DEVELOPMENT OF ADM-AEOLUS PORTABLE LEVEL 2B WIND RETRIEVAL SOFTWARE

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ABSTRACT

ADM-Aeolus is a demonstration mission to be launched by mid 2009 for measuring wind profiles from space with a Doppler Wind Lidar. Portable ADM-Aeolus L2B wind processing software is being developed that may be used by data assimilation centers, e.g., for Numerical Weather Prediction (NWP). Some first and preliminary wind retrieval results are presented using an end-to-end simulation environment. Further research and development is being carried out to perform wind retrieval in more complex and heterogeneous atmospheric conditions.

1 INTRODUCTION

The ADM-Aeolus is primarily a research and demonstration mission, flying the first Doppler wind lidar in space, scheduled to be launched in 2009. This will enable measuring profiles of wind from space for the first time, aiding atmospheric flow analysis for climate studies and NWP. The main objectives for the ADM-Aeolus mission are:

- to measure global wind profiles up to an altitude of 30 km, with an accuracy of 1 m/s in the boundary layer, and an accuracy of 2-3 m/s in the free troposphere and lower stratosphere (not including representativeness errors).
- to determine the average wind velocity over 50 km tracks and measure 120 averaged wind profiles per hour, using 24 vertical rangebins.

The lidar is operated in the UV at 355 nm wavelength, it has a pulse frequency of 100 Hz, 150 mJ pulse energy, a duty cycle of 10 seconds on (of which 3 are used for warming up), 18 seconds off, single frequency (linewidth less then 30 MHz.). It is pointing at an incidence angle of 35 degrees from nadir, but can also be pointed nadir for zero wind calibration mode (see Fig. 1A).

The detection system features a receiver with 1.1 m diameter telescope, and two spectrometers:

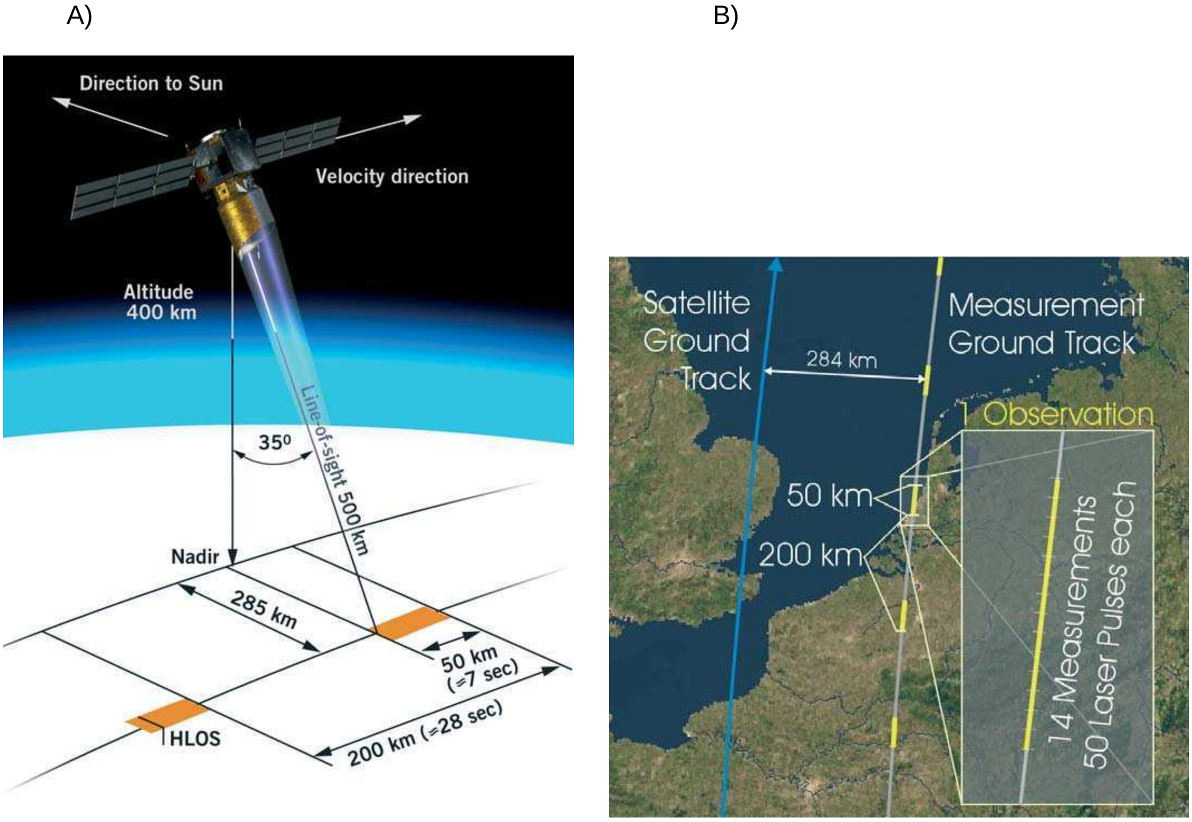

Figure 1: *A) measurement geometry of the ADM-Aeolus lidar system; B) map illustrating the spatial sampling of the ADM-Aeolus lidar system.*

- a smallband frequency channel using a Fizeau spectrometer measuring mainly the Mie scattering on particles (aerosols, water droplets, ice cristals). It will, however, also detect a fraction of the Rayleigh scattered signal, which will be a nearly constant background in the observed Mie spectrum.
- a broadband frequency channel using a Fabry-Perot spectrometer measuring mainly the Rayleigh scattering on atmospheric molecules. The tail of both Fabry-Perot spectrometer channels will however also pick up a fraction of the Mie scattered signal (usually referred to as cross-talk).

Both spectrometer signals can be used for detecting the Doppler shifts, so from both measured spectra the wind profile may be determined from the surface up to a height of 30 km, collected in 24 vertical rangebins.

The satellite will fly in a polar sun synchronous dawn-dusk orbit, with a 97° inclination angle. This has the advantage that the solar panels are illuminated for a large part of the orbit, and that the laser points to the night side of the earth, thus minimising the background radiation from the reflected sun light.

In preparation for the processing of this lidar data specialised software is developed. This processing is typically divided into several steps named Level 0, 1A, 1B, 2A, 2B and 2C, and will generate products on each of these processing levels. This presentation will focus on the level 2B software, which will generate wind component profiles that are representative for an observation scale of 50 km, suitable for input in NWP data assimilation systems.

2 MEASUREMENT PRINCIPLE

The emitted laser light enters the atmosphere and is scattered back both by molecules (Rayleigh scattering), and also by aerosol and cloud particles (Mie scattering). Using rangegating an altitude range from which the backscattered light originates is selected (see Fig. 2A).

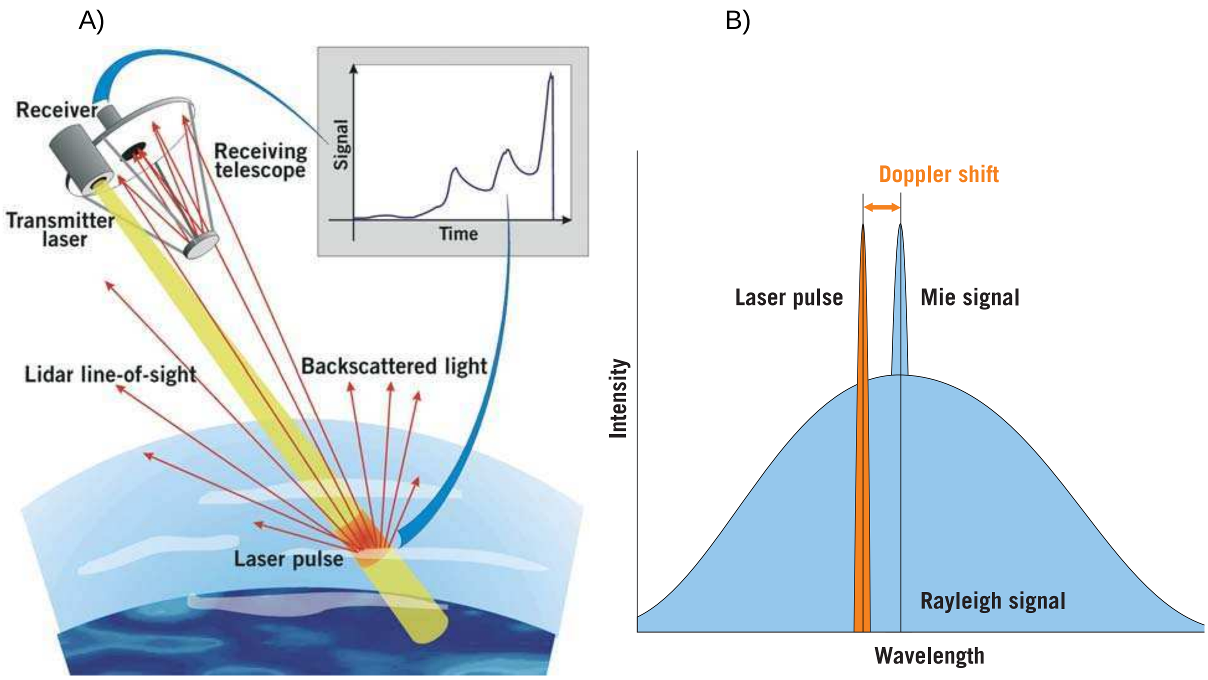

Figure 2: *A) schematic view of the pointing and rangegating used by the ADM-Aeolus lidar system; B) schematic view of the expected spectrum of the backscattered laser light.*

Due to the larger thermal motion of molecules compared to particles like aerosols the Rayleigh backscattered light will have a much broader spectral width than the Mie backscattered light (see Fig. 2B). This property is used to split the light in 2 channels in the receiver, thus obtaining two largely independent measurements for each location.

The light received is Doppler shifted due to the movement of the scatterers in the laser Line-Of-Sight (LOS). There is no substantial Doppler shift associated to the platform motion because the Lidar is looking cross track. Small biases due for example to observing a small component of the platform motion will be removed by performing regular ground detections (which should yield a local zero wind estimate).

A wind profile may be determined from these Doppler shifts from the surface up to a height of 30 km, although typically the upper bound will be restricted to 26 km most of the time. The vertical sampling resolution is adaptable and will typically be 250 m or 500 m close to the surface, 1 km in the free troposphere, and up to 2 km in the stratosphere. The altitude of the lowest rangebin is adjustable and may be moved up or down anticipating the expected local orography. Generally it is expected that at least one rangebin will contain the surface to enable ground calibration. The settings of the rangebin definition can be changed 8 times per orbit, which enables adapting the system to different climate zones.

The measurement horizontal resolution will be between 1 and 3.5 km, along 50 km of the satellite track, followed by a 150 km data gap (see Fig. 1A and B).

Note that usually the LOS wind component along the laser beam will be converted to a horizontal wind component assuming that the vertical motion may be neglected (although this may be disabled in the software if needed).

3 SOFTWARE: PROCESSING CHAIN

A special simulation software package named E2S is available to simulate most aspects of the measurement hardware of this future mission. As input for this simulator a special database of atmospheric properties was constructed. For the current experiment ECMWF ERA-40 data was used to obtain profiles of temperature, pressure, and wind component u,v,w (zonal, meridional and vertical). For aerosol and cloud backscatter and extinction profiles, LITE (Lidar-In-Space-Technology[1]) data was used, which was processed by the algorithms designed by G.J. Marseille et al. [1]. The output of this simulation is passed on to successive levels of processing stages. The processing chain, used for the experiment described in this paper, is as follows:

E2S: The simulation of the hardware (named E2S for “end-to-end simulator”). Inputs are descriptions of atmospheric profiles in xml format. Output is the AISP (Annotated Instrument Source Packet) binary format, identical to the data that will be generated by the actual satellite.

L0: This processing stage sorts the measurements in the order in which they were taken, and writes the results to a dedicated Earth Explorer (EE) formatted binary file format.

L1A: Geolocation data is added at this stage. Input and output are dedicated Earth Explorer formatted binary file formats.

L1B: This processing stage applies calibration to the measured spectra, then calculates wind products both on measurement scale (pulses accumulated over 1 to 3.5 km) and on observation scale (measurements accumulated over 50 km). It ignores variability in the 50km observed scene, as well as temperature and pressure effects on the shape of the Rayleigh spectrum, and cross-talk effects between the Mie and Rayleigh channel. Some signals useful for L2B processing are calculated, especially the useful signals for the Rayleigh A and B channel and an estimate of the scattering ratio on measurement level, which is obtained by comparing the peak height (containing both Mie and Rayleigh scattered light) and background level (containing only Rayleigh scattered light) of the Mie spectrum. For this reason the L2B is based on the L1B rather than the L1A product. Input and output are dedicated Earth Explorer formatted binary file formats.

L2B: This is the processing stage described in the remainder of this paper, details are given in the next section. Input and output are currently the dedicated Earth Explorer formatted binary file formats. In a later stage it is expected to support BUFR file formats as well for input and output. A L1B EE-to-BUFR format conversion tool is already available.

Other processing stages being developed are the L2A and L2C processing. The L2A processing stage, based on the L1B product, will focus on the optical aerosol and cloud properties of the atmosphere, and tries to extract as much detail as possible from the measurements. The L2C processing stage, based on the L2B product, consists of assimilating the HLOS (Horizontal projection of the Line-Of-Sight) retrieved winds into the ECMWF operational NWP forecasting system. Its output contains the full wind vectors at ADM-Aeolus measurement locations retrieved from the analysis, as well as additional confidence data (i.e. deviation of the measurement from the model analysis field). The result of both L2A and L2B processing are given as an Earth Explorer formatted binary file

4 SOFTWARE: PROCESSING ALGORITHMS

Level 2B processing (L2Bp) will allow to:

- correct the pressure and temperature effect on the backscattered molecular spectrum (Rayleigh-Brillouin lineshape broadening effect), which will improve the estimate of the Doppler shift;
- detect and if possible remove cross-talk between both channels. Removing is only possible if both channels sample the same piece of atmosphere. If due to the choosen rangebin definition just the Rayleigh signal is available, still cross-talk may be detected and flagged. This can be achieved by comparing the measured Rayleigh scattering with the expected Rayleigh scattering as estimated by using the advance knowledge of the temperature and pressure profiles;
- classify atmospheric profiles accumulated over small distances (1 to 3.5 km). The backscatter ratio determined in the L1B processing stage will be used for this at first. Later more elaborate optical properties calculations may be added. This will allow to discriminate measurements in clear and cloudy areas (and later maybe also aerosol layers);

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[1] an experiment with 3 lidars flown on the Space Shuttle in 1994.

- accumulate the profiles of each class within the 50 km observation track. There are several reasons why this may be important and may improve the end result. Cloudy rangebins may contain vertical convection which may add a systematic error due to the LOS-to-HLOS conversion. Also cloudlayers may be related to regions of strong windshear in the vertical profile, so reflections on the top of a cloud layer may not be representative for the wind in the rest of the rangebin;
- assign the results to their proper height. Due to the extinction and possibly the non-uniform backscatter in a rangebin, the center of gravity of the signal in a rangebin may be located below or above the actual rangebin center. The L2Bp code will try to correct for this when the extinction in a rangebin is known;
- calculate HLOS wind from both Mie and Rayleigh channels separately for each class. Accumulation over 50 km will improve the representativeness of the result, but only when classification as mentioned above is properly taken into account;
- add quality control flags and uncertainty estimates for the wind information produced. Uncertainty is estimated based on the observed SNR (Signal-to-Noise Ratio) in the spectra and the known relation between the spectral channels and the HLOS. For the Rayleigh channel also the derivatives of HLOS to input temperature, pressure and scattering ratio are determined, which allows to adjust the HLOS result when used in an NWP analysis procedure, by implementing these derivatives in the observation operator.

5 SOFTWARE: IMPLEMENTATION

The L2Bp software has been designed and written with the aim of portability. This is important to allow all interested users/Meteorological centers to run their own copy of the software, which allows them to use their own model results as input for the needed pressure and temperature profiles. This allows for faster processing, which might be very useful when the data needs to be assimilated in a local model, because the ECMWF L2B product will only be generated once every 12 hours. Therefore the software will be made available to those interested in using the ADM-Aeolus L2B data.

To ensure easy portability strict Fortran90 was used for coding. A few extensions to the Fortran90 standard and some c-routines are needed to implement features not available in the Fortran90 language. These are collected in a dedicated directory to minimise any porting effort that might be needed. The software has been written to compile and run on most linux and unix systems, for a range of different compilers.

Two external libraries may be used. ESA has provided precompiled libraries to be used for orbit calculations and xml handling. Since precompiled libraries are not portable by definition, alternative fortran code is available for this functionality. At a later stage also the ECMWF BUFR library will be used when the use of BUFR in- and output files has been implemented.

A full set of Makefiles for standalone compilation and unit testing of the software is provided. Compilation and installation may be executed by a convenience script provided, or by executing the make command in the root of the source directory. A special Makeoptions file is used which will be included in all Makefiles and which may contain an alternative fortran compiler name, or user defined options and library locations.

An external parameter file is used to configure the software, to pass parameters to the different algorithms and to select which algorithms should be used.

The software is setup in a way which allows all key parts of it to be included into an IFS like forecasting system. This will allow direct use of pressure and temperature profiles from the model analysis without the need to pass the data along using files. The user should adapt its main IFS program and makesystem to include the L2Bp files in this case, and write dedicated internal interfaces to use the Fortran datastructures used by the L2Bp.

Documentation on how to compile and use the software, both as standalone tool, and as subroutine within an IFS like system, will be distributed along with the source code of the software.

Currently the software uses the ESA specified Earth Explorer style binary file format. All necessary reading and writing routines to handle this file format will be included in the software. At a later stage BUFR file support will be added.

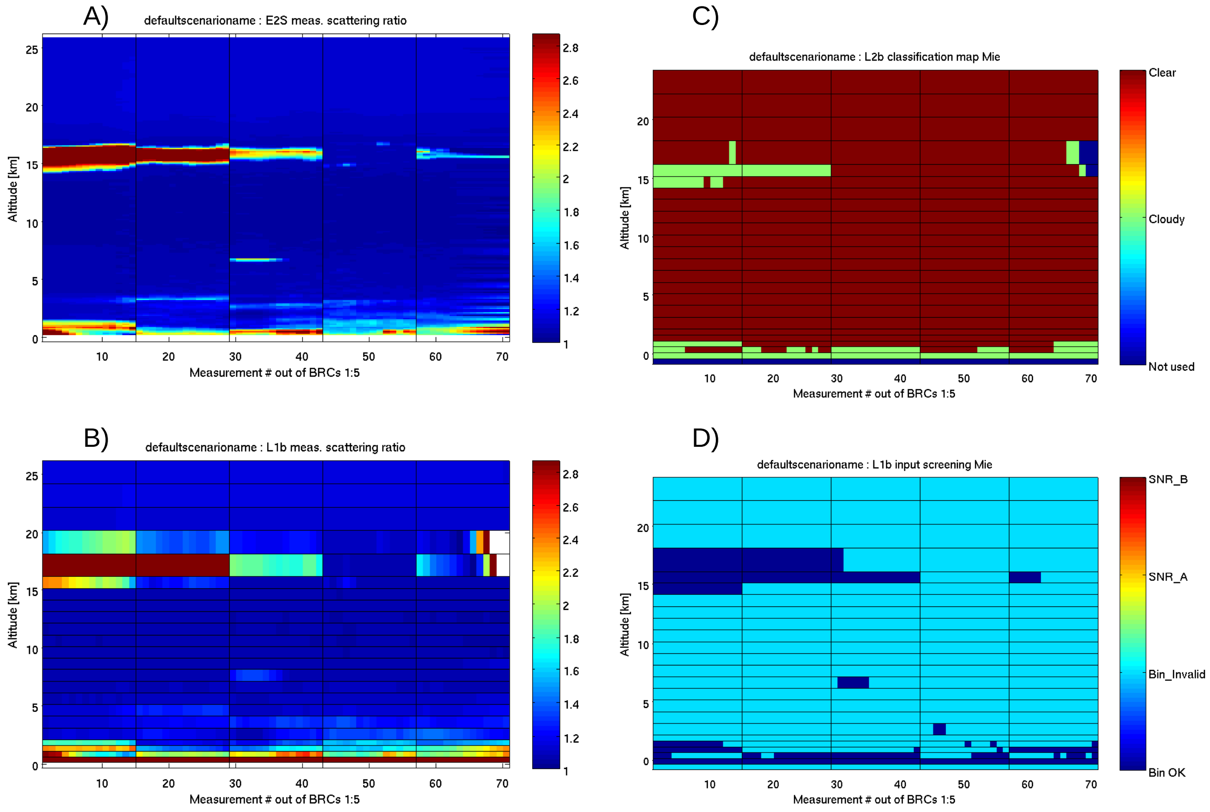

Figure 3: *A) Scattering ratio based on LITE data, as used as input to the E2S satellite simulator; B) scattering ratio found by the L1B processing which will be used as input for the L2Bp; C) Mie channel classification results based on the L1B scattering ratio; D) Mie input screening results, rejecting data with invalid scattering ratio due to too low SNR.*

6 SOFTWARE: TESTING

A dedicated set of Makefiles is provided to automatically run all available unit test programs. At the end of this testing stage a small report is generated, which should give the user a good idea whether compilation has been successfully completed or not.

The unit testing system uses a custom made “diff” tool which allows specifying at which accuracy real numbers are to be compared to the reference output files. This way it is possible to verify the correct functioning of the software on different compilers and/or hardware platforms with different numerical implementations.

An other round of testing performed is the manual validation testing against the requirements list composed by ESA. This is mainly to ensure that all required features have been included in the software.

All algorithms have been subject to scientific testing. Usually this was done ouside the L2Bp context, for example in a Matlab environment, before deciding to include an algorithm into the software.

Finally the software is subjected to “realistic testing” on simulated data. To allow the realistic testing a simulator for the satellite hardware has been constructed (E2S). Input for this simulator is a database holding a variety of academic and realistic atmospheres from various sources (NWP model, LITE, CALIPSO, radiosonde etc.). The simulators results are processed by the L0, L1A and L1B software. The L1B output is then used as input for the L2B software, and the final resulting wind profiles are compared to the input atmospheric scenario used for the simulator.

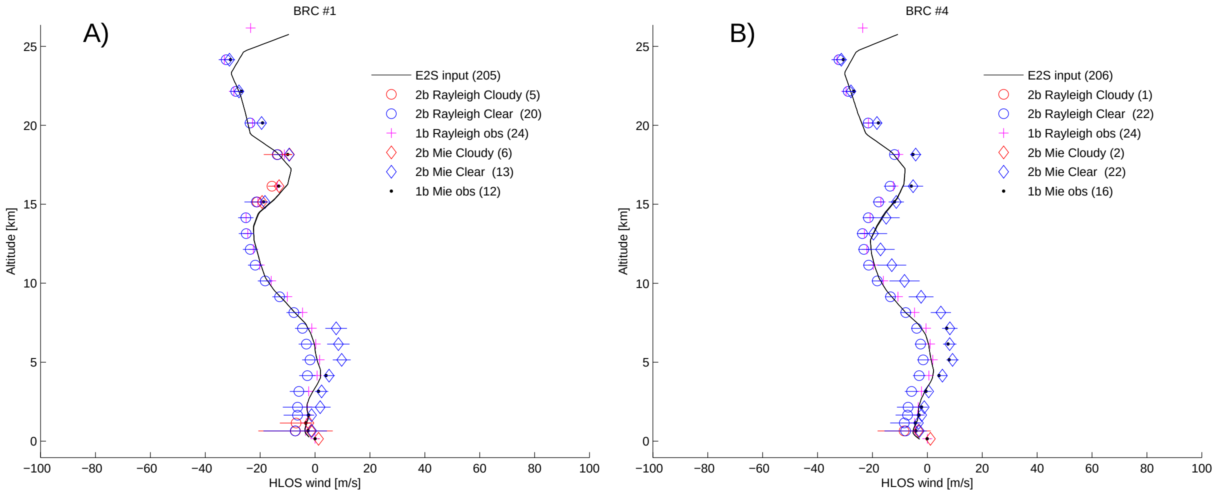

Figure 4: *Horizontally projected line-of-sight wind component found by the L1B and L2B processing software. A) for BRC 1, covering the first 50 km in this test scene. B) for BRC 4, ranging from 600 to 650 km in this test scene. The solid black line denotes the true (input) wind.*

7 FIRST TEST RESULTS

A first test scene was based on collocated LITE and ECMWF data. The data contains a tropical cirrus case above Indonesia, dated 19940910, and some aerosol layers close to the surface below 2 km. No instrument noise has been added yet. Figure 3A shows the scattering ratio used as input from the atmospheric database, and Fig. 3B the retrieved scattering ratio by the L1B processing, based on comparing the peak in the Mie spectrum to the background level in this spectrum. Based on the L1B scattering ratio result, a classification was performed using a threshold of 2.0 (see Fig. 3C). Finally, when the SNR is too low in the Mie spectrum, no reliable scattering ratio can be determined by the L1B algorithm, so these results are flagged and not used (see Fig. 3D).

Figure 4 shows the HLOS wind results both from the L1B and the L2B processing stages, for the observation level (so accumulated over 50 km). The continuous black line gives the 50km average input HLOS wind from the ECMWF model, which was used as input. The crosses and circles give Rayleigh channel results, diamonds and dots give the Mie channel results. The level 2B results have additional error bars as well, giving an estimate of the quality of the data.

Clearly the L2B results are not yet perfect. Some biases in both channels are clearly present. This is probably due to the use of calibration numbers which are not consistent with some recently changed default values in the E2S simulation software.

The input screening, thresholding and classification of the different parts of the scene works as intended. Clearly the cloud and low aerosol layers are detected, and different wind results are generated from this scene.

Also the estimation of the HLOS errors follows the expected behaviour, giving larger errors when less data is accumulated or lower signal levels are present.

The overal result does look very promising, and the system is ready for further tuning and experimentation/testing with several different sets of input data.

8 CONCLUSION

The implementation of the L2Bp software is still in progress, but we are at a stage now where it is possible to use the simulation-processing chain and start fine tuning the software.

Most “todo’s” in the software are clean-up tasks, i.e. finishing of input screening, implementation of proper ground contamination handling and portability issues. The only major new algorithm to be added is the optical properties calculation which will allow the calculation of extinction, which may be used to improve the classification.

The added value of L2Bp still has to be demonstrated, and much more testing is needed. Part of this testing will focus on finding optimal vertical sampling settings for the rangebin definitions of both channels. A new dedicated project to investigate this, is about to start.

9 SEE ALSO

Other ADM-Aeolus related contributions to this conference are:

- “Assessment of post-Aeolus Doppler wind lidar scenarios”, by Ad Stoffelen, KNMI.
- “An improved forecast of the 1999 Christmas storm “Martin” - A cycled SOSE experiment”, by Gert-Jan Marseille, KNMI.
- poster: “ADM-Aeolus - ESA’s space-borne wind profiling LIDAR”, by Anne Grete Straume-Lindner, ESA/ESTEC.
- poster: “Doppler wind Lidar measurement scenarios in the Tropics”, by Nedjeljka Zagar, NCAR.
- poster: “Space-borne Lidar measurements: Advancing the knowledge on aerosols and clouds”, by Dulce Lajas, ESA/ESTEC.

For further reference and more details on the implementation of the L2Bp software see [2] and [3]. For general information on the ADM-Aeolus mission and associated projects, see the ESA website:

- http://www.esa.int/esaLP/LPadmaeolus.html

References

[1] Marseille, G. J., A. Stoffelen and A. van Lammeren; “LITE4ADM: On the use of LITE data for the Atmospheric Dynamics Mission - Aeolus”, 2003, KNMI, intern rapport; IR 2003-01.

[2] Stoffelen, A., P. Flamant, E. Källén, J. Pailleux, J.M. Vaughan, W. Wergen, E. Andersson, H. Schyberg, A. Culoma, M. Endemann, P. Ingmann and R. Meynart, “The Atmospheric Dynamics Mission for Global Wind Field Measurement”, Bull. Amer. Meteor. Soc., 2005, 86, 1, 73-87.

[3] Tan, David G.H., Erik Andersson, Jos de Kloe, Gert-Jan Marseille, Ad Stoffelen, Paul Poli, Marie-Laure Denneulin, Alain Dabas, Dorit Huber, Oliver Reitebuch, Pierre Flamant, Olivier Le Rille and Herbert Nett, “The ADM-Aeolus wind retrieval algorithms”, (Accepted for publication in Tellus 60A, 2008, special edition on ADM-Aeolus).