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Comparison of Aeolus burst and continuous mode concepts

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CHANGE LOG

Version	Date	Comment
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0.2	25 August 2008	AS: Mainly L1B/2A comments Oliver, Dorit
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0.3a	24 September 2008	JdK: responded to ESA comments of 12 Sept. 2008
0.4	26 September 2008	AS: Input from Dorit, Oliver, David, Pierre
0.5	1 October 2008	AS: Most Herbert's points
0.6	3 October 2008	GJM&AS: section 6 up to p27
0.7	6 October 2008	GJM: section 6 finished, reference added
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0.9	7 October 2008	DT: operational L2B/L2C considerations

1 Introduction

The present document presents the comparison of the Aeolus burst and continuous mode concepts with the aim to assess the impact of Aeolus continuous operations on Aeolus processing and application.

In this report a first assessment of a potential change in the Aeolus operations concept will be analyzed. The following aspects are addressed specifically:

- Impact of continuous operation on major error contributions (random and systematic) in routine Level 1B, Level 2B/C and Level 2A processing;
- Impact on the actual Level 1B/2A algorithm baseline (calibration processing, generation of geolocation information, error quantifiers, ...)
- Required changes in L1B / 2A product formats (including auxiliary data)
- Potential enhancements in the processing concept, for example:
  - enhanced detection of cloud/aerosol contaminated scenes in routine wind mode and calibration measurements
  - enhanced sampling strategies in spectral response calibration measurements
  - enhanced detection / characterization of ground echoes (average pulse repeat frequency increased by 20 %,assuming warmup pulses are used in burst mode, or 70% when no warmup pulses should be used in burst mode)
- estimates of amount of work needed to adapt the current software
- issues that need to be addressed in further detailed simulations

The report first addresses the assumptions on the continuous mode, and subsequently its consequences on the functionality and application of calibration modes, the L1Bp, L2Ap, L2Bp and NWP data assimilation. On mission level the performance consequences for L1Bp, L2Bp and NWP data assimilation appear the most crucial. The view of some authors is that the investigations to date are sufficiently convincing to favour the continuous mode, but this view is not shared by others (in particular with regard to the computations in Section 6). The contrasting views are discussed further in Section 9. The starting point in the comparison is the Aeolus burst mode performance specification. Considerations on changes of software, processors and tools have to be taken into account, but should not drive the decision. The table below provides an overview of the latter.

Processing implications. The 3th column refers to the sections for more detailed information.

	Continuous mode in relation to burst mode	Section	Comments
L1B calibration modes	Less time needed (about factor 2) for most modes. Limited development work	3	IRC mode needs the atmosphere and takes about 18 minutes in burst mode. If the same time is taken in continuous mode then a better quality is obtained. The amount of development work is

			related to a change in the file format.
L1B wind mode	More time available for this mode. Parameters need retuning.	4	Available time depends on "lost" time for calibration. No algorithm problems foreseen. E2S code + L1B simulations not applicable to continuous mode. Renewed E2S inputs needed.
L2A	Resolution/coverage trade-off advantageous. Development work if L1B format changes	5	Scope/effort depends on L1B changes
L2B	Must retain BRC concept for L1B input & L2B output. Development work if L1B format changes. Larger file formats.	6	Ground wind terms needed at BRC level. Scope/effort depends on L1B changes.
Aux Met	File size x 2 (for 100 km BRC)		L2B/L2C/AuxMet scale with Num_BRC and model grid resolution
L2C EE-product	No significant impact foreseen		Superset of L2B product
NWP systems	Need L2B BRC concept.		

1.1 Documents

1.1.1 Applicable documents

	Title	Ref	Ver.	Date

1.1.2 References

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1.2 Acronyms

ACCD	Accumulation Charge Coupled Device
AISP	Annotated Instrument Source Packet
AMD	Auxiliary Meteorological Data
AOCS	Attitude and Orbit Control System
BRC	Basic Repeat Cycle
DE2S	DLR End-To-End Simulator
DEM	Digital Elevation Map
E2S	End-to-End Simulator
ECMWF	European Center for Medium-Range Weather Forecast
EE	Earth Explorer

HK	Housekeeping Data
HLOS	Horizontal Line Of Sight
KNMI	Royal Netherlands Meteorological Institute
L1B	Level-1B
L2B	Level-2B
L2Bp	L2B processor
L2C	Level-2C
LITE	Lidar In-space Technology Experiment
LOS	Line-Of-Sight
MDA	MacDonald Dettwiler
MPH	Main Product Header
NRT	Near Real Time
NWP	Numerical Weather Prediction
ODB	Observation DataBase
PDS	Payload Data Segment
PRF	Pulse Repetition Frequency
QRT	Quasi Real Time
RBC	Rayleigh-Brillouin Correction
SNR	Signal to Noise Ratio
SPH	Specific Product Header
WGS84	World Global System 84: Reference Ellipsoid for GPS data.
WMO	World Meteorological Organization

2 Assumptions

Main assumptions. More details are found in the text.

	Burst mode	Continuous mode	Comments
Pulse repetition frequency	100 Hz	50 Hz	50 Hz is taken for simplicity. In practice it may be smaller such that the total number of shots in continuous mode at least equals the number of shots in burst mode (including warm-up shots).
Data readout time	0 seconds	0 seconds	Due to revision of the on board hardware
Duty cycle, seconds on/off	7/21	28/0	No interruptions for data readout in continuous mode
Pulse energy (on average)	baseline (130 mJ)	unchanged	From the above rows: double the energy is emitted into the atmosphere in continuous mode
Calibration constraints and	BRC concept	unchanged	calibration must not last more than 30 minutes for IRC mode

abilities			(section 3)
BRC concept	fixed size	unchanged	To allow for parallel processing at ECMWF at L2B stage
Lifetime	3 years	3 years	Lifetime is a critical parameter for NWP centers.
Instrument performance	Mission requirements	Performance specified over 100 km integration	The mission requirements on HLOS wind quality are the main driver of concept selection.

The following system properties are assumed (see table above):

- A pulse repeat frequency (PRF) of 50 Hz - for continuous operation. A PRF of 100 Hz - for burst mode operation, with a 28 s basic repeat cycle with a burst length of 7 seconds, not including warm-up shots.
- There will be a revision of the on board hardware, so we will not need any time for readout of the data after each BRC has been measured.
- BRC size remains 200km. Keeping the BRC concept is necessary at the L2B processing stage to allow for parallel processing of the data at ECMWF. The exact value of the BRC size is less important, and may be implemented as an adjustable input parameter to the L1B stage (N). For the L2B processing stage a few 100 km would be most convenient. The L2Bp could provide smaller scale profiles through its classification scheme, depending on need. Also the number of pulses per measurement (P) can remain variable, as it is now. For some processing steps, multiple the reading of two or more simultaneous BRCs may be needed in continuous mode.
- The assumed average pulse energy is assumed to remain the same. This means that the energy spend in the atmosphere over 200 km increases by 100%, in a continuous mode as compared to a burst pulse.
- It is assumed that the increased total energy produced by the instrument will not affect the mission lifetime. This is a very important point! since if the mission lifetime would be significantly reduced this would have implications for NWP centres deciding to invest effort/resources in preparing for the improvement, background error modelling etc.
- For IRC/ISR a stepping in frequency is needed, which automatically leads to grouping of the measurements, so also for this case the BRC concept will be kept. A major system requirement for this calibration mode will remain that the calibration must not last more than 30 minutes (when the power from the solar panels will be reduced substantially).
- In calibration mode the laser needs 320 ms locking time to jump 25 MHz to the next frequency (therefore in continuous mode 16 pulses cannot be used for measuring when this happens)
- It is assumed the laser also needs some locking time to jump from one phase setting to the next in LCPA mode (TBC)

- It is assumed that frequency changes can be commanded up to 5 times per BRC for certain calibration modes.

3 Calibration modes

For calibration processing, we assume that the amount of pulses per frequency step needs to remain at least the same. Over 200 km, 100% more energy is spent by the continuous mode on measurement data, compared to burst mode, which means that the time spend on calibration modes may decrease by the same percentage to achieve a similar calibration quality. This leads to the following considerations:

- Decreasing the calibration time will be the best choice for ISR and IAT modes (which only use internal reference pulses).
- For ISR mode 147 observations of 14 measurements are required to scan the full frequency range with 25 MHz steps, taking 68 min. 36 s in burst mode. Only internal reference pulses are used in this mode, and no atmospheric or ground returns, so variation in ground or atmospheric variability is of no importance when the timing is changed. Note that switching from one laser frequency to the next takes some time for the laser to stabilize to its new frequency, which is of no relevance for BURST mode since it can be done in the inactive or warmup period.

  Assuming one measurement is lost for switching to the next frequency (due to the time needed by the laser to stabilize to its new frequency), 15 measurements are needed per frequency in continuous mode. This means scanning 147 frequencies will take 147*15-1=2204 measurements, so 79 BRC's, which takes 36 min. 52 s.
- The IRC mode (which generates both MRC and RRC data) uses 40 BRC's of 14 measurements for scanning the frequency range (at 25 Mhz steps) in burst mode, and again for continuous mode some time must be reserved for stepping to the next frequency (this takes 18 min. 40 s.). Thus for continuous mode scanning 40 frequencies, and using 15 measurements per frequency, a total of 40*15-1=599 measurements are needed to obtain the same calibration result. This will take 22 BRC's, and has a duration of 10 min. 16 s. Therefore the calibration duration may be decreased by 8 min. 24 s. If it is more convenient for processing at L1B stage, the BRC size might be adjusted to still have one frequency step per BRC. Alternatively the choice can be made to increase the integration time per frequency to a full BRC, which increases the amount of measurements used per frequency to 27, and still takes the same time of 18 min. 40s. An increase in integration time will increase the detected amount of photons by 93% and thus this is the preferred option for the IRC mode (since its result depends on actual observed atmospheric/ ground returns).
- The DCC mode does not use atmospheric and ground returns. It also does not observe the internal reference pulses. It is assumed that the signal is only accumulated during 7 s in burst mode, and 28 s during continuous mode. This means only the total duration of the test matters, so 50 BRC's*7 s=350 seconds for burst mode may be replaced by 13 BRC's in continuous mode (13 BRC's*28 s=364 seconds). This means the total time for this calibration will decrease from 23 min. 20 s to 6 min. 4s.
- The LCPA mode again does not use atmospheric and ground returns. It scans the laser phase in 10 steps, and records the straylight into the receiver for 5 BRC's, so takes in total 50 BRC's, and 23 min. 20 s. Recording straylight depends only on the amount of laser pulses, but as for the frequency scanning the time of 1 measurement is assumed necessary for the laser to stabilize to its new phase.

This means that when in burst mode 5 BRC's of 14 measurements, so 70 measurements, are needed for each phase step, then in continuous mode 71 measurements will be needed for each phase step. For 10 phase steps this takes 710-1=709 measurements, so 26 BRC's or 12 min. 8 s.

- For LDT mode no sufficient details are known to assess the impact of changing from burst to continuous mode
- IDC mode uses 10 BRC's and has 33 image readouts per BRC. Assuming it uses the internal reference pulses for illumination of the ACCD's this is done in 7 s for burst mode. A BRC in continuous mode has a doubles amount of pulses, so it is assumed the same calibration will be feasible in 5 BRC's when continuous mode is choosen.
- The OWV mode should be largely identical to WVM, so the same considerations apply.
- Fast calibration (scanning 3 frequencies per BRC of 14 measurements) is used by the IAT. In burst mode 4 measurements are used per frequency, and the 2 remaining measurements in the BRC are needed to jump to the next frequency step. This is used for 54 different BRC's (17 large 250 MHz. steps, 20 small 25 MHz. steps and again 17 large 250 MHz. steps), and takes 25 min. 12s. In continuous mode therefore 5 measurements are needed per frequency step. Scanning 54 frequencies will take 54*5-1=269 measurements, so 10 BRC's or 4 min. 40 s.
- For the IRC mode, the longer integration of 7.14 km per measurement in the atmosphere may still be considered at constant NWP model state (see section on representativeness later on). For the same pulse strength and pulses per measurement, the quality control on the IRC measurements should remain similar as well.
- Assuming a NWP model grid size of 50 km is used, RRC needs multiple NWP collocation points over 200 km continuous. For burst mode only one NWP collocation point per BRC is needed.

3.1 Required changes in Calibration files product format

The following changes are foreseen in the various calibration file formats:

- Assuming a NWP model grid size of 50 km is used, AuxMet files collocated with L1B product files will have multiple NWP collocation points over 200 km continuous. For burst mode only one NWP collocation point per BRC is needed. This has as consequence that the size of the Auxiliary Meteorological (AUX_MET) data file will increase significantly.
- AuxMet files generated using predicted orbit files remain the same.
- ISR and IAT files need no change since the results are reported for each frequency, and the frequency stepping and number of measurements per frequency, remain the same.
- MRC and RRC files also report most results for each frequency. Both files include geolocation information on observation level. Since it is proposed to keep the amount of observations the same to increase the available amount of detected photons, this means there is no change expected in file format or size for these file types.
- LCPA files need no change since the results are reported for each phase, and the number of phase steps remains the same.
- DCC files contain results on observation level. Since the amount of observations decrease, the size

of this file will decrease accordingly. The number of measurements will remain the same, so the data reported on measurement level will not change. Also the file format itself need not to be changed.

- IDC files have a fixed number of image readouts, and no observation level reports are reported. Therefore the change to continuous will not affect the file format.
- LDT and OWV files have the same format of WVM files, so see the comments for that file type.
- ZWC reports accumulated results on observation level, and since the number of observations per orbit will remain the same if 200 km BRC's are chosen, the file format and size will not change.

3.2 Potential enhancements in the Calibration concept

For the RRC and MRC modes the instrument has to point nadir, thus we only have those 30 minutes. In continuous mode we will save about half of the time, so we could try to go in 12.5MHz steps. Better spectral resolution may improve the wind performance. Whether this yields better calibration results than the increase in integration per frequency step, as proposed above, is not clear yet, and needs further study.

3.3 Estimate of the amount of work needed to adapt the calibration software

A higher resolution RRC and MRC as proposed in the previous section requires E2S and L1Bp software changes and some renewed R&D.

All other calibration file definitions seem not affected by the move from burst to continuous mode, and only the file sizes of some of them may change somewhat.

Regarding the calibration modes, the required changes to the E2S and L1Bp software seem minor. These calibration modes are not directly used by the L2Bp software, so this is not affected.

The AUX_CSR tool will be affected by a changed format of the RRC file, since its output file AUX_PRR should have the same format, but again the changes seem minor.

4 Impact of modified operations concept on L1B processing

This assessment is based on document review, previous work on this subject, and simple mathematical calculations/estimates. No advanced simulations are run at this stage.

4.1 Impact on error contributions in L1B processing

Good SNR needs longer time integration for continuous in all modes in order to obtain the number of pulses and quality as specified for burst mode. To obtain similar signal levels and thus performance in clean air, the number of pulses per measurement must remain identical for continuous mode. The default accumulation length, needed to suppress readout noise, along the ground track thus increases from 3.57 km at 100 Hz in Burst mode to 7.14 km in continuous mode (assuming P=50,N=14 in burst mode).

For the same reason the integration length of an observation (of 700 accumulated pulses) has to increase, from about 50 km to 100 km in order to meet the wind quality specification of the burst mode. Therefore the atmospheric and surface variability will increase significantly within an observation, as does the representation scale.

When the number of pulses remains the same, the probability of cloud remains to first order the same as well in an observation, since the cloud correlation length is only a few hundred meters. Moreover, cloud cover statistics on the 100-km scale are similar to those on the 50-km scale. On the 100-km scale for continuous mode the cloud statistics will thus be similar to 50 km for burst mode.

Some error contributions could increase for continuous mode due to the increased variability over 100 km of atmosphere and surface, as compared to the same signal level achieved over just 50 km in burst mode. On the other hand, the increased variability may facilitate QC.

TBD (related with DLR results from 2002 silumations? Oliver could not answer this one).

4.2 Impact on L1B processing

The Mie core and Rayleigh algorithms have been tuned for burst mode. When we assume operation by 7 km accumulation and 100 km integration the SNR characteristics are expected to be similar (they are the same for constant background and atmospheric conditions over 100 km). The main change with respect to a real atmosphere is an increased wind variance over 100 km of about 150% w.r.t. 50 km. However, climatological integrated wind variance for 100-km scales is about 3 m^2s^{-2} (wind SD of 1.7 m/s), which is small compared to the equivalent 18 m/s width of the laser pulses and is not expected to much change performance thresholds.

Both for continuous and burst modes, clouds and PBL aerosol may frequently provide sufficient SNR for wind assessment on scales smaller than 100 km and 50 km respectively. However, most of the time we rely on Rayleigh observations for a reasonable wind performance in the free troposphere and stratosphere (e.g., Stoffelen et al., 2005).

The DEM and elevation and albedo changes will be larger as well for the continuous mode over 100 km with respect to the burst mode. However, the continuous mode results in more samples over 200 km. Impact on L1Bp needs to be assessed.

In summary, the error budget over 100 km of continuous operation is expected to be very similar to the error budget of a burst mode observation over 50 km.

4.3 Required changes in L1B product format

When the BRC and observation concepts are not kept, format changes would be major:

- All observation related fields have to be removed then. This would also affect the L2Ap and L2Bp software, which read this file format.

Assuming that the BRC and observation concepts are kept the changes are minor:

currently the L1B product file does not contain fields explicitely related to warm-up pulses. All other fields already have a variable size, depending on N,P and NumBRC in the file, so no format change is needed for that. When we stick to a fixed BRC observation length of for example 100 or 200 km, limited further changes may be needed. Maybe some fields should be promoted to a bigger integer when more signal becomes accumulated within a BRC (remember the overflow we had in the accd counts for the internal reference pulses.)

4.4 Potential enhancements in the L1B processing concept

Ground echo detection is feasible over a limited portion of the Earth's surface. In areas where ground echo detection is possible, we would obtain twice the amount of useful returns for continuous mode as compared to burst mode, since twice the amount of measurements is available. When we assume that all useful returns are added and used for the zero wind determination, we may conclude that half the number of burst orbits is needed for continuous mode to achieve a certain zero wind calibration quality.

4.5 Estimate of the amount of E2S/L1B work needed to adapt the software

When the BRC and observation concepts are not kept, L0, L1A, L1B format changes would be major and the effort to repair the software and data moderate. If they are kept the changes are minor.

Since the atmospheric database has not been tuned to the burst cycle, no changes are needed in the test data, when a new concept is adapted. Both the high-resolution Lite and Calipso data are available at a small horizontal stepping of about 3.5 km over the full scenario length (of respectively 800 and 20.000 km).

The E2S generates data on measurement level, also HK data is provided on measurement level. So changes to the AISP format are rather _moderate_. But processing the E2S input data, that define the satellite attitude and especially the atmospheric parameters, etc., and are provided in segments with time stamps, needs to be re-organized. Changes to the generation of the measurement level data are rather _moderate_, but feeding those routines with the proper input is a _significant_ effort.

5 Impact on L2A processing

More pulses of given energy are available and over a much longer stretch of atmosphere; therefore, atmospheric sampling of cloud and aerosol much increases for continuous mode. On the other hand, as for L1Bp, continuous mode decreases horizontal resolution for detection and classification of cloud by a factor of 2. Both the basic resolution for suppressing readout noise differs by a factor of 2 and the required horizontal integration length to achieve a given SNR.

Continuous operation is very beneficial for aerosol and cloud observations; the aerosol science community is strongly arguing for continuous mode operation, because of the high horizontal variability of the aerosol. Scene classification with clouds/aerosol would strongly benefit from a continuous coverage; a continuous coverage of cloud and aerosol types could be obtained. Derivation of cloud statistics of cloud coverage would be straightforward with continuous mode; the burst mode is hampered by the long data gaps of 150 km within each 200 km cycle.

Long range transported thin aerosol layers (desert dust, biomass) may be better detected in continuous mode since these extend usually over 50 km. Clouds are generally not homogeneous and have a small scale correlation length (< 1 km). Moreover, clouds generally provide strong returns and are well detected over 50 km.

5.1 Required changes in L2A product format

Format changes at L2A level are minor.

5.2 Potential enhancements in the L2A processing

Possibly long range transported thin aerosol layers may be better detected in continuous mode, since these usually extend over 50 km.

5.3 Estimate of the amount of L2Ap work needed

Minor changes to the calibration file inputs need to be accounted for. A moderate effort is foreseen in adaptation to the L1B input. Processing over multiple BRCs will become possible in continuous mode, which needs to be tested.

6 Impact on L2B/C processing

The ADM burst and continuous modes are studied with respect to their performance to sample the atmosphere and their impact in numerical weather prediction (NWP). This section summarizes and extends on earlier studies related to this issue, more in particular the note to the ADM-Aeolus mission advisory group on spatial representativeness (Stoffelen and Marseille, 2002; update in 2006) and a trade-off study performed at KNMI in 2001 using LITE data to assess the impact of clouds, which has been presented to ESA[1].

In burst mode, the atmosphere is sampled usefully over 50 km at 100 Hz pulse repetition frequency (PRF). Subsequently, the laser is turned off until the next observation cycle starts, which results in a 150-km measurement gap, i.e., observations are provided every 200 km. In continuous mode the laser is always turned on and is operated at 50 Hz PRF. The laser energy per pulse is now assumed identical for both modes, implying that double the amount of energy is emitted into the atmosphere in continuous mode as compared to burst mode (see chapter 2). This assumption deviates from earlier studies in that more energy is guaranteed in continuous mode, which warrants a renewed comparison to burst mode operation.

The main drivers for the 50 km accumulation, 200 km observation spacing burst mode scenario

[1] Martin Endemann and Paul Ingmann visited KNMI in Aug. or Sept. 2002 to discuss an intermediate KNMI study (on ESA request) on burst versus continuous mode using LITE data. A summary of the discussion and results of the study are found in an e-mail from Ad on Thu, 05 Sep 2002 15:15:24 +0200, subject: Burst versus continuous, recipients: Alain Culoma aculoma@esa.int, David Tan <David.Tan@ecmwf.int>, Peter.dubock@esa.int, Roland Meynart <rmeynart@estec.esa.nl>, Paul Ingmann <pingmann@esa.int>, Michael Vaughan <michael@gladeantiques.com>, Erik Andersson <daa@ecmwf.int>, Martin Endemann <mendeman@esa.int>, Pierre Flamant <flamant@lmd.polytechnique.fr>, Mans Hakansson DM <mosse@misu.su.se>, Jean Pailleux <jean.pailleux@meteo.fr>, Harald Schyberg <Harald.Schyberg@dnmi.no>, Werner Wergen <Werner.Wergen@dwd.de>, Erland Kallen <erland@misu.su.se>, Gert-Jan Marseille <marseill@knmi.nl>

presented in Granada (1999) were:

1. 50 km accumulation. (i) The 50 km accumulation was found a good compromise between the required SNR to retrieve good-quality winds and the expected model grid size of global NWP models in 2007 (the in 1999 expected launch date of ADM). (ii) In 1999 it was expected that models would increasingly be better capable to resolve atmospheric structures at increasingly smaller scales. With the advent of AIRS and IASI, resolving 100-150 km scales, it was expected that ADM could make its mark at the smallest scales, i.e. around 50 km. Sharp atmospheric structures (e.g. fronts) could be better resolved with 50 km ADM observations. (iii) In 1999 it was technically not possible to assimilate observations whose sampling extends over more than one model grid point (column).

2. 200 km observation spacing. 200-250 km is a typical value of horizontal correlation for a 6-hour lead NWP model error field (structure function of the background error covariance matrix). A 200 km observation distance then ensures to have reasonably independent observation for correcting the model estimate.

Comments and updated insights on the 1999 assumptions.

Ad 1. Indeed, global NWP models in 2007 had a model grid size of order 50 km. Indeed, models have improved substantially and better resolve small scale structures as compared to 1999. However, as the detailed analysis below shows, probably not to the extent as expected in 1999. Atmospheric structures of scales below 200 km are still not well resolved by current global NWP models. The updated launch date for ADM is end of 2010. Nowadays operational global models have a model grid size of about 25 km and most probably 15 km in 2010. If the technical problem is still on the table then it should be resolved anyway, irrespective of the choice for burst or continuous mode.

Ad 2. The length scale of the background error covariance matrix still is of the order of 200-250 km, another indication that models are still not well capable to resolve the smaller, below 200 km, scales. Thus the assumption on observation error correlation, made in 1999, is still valid and should be taken into account in the continuous mode scenarios because continuous mode allows configurations with observation spacing below 200 km, up to about 50 km.

The potential added value of an observation for a numerical weather model is related to

- The measurement error. This is the error induced by the instrument and the atmosphere. The measurement error is related to the SNR of the measured signal from which the Doppler shift is extracted. The SNR is a function of instrument characteristics and variable atmospheric conditions such as aerosol loading and cloud presence. The measurement error is generally assumed unbiased and quantified through its standard deviation of error.

- The representativeness error. For a DWL this error mainly relates to a discrepancy of the spatial scales resolved by the observation and those resolved by the model in which the observation is ingested. If the model cannot represent (resolve) the scales measured by the observation then the impact of the observation in the assimilation is reduced by decreasing its weight in the analysis through adding a representativeness error to the observation error, i.e., the observation error variance = measurement error variance + representativeness error variance. This is further explained in sections 6.1 and 6.2.

- Observation correlation. ADM-Aeolus provides independent wind measurements, however the information content of observations at close distances is generally not independent from a model perspective and reduces with increasing correlation of neighbouring observations (mainly due to the representativeness error). Observation correlation is not well treated in nowadays data assimilation systems, mainly because the correlation is generally not well known and weather dependent. For this reason, the operational practice is generally to "thin" or "super-ob" closeby measured observations, to force observation independence. The Aeolus observation cycle length has been taken compatible with the thinning scale typical for global NWP.

An important issue to assess the added value of ADM-Aeolus HLOS winds for NWP models is thus in the observation spatial representativeness error. The representativeness and instrument (random) error determine the weight of the observation in the meteorological analysis. If not well determined, the observation impact is either negligible or too strong. Both options are undesired, the later may even be detrimental for the analysis and subsequent forecasts. The detailed analysis below shows that averaging over longer distances along track reduces the representativeness error and thus potentially increases the observation impact. A side effect is the observation error correlation that will increase with increasing accumulation. These aspects are taken into account below.

Error! Reference source not found. summarizes the main results of this section, including HLOS wind error and observation impact for burst and various continuous mode scenarios.

Table 1. ADM-Aeolus properties for burst mode and various continuous mode scenarios. The 2nd column is the HLOS wind error standard deviation (including representativeness error) in the free-troposphere and in the Planetary Boundary Layer (between brackets). The 3rd column is observation compact for NWP. Values are in the interval [0,1], 0 denoting no impact, 1 denoting maximum impact. The 4th column summarizes the impact of cloud coverage. Here, only the percentage of good quality winds for the Mie/Rayleigh channel near the surface is displayed for the following climate zones: North Pole, NH-midlatitudes, NH-subtropics, Tropics, SH-subtropics, SH-midlatitudes. Details are found in the text.

	σ_0 of ADM (ms^{-1})	Observation impact ([0,1])	Observation coverage (%)	Comments
Burst mode. Presented in Granada	2.62 (1.97)	(not presented in Granada)	(not presented in Granada)	50 km on, 150 km off, 100Hz. 50 km accumulation, 200 km observation separation
burst mode	2.60 (1.94)	0.5259	42/82, 15/60, 20/66, 16/70, 23/72, 8/52	See above
Continuous mode - 1	2.54 (1.86)	0.5416	No analysis performed	*50* Hz, 100 km accumulation, *200* km observation separation. The number of observations is the same as in burst mode
Continuous mode - 2	2.54 (1.86)	0.6176	50/91, 20/73, 28/77, 21/82, 31/84, 10/68	*50* Hz, 100 km accumulation, *100* km observation separation. The number of observations is twice the number of mode 1.
Continuous mode - 3	1.99 (1.57)	0.6313	No analysis	*50* Hz, *200* km accumulation, *200*

			performed	km observation separation. The number of observations is the same as in burst mode

The mentioned items are further discussed in the subsequent sections and applied to the burst and continuous modes of ADM-Aeolus. Section 6.1 discusses NWP model spatial representation that is closely related to the representativeness error as discussed in section 6.2. An important conclusion from section 6.1 is that although the spectral truncation of the ECMWF model has been relaxed substantially between the early 1990's and 2008, the horizontal spatial scales that are resolved by the model have increased to a lesser degree. This conclusion has an impact on the sampling of ADM as explained in section 6.3.

6.1 Spatial representation

Spatial representation of NWP models is an important concept for ADM since it determines to a substantial extent the Aeolus performance specification. The concept is discussed extensively by Lorenc et al (1992), and later on it is used by Stoffelen et al. (1994) in the ADM simulator. Stoffelen (1998) discusses the requirements for ADM in the context of the meteorological data assimilation problem and in particular explains the spatial scales involved. In the 1990's it was foreseen that the grids and spatial scales resolved by NWP models would increase substantially in the period until the launch of ADM. Based on all this, lidar burst mode operation was brought forward, providing independent wind profiles every 200 km. This section intends to clarify and summarise the issue of spatial representation that is important for the understanding of observation error contributions in data assimilation. An important aspect is in the spectral representation of spatial scales of observations and NWP model as discussed in the next section.

6.1.1 Spectral truncation

In meteorological analysis, the atmospheric state may be represented in spectral space. The spherical harmonics are truncated at a certain wave number. For instance, the current operational version of the ECMWF model is truncated at wave number T=799 (T799). This corresponds to a model grid box size $s_{box} = 2\pi R / 2T$ of about 25 km. Here, R is the earth's radius in km.

Lorenc et al. (1992) describes wind component variability by a wind component energy density spectrum following both experimental and theoretical evidence

$$E(k)dk = E_0 k^{-5/3} dk \qquad (1)$$

Lorenc et al. (1992) uses k for wave number (m^{-1}), which is related to spatial scale s through $k=1/s$, with s in meters. Lorenc (1992) suggests a climatological value E_0=5.36 10^{-4} (m^{3}s^{-2}). Integration from wave number k to infinity (0 km spatial scale) gives the variability of the wind component on scales less than s as

$$r^2 = \frac{3}{2} E_0 k^{-2/3} \qquad (2)$$

This result means that if the model spectrum is truncated at wave number k_{trunc} and the model is capable to capture all scales below k_{trunc} (i.e., above the corresponding spatial scale $s_{\text{trunc}}=1/k_{\text{trunc}}$), then the variability of the wind that can not be resolved by the model equals $3/2E_0k_{\text{trunc}}^{-2/3}$, i.e., the variability of a wind component in a box of size s_{trunc}. This variability is not resolved by the model. Theoretically, the smallest scale that can be resolved on a model grid is given by twice the grid length, i.e., ~50 km for the operational ECMWF model. If the model can fully resolve all scales above 50 km and none below 50 km then it follows from Eq. (2) with $k=k_{\text{grid}}=1/(50.10^3)$ that the remaining variability not resolved by the model equals 1.1 m^2s^{-2}.

However, NWP models do generally not contain these theoretically smallest scales. NWP models artificially dissipate kinetic energy in the high-wavenumber part of the motion spectrum. Implicit diffusion exists in the interpolation step of the advection scheme, but explicit numerical diffusion schemes in both horizontal and vertical are applied in addition (e.g., Bechtold et al., 2008). **Figure** 1 shows that a strict distinction between resolved and unresolved scales can not be made for the ECMWF model. The green line corresponds to the $k^{-5/3}$ spectrum and is positioned such that the area below the curve between $k = 10^{-5.53}$ (340 km) and $k = \infty$ (0 km) equals 3.95 m^2s^{-2}, in agreement with Lorenc (1992). ***The green curve is in the remainder denoted Lorenc-curve and is assumed representative for the real atmospheric variability on all scales below 500 km***.

The Lorenc curve has been validated with wind power spectra measured by Nastrom and Gage (1985). They found 2.03-2.22 (m^2/s^2) on average for the zonal wind variance for scales between 150 and 400 km. Integrating the Lorenc curve in Eq. (1) over these scales yields 2.11 (m^2/s^2). Nastrom and Gage (1985) found a k^{-3} spectrum for scales larger than 500 km (red curve) in the troposphere. This result could not be confirmed by Wikle et al. (1998). However, this tropical field campaign was limited to 10 meter winds over the ocean surface. Wikle et al. (1998) found a spectrum closer to k^{-2} at the larger scales, compatible with scatterometer winds, see also Figure 4. The slope of the model spectra in the linear part between $k = 10^{-6}$ (1000 km) and $k = 10^{-5.3}$ (200 km) for the three pressure levels in **Figure** 1 and other pressure levels (not shown) are summarized in Table 2.

Pressure (hPa)	1000	925	850	700	500	400	250
spectrum	-2.21	-2.34	-2.31	-2.46	-2.65	-2.82	-3.25

Table 2. Slope of ECMWF model wind variability spectra at various pressure levels.

The ECMWF model does partly resolve scales below 50 km although the energy (wind variability) at 250 and 500 hPa is more than an order smaller than for the Lorenc-curve. On the other hand, the model only partly resolves spatial scales above 50 km as well. These results are confirmed by the ECMWF observation statistics for radiosondes. The weight of the observation in the analysis may be retrieved from the ratio of the (o-b) and (o-a) statistics. The instrument error of a radiosonde is small (less than 1 ms^{-1}) implying that the observation weight is dominated by the representativeness error. For a typical 1.4-1.8 ratio between (o-b) and (o-a), depending on altitude, an assumed background error standard deviation of 2.5 ms^{-1} and 1 ms^{-1} instrument error it can be shown that the representativeness error is in the range of 2.6-3.8 ms^{-1}. These relatively large values are needed to avoid the introduction of small scale structures in the observations, but which the models are not yet capable to handle.

Above about 450 km (at), the 250 and 500 hPa model curves exceed the Lorenc-curve and closely follow the k^{-3} red curve spectrum as found by Nastrom and Gage (1985). The 1000 hPa more closely follows a k^{-2} spectrum, see Table 2, in agreement with scatterometer spectra, e.g., Wikle et al (1998).

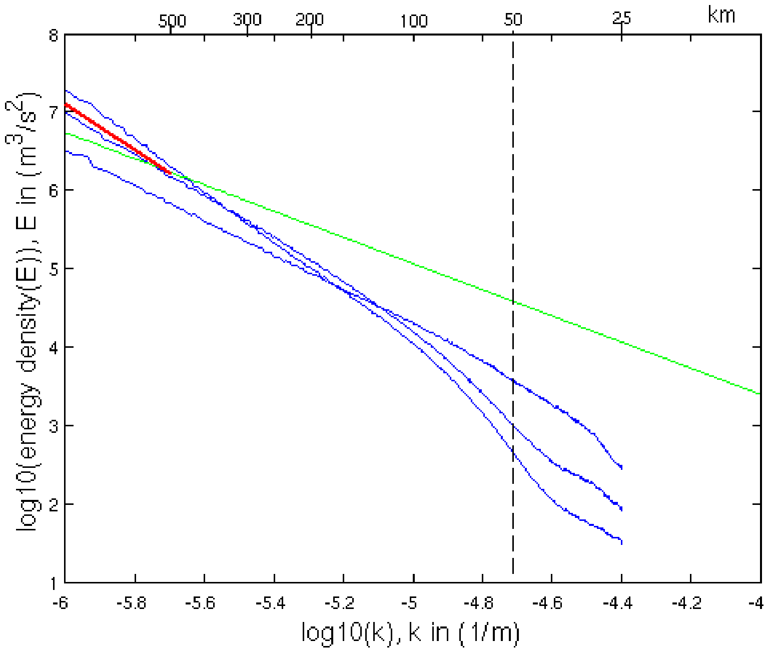

Figure 1. Wind component power spectra as a function of wavenumber. The blue lines correspond to the spectra over sea at 1000, 500, 250 hPa (top to bottom) for the 2008 operational ECMWF model (T799). The green line is the Lorenc-curve that is based on a $k^{-5/3}$ power spectrum. The red line starting at 500 km corresponds to a k^{-3} spectrum found by Nastrom and Gage (1985). The reference dashed line denotes the theoretically smallest scales (50 km) that can be resolved by the 2008 operational ECMWF model.

Integrating the spectra in **Figure** 1 from wavenumber k to infinite yields the total integrated wind component variability on all spatial scales below $s = 1/k$. The result is displayed in **Figure** 2 and shows that the total wind component variability in scales up to 250 km is about 1 ms^{-1}, i.e., in the order of the ADM instrument noise. Note that the value of the green Lorenc-curve at 340 km equals 3.95 m^2s^{-2}, in agreement with Lorenc (1992).

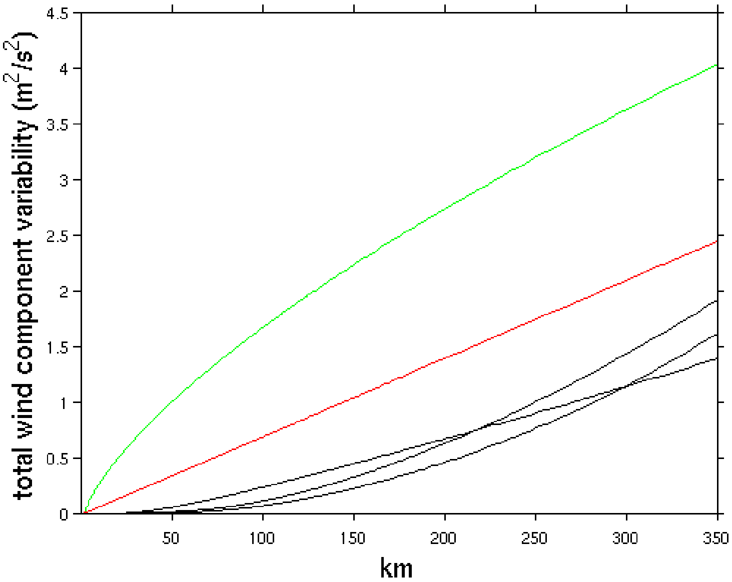

Figure 2. Total wind component variability as obtained from integrating the spectra in Figure 1. The black lines correspond to the black lines in Figure 1 at 250, 500 and 1000 hPa, the green line corresponds to the Lorenc-curve of Figure 1 and the red line corresponds to a k^{-2} wind variability spectrum and is used for verification (see text).

From Figure 1 and Figure 2 it is clear that there is no strict truncation value that discriminates between resolved and non-resolved model scales. Figure 2 shows that the Lorenc-curve grows faster at the smallest scales as compared to the ECMWF model. The turning point is defined as the scale value where the local steepness of the model curve equals that of the Lorenc curve, i.e. the model variability drops/grows relatively fast below/above the turning point as compared to the Lorenc curve. For simplicity we assume in the remainder that the model fully represents all scales above the turning point and no variance in the scales below. This enables the use of Eq. (2) to compute the wind variability on scales not resolved by the model. This turning point is in the remainder also denoted the size of "model resolution cell (MRC)", see section 3.

Table 3 shows the model resolution cell and corresponding truncation wave number for a number of pressure levels. Next, Eq. (2) is used to determine the unresolved wind variability on these scales. An interesting conclusion from **Table** 3 is that these numbers do not differ substantially from the numbers presented by Lorenc (1992). The size of the resolution cell is somewhat height dependent and maximum at 700 hPa and near the jet level.

The conclusion is that although the computational grids of global NWP models have increased substantially over the last 15 years, the horizontal scales that are resolved by these models have increased to a much lesser extent.

Pressure (hPa)	MRC size (km)	MRC equivalent wave number	unresolved wind variability (m^2s^{-2})	resolved wind variability (m^2s^{-2})
1000	340	59	3.94	1.3

925	232	86	3.06	1.0
850	253	79	3.24	1.1
700	312	64	3.72	1.2
500	263	76	3.30	1.0
400	229	87	3.03	1.0
250	312	64	3.72	1.2

Table 3. Model resolution cell (MRC) size and corresponding global NWP model wave number indicating the smallest spatial scale that is well resolved by the ECMWF model. The last two columns are the total unresolved wind variability and the resolved wind variability within the MRC according to the Lorenc spectrum and Figure 2 respectively.

The generation of the curves in Figure 1 and Figure 2 has been constrained to locations over sea to avoid contamination due to orography. Orographic forcing in the NWP model follows from the interaction of the large-scale flow with the terrain, and improved terrain description at high spectral truncation delivers improved local weather conditions over land. For instance, the top left panel in **Figure** 3 shows the model wind variability at 500 hPa on scales smaller than 60 km. The mountainous regions clearly show up, while other land parts appear relatively invariable. On the other hand, over ocean regions orographic interaction is absent and atmospheric motion is largely undetermined at these scales. In these poorly-observed regions, most Aeolus impact is expected by determining small-scale atmospheric motion. Therefore, to obtain a representative picture of expected ADM impact, we excluded land areas in the analysis above. Note also that in some mountainous areas 500 hPa will be below the earth's surface and which areas clearly should be avoided. At larger scales, the orographic features become less distinct, yet the total wind variability over sea is about half that of the global variability including land, see Table 4. For the January period, the wind variability is smallest in the tropical region, while the maximum variability is found over the Northern Hemisphere oceans, as expected.

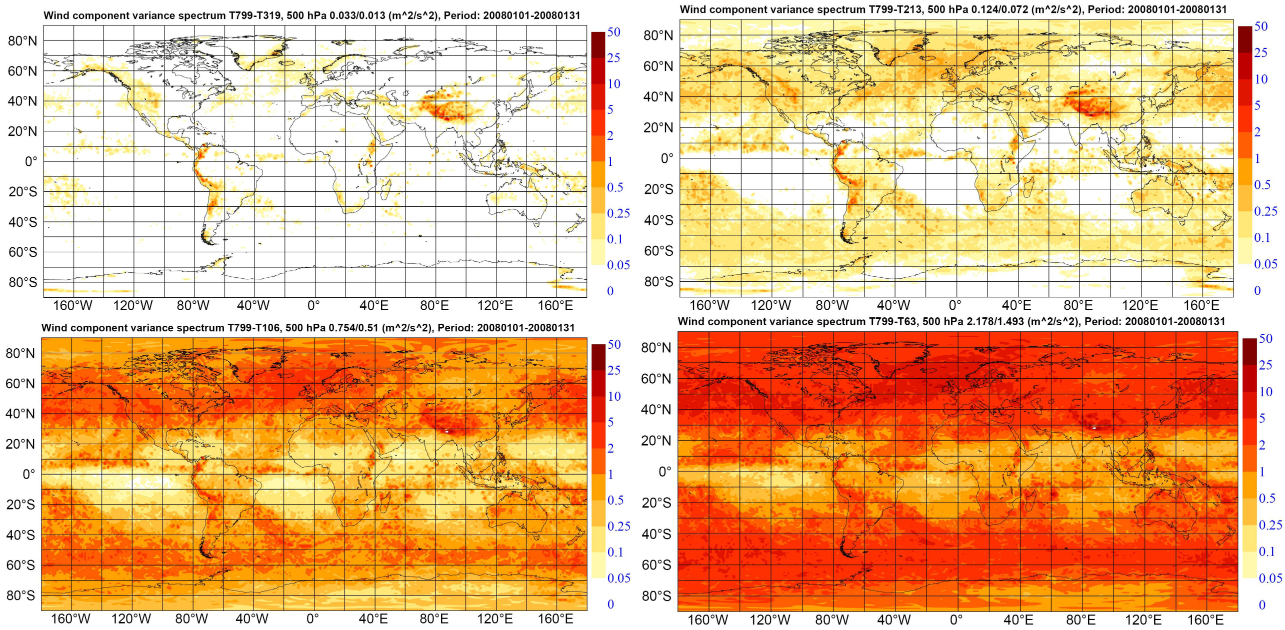

Figure 3. Geographic distribution of the variability of the zonal wind component for the 2008 operational ECMWF model (T799) at 500 hPa for spatial scales smaller than 60 km (top left), 100 km (top right), 200 km (bottom left) and 320 km (bottom right).

	wind component variability (m^2s^{-2}) on scales smaller than				
Pressure (hPa)	60 km	100 km	200 km	320 km	475 km
1000	0.130/0.043	0.294/0.128	0.859/0.488	1.692/1.084	2.796/1.921
500	0.033/0.013	0.124/0.072	0.745/0.510	2.178/1.493	4.506/3.084
250	0.013/0.006	0.071/0.044	0.538/0.374	1.749/1.263	4.310/3.155

Table 4. ECMWF wind component variability (global/sea) for various spatial scales.

To experimentally verify the results above, Figure 4 shows a spectral analysis of the ECMWF model compared with collocated scatterometer winds at 25 kilometer resolution. The model is well able to represent atmospheric features of 1000 km scale, i.e., the wind variance of the model is compatible with the measured wind variability. However at 100 km scales, the scatterometer product still contains substantial variance, but the variance in the model is 4 times less. From the figure it follows that scatterometer winds may be modelled with a k^{-2} spectrum. The red curve in Figure 2 shows a k^{-2} spectrum. Its position in Figure 2 is determined such that the model wind variability at mean sea level (bottom black 1000 hPa curve) is 25% less as compared to the red curve for 1000 km scales, in agreement with Figure 4. Then, at 100 km scales the wind variability represented by the model and k^{-2} curve are 0.23 and 0.68 m^2/s^2 respectively, i.e., a factor of 3. This is in close correspondence to the factor of 4 of Figure 4, considering that the wind variability is not uniform over the globe, see **Figure** 3.

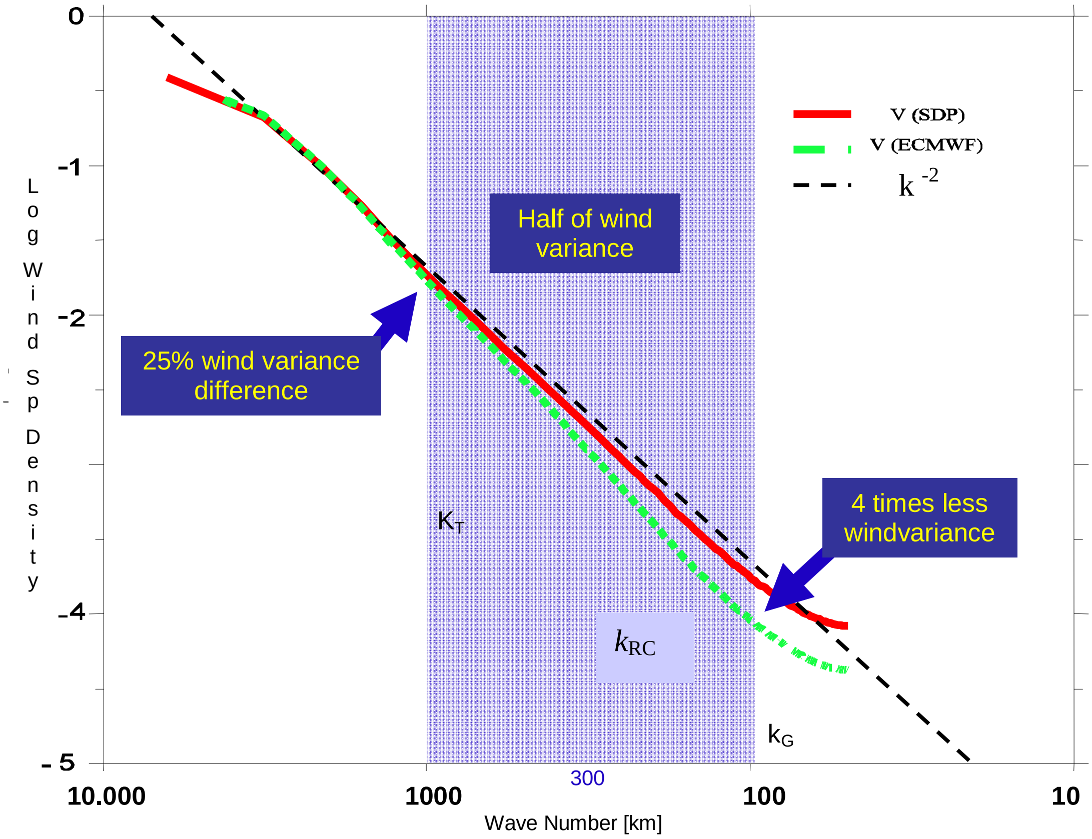

Figure 4. Illustration of representativeness error model. The curves represent a spectral shape of k^{-2}, an estimate of the KNMI SeaWinds 25-km wind product, and the collocated ECMWF 10-m wind spectral content in log-log scale (Vogelzang, 2006). With respect to the two other curves, the NWP spectral curve drops faster in variance over the blue shaded spectral range from corresponding wavelengths of 1000 km to 100 km.

The spectral gap of the NWP model centered around k_{RC}. will in general extend from k_T., the lowest wave number where truncation is present, to k_G., the highest wave number with any variance, usually corresponding to a few times the grid box size.

6.2 Representativeness error

The small scale variability which is sampled by some individual observations, but which the model is incapable of representing, is referred to as the representativeness error. To avoid ingesting small-scale structures in the model state, the impact (weight) of the observation in the analysis is reduced by increasing the observation error with the representativeness error, i.e., observation error variance = measurement error variance + representativeness error variance.

Because NWP models do generally not contain the smallest possible scales, the concept of a grid box as a proxy for a resolution cell does not work well. NWP analyses are performed on the "resolved" NWP model scales, called here "resolution cell". In each resolution cell, the best mean meteorological state is sought for. No representativeness error needs to be added for an instrument that samples the resolution cell in the way that the NWP model represents it. However, observations, like those from radiosondes and ADM, do generally not provide volume-mean quantities. As such spatial representation errors exist. For a point measurement the spatial representativeness error in a wind component is related to the wind variability within the resolution cell. For a radiosonde this was estimated in the early 1990's to be 2-3 m/s, depending on height (Stoffelen et al, 1994). From **Table** 3 it follows that these values may have slightly decreased to 1.7 - 2 m/s for the 2008 operational ECMWF model. If the resolution cell size decreases, the spatial representativeness error of the point measurement should decrease, since less unresolved wind variability is captured by the cell. This can be verified by looking at differences between the NWP model state and such point observations (e.g., o-b statistics), although this is not trivial since o-b statistics are a mixture of three errors: the measurement error (part of o), representativeness error (part of o) and model background error (b). Note however that both the background and the observation representativeness errors change when NWP model resolution (variability) changes due to the error model defined below. From section 6.1, nowadays a horizontal resolution cell of ~250-300 km may be taken as representative for global NWP models.

6.2.1 ADM-Aeolus representativeness error

The ADM DWL is side-looking and describes a linear track on the Earth's surface. We distinguish the along-track and across-track LOS wind component variability, where across-track is taken in the direction of the LOS. We assume that the along- and across-track variabilities are independent, but of equal size in amplitude, i.e., $0.5r^2$.

In the across-track direction we only obtain one measurement location, and as such the wind variability within a resolution cell in this direction is not resolved. The LOS wind component representativeness error thus amounts to $r^2_{\text{across}}=0.5r^2$.

In the along-track direction we may obtain up to N accumulations over the observation sampling length. If the N samples are uniformly distributed over the observation sampling length then the representativeness error variance over this distance is reduced by a factor N. The remaining along-track wind variance in the resolution cell that is not sampled equals $0.5r^2$ minus the sampled variance. The along-track error variance contribution thus equals

$$r^2_{\text{along}} = 0.5\left[1-\left(\frac{\text{sample length}}{\text{resolution cell}}\right)^{2/3}\right]r^2 + 0.5\left(\frac{\text{sample length}}{\text{resolution cell}}\right)^{2/3}\frac{1}{N}r^2 \qquad (3)$$

For instance, in burst mode the observation sampling length is 50 km, N=14 and by taking a resolution of about 250 km (see section 2), Eq. (3) yields $0.33r^2 + (0.17/14)r^2$, or a reduction of the along-track representativeness error of about 36% as compared to a point measurement.

In addition to these inevitable spatial representativeness errors, we unfortunately also have to deal with measurement errors, i.e., m^2. For ADM, the measurement error variance is proportional to the photon count on the detector. m^2 depends on the product of Pulse Repetition Frequency, PRF, and laser shot energy and this product should be optimised. Changing either energy or PRF of the laser by the same relative amount thus has a very similar effect. For N measurements in one observation, the error is reduced to m^2/N. This error is further denoted instrument error. The ADM requirement for the instrument (random) error of a HLOS wind component (excluding representativeness error) is 1 ms^{-1} in the lowest 2 kilometre of the atmosphere and 2 ms^{-1} between 2 and 16 kilometre. The requirement for HLOS winds above 16 km follows from the ones below 16 km.

So, let us define the total error variance as

$$o^2 = r^2_{across} + r^2_{along} + m^2/N \qquad (4)$$

Consider ADM in burst mode with $N = 14$. For a 50 km sample length and a 250 km resolution cell the total observation error according to Eqs. (3,4) equals $o^2 = (0.5 + 0.33 + 0.17/14)\, r^2 + m^2/14 = 0.84r^2 + m^2/14$. In continuous mode, the PRF is halved. Averaging over 100 km then yields the same instrument error as in burst mode. However, increasing the sample length reduces the along track representativeness error according to Eq. (3). The total error variance then equals $o^2 = (0.5 + 0.23 + 0.27/14)\, r^2 + m^2/14 = 0.75r^2 + m^2/14$. Further increasing the sample length to 200 km reduces the variance of the measurement error as compared to burst mode by a factor of 2. In addition the representativeness error is further reduced, yielding a total error variance of $o^2 = (0.5 + 0.07 + 0.43/14)\, r^2 + (1/2)m^2/14 = 0.60r^2 + (1/2)m^2/14$.

Table 5 summarizes the expected standard deviation of errors at 500 hPa as obtained from various ADM modes. Constant values for ($m^2/14$) of 1 and 4 m^2s^{-2} are used for the instrument error variance for the lowest 2 km (PBL) and between 2 and 16 kilometre (free-troposphere) respectively, i.e., the mission requirement. However, for 200 km accumulation in continuous mode the variance of the instrument is half these values because of a doubling of the energy into the atmosphere. The second row is the reference burst mode as presented in the Granada report. The expected quality for ADM in burst mode from this study (third row) is close to what has been presented in Granada. Increasing the sample length reduces the representativeness error and thus the total observation error when the instrument error is the same (continuous mode 100 km sample length) or reduced (continuous mode > 100 km sample length). Increasing the sample length is at the expense of an increased correlation between adjacent observations. On the other hand and in contrast to burst mode more than one observation may be obtained over a 200 km interval in continuous mode. The implications are further discussed in the next section.

500 hPa	representativeness error (ms^{-1})	σ_0 of ADM (ms^{-1})	sampled variance (m^2s^{-2})	NWP resolved (% of sampled)
50 km (Granada)	1.7 (Granada)	2.62 (1.97)	0.53	1
50 km burst (2008)	1.66 $(0.84\, r^2)^{1/2}$	2.60 (1.94)	0.53	1
100 km continuous	1.57 $(0.75\, r^2)^{1/2}$	2.54 (1.86)	0.83	4
200 km continuous	1.41 $(0.60\, r^2)^{1/2}$	1.99 (1.57)	1.37	21

Table 5. ADM HLOS wind error standard deviation and resolved variance at 500 hPa for various modes. The third column shows the standard deviation of the total error (including representativeness and instrument errors) in the free-troposphere (and PBL). The value for r^2 is obtained from Table 3 and equals 3.3 m^2s^{-2} at 500 hPa. Column 4 shows the estimated along-track sampled true variance (by the Lorenc curve). The values are obtained from Figure 2 by taking 0.5 times the value of the green curve to the corresponding accumulation length. The factor 0.5 is applied because only the along-track variability is (partly) resolved. Column 5 is the ECMWF variance in the sample as a percentage of this estimated true variance.

As the sampling length increases, it is favourable that we integrate the unresolved scales. However, at long integration lengths, we may also integrate NWP model state resolved variance. The resolved variance may be obtained from Figure 2. When the resolved variance is substantial with respect to the observation error, we will need to represent the observation by more than one grid point and sample integration becomes unfavourable. **Figure** 2 and the table above indicate, however, that the unresolved variance clearly dominates the resolved variance on all scales below 100 km. On the other hand, for 200-km integration, the along-track sampled true variance is 1.37 m^2s^{-2} of which 21% is resolved variance by ECMWF.

Note that the resolved ECMWF variance could be either error or true variance. In the former case the variance is part of the specified background error. In the latter case it is part of the model state. In both cases, integration of resolved variance by observations is undesirable.

6.3 DWL ANALYSIS impact

In this section quantification of the DWL impact in the analysis, taking into account representativeness errors and associated observation error correlation in case of continuous mode, are discussed. The burst mode is optimised to provide independent good-quality observations to the data assimilation system. Independency is warranted by observing every 200 km, such that neighbouring observations do not correct the same resolution cell of the NWP model. Sticking to the 50-km accumulations, we would in principle obtain four observations within a 200-km stretch in continuous mode. These observations are, however, no longer providing independent information to the NWP model analysis, since the resolution cells overlap. Since the resolution cells corresponding to the observations overlap, their total observation errors computed according to eq.3 would be correlated due to the overlapping representativeness error contributions. In line with this, it has up to now generally proven difficult to exploit such “dependent” high-resolution observations in data assimilation systems.

The theoretical mean impact of observations on the analysis is obtained from the analysis equation:

$$A = B - \mathbf{BH}^T \left[\mathbf{HBH}^T + R\right]^{-1} \mathbf{HB} \qquad (5)$$

with **A** the analysis error covariance matrix, **B** the background error covariance matrix, **H** the observation operator that maps observations to the model grid space and **R** the observation error covariance matrix. **B** and **R** are positive definite matrices and we assume unbiased observations. The second term on the right hand side of Eq. (5) is positive definite meaning that all observations add to the analysis, i.e. the analysis error covariance is always smaller than the background error covariance matrix or (**B-A)** is positive definite. The observation impact may be quantified through the reduction of the model state variance as compared to the background model state:

$$\text{observation impact} = \frac{\text{trace}(B) - \text{trace}(A)}{\text{trace}(B)} \qquad (6)$$

with trace denoting the sum of the matrix diagonal elements. The observation impact is a value between 0 and 1, 0 denoting no impact and 1 denoting maximum impact corresponding to a zero analysis error covariance or a perfect estimate of the model atmosphere.

For the B matrix we may assume a simplified Gaussian-shape error correlation model that is widely used in literature, see also e.g. MERCI (2002):

$$\rho_{\mathbf{B}}(i,j) = e^{\frac{(x_i - x_j)^2}{2L_B^2}}, \quad B(i,j) = \sigma_b^2 \rho_{\mathbf{B}}(i,j) \tag{7}$$

with σ_b the background error standard deviation that is assumed constant, (x_i-x_j) the distance (km) between two grid point locations and L_B the correlation length scale.

6.3.1 Observation error correlation

The information content of closely separated observations is generally not independent since they sample the same representativeness error and the assumption of a diagonal observation error covariance matrix **R**, as is usually done in operational NWP, is not valid. A similar Gaussian-shape model as for the background error covariance can be adopted for the observation error covariance matrix due to the spatial correlation of the representativeness error:

$$R_{rep}(i,j) = \sigma_r^2 \rho_{\mathbf{R}}(i,j) \quad \text{with} \quad \rho_{\mathbf{R}} = \mathbf{H}\rho_{\mathbf{B}}\mathbf{H}^{\mathrm{T}}, \tag{8}$$

σ_r the observation error standard deviation, $\rho_{\mathbf{R}}(i,j)$ the error correlation between two adjacent observations. Defining the error correlation above as a function of the background error correlation implies that when the model resolution increases (the model is better capable of resolving small scale structures), L_B decreases accordingly which reduces the correlation between observations.

In addition to the representativeness there is the measurmement (instrument) error that we assume to be Gaussian distributed and independent for different observations. The corresponding measurement error covariance matrix, $\mathbf{R}_{\mathrm{m}}$, may thus be modelled as a diagonal matrix with values equal to the measurement error variance, σ_{m}^2. The observation error covariance matrix is then obtained from

$$R = R_m + R_{rep} \quad \sigma_m^2 I + \sigma_r^2 \rho_{\mathbf{R}} \tag{9}$$

with **I** the identity matrix. .

6.3.2 Numerical example

We consider a 2-dimensional square model area of size 2,500 km in the mid-troposphere at 500 hPa. The model grid size is 25 km, in agreement with the operational ECMWF model. The model area thus contains 100x100=10,000 grid points. We set σ_b=2.5 ms^{-1} and L_B equal to the resolution cell size i.e. 250 km as derived in sections 2 and 3, see Figure 5. The **H** and **R** matrices depend on the sampling strategy for ADM and are discussed in the following subsections.

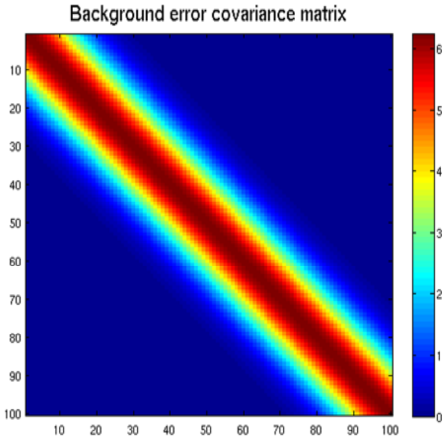

Figure 5. Background error covariance matrix, see Eq. (7) used in the numerical examples.

6.3.3 ADM burst mode

In burst mode, the atmosphere is sampled over 50 km at 100 Hz pulse repetition frequency (PRF). Next the laser is not used over 150 km before laser returns are processed again, etc. The observation distance is 200 km, yielding 12 observations in the model area, see the panel in Figure 6. The laser energy per pulse is 0.13 J. We assume an accumulation interval of 3.5 km, i.e., a wind observation is obtained from N=14 measurements.

Note that the observation sampling length of 50 km exceeds the model grid size of 25 km. Although, the ECMWF model does not resolve any substantial 50-km variance, we chose to use two neighbouring elements in the **H** matrix for the innovation, y-$\mathbf{H}x_b$, of observation y.

The along track representativeness error is obtained from Eq. (3) with a 50 km sample length and an about 250 km resolution cell, see **Table** 3. The wind variability for this cell equals r^2 = 3.3 m^2s^{-2} (mid-troposphere case, see Table 4). These values are identical to those used in section 3.1, yielding a total representativeness error variance of 0.84r^2 = 2.77 m^2s^{-2} and a total observation error of 6.77 m^2s^{-2} in the troposphere, from Eq. (4) with $m^2/14$ = 4 m^2s^{-2}, i.e., the ADM requirement. The resulting observation error covariance matrix, according to Eq. (9) is displayed in the middle panel of Figure 6. Substituting the B, H and R matrix in Eq. (5) yields the analysis error covariance in the right panel of figure 6 and an observation impact of 0.5259.

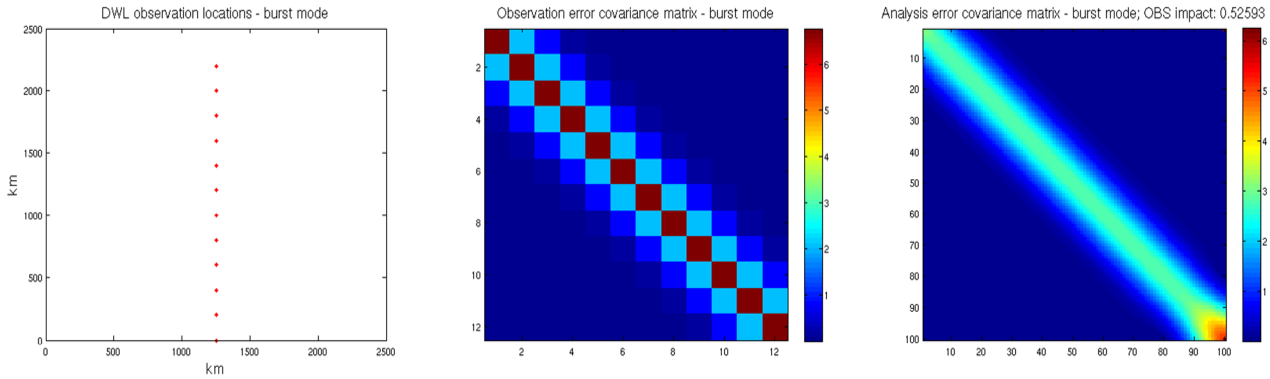

Figure 6. Burst mode. DWL observation sampling (left panel) with 200 km spacing, observation error covariance matrix R, see Eq. (9), (middle panel) and analysis error covariance matrix (right panel). The diagonal elements of matrix R equal 6.76, i.e., the squared value of the ADM error in Table 5. The observation impact is 0.5259

6.3.4 Continuous mode

In continuous mode we take a PRF of 50 Hz. The laser energy per shot is taken the same as in burst mode, i.e., 0.13 J. This means that double the amount of energy is emitted into the atmosphere in continuous mode as compared to burst mode over 200 km. The accumulation length is taken the same as in burst mode, i.e., 3.5 km, but 7 km length would yield the same results. The number of shots within one accumulation (measurement) is now 25 instead of 50 for burst mode. The variance of the measurement error over a 50 km observation length is thus doubled as compared to burst mode and with a total representativeness error variance of $0.84r^2 = 2.77\ m^2s^{-2}$, yielding a total observation error of $10.77\ m^2s^{-2}$, from Eq. (4), in the troposphere with $m^2/14 = 8\ m^2s^{-2}$.

However, the continuous mode offers a number of potential options to accumulate the measurements to observations. Some of them are summarized in **Table** 6. Figures 7-9 show the observation spacing and **R** and **A** matrices.

Observation length	Observation spacing (km)	Number of	Obs. Impact
50	200	12	0.4431
100	200	12	0.5416
200	200	12	0.6313
50	100	25	0.5417
100	100	25	0.6176
50	50	50	0.6016

Table 6. Continuous mode scenarios and observation impact. For reference, the observation impact for burst mode is 0.5259.

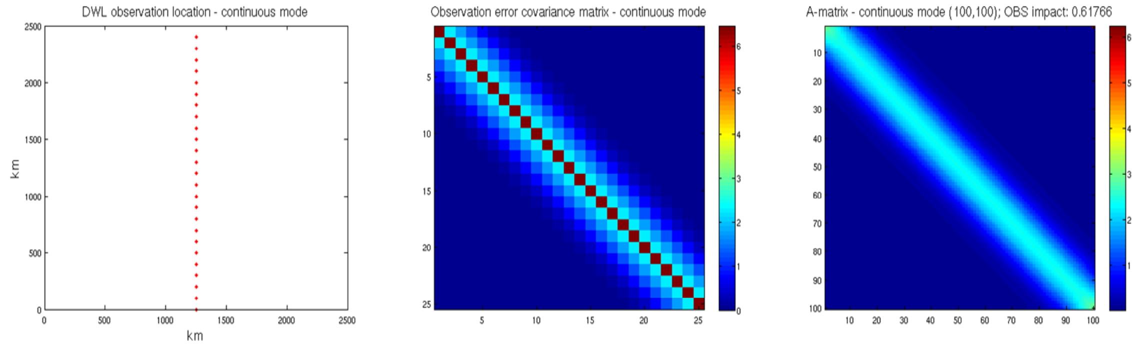

Figure 7. Continuous mode, 100 km accumulation, 100 km observation spacing. The observation impact is 0.6176.

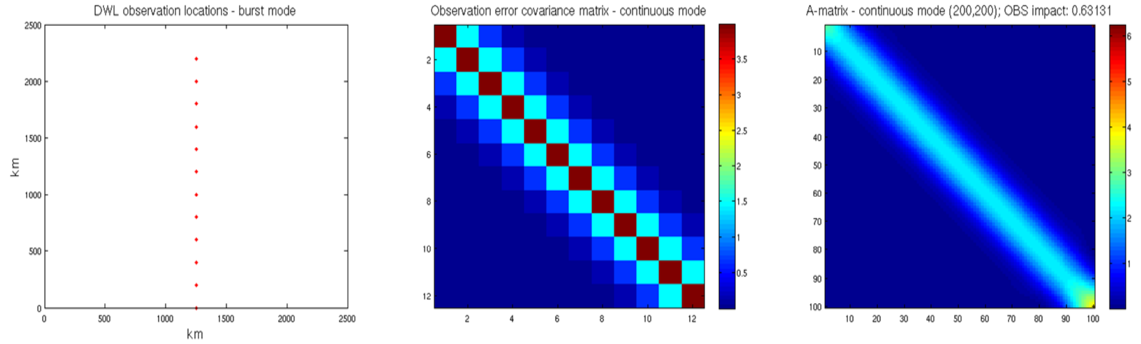

Figure 8. Continuous mode, 200 kmaccumulation, 200 km observation spacing. The observation impact is 0.6313.

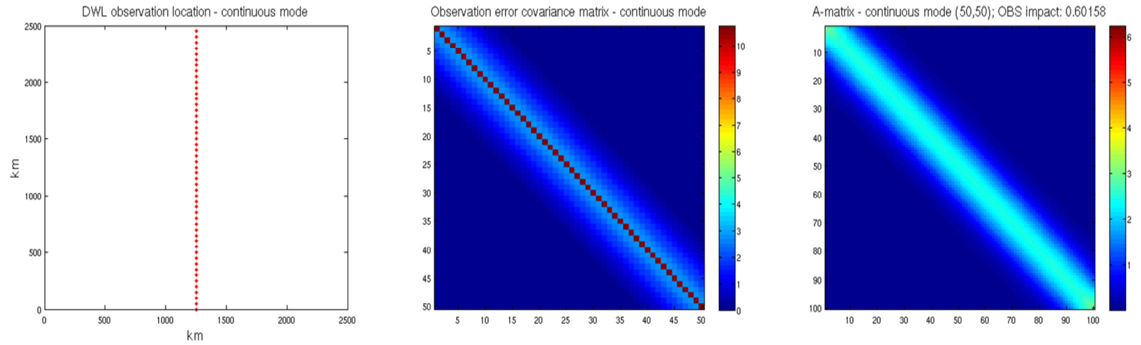

Figure 9. Continuous mode, 50 km accumulation, 50 km observation spacing. The observation impact is 0.6016.

The conclusion from the results above is that in an idealistic setting without clouds, the impact of DWL observations in continuous mode is larger than in burst mode. This is not surprising because the energy emitted into the atmosphere has doubled in continuous mode. ***However, for the continuous mode configuration of 100 km accumulation and 100 km observation spacing the additional impact is about 17% as compared to burst mode.*** This relatively low additional impact, considering a doubling of the energy over a 200 km track, is explained by the correlation of adjacent observations separated by 100 km or less. In other words the observations are partly redundant. The correlation is essentially due to observations in spatially overlapping resolution cells and it is therefore expected to be generally applicable in both clear and cloudy conditions.

Another conclusion from the results above is that additional observation impact is achieved by reducing the representativeness error, leaving the measurement error constant, i.e., the measurement error for burst mode and continuous mode at 100 km observation length is the same while the representativeness error of the latter is smaller. For a 200 km observation length both the representativeness and measurement error are smaller than for burst mode. Note however that over a 200-km cell the ECMWF NWP model resolves appreciable wind variability, which has been disregarded here. Also, increasing the number of observations (50 km observation length in continuous mode) does not automatically increase the observation impact, since increased measurement error and increased observation correlation are present; see Figure 9.

From Table 6 it also follows that the observation impact does not change dramatically for the different continuous scenarios and stays within 20% of burst mode. The situation would have been much different in case of a model that is capable to resolve 50 km spatial scales. This reduces the representativeness error substantially since the wind variance on scales smaller than 50 km is only 1.1 m^2s^{-2}, see the green curve in Figure 2. The background error covariance matrix with 50 km correlation length is displayed in Figure 10. Observation errors are now uncorrelated in burst mode, see centre panel of Figure 11 and the amplitude has reduced because of a substantially reduced representativeness error. However, the observation impact is much less, because it is much more localized to the observation locations, see the right panel in Figure 11.

Continuous mode almost enables doubling the observation density as compared to burst mode, see the left panel of Figure 12. The observation length of 50 km, the same as in burst mode, leads to almost a doubling of the measurement error variance, see centre panel of **Figure** 12. Despite the increased observation error as compared to burst mode, the observation impact increases substantially by almost 45% from 0.2412 to 0.3500. This is because of the observation doubling and despite the doubling, the observations are assumed uncorrelated here.

Even further doubling the observation density was not effective for a 250 km representativeness error correlation length, but is effective at 50 km scales, see Figure 13. Observations are still only very weakly correlated and the large observation density enables a uniform analysis improvement along the track. The observation impact has increased by 110% from 0.2412 to 0.5054 as compared to burst despite a doubling of the observation error variance of individual observations. Note that the NWP-resolved variance on scales < 50 km is not accounted for here, leading to somewhat optimistic impact.

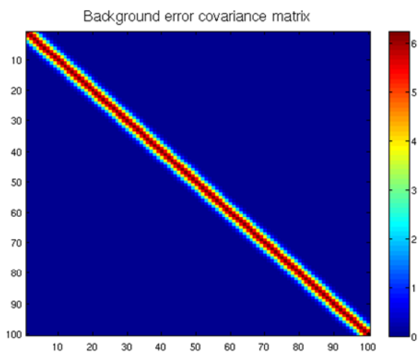

Figure 10. Background error covariance matrix. Same as Figure 5 but now with a 50 km correlation length.

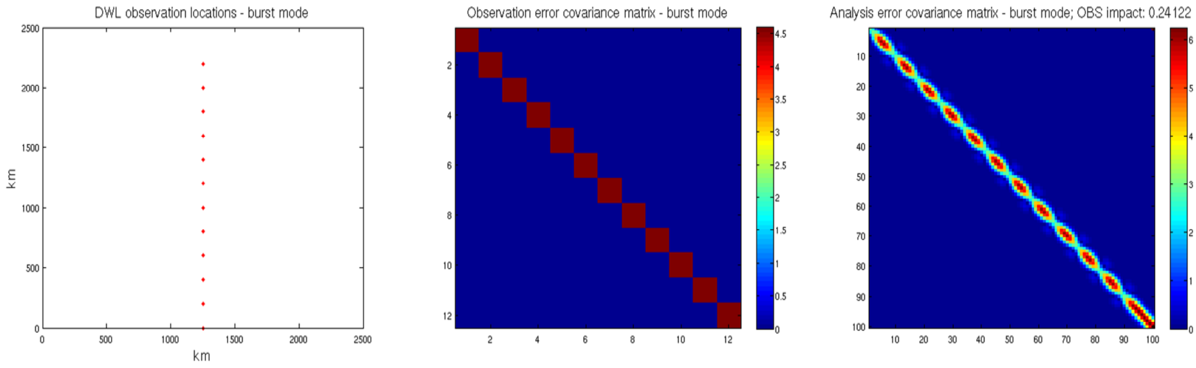

Figure 11. Burst mode. Same as figure 6 but for a model that resolves structures at 50 km spatial scales. The observation impact is 0.2412.

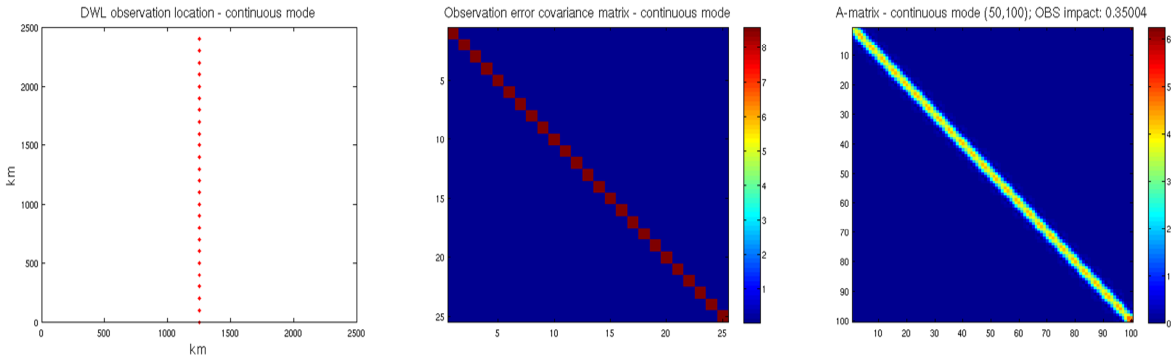

Figure 12. Continuous mode. Same as Figure 11 but with 100 km spacing. The observation impact is 0.3500.

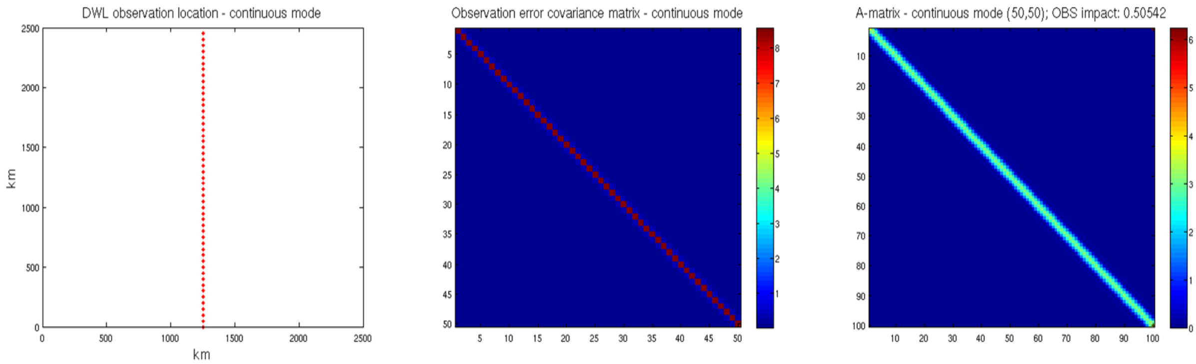

Figure 13. Continuous mode. Same as Figure 11 but with 50 km spacing. The observation impact is 0.5054.

The main problem in data assimilation is in an imperfect specification of B. This leads to a suboptimal use of observations, in particular when correlated. This has not been simulated here.

6.4 CLOUDS and AEROSOL

For a cloud-free atmosphere good quality wind profiles are obtained by ADM in burst mode throughout the atmosphere, i.e., above the PBL from the Rayleigh channel and in the PBL from the Mie channel.

The same is true for the continuous mode when sampling over 100 km. Then the instrument error is the same as in burst mode, but the representativeness error is smaller as discussed in the previous section. In addition, in continuous mode potentially 2 observations are obtained over a 200 km interval as compared to a single one in burst mode. Assimilating both 100 km observations increases the correlation of observations, but is still favourable compared to neglecting one of the two observations, see **Table** 6. Another option is to select at each altitude the best of the 2 observations. This reduces the correlation of observations while the observation quality will generally be larger than in burst mode. This mode is in the remainder denoted SS100, with SS the abbreviation for steady-state. The measurement errors for burst and SS100 are identical in a cloud-free and constant aerosol atmosphere. The representativeness error is smaller for SS100, but the observation correlation is smaller for burst mode, because the separation between adjacent observations is at least 200 km.

In scenes with clouds and variable aerosol density, the situation is less obvious. For instance, parts of the atmosphere may be (partly) blocked by overlying clouds, thus reducing the quality of Rayleigh retrieved winds. In addition, winds may be retrieved from the Mie channel in cloudy areas, ignoring height assignment issues. We used one month (January 2007) of cloud and aerosol data retrieved from CALIPSO, Stoffelen et al. (2008), to assess the impact of clouds and aerosols on the quality, representativeness error and observation correlation for the burst and SS100 mode. The vertical sampling scenario is the same for both modes and assumes maximum overlap between Mie and Rayleigh bins as depicted below.

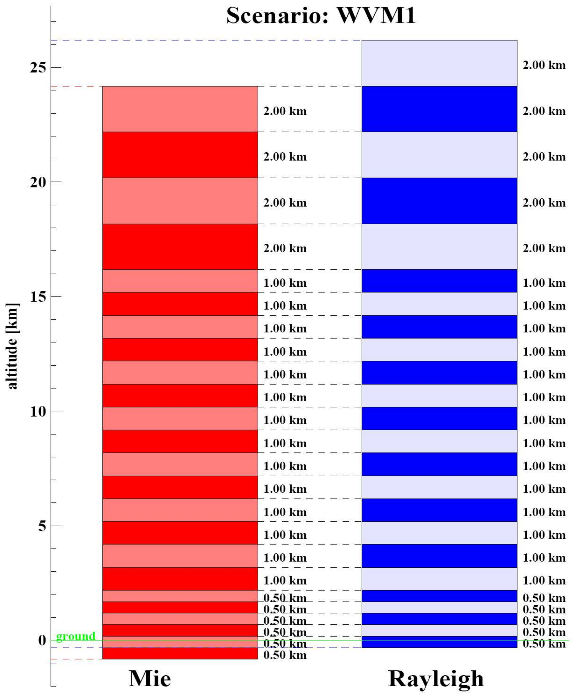

Figure 14. Vertical sampling scenarios for the Mie (left) and Rayleigh (right) channels.

6.4.1 CLOUDS and AEROSOL - observation quality

For the Rayleigh channel it is assumed that all vertical bins in burst and SS100 mode provide a good quality wind, meeting the ADM requirements, in a cloud-free atmosphere. This is true above the PBL, but generally not in the PBL, because of the increased resolution (smaller bins) in the lowest 2 km. The quality of Rayleigh winds is reduced in the presence of clouds and aerosols. The quality reduction is directly related to the signal loss due to particle extinction and absorption (2-way transmission). Three classes are defined: the 2-way transmission is larger than 0.5, between 0.25 and 0.5 and less than 0.25. For the first class the quality of Rayleigh winds will still be good (maximum increase of error standard deviation of sqrt(2)), for the second class the quality is moderate and for the third class the quality is bad (more than doubling of the wind error variance).

For the Mie channel, good quality winds are found only in the PBL in a cloud-free atmosphere with no substantial aerosol above the PBL. Good quality winds may be obtained from the Mie channel if the mean attenuated backscatter is at least 10^{-6} $m^{-1}sr^{-1}$ over the observation length. This threshold value is typically found in the PBL at 355nm (Marseille and Stoffelen, 2003). Also for the Mie channel three classes are defined: the attenuated backscatter is larger than 0.5 times the threshold value, between 0.25 and 0.5 times this value or less than 0.25 the threshold value. Again the first, second and third class correspond to good, moderate and bad Mie winds respectively.

Figures 15 to 20 show the fractions of the Rayleigh and Mie winds in the three classes. The plots cover 1 month of CALIPSO data. In continuous mode 2 observations are obtained over a 200 km distance. The default is that the wind from the first observation is selected. Only, if the corresponding wind in the second observation is in a higher class than the wind from the second observation is selected. This procedure maximizes the distance between two observations at a certain level and thus minimizes observation correlation. As a result, the distance between 2 observations is 200 km in the UTLS above clouds. When going down into the atmosphere, the role of clouds becomes more prominent. In the lower troposphere/PBL about 10% of the observations are separated by 100 km, 70% by 200 km, 10% by 300 km and 10% by 400 km or more. Larger than 200 km separation may occur if no observations are present in the neighbouring profiles. By using smaller shifts than 100 km and by selecting the best of a set of overlapping observations (e.g., each shifted by the measurement scale of 7 km), a more refined distribution of quality gain and horizontal observation separation may be obtained.

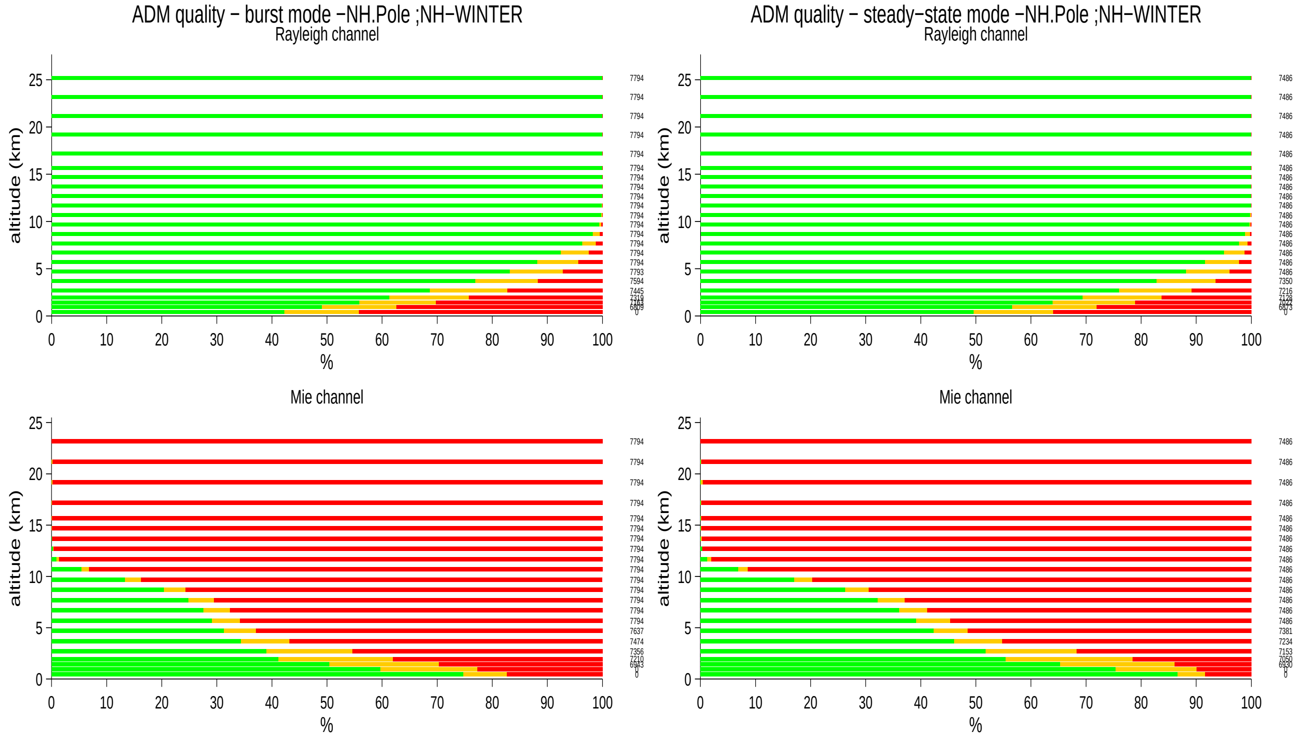

Figure 15. ADM wind quality for the North Pole, left for burst mode, right for continuous 100 km accumulation (SS100), for Rayleigh (top row) and Mie (bottom row). Green/orange/red correspond to class 1,2,3, see text.

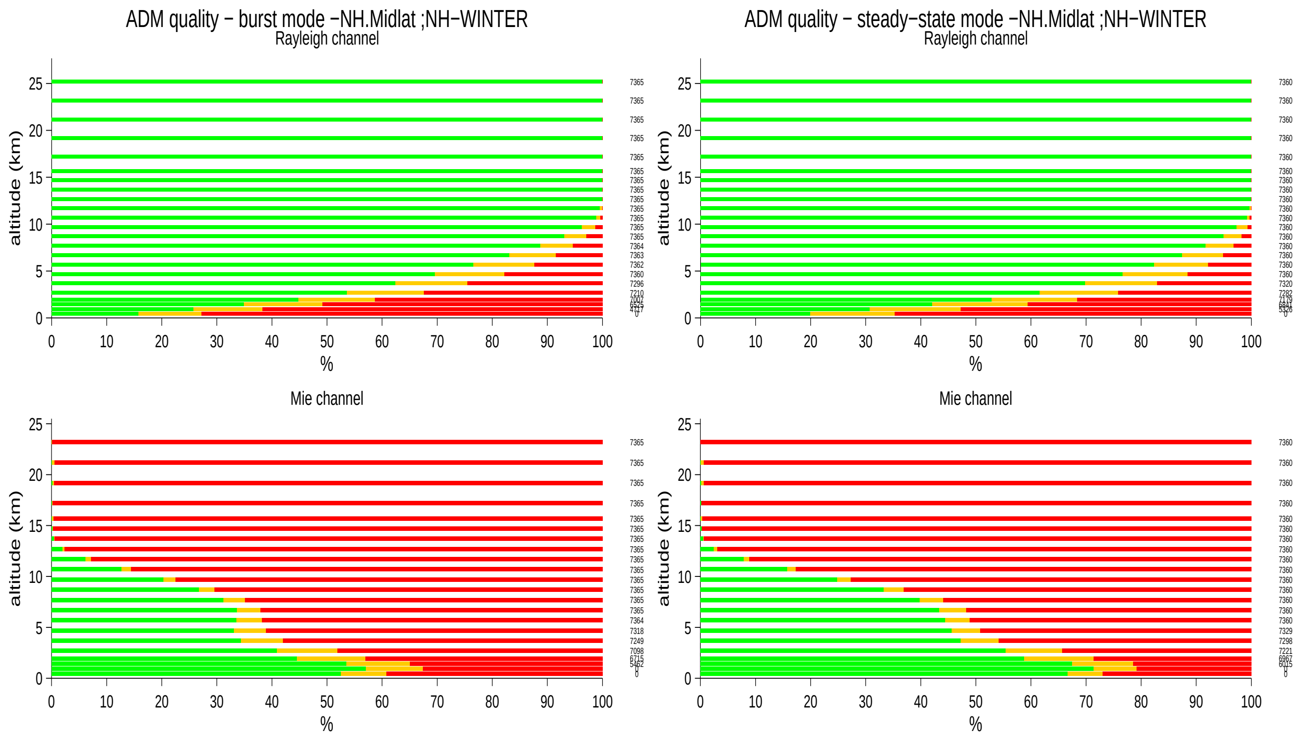

Figure 16. Same as Figure 15, but now for the NH mid-latitude region.

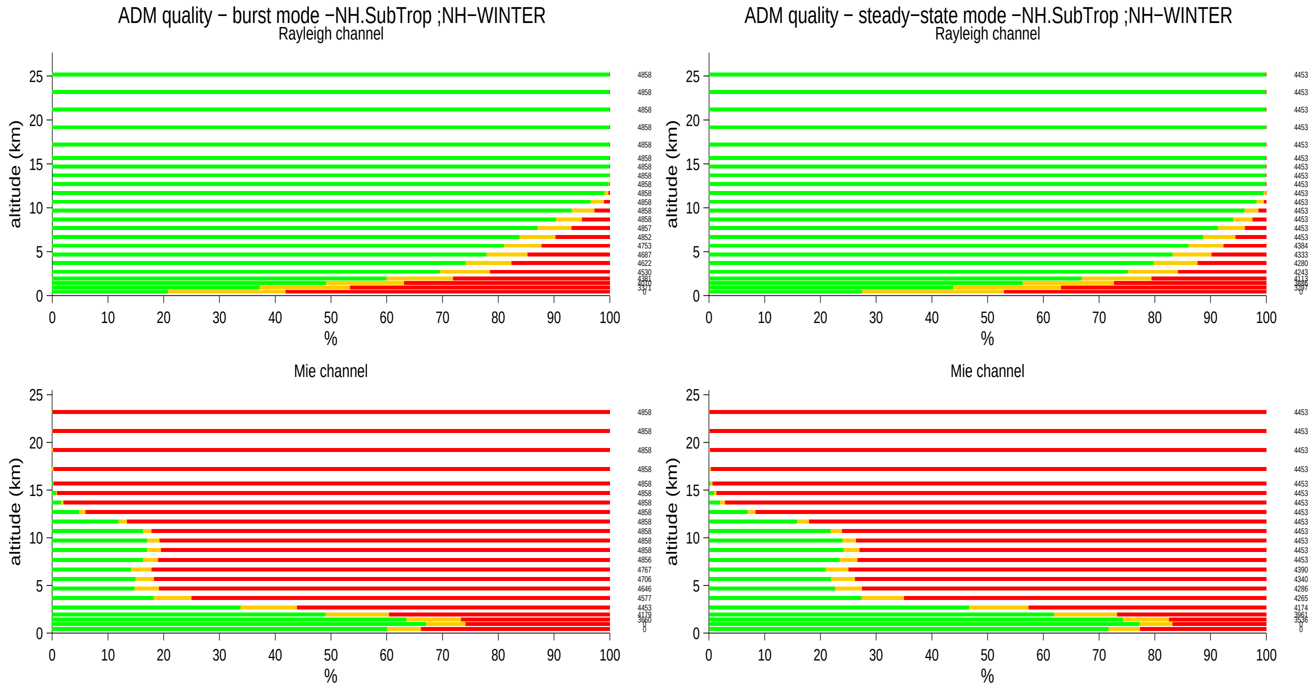

Figure 17. Same as Figure 15, but now for the NH sub-tropical region.

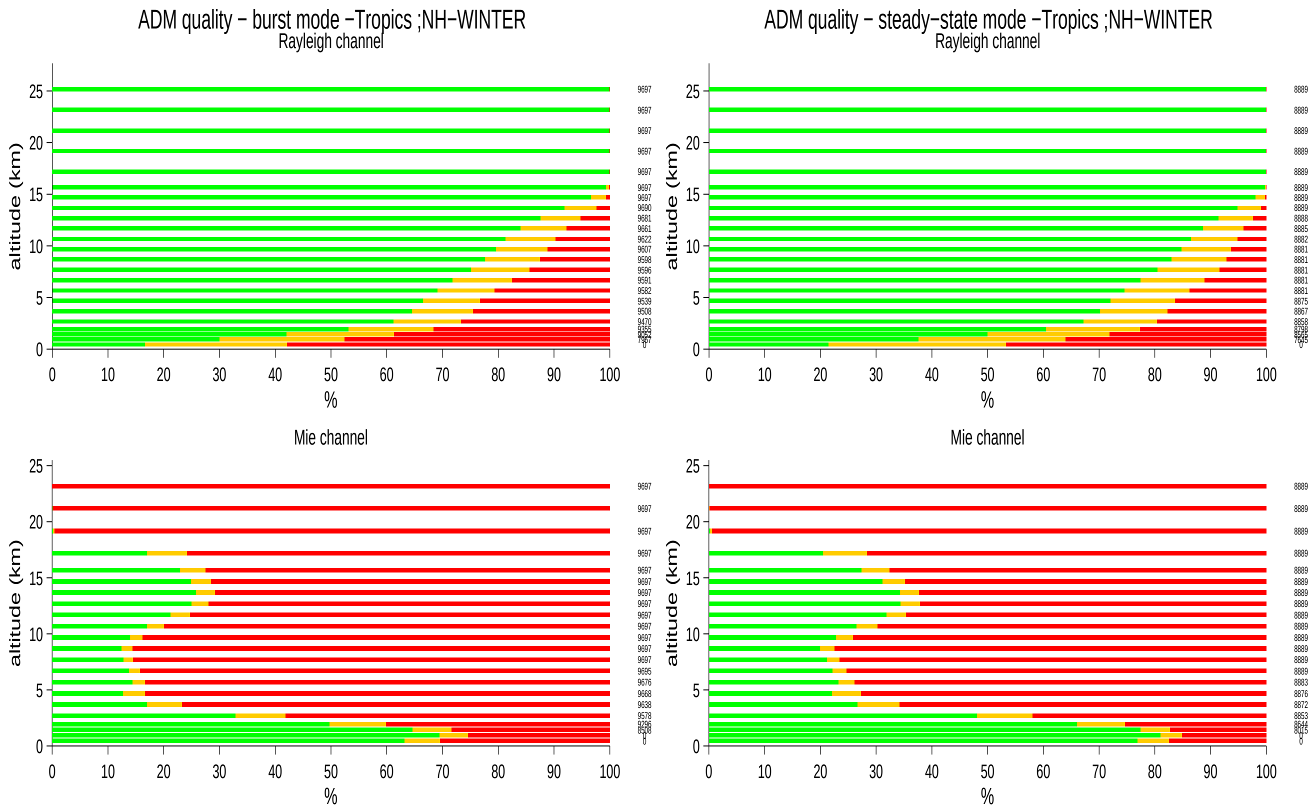

Figure 18. Same as Figure 15, but now for the tropical region.

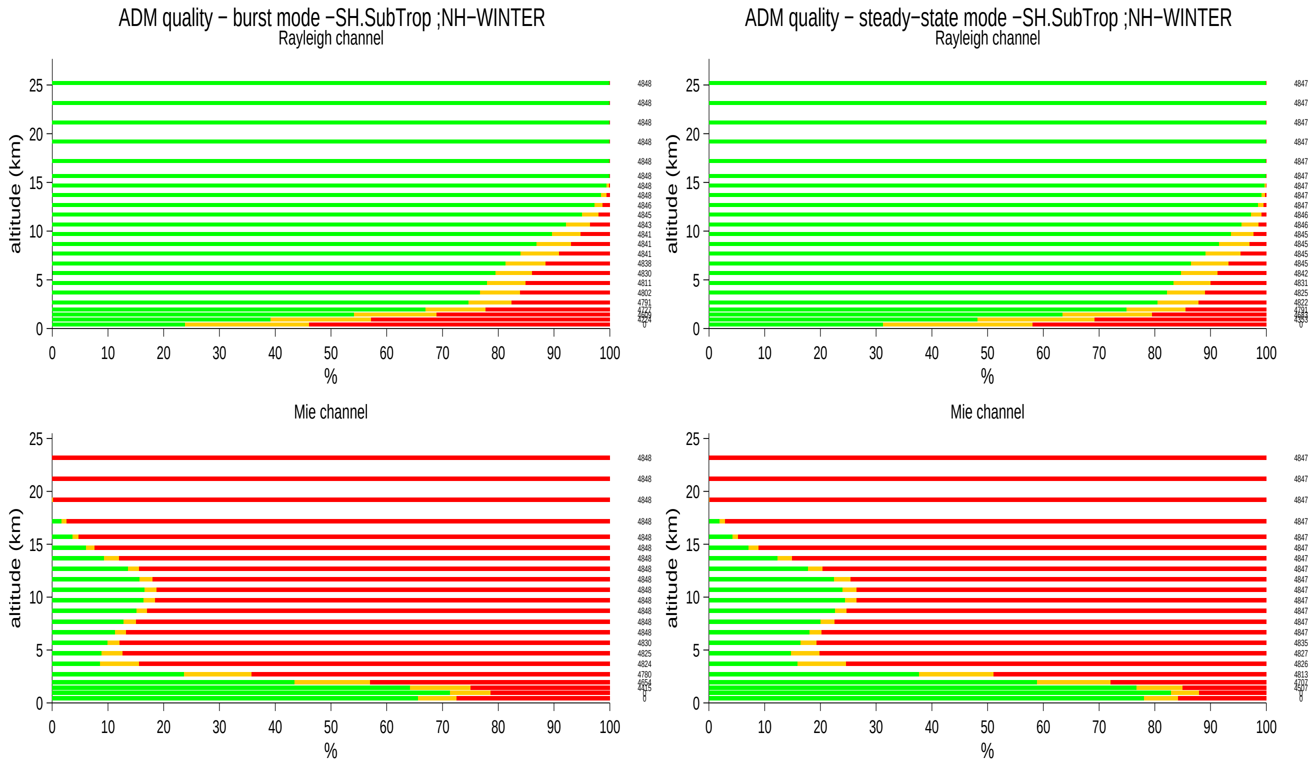

Figure 19. Same as Figure 15, but now for the SH sub-tropical region.

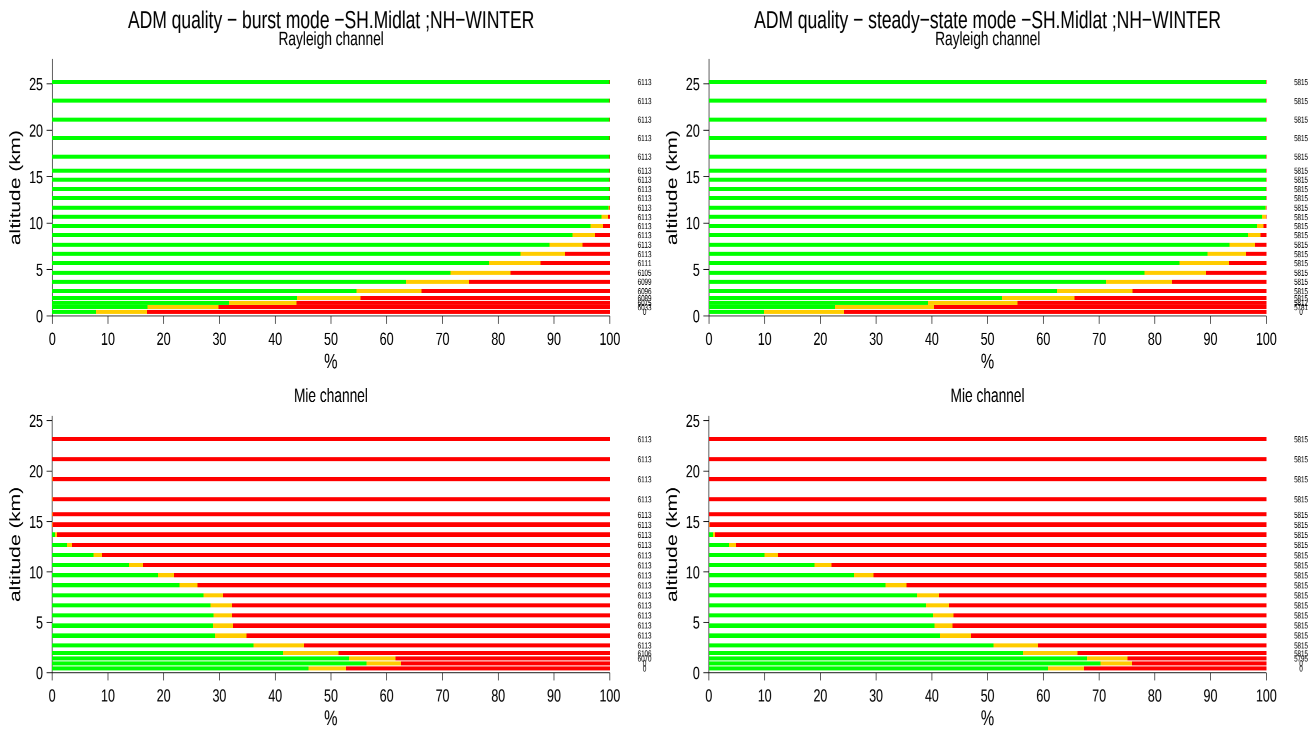

Figure 20. Same as Figure 15, but now for the SH mid-latitude region.

In conclusion, the quality of winds in continuous mode (SS100) is better than in burst mode. A potential problem in SS100 mode is the correlation of adjacent observations. However, it turns out that only 10% of the profiles are separated by 100 km, the remaining profiles are separated by at least 200 km as for burst mode.

6.4.2 CLOUDS and AEROSOL – representativeness error

In obtaining equation 3, we assumed uniform linear sampling in an accumulation cell. However, due to cloud, we will not often have true uniform sampling in the horizontal. In this case, the along-track representativeness error will increase as samples are missing, and even more so when subsequent samples are missing, due to the spectral characteristics of spatial wind variability. In other words, the cloud pattern will determine the true LOS wind component representativeness error. Moreover, equation 3 assumes a constant m^2, which in reality will be modulated by the cloud and aerosol presence, both aloft and in the range gate under consideration. Due to the varying photon count, the reduction in along-track representativeness error will be **less** effective than presented in equation 3. Moreover, variable aerosol and cloud conditions may in practice be generally associated with cases of increased wind variability.

In the simulations of ADM-Aeolus at KNMI, we have assumed that the cloud cover varies from one measurement (1-3.5 km) to the next, but rather not within measurements. This is motivated by the fact that cloud cover occurrence may be described by a spectral power law similar to equation 2 (Stoffelen et al, 1998; e.g., Feijt and Jonker, 2000). This implies that cloud cover variations from shot to shot within a measurement are generally assumed rather minor as compared to cloud cover variations from measurement to measurement within a stretch of 50 km. In other words, the constant-cloud measurements are a good statistical representation of the real laser cloud hit statistics within a BRC.

The relative increase of the representativeness error, due to clouds, is larger in continuous mode than in burst mode. However the total representativeness error remains generally smaller in continuous mode, since the number of laser shots is the same for both modes (over 100 km), while the distance between them and thus the general wind variation from shot to shot is larger for continuous mode.

The current burst mode operation of the laser introduces strong temporal variations of the spectrometer illumination during the burst period. Thus it is recommended, not to use the frequency from the laser internal reference on a measurement scale (see TN by ASF). The frequency from the laser internal reference should be used only for an observation of 700 pulses. An additional error in the L2b processing is introduced, when grouping of the measurements is used for burst mode operation. This temporal variation of the laser beam shape is not present in continuous mode, and thus this error on the laser internal reference frequency is not contributing anymore.

6.5 Quality control

As said before, variable aerosol and cloud conditions may in practise be generally associated with cases of increased wind variability. ADM is safeguarded against detrimental impact of unrepresentative data by oversampling the horizontal; each 50-km observation is split into several km-scale measurements. As such, the signal (and Doppler shift) fluctuations within the 50-km stretch can in principle be exploited to detect large errors due to spatial representation. It is common practise and common sense to reject these observations, since interpretation of the observation as a mean resolution cell weather quantity is extremely difficult in these variable cases. Data assimilation systems are known to be very sensitive to rejection citeria, i.e., to quality control. This means that data assimilation systems will also be sensitive to our ability to detect signal variability within an ADM observation.

Continuous mode provides with respect to burst mode mainly (1) larger wind variability due to the larger integration length which facilitates QC and (2) slightly less cases of totally clear and totally cloudy, i.e., somewhat more mixed cases thus increasing the need for effective QC.

6.6 Required changes in L2B/C product format

For continuous mode the L2Bp could provide smaller scale profiles than a BRC length of 200 km through its classification scheme, depending on need and further development of the L2Bp.

This will have consequences for the algorithms that combine data vertically (i.e., the optical properties estimations and L2B or classification and QC codes). These algorithms will have to implement their own grouping, based on measurement level, which may differ from the grouping used on L1B level.

Elaborate on the following points:

- L2B/C auxiliary data files

TBD

6.7 Estimate of the amount of L2B/Cp work needed

Both in burst and continuous mode a flexible strategy in processing BRCs, depending on SNR and atmospheric variability conditions will be benefical. This is a substantial amount of work. For continuous mode, the options for flexible processing increase probably, and the priority to carry out this R&D work increases.

Substantial.

TBD

7 Conclusions of the L1B/L2A authors

The current nominal Aeolus burst mode operation is compared with a prospective Aeolus continuous mode concept. Earlier trade-offs between burst and continuous modes have assumed generally a more comparable amount of energy put into the atmosphere. In the current trade-off this changes with twice the amount of energy available for the continuous laser operation mode.

A pulse repeat frequency (PRF) of 50 Hz for continuous operation is assumed. A PRF of 100 Hz for burst mode operation, with a 28 s basic repeat cycle with a burst length of 7 seconds, not including warm-up shots is the baseline. It is assumed we will use a 200 km BRC for continuous over 28 s. The L2Bp is expected to provide smaller scale profiles through its classification scheme, depending on need and further development of the L2Bp.

The assumed average pulse energy is assumed to remain the same. This means that the energy spend in the atmosphere over 200 km increases by 100% in a continuous mode as compared to burst. It is assumed that the increased total energy produced by the instrument will not affect the mission lifetime. This is a very important point, since if the mission lifetime would be significantly reduced, this would have implications for NWP centres deciding to invest effort/resources in preparing for the improvement due to Aeolus.

Although the main changes from burst to continuous are concerned with the wind performance, a first analysis of the calibration modes is performed. For IRC/ISR a stepping in frequency is set, which automatically leads to grouping of the measurements, so also for this case the BRC concept will be kept. A major system requirement for this calibration mode is that the calibration must not last more than 30 minutes. In calibration mode the laser needs 320 ms locking time to jump 25 MHz to the next frequency (therefore in continuous mode 16 pulses cannot be used for measuring when this happens). It is assumed that frequency changes can be commanded up to 5 times per BRC for certain calibration modes (TBC). Continuous mode would lead to slightly more ground returns, but the limited geographical distribution of suitable targets (smooth high-albedo land, ice) will obviously not change.

The starting point in the comparison is the Aeolus performance specification. For L1B/L2A we basically consider the HLOS performance without spatial representativeness error considerations. Thus for the same SNR (performance) twice the accumulation length is needed. In the L2B part we add spatial representation and conclude basically that 100-km observations are more representative of the ECMWF model scales. Such analysis does not pre-empt any development in the processing to deliver information on a 50-km scale in continuous mode when feasible and desired (or, similarly, on a 25-km scale in burst). The Aeolus performance specification provides a clean basis for comparison of the two modes.

L1B changes appear minor when the BRC concept is kept.

The properties of NWP data assimilation systems and global NWP models have played a major role in the design of ADM-Aeolus last century. Although the NWP model grids have increased substantially between 1992 and 2008, the horizontal scales that can be resolved by NWP models have increased to a much lesser degree.

After providing a model for the total observation error and considering the meteorological data assimilation problem, it is clear that a 100 km accumulation length may be used for continuous mode scenarios. Global NWP models do not determine substantial true variance on scales below 100 km in most data sparse areas, like over the oceans.

The specification for quality on a 100 km observation scale for the continuous mode is similar to burst mode quality on a 50-km integration scale. More information could be provided in continuous mode by increased observation density, but up to this date it turns out to be difficult to exploit high-resolution observations. In fact, data thinning procedures that reject observations that are closeby (within 100 or 200 km) are commonly used nowadays. This is in line with the analysis presented in this document, suggesting correlated spatial representativeness errors on these scales. Academic studies with increased NWP model resolution and thus much reduced spatial representativeness error, show less ADM-Aeolus impact (since the NWP model is better), but increased importance of the continuous mode (since it provides more independent observations).

Other considerations for the continuous mode concern the skill to control quality and cloud presence, but no clear conclusion is drawn here. Quality control capability is important for achieving beneficial impact in NWP analysis. The link between quality control effectiveness and data quality has to be further elaborated in order to make an informed decision on the change of ADM specification. However, the a priori analysis suggests that 100-km continuous observations sample generally more atmospheric variability, thus providing slightly more mixed scenes (con), but at the same time provide better detectable QC thresholds within a wind profile (pro).

The current burst mode operation of the laser introduces strong temporal variations of the spectrometer illumination during the burst period. Thus it is recommended, not to use the frequency from the laser internal reference on a measurement scale (see TN by ASF). The frequency from the laser internal reference should be used only for an observation of 700 pulses. An additional error in the L2b processing is introduced, when grouping of the measurements is used for burst mode operation. This temporal variation of the laser beam shape is not present in continuous mode, and thus this error on the laser internal reference frequency is not contributing anymore.

Although, there is as of yet mixed evidence that ADM performance in cloudy scenes is actually most relevant, cloudy scenes may be relatively more important for demonstrating the beneficial impact of ADM than only fully clear scenes.

Other L2B/C considerations …

Continuous operation is very beneficial for aerosol and cloud observations; the aerosol science community is strongly arguing for continuous mode operation, because of the high horizontal variability of the aerosol. Scene classification with clouds/aerosol would strongly benefit from a continuous coverage; a continuous coverage of cloud and aerosol types could be obtained. Derivation of cloud statistics with cloud coverage would be possible with continuous mode; burst mode lacks strongly from the long data gaps of 150 km within 2005 km

The change from burst to continuous has minor effects on the L2A processing.

The validation of the ADM-Aeolus products with ground and airborne observations will provide up to a factor of 2-4 more or closer collocations with continuous mode operation.

The change from burst to continuous affects the E2S processing, since processing the E2S input data, that define the satellite attitude and especially the atmospheric parameters etc. and are provided in segments with time stamps, needs to be re-organized.

Product size changes per orbit appear of minor concern:

- Calibration result files will be of similar size;

- AuxMet files are expected to be 4 times larger, pending technical implementation;

- L1B files will typically be 2 times larger (scales primarily with Nmeas);

- L2B and L2A files will typically be about 2 times larger (scales primarily with Nmeas since the PCD is the largest dataset, and that one reports many results on measurement scale).

8 Recommendations of the L1B/L2A authors

Several hardware considerations and considerations on optical stability have not been addressed in this document, but should be addressed before further assessment by the L1B/L2B teams of burst versus continuous can be made. Lifetime considerations are crucial to most applications of ADM-Aeolus data.

Based on the synthesis in this report, and assuming equal mission lifetime, the double amount of energy emitted in the atmosphere by the continuous mode slightly favours this mode in general.

Further study is needed to adopt a good strategy for continuous mode data assimilation. However, continuous mode with target at 100-km observation integration and 7 km measurement accumulation appears compatible with the burst mode performance specification and can be a basis for L2B processing and data assimilation.

We strongly advice to keep BRCs of 200 km on all processing levels. This minimizes format changes and does not result in clear restrictions in the use of the data.

In the continuous mode the spectral resolution of calibration may be improved.

…

9 Considerations for operational Level-2B/Level-2C processing

9.1 Preamble

A number of ECMWF employees have read with interest Sections 1 to 8. Those sections have been prepared entirely by those authors who participate in the development work related to Level-1B and Level-2A products, save for the indication in the Introduction that there is a difference of opinion regarding whether the investigations to date are sufficiently convincing to favour continuous mode ADM-Aeolus from the perspective of Level-2B/2C processing at operational NWP centres (i.e. Level-2B wind retrievals and their subsequent use in data assimilation). While it may have been possible to arrive at a compromise text, it was also recognized that it could be more useful to give full scope for different views to be represented, thereby better reflecting the range of views that might be expected amongst the user community. It was considered pragmatic to group the views separately and hence Section 9 has been written to contain ECMWF's perspective on operational Level-2B/2C processing.

9.2 Issues affecting operational Level-2B/Level-2C processing

At this point, it seems worthwhile to acknowledge one scenario for which continuous mode would be preferable to burst mode. This scenario relates to an atmosphere with an aerosol loading that is sufficiently high to permit the continuous mode to produce wind retrievals with the accuracy and horizontal integration length stipulated for the baseline burst mode, but with the added benefit of denser sampling (Level-2B retrievals every 50 km, without gaps of 150 km). In this scenario, accuracy would be maintained, and the denser sampling of continuous mode would offer improved localization of small-scale features (strong wind gradients, such as jets and fronts, and intense cyclones). Furthermore, there would be potential to use Aeolus data to improve modelling of background errors at the 50 km scale.

For other scenarios, where maintaining accuracy requires an increase in horizontal integration, ECMWF has not been persuaded that there is a definitive set of results that favours one mode over the other. Rather, the comments in the remainder of this sub-section summarize what are viewed by ECMWF as the main areas of uncertainty.

The prospect of longer integration lengths adds a significant amount of complication to the assimilation of Level-2B data, arising from both scientific and technical issues. The scientific issues include the increased difficulty for the Level-2B retrievals to accurately capture (in terms of location and resolution) information about small-scale features, and for the assimilation system to benefit from this information. It is on the smallest scales that ADM-Aeolus has the largest opportunity to contribute to data assimilation, and uncertain whether this contribution could be realized with less accurate and/or less resolved retrievals. There is therefore the risk that needing to use longer averaging distances in continuous mode would lose much of this opportunity. It is difficult to see how the results of Section 6 provide enough illumination on these issues, because the statistical approach gives relatively low weight to what are arguably the priority regimes, and this is one sense in which those results have not been sufficient to persuade ECMWF that continuous mode is either definitely better or definitely worse than burst mode. (Other open questions about the results from the statistical approach include their robustness to uncertainties in the parameters used, for example with respect to variations in the different error levels that may arise in different NWP systems; to the addition of multiple levels and more realistic background error covariances; and to the addition of other observational data).

Regarding the technical issues associated with a longer integration length:

1. The implementation of accurate horizontal averaging operators would have to be developed within data assimilation systems. This has been done at ECMWF for limb-sounders but the effort needed to transfer that to Aeolus Level-2C processing is still significant. The effort for other NWP centres could be even greater.

2. There would be a need to consider options for upgrading the generation and provision of Auxiliary Meteorological Data from ECMWF (in its capacity as the Level-2B processing facility). One option that is neutral from the technical perspective is to maintain the current baseline provision as designed for burst mode operation, which involves the provision of one meteorological profile for each Level-1B BRC. The baseline provision becomes somewhat less representative for continuous mode if the BRC length is increased to say 200 km, and the impact on L2B product quality has not been quantified so there is a risk of an adverse scientific impact. Another option for consideration is to provide multiple meteorological profiles for the increased-length BRC, but whether this is feasible from the technical perspective remains to be established.

9.3 Summary for operational Level-2B/Level-2C processing

The relative merits of burst mode and continuous mode depend on many factors. Some, such as the aerosol loading of the atmosphere after launch, cannot be anticipated now. It therefore seems prudent to incorporate flexibility wherever practical in the data processing. To a large extent, this need for flexibility has already been recognized even for the baseline burst mode. For example, the design of the

Level-2B processor provides a framework that permits the development of increasingly sophisticated schemes to group Level-1B "measurement data" (on horizontal scales of 1-10 km) into a number of "observation classes". In a general sense, continuous mode processing is compatible with this framework. Subject to extension of the grouping schemes developed for burst mode, and retention in Level-1B products of all parameters needed for Level-2B processing, it would appear feasible to adapt the Level-2B software to continuous mode Aeolus.

A realistic baseline for further investigation would be

- to retain the concept of a BRC in all products,
- to allow the BRC size to be configurable during the mission,
- to adopt 200 km as the nominal BRC size until further notice,
- to extend the grouping schemes with L2B processing to produce retrievals within a maximum integration distance (configurable, nominally 50 km)

This baseline is expected to be beneficial for the high-aerosol scenario describe above. The prospects for accommodating other scenarios remains less clear. Many aspects of the technical and scientific development needed to exploit the anticipated retrievals within data assimilation systems remain unexplored, particularly where degraded resolution is involved, and it would be advisable to not underestimate the effort required to resolve the uncertainties.