</tr>
<tr>
<td>Eq.</td>
<td>equation</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>FEP</td>
<td>Front-End Processor</td>
</tr>
<tr>
<td>FFM</td>
<td>Flip-Flop Mechanism</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
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<tr>
<td>FH</td>
<td>Fixed Header</td>
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<td>Fig.</td>
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</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectral Range</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GADS</td>
<td>Global Annotation Data Set</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HBE</td>
<td>Harmonic Bias Estimator</td>
</tr>
<tr>
<td>HLOS</td>
<td>Horizontal Line-of-Sight</td>
</tr>
<tr>
<td>HWP</td>
<td>Half-Wave Plate</td>
</tr>
<tr>
<td>IAT</td>
<td>Instrument Auto Test</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
</tr>
<tr>
<td>IDC</td>
<td>Instrument Defocus Characterisation</td>
</tr>
<tr>
<td>IFF</td>
<td>Interference Filter</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>IODD</td>
<td>Input Output Data Definitions Interface Control Document</td>
</tr>
<tr>
<td>IRC</td>
<td>Instrument Response Calibration</td>
</tr>
<tr>
<td>ISR</td>
<td>Instrument Spectral Registration</td>
</tr>
<tr>
<td>ITRF</td>
<td>International Terrestrial Reference Frame</td>
</tr>
<tr>
<td>KVT</td>
<td>Key Value Terminator</td>
</tr>
<tr>
<td>L1</td>
<td>Level 1</td>
</tr>
<tr>
<td>L1B</td>
<td>Level 1B</td>
</tr>
<tr>
<td>L1BP</td>
<td>Level 1B Processor</td>
</tr>
<tr>
<td>LBO</td>
<td>Lithium-Borate</td>
</tr>
<tr>
<td>LCA</td>
<td>Laser Chopper Assembly</td>
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<td>LCM</td>
<td>Laser Chopper Mechanism</td>
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<td>LDTA</td>
<td>Laser Diode Temperature Adjustment</td>
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<td>Light Detection and Ranging</td>
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<td>LSB</td>
<td>Least Significant Bit</td>
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<td>LTAN</td>
<td>Local Time of Ascending Node</td>
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<td>Look Up Table</td>
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<td>Local Vertical Local Horizontal</td>
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<td>MAD</td>
<td>Master Algorithm Document</td>
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<td>MAG</td>
<td>Mission Advisory Group</td>
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<td>MDS</td>
<td>Measurement Data Set</td>
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<tr>
<td>MOPA</td>
<td>Maser Oscillator Power Amplifier</td>
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<td>MPH</td>
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<td>MRC</td>
<td>Mie Response Calibration</td>
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<td>Abbreviation</td>
<td>Description</td>
</tr>
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<td>--------------</td>
<td>-------------</td>
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<tr>
<td>MSP</td>
<td>Mie Spectrometer</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>Neodymium doped Yttrium-Aluminium-Garnet</td>
</tr>
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<td>No.</td>
<td>Number</td>
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<td>Numerical Weather Prediction</td>
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<td>Product Confidence Data</td>
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<td>PDS</td>
<td>Payload Data Segment</td>
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<tr>
<td>PLH</td>
<td>Power Laser Head</td>
</tr>
<tr>
<td>Pol</td>
<td>Polarising Beamsplitter</td>
</tr>
<tr>
<td>QC</td>
<td>Quality Control</td>
</tr>
<tr>
<td>QWP</td>
<td>Quarter-Wave Plate</td>
</tr>
<tr>
<td>RAAN</td>
<td>Right Ascension of ascending node</td>
</tr>
<tr>
<td>resp.</td>
<td>respectively</td>
</tr>
<tr>
<td>RLC</td>
<td>Rayleigh Detection Chain Linearity Correction</td>
</tr>
<tr>
<td>RLH</td>
<td>Reference Laser Head</td>
</tr>
<tr>
<td>rms</td>
<td>root mean square</td>
</tr>
<tr>
<td>RMA</td>
<td>Reference Model Atmosphere</td>
</tr>
<tr>
<td>RRC</td>
<td>Rayleigh Response Calibration</td>
</tr>
<tr>
<td>RSP</td>
<td>Rayleigh Spectrometer</td>
</tr>
<tr>
<td>SiC</td>
<td>Siliciumcarbid</td>
</tr>
<tr>
<td>SID</td>
<td>Structure Identification</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise-Ratio</td>
</tr>
<tr>
<td>SoW</td>
<td>Statement of Work</td>
</tr>
<tr>
<td>SPH</td>
<td>Specific Product Header</td>
</tr>
<tr>
<td>SRD</td>
<td>System Requirements Document SRD</td>
</tr>
<tr>
<td>TBC</td>
<td>to be confirmed</td>
</tr>
<tr>
<td>TBD</td>
<td>to be defined</td>
</tr>
<tr>
<td>TC</td>
<td>Telecommand</td>
</tr>
<tr>
<td>TM</td>
<td>Telemetry</td>
</tr>
<tr>
<td>TN</td>
<td>Technical Note</td>
</tr>
<tr>
<td>TOBS</td>
<td>Tripod Obscuration</td>
</tr>
<tr>
<td>TRO</td>
<td>Transmit-Receive Optics</td>
</tr>
<tr>
<td>USR</td>
<td>Useful Spectral Range</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VCDU</td>
<td>Virtual Channel Data Unit</td>
</tr>
<tr>
<td>VH</td>
<td>Variable Header</td>
</tr>
</tbody>
</table>
WGS84  World Geodetic System of 1984
wrt.    with respect to
WVM     Wind Velocity Measurement
XML     Extensible Markup Language
ZWC     Zero-Wind Calibration
## 10 Symbols and Constants

### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Albedo</td>
<td>1</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Collecting area of the telescope (optical aperture)</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_0/r^2$</td>
<td>Acceptance solid angle</td>
<td>rad</td>
</tr>
<tr>
<td>$B$</td>
<td>Backscatter ratio, Scattering Ratio</td>
<td>1</td>
</tr>
<tr>
<td>$C(\lambda)$</td>
<td>Instrument function depending on wavelength $\lambda$</td>
<td>1</td>
</tr>
<tr>
<td>$E_L$</td>
<td>Energy of the laser pulse</td>
<td>mJ</td>
</tr>
<tr>
<td>$E_{\text{micron}}$</td>
<td>Earth background radiant energy per micron wavelength</td>
<td>J $\mu$m$^{-1}$</td>
</tr>
<tr>
<td>$f_0$</td>
<td>Frequency of the transmitted laser pulse</td>
<td>Hz</td>
</tr>
<tr>
<td>$L_a$</td>
<td>Aerosol Lidar ratio (aerosol extinction-to-backscatter ratio)</td>
<td>sr</td>
</tr>
<tr>
<td>$L_m$</td>
<td>Molecular Lidar ratio (molecules extinction-to-backscatter ratio)</td>
<td>sr</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of measurements per observation</td>
<td>1</td>
</tr>
<tr>
<td>$N_{\text{mol}}$</td>
<td>Number of molecules per volume</td>
<td>m$^{-3}$</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$P$</td>
<td>Number of laser pulses per measurement</td>
<td>1</td>
</tr>
<tr>
<td>$r$</td>
<td>Distance from instrument to target</td>
<td>m</td>
</tr>
<tr>
<td>$S$</td>
<td>Solar spectral radiance</td>
<td>W m$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T^2$</td>
<td>Atmospheric two-way transmission</td>
<td>1</td>
</tr>
<tr>
<td>$t_0$</td>
<td>Detection time</td>
<td>s</td>
</tr>
<tr>
<td>$v_{\text{LOS}}$</td>
<td>Line-of-sight wind speed</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$z$</td>
<td>Altitude</td>
<td>m</td>
</tr>
</tbody>
</table>

Symbols included except from chapter 8, which are included in separate Tables at the end of each subchapter.
Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_A$, $\alpha_{\text{Mol}}$</td>
<td>Extinction coefficient (aerosol, molecular)</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$\beta_A$, $\beta_{\text{Mol}}$</td>
<td>Backscatter coefficient (aerosol, molecular)</td>
<td>m$^{-1}$ sr$^{-1}$</td>
</tr>
<tr>
<td>$\Delta f_D$</td>
<td>Doppler-shifted frequency difference</td>
<td>Hz</td>
</tr>
<tr>
<td>$\Delta \lambda_D$</td>
<td>Doppler-shifted wavelength difference</td>
<td>pm</td>
</tr>
<tr>
<td>$\Delta \lambda_{\text{FWHM}}$</td>
<td>FWHM of a Gaussian or Lorentzian function</td>
<td>pm</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>Range bin resolution</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta R_{\text{min}}$</td>
<td>Minimal range bin resolution</td>
<td>m</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of a signal spectrum</td>
<td>pm</td>
</tr>
<tr>
<td>$\sigma_{\text{Mol}}$</td>
<td>Rayleigh backscattering cross section</td>
<td>m$^2$ sr$^{-1}$</td>
</tr>
<tr>
<td>$\tau_L$</td>
<td>Physical length of the laser pulse</td>
<td>ns</td>
</tr>
<tr>
<td>$\Omega_0$</td>
<td>Acceptance solid angle</td>
<td>sr</td>
</tr>
</tbody>
</table>

Constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avogadro constant</td>
<td>$N_A = 6.0221 \times 10^{23}$</td>
<td>mol$^{-1}$</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>$k = 1.3807 \times 10^{-23}$</td>
<td>J K$^{-1}$</td>
</tr>
<tr>
<td>Loschmidt's number ($T = 273.15 \text{ K} / \rho = 1013.25 \text{ hPa}$)</td>
<td>$N_L = 2.68678 \times 10^{25}$</td>
<td>m$^{-3}$</td>
</tr>
<tr>
<td>Mean molecular air mass</td>
<td>$m_{\text{air}} = 2.885 \times 10^{-2}$</td>
<td>kg mol$^{-1}$</td>
</tr>
<tr>
<td>Planck's constant</td>
<td>$h = 6.6261 \times 10^{-34}$</td>
<td>J s</td>
</tr>
<tr>
<td>speed of light (exact)</td>
<td>$c = 2.99792458 \times 10^{8}$</td>
<td>m s$^{-1}$</td>
</tr>
</tbody>
</table>
## Processor Settings for L1B, V 6.03

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Chapter Ch., Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind Mode Processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum no. of bad pulses per measurement</td>
<td>3</td>
<td>Ch. 8.1</td>
</tr>
<tr>
<td><strong>Rayleigh wind mode processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rayleigh filter A pixel positions $j_{\text{min}}$ to $j_{\text{max}}$</td>
<td>3-10 (11-18)</td>
<td>Eq. 8.2</td>
</tr>
<tr>
<td>Rayleigh filter B pixel positions $j_{\text{min}}$ to $j_{\text{max}}$</td>
<td>11-18 (3-10)</td>
<td>Eq. 8.2</td>
</tr>
<tr>
<td>Minimum no. of Rayleigh ground measurements per observation</td>
<td>$&gt;$0</td>
<td>Eq. 8.34</td>
</tr>
<tr>
<td><strong>Mie wind mode processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mie core 1 Gaussian width $\sigma$</td>
<td>3 (1.27) pixel</td>
<td>Eq. 8.40</td>
</tr>
<tr>
<td>Mie core 1 max. no. of iterations</td>
<td>25 (30)</td>
<td>Eq. 8.47</td>
</tr>
<tr>
<td>Mie core 1 residual error threshold</td>
<td>$10^{-7}$ ($10^{-3}$)</td>
<td>Eq. 8.47</td>
</tr>
<tr>
<td>Mie core 2 start FWHM $\Delta x_{\text{start}}$</td>
<td>1.66 pixel</td>
<td>Eq. 8.48</td>
</tr>
<tr>
<td>Mie core 2 residual error threshold</td>
<td>$10^{-5}$ ($10^{-3}$)</td>
<td>Eq. 8.6, step3</td>
</tr>
<tr>
<td>Mie core 2 max. no. of iterations</td>
<td>30</td>
<td>Step 3</td>
</tr>
<tr>
<td>Mie core 2 no. of spectral subsamples $n_s$</td>
<td>5</td>
<td>Eq. 8.52</td>
</tr>
<tr>
<td>Mie core 2 max no. of downhill simplex algorithm iterations</td>
<td>20 (50)</td>
<td>step 2</td>
</tr>
<tr>
<td>Mie core 2 minimum decrease in residual error in downhill simplex</td>
<td>$10^{-2}$ ($10^{-3}$)</td>
<td>Eq. 8.56, step 2</td>
</tr>
<tr>
<td>Minimum no. of Mie ground measurements per observation</td>
<td>$&gt;$0</td>
<td>Eq. 8.66</td>
</tr>
</tbody>
</table>

Selection of settings from the operational L1B Processor V 6.03 from the file AUX_PAR_1B; values in parentheses are recommended settings for next update of the file.
Satellite Characterisation File

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Chapter Ch., Equation Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind Mode Processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser frequency $f_0$</td>
<td>844.5070423 THz</td>
<td>Eq. 8.1, 8.3, 8.30, 8.33, 8.35, 8.63, 8.65, 8.67</td>
</tr>
<tr>
<td>Laser wavelength $\lambda_0$</td>
<td>844.961832 THz (355 nm)</td>
<td>Eq. 8.39</td>
</tr>
<tr>
<td></td>
<td>355 nm (354.8 nm)</td>
<td></td>
</tr>
<tr>
<td><strong>Rayleigh wind mode processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rayleigh detection chain linearity error $E_{RLC}$</td>
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<td>Eq. 8.17</td>
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<tr>
<td><strong>Mie wind mode processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mie Tripod Obscuration Correction $C_{TOBS}$</td>
<td>Array of 16 values between 0.88 and 1.0</td>
<td></td>
</tr>
</tbody>
</table>

Selection of the satellite characterisation file used for L1B Processor V 6.03 from file AUX_CHAR.
11 References


EADS-Astrium (2012): End to End Simulator Instrument input parameters. AE.TN.ASF.AL.00458, Issue 02, Rev. 02, 4 July 2012.


