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TN8.3: Aeolus Level-2B processing of A2D airborne campaign data

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Michael Rennie

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TN8.3

Aeolus Level-2B processing of A2D airborne campaign data

Authors

MICHAEL RENNIE
ECMWF

CHANGE LOG

Version	Date	Comment
1.0	10 Dec 2013	MR: Initial draft
1.1	16 Dec 2013	MR: update with comments from L1B team
1.2	3 Jan 2014	MR: minor updates
1.3	7 Mar 2014	MR: have taken on comments from ESA and Lars
1.4	18 Dec 2014	MR: New work on A2D extended flights drafted
1.5	7 Jan 2015	MR: Update following OR, UM and LI review
1.6	18 Mar 2015	MR: Update following comments of AGS

Contents

1 Introduction

Measurements from the ALADIN Airborne Demonstrator (A2D) have provided the first opportunity to test the L2B algorithms and software with real atmospheric scene data.
In total two ground-based and three airborne campaigns have taken place under ESA contract 4200018366 [RD 7-9]. During each campaign, the A2D was operated either from ground or from the air in conjunction with other wind observation instrumentation. This allowed for a thorough calibration and validation of the A2D measurements [RD 8-10].

This technical note assesses the behaviour of the Aeolus Level-2B (L2B) processing and assesses the resultant L2B products when applied to A2D data which has been converted to the Aeolus Level-1B (L1B) file format by the L1B team. The data were taken during the third airborne campaign in 2009, which took place in Iceland and Greenland.

This technical note is a delivery from WP 2230 of ESA contract 4200018555. Throughout this document, members of the L1B team will be referred to by the following acronyms:
DH=Dorit Huber (DoRIT)
OR=Oliver Reitebuch (DLR)
UM=Uwe Marksteiner (DLR)
AD=Alain Dabas (Météo-France)

1.1 Documents

1.1.1 Applicable documents

	Title	Ref	Ver.	Date
[AD1]	Statement of Work for Change Request #4 “Aeolus Level 2B/C Processor - Implementation of Continuous Mode Operations & Extended Pre-Launch Support”. Contract 18555/04/NL/MM	AE-SW-ESA-GS-038	1.0	Dec 2010
[AD2]	ESTEC Contract No. 18555/04/NL/MM “Change request for CCN No.4”	N/A	1.0	Feb 2011

1.1.2 Reference documents

	Title	Ref	Ver.	Date
[RD1]	TN15.1 Inventory of Aeolus Target Assimilation Systems	AE-TN-ECMWF-GS-151	1.3	Oct 2012
[RD2]	ADM-Aeolus level-2B algorithm theoretical baseline document	AE-TN-ECMWF-L2BP-0024	2.4	Dec 2012
[RD3]	The interaction between model resolution, observation resolution and observation density in data assimilation: A one-dimensional study	By Z. Liu and F. Rabier, Q. J. R. Meteorol. Soc. (2002), 128, pp. 1367-1386		2002
[RD4]	TN3.1a Test cases for the L2B processor	AE-TN-KNMI-GS-0031a	1.0	Feb 2011
[RD5]	TN3 of ESA study contract 4000104080: Synthesizing of draft Aeolus observation requirements, collection of simulated observations and support to VAMP CCN2 contract studies	AE-TN-ECMWF-impact-study-003	4.1	Jan 2013
[RD6]	ADM-Aeolus Level-2B/2C Processor Input/Output Data Definitions Interface Control Document	AE-IF-ECMWF-L2BP-001_20121211_IODD_Iss 2.00	2.00	Dec 2012
[RD7]	Final Report, ADM-Aeolus Campaigns, Contract 18366/04/NL/MM	AE.FR.DLR.A2D.150612	1.0	15.06.2012
[RD8]	Technical Note TN 5.1 ADM-Aeolus Ground Campaigns Results	AE.TN.DLR.A2D.TN51.260210	1.1	26.02.2010

[RD9]	Technical Note TN 5.2, ADM-Aeolus Airborne Campaigns Results	AE.TN.DLR.A2D. TN52.240212	3.0	24.02.2012
[RD10]	Airborne wind lidar observations for the validation of the ADM-Aeolus instrument	Thesis of Uwe Marksteiner ISSN 1434-8454		2013
[RD11]	End-to-end testing of the continuous mode L2B processor	AE-TN-ECMWF-GS-153	3.1	19/3/2014
[RD12]	ADM-Aeolus, Ocean Albedo	TN on Ocean Albedo	1.0	15-April-2008

1.2 Acronyms

A2D	ALADIN Airborne Demonstrator
AISP	Annotated instrument source package
ATBD	Algorithm Theoretical Baseline document
BM	Burst mode
BRC	Basic Repeat Cycle
CM	Continuous mode
DA	Data assimilation
DEM	Digital Elevation Model
DWL	Doppler Wind Lidar
ECMWF	European Centre for Medium-Range Weather Forecasts
EGM	Earth Gravitational Model
HLOS	Horizontal Line Of Sight
IODD	Processor Input/Output Data Definitions Interface Control Document
ISR	Instrument Spectral Registration
KNMI	Royal Netherlands Meteorological Institute
L1B	Level-1B
L2B	Level-2B
L2Bp	L2B processor
MAD	Master algorithm document
MRC	Mie response calibration
MSP	Mie spectrometer
N/A	Not applicable
NWP	Numerical weather prediction
PCD	Product Confidence Data
QC	Quality control
RBC	Rayleigh Brillouin Correction
RMA	Reference model atmosphere
RRC	Rayleigh response calibration
RSP	Rayleigh spectrometer
SNR	Signal to noise ratio
SRD	System requirements document
TBD	To be determined
TN	Technical note
VHAMP	Vertical and Horizontal Aeolus Measurement Positioning
WGS	World Geodetic System
XML	Extensible Markup Language
ZWC	Zero wind correction

2 Initial functional testing with a three-BRC A2D scenario

The L1B team provided the L2B team with a L1B EE-format file which contains three BRC's of A2D data measured on the 26th September 2009 at around 15:06 UTC. This data is from flight #08 as listed on page 36 of [RD7], and was collected over southern Greenland during the period 14:34 and 18:10. The main purpose of this flight from Kangerlussuaq (Greenland) to Keflavik (Iceland) was to measure the sea-surface reflectance under various angles on the way back from Greenland to Iceland.

UM provided some information on the ground elevation and the Mie signal levels from this flight as shown in Figure 1 and Figure 2 respectively. Figure 1 shows that the ground elevation over Greenland at the time of the data (i.e. 15:06) is approximately 2300 m; based on the DEM (black) and A2D (red) estimates of the ground surface altitude.

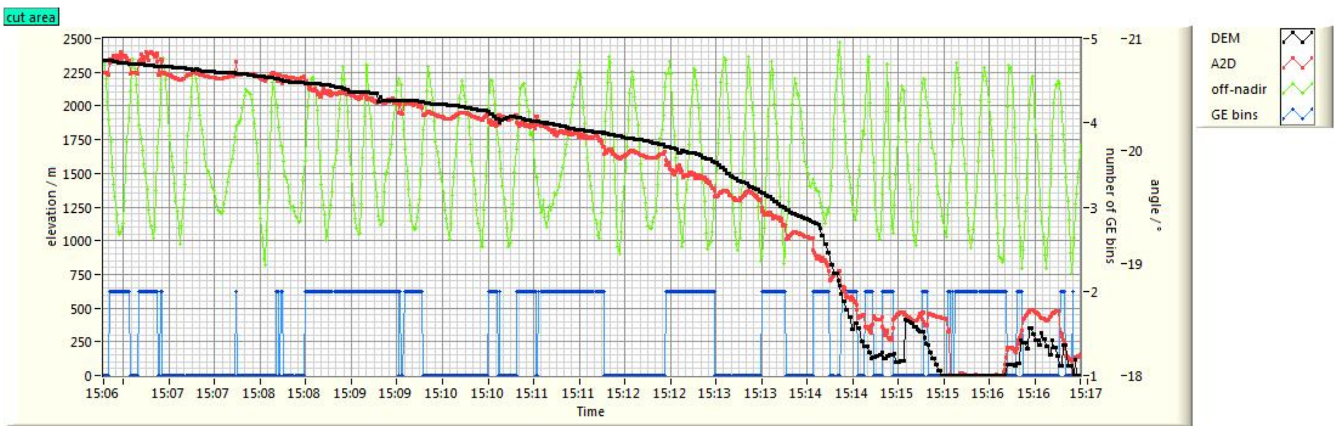


Figure 1. Ground altitude versus time of the digital elevation model (DEM, ACE1) in black and the A2D measured ground return altitude for the investigated flight (in red). The time of the 3 BRC scenario was 15:06 i.e. only the very start of this scene.

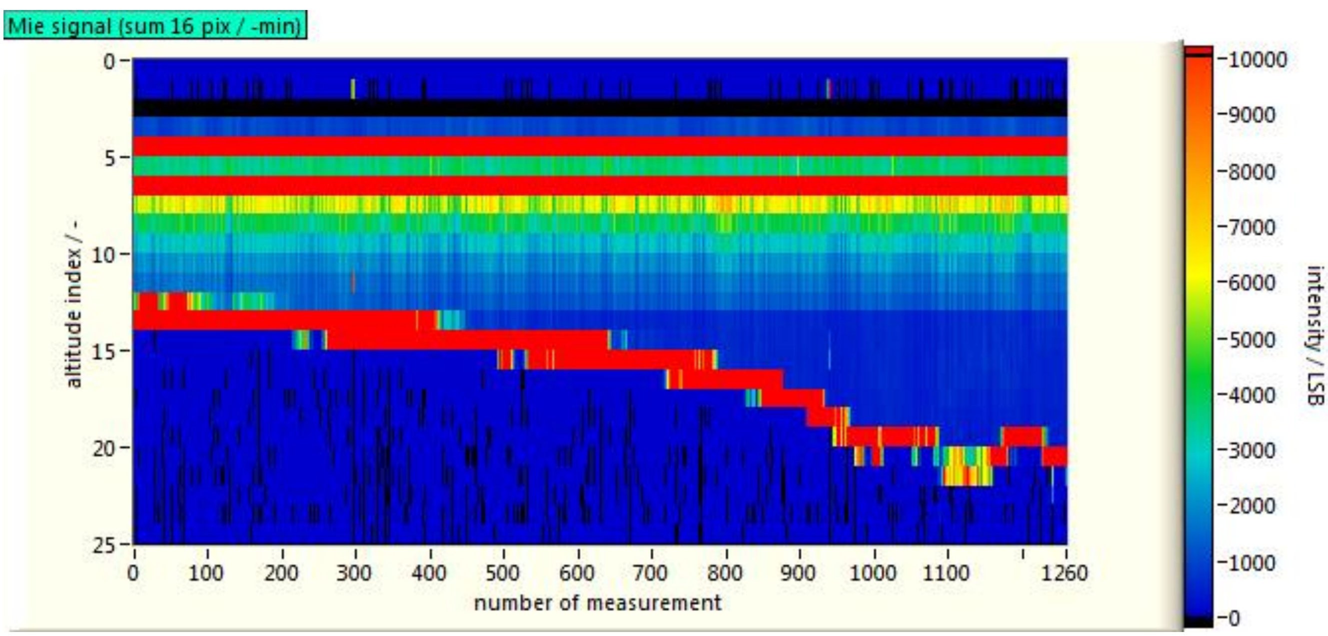


Figure 2. The signal strength of the Mie channel along the flight path.

In December 2013, the Aeolus L1B team (particularly DH and UM) processed this 3 BRC A2D test dataset to generate the AISP data suitable for continuous mode Aeolus processing. The L1A file was then reprocessed with some modified geolocation information (modified from the E2S "template" values to real A2D values from the flight) to a L1B EE-format file. The altitudes provided in the geolocation file are incorrect (to some extent) due to a mismatch in the zero reference for A2D and L1B data.

L2B processing of this L1B product provides a functional test (but not a scientific test) of the L2B processor with the A2D for the following reasons:

1. The Mie calibration information (MRC) in the L1B file is not applicable to A2D data because it is from an E2S simulation for the Aeolus satellite. The real A2D MRC data is of good quality according to the L1B team, but it is flagged invalid in L1B processing, as the calibration is non-monotonic and so it could not be used (with the L1B processor version available at the time of L1B file production). However the A2D MRC value for the sensitivity and offset (both for measurement and reference) are quite similar to the E2S MRC value, so the Mie winds should correspond reasonably well to the real Mie winds (but with some wind dependent bias).
2. The L2B processor Rayleigh calibration information (as provided via an AUX_RBC_L2 file) *is* derived from a real A2D ISR calibration mode (by AD, but with no consideration of étendue effect), so the Rayleigh winds should resemble to some extent the real winds. However, for A2D the sensitivity and offset values of the calibration are strongly range/altitude dependent, which is not accounted for in the Aeolus calibration processors and L2B processors at the time of writing. Recently (2013) Astrium discovered that also the satellite instrument ALADIN will have a range dependent LOS wind bias. The introduction of a dedicated calibration mode to characterize and remove this is currently under investigation.
3. Also the L1B Rayleigh wind observations (from the provided L1B product) used an E2S simulated satellite RRC (without range dependent bias) and hence will have little correspondence with the real winds. This E2S RRC was required because the A2D RRC data is non-monotonic, which is not accepted by the L1B processing (the version used at the time of processing). Therefore we do not expect the L1B and L2B Rayleigh winds to match. The applied AUX_MET_L2 file (used to correct the temperature effects (pressure was not considered in the corresponding AUX_RBC_L2) on the Rayleigh spectrum in the L2B winds) is from an arbitrary simulated orbit and therefore will not match the real temperature profiles at the geolocation of the A2D data; this will also introduce some bias.
4. The sample size is too small to do scientific investigations of the quality of the resultant L2B winds.

Given the above limitations, we cannot expect the resultant L2B winds to be accurate from processing this A2D L1B file. However, the algorithms (e.g. classification, Mie core algorithm, ILIAD retrieval) should still function, providing a useful test for the processing methods. Also plausible HLOS values (i.e. in the expected physical range) should be produced. A lot can be learnt from this dataset, despite some major differences with respect to ALADIN measurement characteristics. This exercise will test the flexibility of the software in preparation for the real ALADIN data.

2.1 A2D ISR data

The AUX_RBC_L2 file contains (amongst other datasets) the ISR (Instrument Spectral Registration) data, which is used to derive the L2B processor's Rayleigh calibration curves (both internal reference and atmospheric). Figure 3 shows the ISR data from the two A2D AUX_RBC_L2 files (as provided by AD, data from 31 January 2009 during the BRAINS campaign, this is also referred to as A2D ISR 1 and 2). The A2D ISR has much larger signal levels than an E2S simulated ALADIN ISR (shown in blue in Figure 3 and in Figure 4). This difference in signal level is now understood to be due to the ALADIN ISR mode signal being a mean over 190 pulses, whereas for A2D it is a summation of pulse signals during 1 observation of 700 pulses. It is worth noting that the Fabry-Perot A and B transmission filters are defined differently in the two datasets. For A2D ISRs the direct path is always labelled A and the indirect path labelled B. For ALADIN this labelling is a user setting, but the nominal setting is also A (direct) and B (reflected). Also, the filter cross-point closest to the zero offset for the A2D ISR lies at around +1 GHz frequency offset whereas it is closer to -0.2 GHz for the E2S simulated ISR. The position of the filter cross-point (or zero-frequency) in the E2S and A2D is not of any instrumental relevance. The zero-frequency is just an offset to a real frequency, which is defined differently for E2S and for this A2D data set. The A2D ISR data looks very much noisier than the E2S simulations of ISRs. OR explained some of the differences:

"The A2D has the opportunity to adapt the signal levels in the internal reference in the case that we are doing ISR mode calibration compared to wind mode or IRC. We are using different fibres or signal dampers for that purpose to optimize the dynamic range of the signal and maximize the signal level. This is not possible for the satellite instrument ALADIN, thus the E2S has only one transmission parameter for the internal reference signal. Also, the internal reference signal is acquired per shot for ALADIN, but accumulated over P shots for the A2D. Together, this makes a difference in signal levels. I agree that we have much higher noise on our internal reference signal than expected from Poisson noise (a factor of 6-8). That is the reason for the A2D noise study, which we are currently performing."

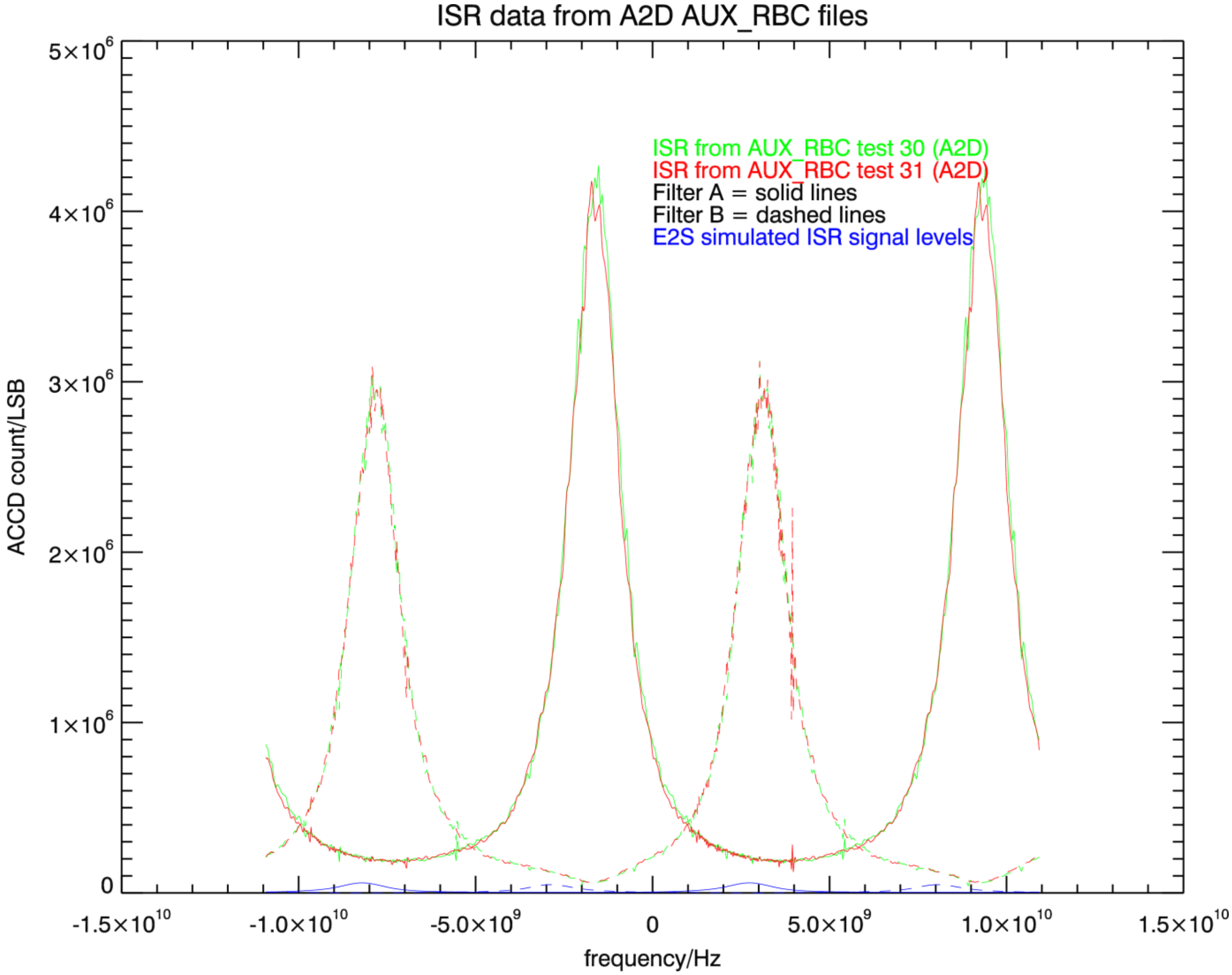


Figure 3. The Fabry-Perot (RSP) transmission functions for two example A2D ISRs (red and green). For comparison, transmission functions from an E2S simulation of ISR for the Aeolus satellite are shown in blue (the signal levels are ~50 times lower).

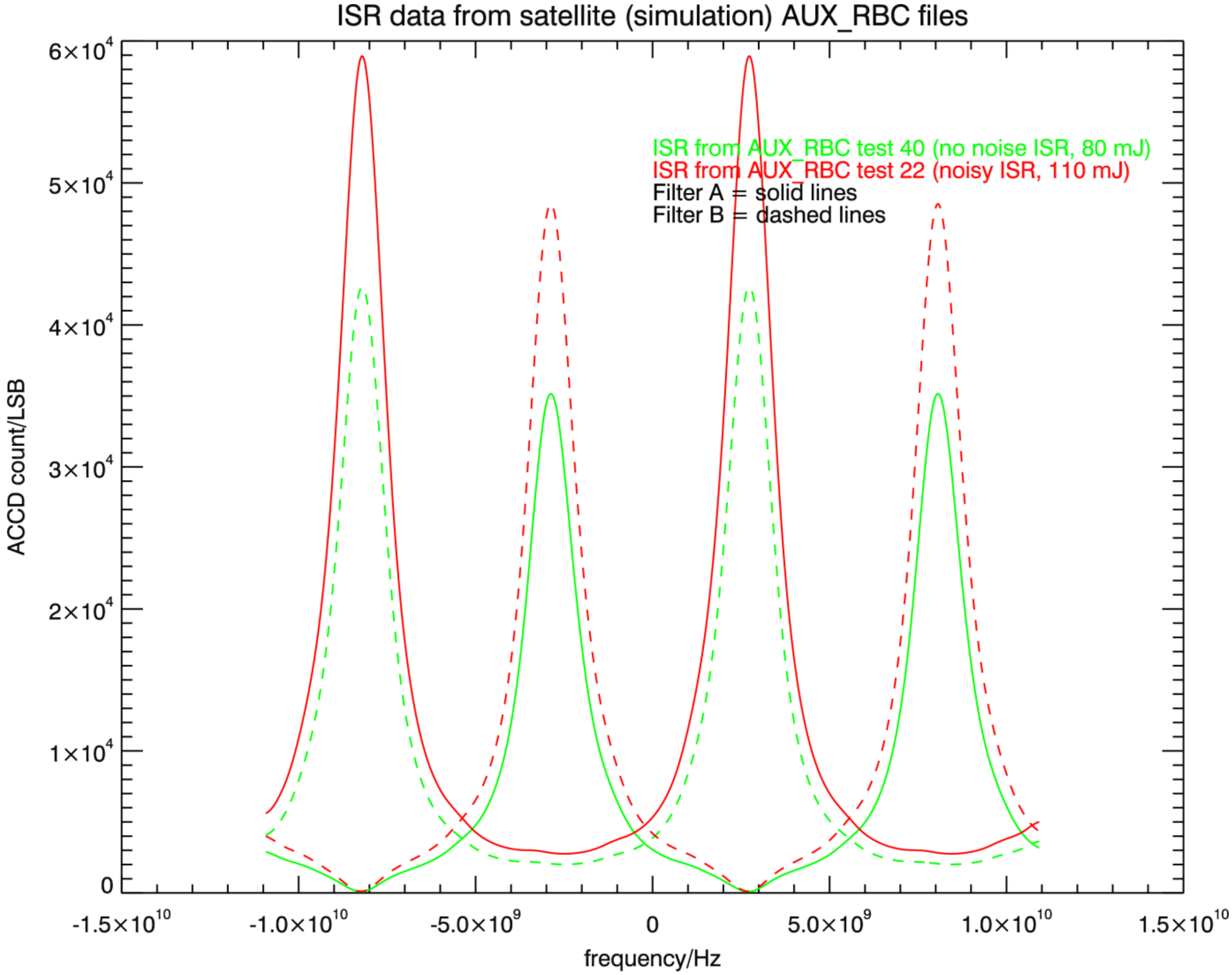


Figure 4. E2S simulation of satellite ISR data for comparison to A2D data in Figure 3.

Figure 5 shows the internal reference Rayleigh response (i.e. $(T_A-T_B)/(T_A+T_B)$) calibration curves (extracted from the AUX_RBC_L2 files) as calculated from the corresponding ISR data. The responses are quite different for the Aeolus simulation and for the A2D. For example, the A2D slope is negative and the zero is shifted by +1.2 GHz with respect to the E2S simulation: this is in agreement with the transmission functions of Figure 3 being flipped. OR had an important comment about the filter cross-points:

"The sign of the response slope is not only depending on the pixel assignment for A and B on the ACCD, but also on the choice of the filter crossing point (of the two to choose from). If you have a closer look on the data of Figure 3, you will notice that the A2D filter A and B spacing is not equal, e.g. there is a larger frequency difference between the first filter B to A maxima, than between the next filter A to B maxima. We had performed our wind measurements in the past at the filter crossing point with the wider frequency span, so e.g. around -5 GHz or +6 GHz in your plot. So from Figure 5 it seems that filter crossing point close to 0 MHz was used for calculation of the internal RRC, which gives the offset of 1.2 GHz and the negative slope; instead the other one should be used at -5 GHz or +6 GHz."

This would imply that the AUX_RBC_L2 file generated from the A2D ISR has chosen the wrong filter-cross point and is therefore inappropriate. Also there is a very large difference between the two A2D response curves (green and blue) noticeable at frequencies greater than 1 GHz. OR suggested:

"The difference in the two A2D RRC curves is probably due to a drift in the laser frequency in the ISR measurement from 10:52 UTC, which we have recorded with our wavemeter and is not so obvious from Figure 3, because you are showing a very large frequency interval; maybe a zoom in Figure 3, provides some insights.

The difference is mainly in the slope of both RR curves, rather than pointing to frequencies > 1 GHz. This could be due to a laser frequency drift during the ISR calibration. The negative slope for A2D curves is definitely resulting from the use of the inappropriate cross-point at around 1 GHz."

The normal behaviour for E2S simulated internal Rayleigh response is shown in "test 22" (red). The curve for "test 40" (pink) resulted from a mistake: an inconsistent assignment of the A and B channels to ACCD pixels in the default settings of E2S v3.03 and L1Bp v6.02.

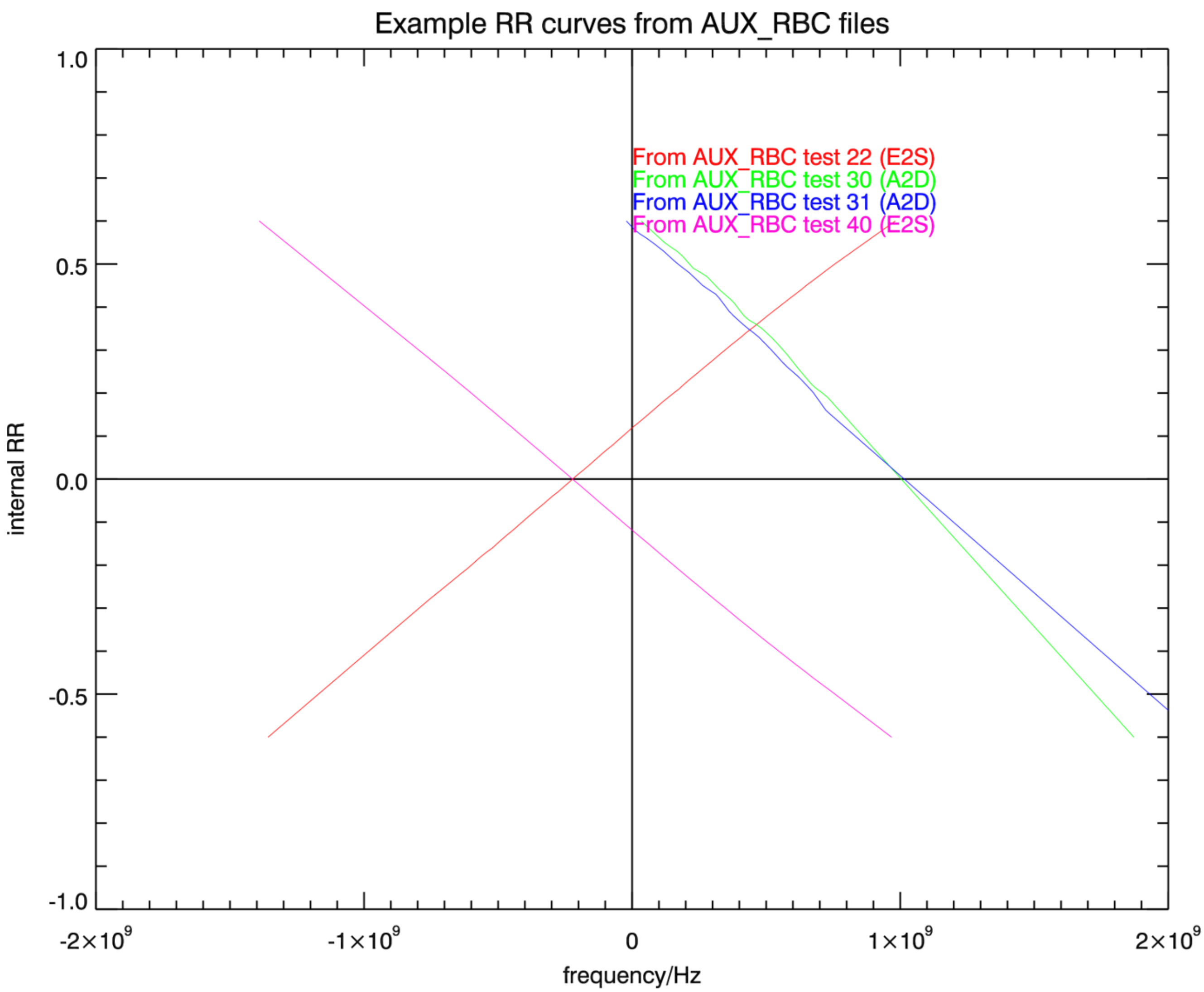


Figure 5. Internal Rayleigh response calibration curves from the AUX_RBC files for A2D data and for different settings of E2S/L1B processing.

2.2 L2B processing with the example A2D L1B data

After setting up an appropriate working directory, with all the necessary input auxiliary files, the L2B processor (v2.00 + several bug-fixes) was run using the A2D L1B product (v6.02). The AUX_MET_12 data is an arbitrary file from a chain of processors test case. This can be used since the AUX_PAR_2B settings for AMD Match-up is set to “Dummy”, meaning it does not search for a geolocation match, but just accepts AMD dataset record *n* for measurements in BRC *n* (so arbitrary global temperature profiles are used for observations over Greenland).

On the first attempt at running the L2B processing it stopped with an error message because the A2D Rayleigh calibration curves were outside the expected range for the Aeolus satellite. This error was easily avoided by increasing the valid frequency range in the L2B code (these are currently hard-coded values based on expected ranges for the ALADIN mission). After doing this, the L2B processing ran without error messages and produced a L2B product.

2.3 Analysing the L2B product

The L2B winds and associated data can be analysed using verification plotting tools developed at ECMWF (using IDL). One major difference in comparison to analysing results from the chain-of-processors simulation (E2S) testing, is that for the A2D data we do not have the true winds for verification. Of course with E2S simulations, the “truth” is available via the E2S input format data. However we can still examine the wind results to learn something about how the processing behaved, and qualitatively see if the results agree with DLR A2D results.

As mentioned earlier, the inappropriate calibration means the wind results will often be far from the true atmospheric winds anyway. The ECMWF NWP model winds can be used as a proxy for the truth. ECMWF winds have been used to qualitatively assess the results, rather than co-locating and producing verification statistics, since this is a considerable effort for such a small scenario and would provide little benefit. Another way of assessing the results is by comparisons of the L2B and L1B wind results; often this is useful for spotting inconsistencies between the processors.

The three BRC A2D L2B wind results are located over southern Greenland, see Figure 6. The geolocations were taken from the L2B observation latitude/longitude data (i.e. passed on from the L1B file). The aircraft moved eastwards (based on the position and time of each observation). The ECMWF operational short-range forecast (see Figure 7) for the time and location of the observations has north-westerly winds which tend to increase in speed from pressure level 850 hPa to 200 hPa (this flow pattern agrees with that shown on page 106 of [RD7]). If the laser is pointing roughly perpendicular (and to the right) of the aircraft velocity, then a modest positive HLOS wind could be expected, say around 10 m/s (Figure 8 shows the ECMWF v (meridional)-component of the wind, the negative of which is roughly the HLOS that the aircraft would measure when travelling eastwards).

Figure 6. Map of the 3 BRC A2D L2B wind results locations (red dot), in Greenland.

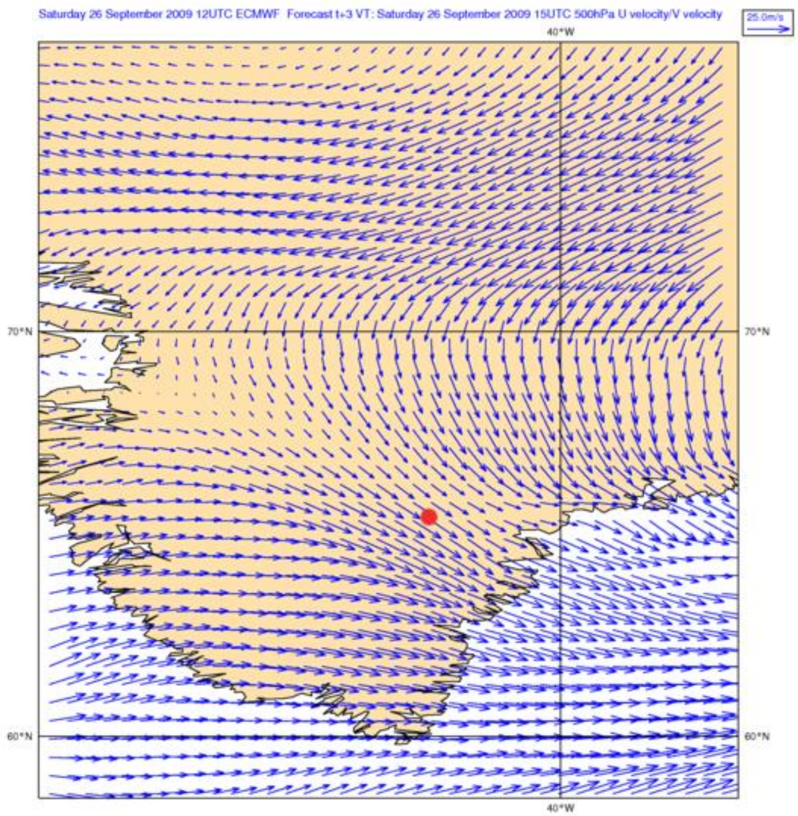


Figure 7. 500 hPa (~5 km above mean sea level) ECMWF forecast wind field (T+3 hrs) valid at 15:00 on 26/09/2009. Red dot shows approximate location of the A2D data.

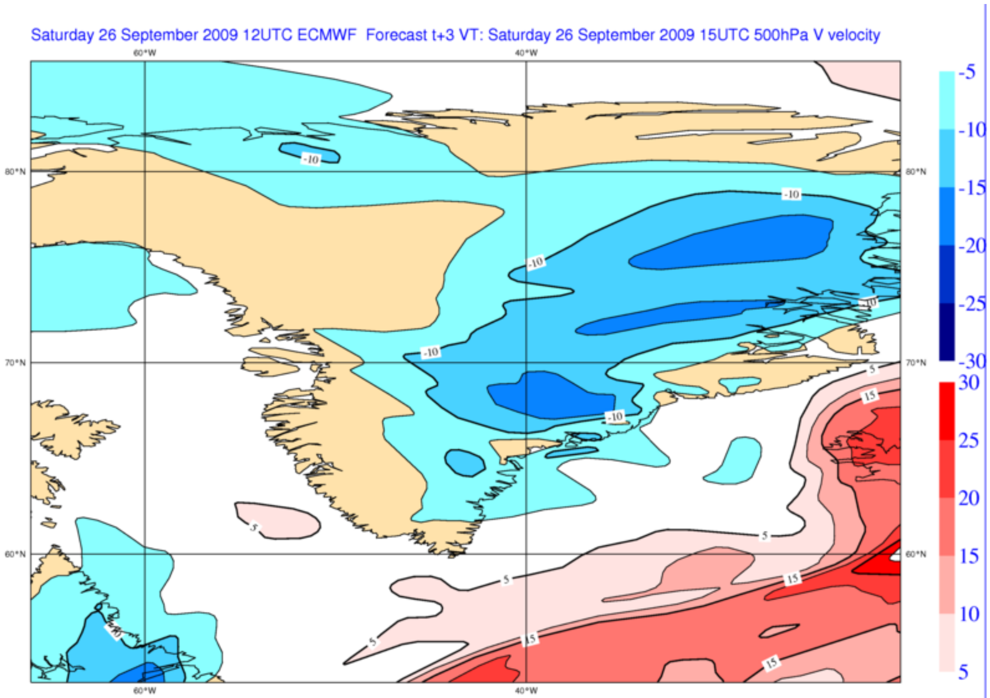


Figure 8. 500 hPa (~5 km above mean sea level) ECMWF forecast v-component of wind (T+3 hrs) valid at 15:00 on 26/09/2009.

NASA Aqua/MODIS imagery for Greenland is shown in Figure 9 which suggests that the region of the test case may be mostly clear of clouds.

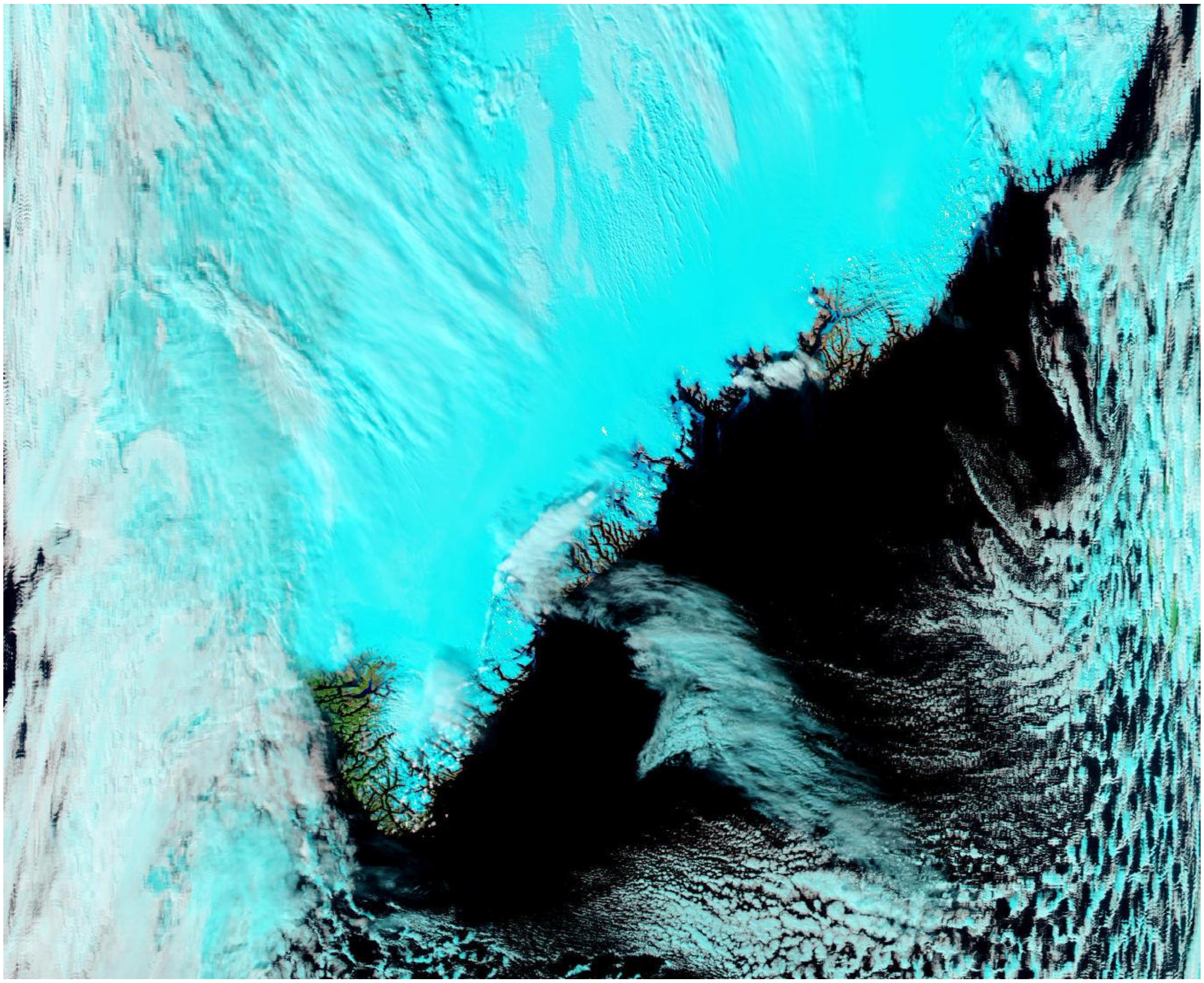


Figure 9. Band 7-2-1 from NASA's Aqua/MODIS satellite imagery valid at 15:15 UTC on 26/09/2009. Courtesy of NASA.

Figure 10 plots the observations positioned in altitude and along-track distance with the HLOS wind values (given by the colour scale) of the L2B Rayleigh-clear wind results for the 3 BRC A2D case. The L2B Rayleigh-clear winds are restricted to a vertical band between around 3 and 7 km altitude. This is consistent with the ground surface being positioned at around 2.3 km i.e. winds should not be available below. The horizontal resolution of the wind observations as shown in the plot was estimated assuming that the Falcon aircraft is travelling at 210 m/s (taken from [RD7]) relative to the ground and using the times of the observations. The HLOS winds are positive (at around 20 m/s) which is reasonably close to the ECMWF model-estimated HLOS value (~10 m/s). The increase with altitude to 40-50 m/s at 6-7 km is likely due to the atmospheric path effect (range dependent bias, due to changing angles of incidence at receiver) in the A2D data (which is not accounted for in the AUX_RBC_L2 file, nor in the L2B processing). Also, note that the L2B A2D HLOS winds still contain the aircraft ground speed component, which could be significant for the A2D (0-20 m/s).

Figure 11 shows the L1B Rayleigh wind observations, which can be compared to the L2B observations of Figure 10. An obvious difference between the L1B and L2B winds is that the L1B winds are produced for all range bins (whereas L2B winds are missing on some range bins). However,

Figure 12 shows the validity flag of the L1B wind observations and it is seen that only winds in the 2 and 7 km vertical band are classed as valid, which agrees well with where the L2B Rayleigh-clear observations are available (however there are 7 more L1B Rayleigh valid winds at the edges of the block of L2B winds). The HLOS winds of the L1B and L2B products are very different (of opposite sign) because of the mismatch in calibration explained earlier (but also perhaps for reasons explained in Section 3.5.2). However, there appears to be some correlation of the values which can be expected given the same A2D spectrometer counts are being used.

These results indicate that functionally the L1B and L2B processors are able to handle the A2D Rayleigh data without major obstacles.

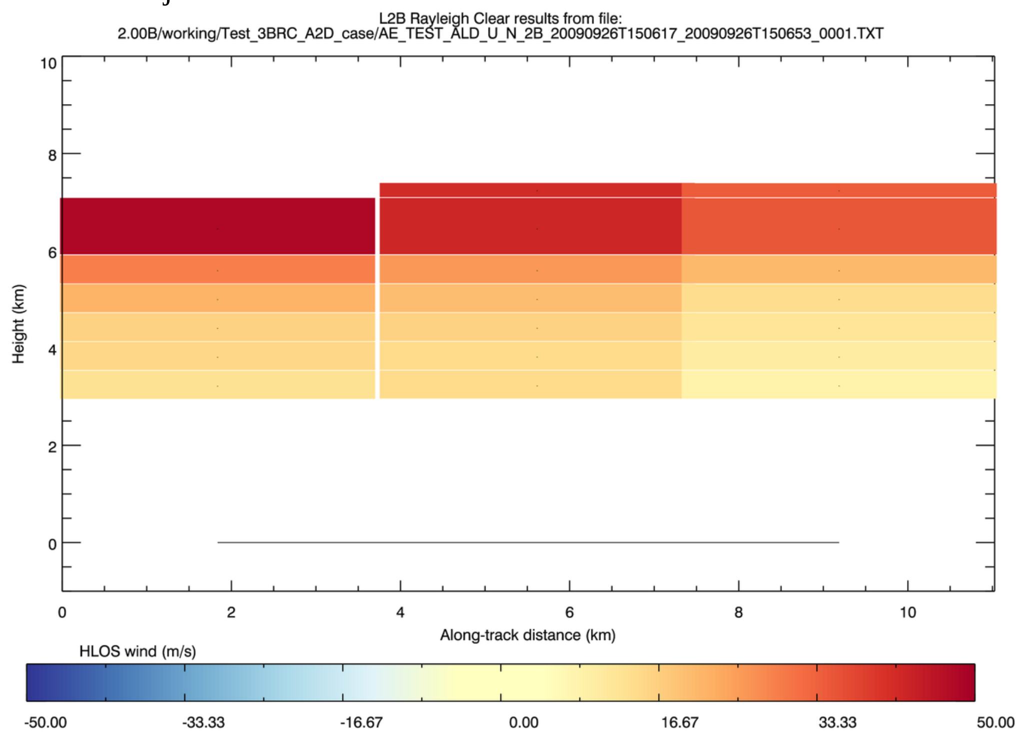


Figure 10. Cross-sectional view of the L2B Rayleigh-clear wind observations from the 3 BRC A2D example. Colours indicate the HLOS wind value - white is an absence of wind results.

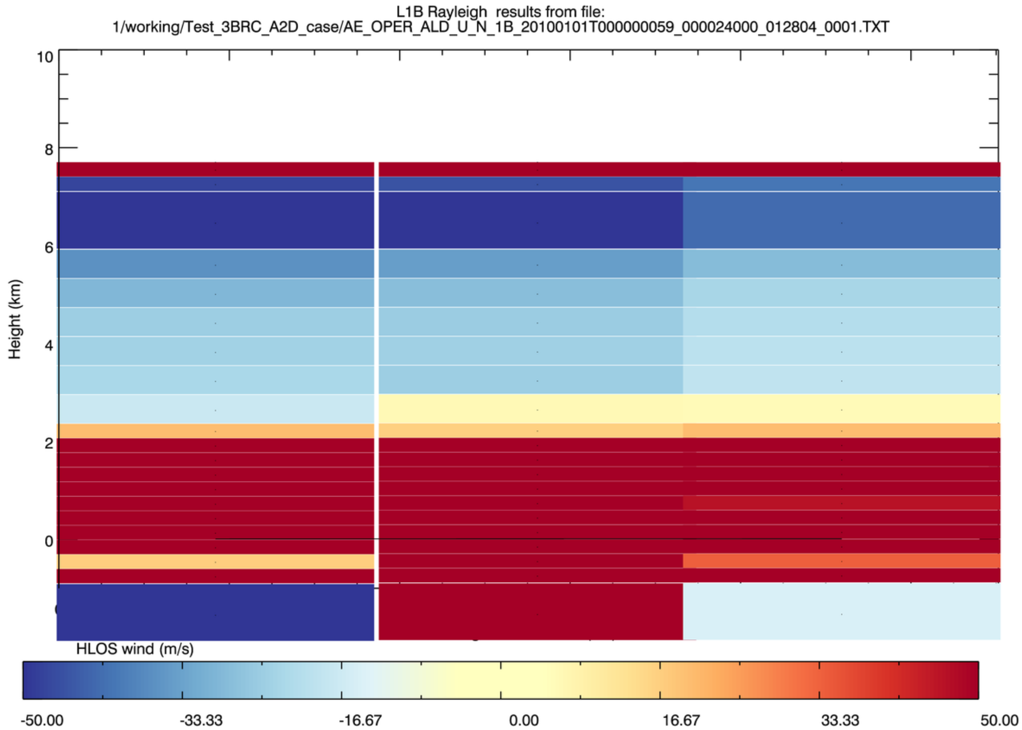


Figure 11. Cross-sectional view of the L1B Rayleigh wind observations from the 3 BRC A2D example. Colours indicate the HLOS wind value - white is an absence of wind results.

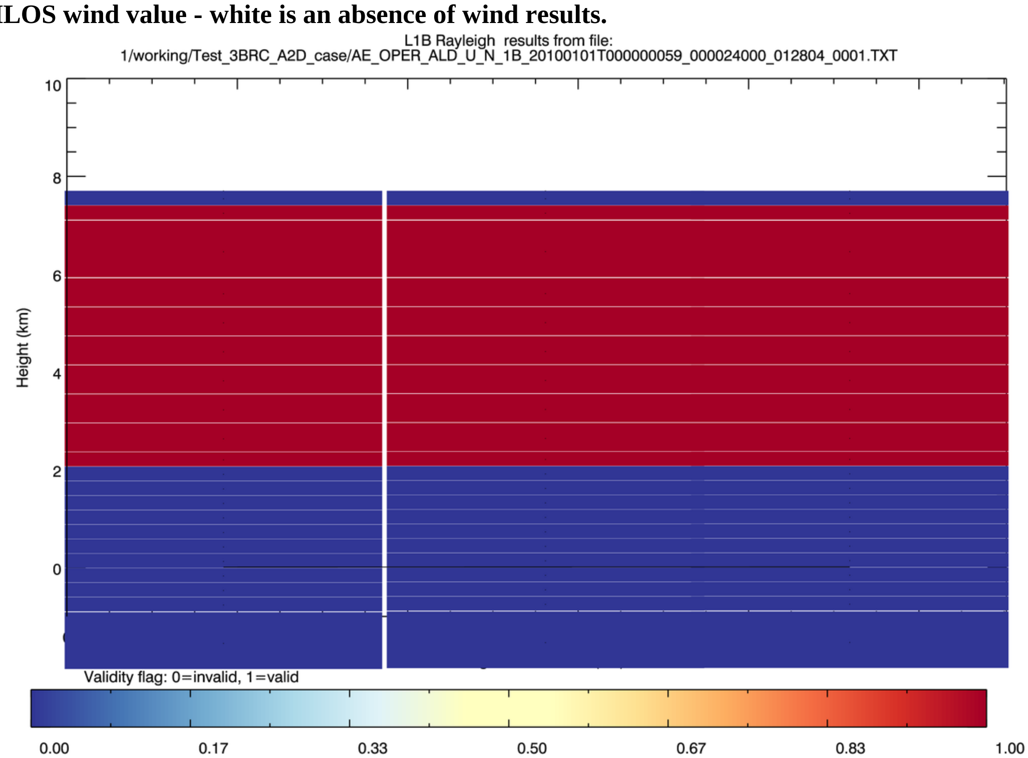


Figure 12. Cross-sectional view of the L1B Rayleigh wind observation validity parameter from the example 3 BRC A2D L1B data. Red is valid, blue is invalid.

Next we discuss the Mie results. Figure 13 shows the L2B Mie-cloudy wind observations. The Mie results are restricted to two vertical range-bins from 2 to 3 km. This is around where we expect ground returns. The L1B Mie observations and validity flags are shown in Figure 14 and Figure 15 respectively. It appears that the Mie and Rayleigh range-bin definitions are the same for the A2D data (nominal setting). L1B Mie wind results are produced for a greater proportion of the scene. However, as for the Rayleigh, the valid results match the L2B wind result locations well, except one more vertical range-bin at 2 km is included in the L1B results. An agreement in terms of the HLOS values between the L1B and L2B Mie HLOS wind values is seen. This is expected since both use the same MRC (satellite E2S simulated) data, and same Mie-core algorithms. It is unclear whether there is some cloud/aerosol adjacent to the Earth's surface, and whether the processors are correct in producing Mie winds i.e. it could be ground returns interpreted as particulate return. However, there is some evidence for clouds/aerosol in Figure 1 (first 100 measurements), because the calculated A2D elevation (red) is slightly higher than DEM. This is due to some signal in bin no. 12 (with ground in bin no. 13).

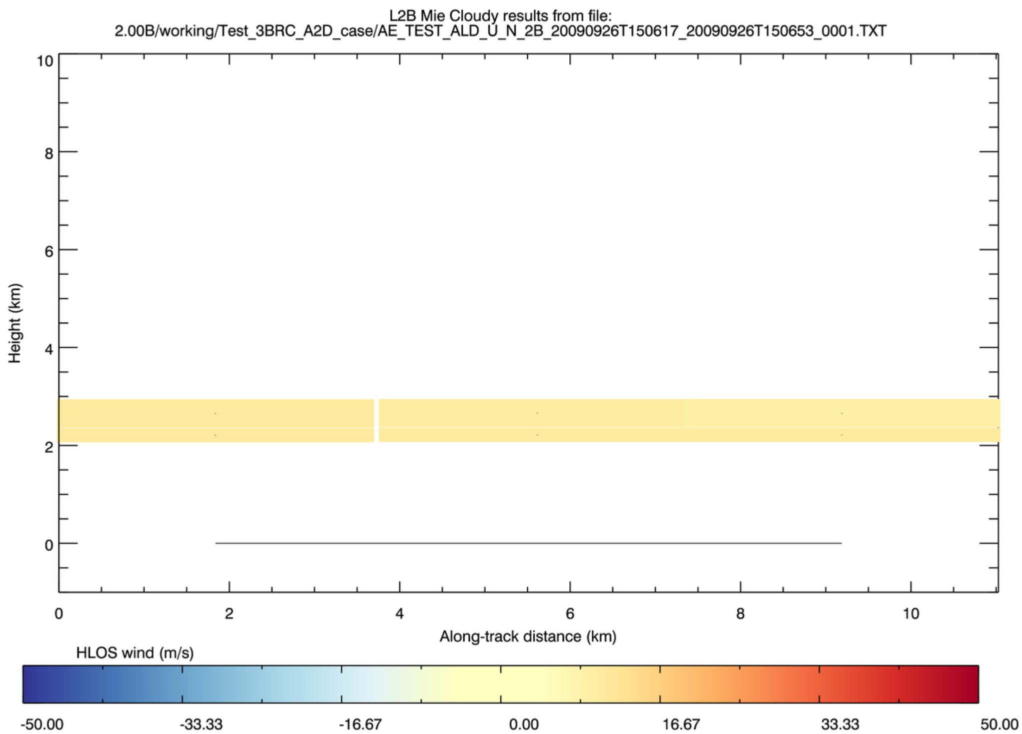


Figure 13. Cross-sectional view of the L2B Mie-cloudy wind observations from the 3 BRC A2D example. Colours indicate the HLOS wind value - white is an absence of wind results.

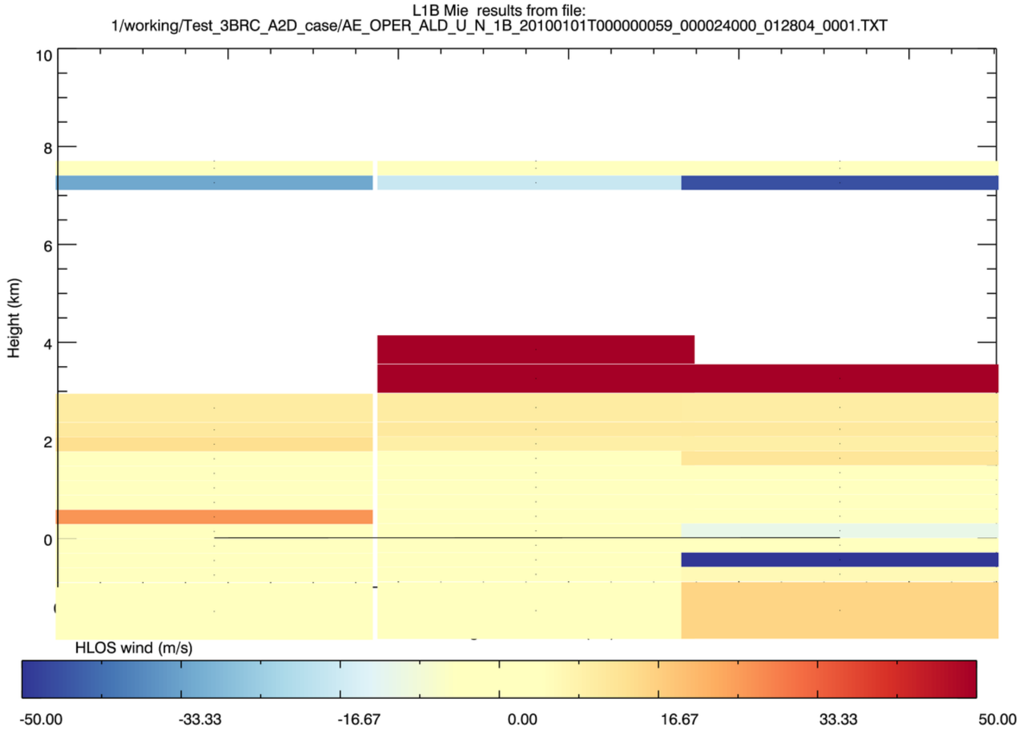


Figure 14. Cross-sectional view of the L1B Mie wind observations from the 3 BRC A2D example. Colours indicate the HLOS wind value - white is an absence of wind results.

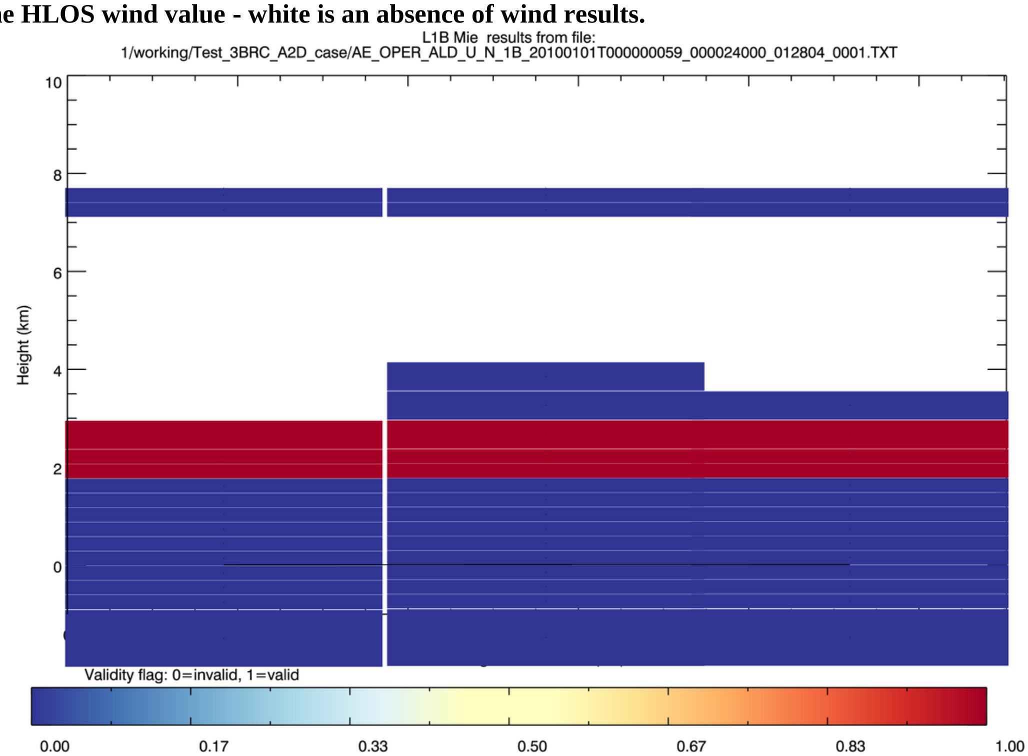


Figure 15. Cross-sectional view of the L1B Mie wind observation validity parameter from the 3 BRC A2D example. Red is valid, blue is invalid.

2.4 L2B classification and QC triggered in L2B processing

The L1B measurement-bin refined scattering ratio (SR) estimates are used in the classification step of the L2B processing to determine whether a measurement is classed as clear or cloudy; the L1B refined SR values from the 3 BRC A2D data are shown in Figure 16 below:

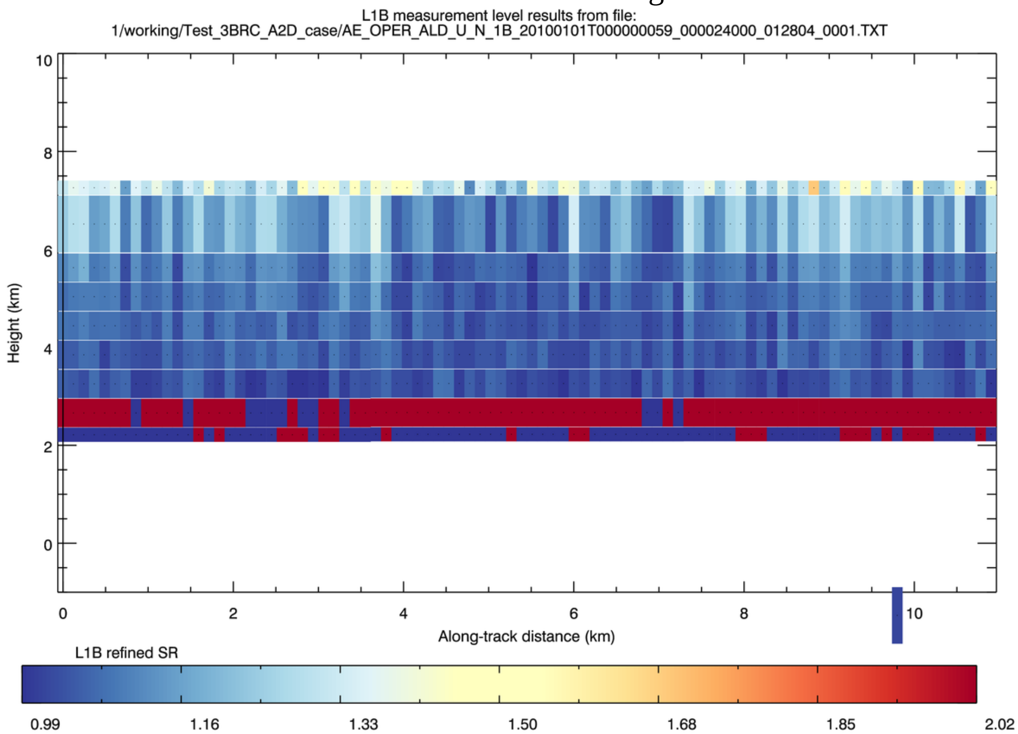


Figure 16. L1B measurement-level "refined" scattering ratio values.

Note that following the L2B processor classification algorithm, the processing uses the measurement-bin level QC data to further reject suspicious measurements.

The AUX_PAR_2B settings for the L2B observations of this case have a SR threshold of 1.15, so measurements with values greater than this are classified as cloudy and those with values less as clear. The white areas indicate an absence of SR data, either because the range-bins are absent or because the values are set to missing values due to a L1B processing (v6.02) issue. SR values in Figure 16 are mostly near 1.0 (i.e. clear atmosphere), except for a layer of greater than 2.02 SR at ~2-3 km and values of ~1.3 closer to the aircraft. The layer of high SR is believed to be due to ground return signal or very low cloud/aerosol, based on the elevation estimates from Figure 1. One can see that below the layer of high SR there are no SR values due to "missing" values — presumably this is because there is no signal below due to the ground. This strong scattering layer coincides with where the L1B valid Mie and L2B Mie winds (or ground returns) are located, so the processing is behaving nominally. Notice how the L2B Rayleigh-clear winds of Figure 10 are above this layer.

It is interesting that the L1B processor does not detect any ground returns for this example i.e. no measurement-bins are flagged as containing ground return signal. The ground is suspected to be at around 2.3 km altitude for this case over Greenland and presumably these are strong returns (Figure 2 concurs) from ice**. This occurs because the DEM values in the L1B processor were not correctly set for this scene, hence the L1B processor searches in the wrong range-bins for ground return signal, and so does not find any.**

It is interesting to look at the L2B processor's measurement-bin level QC decisions. Figure 17 shows the measurement-bins rejected or accepted from L2B Mie processing through use of the L1B processor Product confidence dataset of the measurement-bins: invalid (red), valid (blue). The L2B processor settings can be changed to ignore the L1B processor measurement-bin PCD, but for this test case it was used. This QC shows why the L2Bp only uses two vertical range-bins (blue in Figure 17) to produce Mie results. If the measurement-bins containing ground return had been detected by the L1B processor, this would have been shown in the QC decisions of Figure 17 i.e. all the bins would have been invalid. Apparently the L1Bp (v6.02) ignores its own measurement-bin QC when constructing BRC level wind observations.

Figure 18 shows the measurement-bin QC applied by the L2B processor for the Rayleigh winds. The "good" bins (dark blue) match well with the L2B Rayleigh-clear wind observations. The remaining measurement-bins are rejected due to the L1B Rayleigh channel A/B SNR estimate being outside the chosen acceptable range (0-400; defined in the AUX_PAR_2B file). In this case, the rejections are actually where the L1B SNR values are missing (so the QC is appropriate). These missing values tend to occur when the SNR is very low; in this case there must only be noise below the ground at 2.25 km.

The "non-missing" L1B Channel A SNR measurement-bin values are plotted in Figure 19. One can see that the SNR values are absent (i.e. missing values) below the ground surface backscatter layer seen in Figure 16 at ~ 2 km.

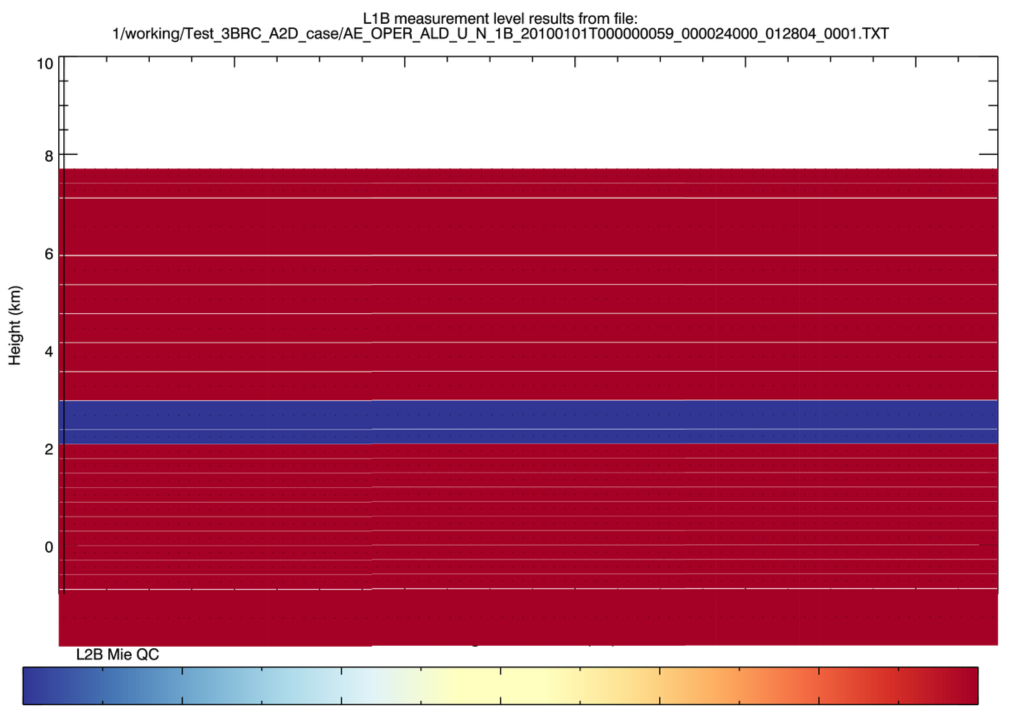


Figure 17. L2B Mie QC on the measurement-bin level. Red (1) corresponds to the measurement-bin being flagged as invalid by the L1B processor - hence the L2B processor did not use it. Blue (0) means the measurement-bin is OK.

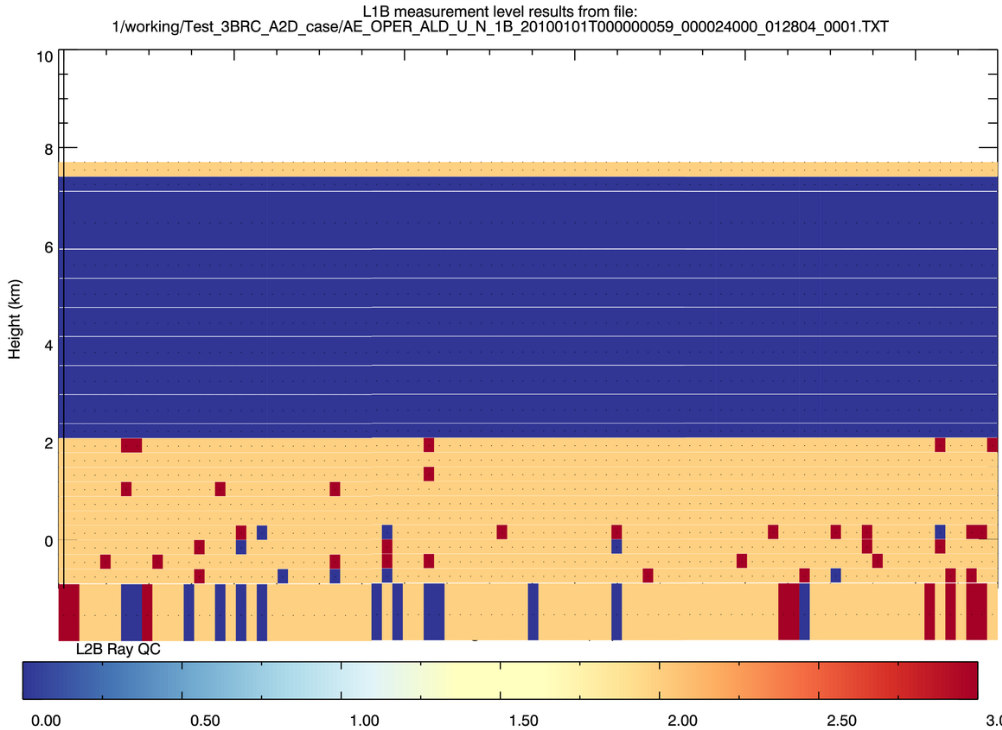


Figure 18. L2B Rayleigh QC on the measurement-bin level. Red (3) corresponds to the measurement-bin Rayleigh L1B Channel B SNR estimate being out of range and similarly for Channel A in peach (2). Blue (0) means the measurement-bin is OK.

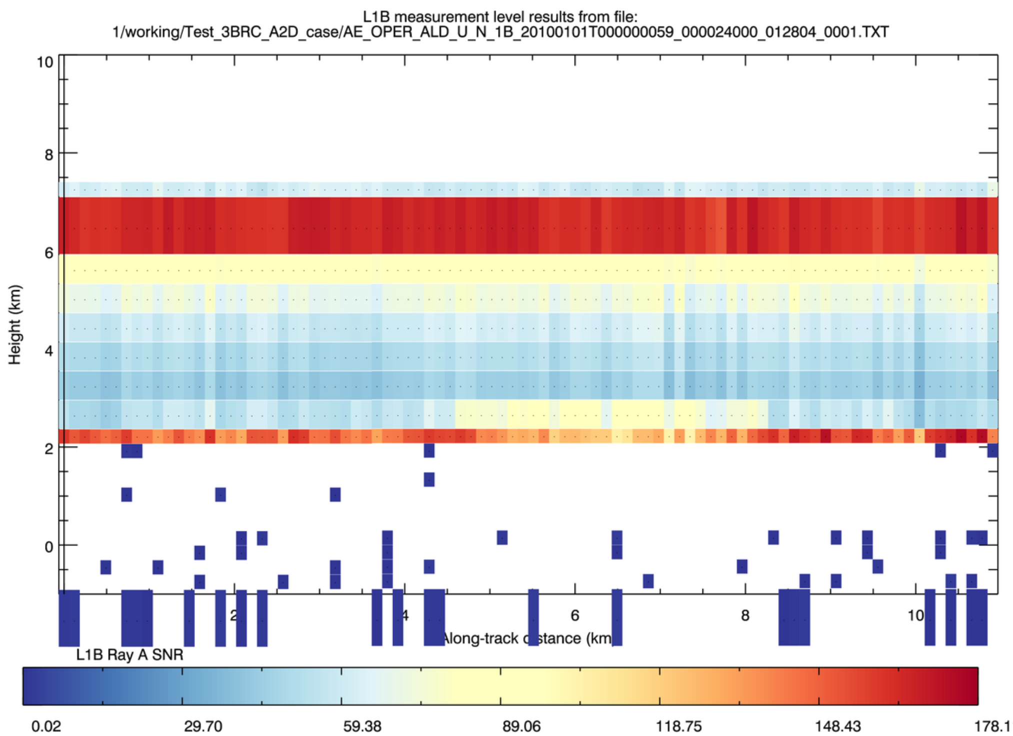


Figure 19. L1B measurement-bin level Rayleigh channel A SNR estimate values.

By examining the L2B measurement-bin QC decisions in detail, a bug in the code was found: if rejected, the measurement-bin was always flagged as one type of decision, even though it could have been QC'ed for another reason. This emphasizes the benefit of looking at real data from A2D. This bug-fix is in L2Bp v2.10.

2.5 Conclusions from the initial testing with A2D data

The L1B processor product and the L2B product are behaving in the nominal way when processing this small three BRC example of A2D data. The quality of the results is reasonable given the limitations of the calibration data and other issues such as lack of the correct DEM data.

It can be argued that the testing done for this section is more than just a functional test. It helped to find a bug in the L2B processor related to QC decisions, with a larger sample (see section 3) we hope to make a more comprehensive evaluation of data quality that will help us in the preparations for the arrival of real Aeolus data.

The issues found with the L2B processing:

- If rejected, the measurement-bin is always flagged as one type of decision, even though it could have been QC'ed for another reason. This has subsequently been fixed.

3 Testing with more extensive A2D scenes

3.1 Introduction

The L1B team, in particular DH and UM provided some more A2D airborne campaign data converted to Aeolus L1B file format, as part of work defined under the L1B contract (CCN10, WP2220). The A2D measurements are from scenes which DLR has processed to winds with a reasonable accuracy (after significant effort on processing, calibration etc.) as reported in UM's thesis [RD10]. The scenes cover much greater swathes of the atmosphere than the 3 BRC example investigated in the first part of this technical note.

The data is available on the e-room under: AEOLUS > UPLOAD_DLR > CCN10 > WP22x0 > A2D-WVM-Data, which has several sub-directories for different A2D flights. This investigation focusses on processing the A2D L1B wind mode data up to L2B products and on verification of the quality of the wind results by comparison to the results of DLR in [RD10] or the ECMWF model (if appropriate). Two A2D datasets are considered:

- A2D_GREENLAND_COAST
    - 97 BRCs in mostly clear atmosphere with a jet stream at higher levels and katabatic winds near the surface. Flying in a south-westerly direction off the Southern Greenland coastline. Measurements made on 26/09/2009.
- A2D_ICELAND_NORWAY
    - The largest scene with 216 BRCs in partially cloudy atmosphere, with some wind shear. Flying in an easterly direction between Iceland and Norway. Measurements made on 1/10/2009.

Each e-room directory includes the L1A, L1B and associated auxiliary data. The L1B processor products are version 6.03 and were provided on the e-room in May 2014.

The L1B team also provided some A2D calibrations in L1B formats for use in the processing. Genuine A2D calibrations that are thought to be applicable to the chosen flights have been extracted to L1B products by the L1B team. These A2D IRC products are also available on the e-room:

AEOLUS > UPLOAD_DLR > CCN10 > WP22x0 > A2D-IRC-Data, of which there are two sub-directories:

- A2D_CAL1
- A2D_CAL2

Each sub-directory contains IRC files (e.g. AUX_RRC, AUX_MRC). The L1B team produced the A2D L1B wind mode products using the A2D_CAL2 calibration. Note that the L2Bp uses the MRC information (i.e. sensitivity, offset and non-linearity) provided via the L1B wind product; therefore the L2B products will also use the A2D_CAL2 calibration for the Mie processing.

The noise levels in the A2D calibration can trigger QC in the L1B wind mode processing i.e. because the L1B calibration processing includes checks for the monotonicity of the data, the calibration can be flagged invalid. If the calibration input is flagged invalid (as it was with A2D data), then the

L1B processor exits with an error. DH overcame this by manually editing the <Calibration_Valid> parameter in the AUX_MRC file, and the <Calibration_Valid> and <Ground_Calibration_Valid> parameters in the AUX_RRC file, by setting the values to TRUE rather than FALSE: hence the L1B processor can run with the real (but non-monotonic) A2D calibrations.

For Rayleigh processing, the L2B processor requires an AUX_RBC_L2 file and an AUX_MET_12 file. For functional testing the AUX_RBC_L2 file can be generated via the calibration suite running on an E2S simulation, however to attain accurate wind results comparable to those in [RD10] then the calibration needs to be appropriate for the specific A2D flights. Using a correct AUX_MET_12 file is a second order source of error to correct.

To generate a reasonable A2D AUX_RBC_L2 file requires an A2D ISR file i.e. requires knowledge of the A2D instrument A and B Rayleigh transmissions functions as a function of relative frequency. In June 2014 UM updated the A2D ISR ASCII files with new columns for the energy, the number of pulses, and the Fizeau signal. DH in turn updated the tool that reformats the data into EEF, and also added a few lines to scale the Fizeau signal with the energy and some plot functionality. The tool and the reformatted ISR data are available on e-room under UPLOAD_DLR > CCN10 > WP22x0 > A2D-ISR-Data

The L1B team added another ISR: A2D_ISR4 which was measured closer in time to the Greenland flights. Unfortunately this data has larger frequency steps than usual, at 250MHz.

AD provided two AUX_RBC_L2 files derived from the A2D ISRs (A2D_ISR1 and A2D_ISR4). In both cases a functional fit to the ISR transmissions was performed (which reduces the effect of the noise in the A2D ISRs, the alternative resampled (no functional fit) ISR versions have not been tested in this investigation). Étendue effects were not considered in the generation of the AUX_RBC files, because the calibration software is only suitable for ALADIN étendue effects which differ from A2D étendue effects i.e. **no attempt was made with the CSR updater to fit to a measured A2D RRC**.

Finally, it is important to note that the *Data_Source* tag in the AUX_PAR_1B file was set to *A2D* when processing the L1B wind products. This should make the L1B processor calculate winds with the same sign convention of the Doppler shift as chosen by DLR for the A2D (the alternative, normal setting is *E2S*); see section 3.5.2 for some ramifications of this.

3.2 Steps needed to run the L2B processor

The L2B processor which is compatible with L1B v6.03 format is L2Bp v2.10 (released on 1st July 2014). A2D data is of course not equivalent to ALADIN data (nor E2S generated ALADIN style data) and hence the L2Bp did encounter an issue that needed resolving for it to run. The L1B product with the A2D MRC and RRC has 73 frequency steps, but the L2B processor had an allowed maximum of 60 (matching ALADIN expectations), therefore the L2Bp exited with an error message. This was easily bypassed **by changing the code to have an upper limit of 73 instead of 60**. After which the L2B processing ran OK. A recommendation w.r.t. this change is given in section 3.8 below.

Some QC threshold parameters required adjustment to obtain more sensible wind results. Such adjustments are not needed for the L2B processor to function (run). These parameters were mostly related to the RBC e.g. often $\partial HLOS/\partial \rho$ was found to be outside the expected ranges, presumably because the A2D Rayleigh transmission functions differ significantly from E2S simulated ALADIN. Ideally the expected range parameters should be moved to the AUX_PAR_2B file, since they may need adjustment in Aeolus' Commissioning Phase, and it would be highly inconvenient to have to update the operational code (hardcoded in hlos_retrieval.F90) as the Rayleigh spectrometer evolves (possibly) during the mission. This is recommended in section 3.8 below.

The L2B processing ran without problems for both extended scenes i.e. it produced a functional product (after the one change in the code mentioned above).

3.3 Known sources of error in the wind results

One source of disagreement between DLR's A2D wind results (as documented in [RD10]) and those of the L2B processor is that DLR's results are LOS winds and the L2Bp are HLOS winds. The L2B processor v2.10 does have an AUX_PAR_2B switch <Line_of_Sight_Wind_Flag>, which should allow calculation of LOS winds instead of the default HLOS winds, however this had no effect in the code i.e. the HLOS wind is always calculated — **this will be fixed in the next L2Bp version (v2.20).**

The HLOS winds were also incorrect for another reason: because the L1B geolocation information was found to have incorrect elevation angle values for the airborne campaign; i.e. the L1B products had ~37.5 degrees (i.e. Aeolus nominal values) rather than the correct ~20 degrees for these flights. Hence to obtain correct HLOS winds requires multiplication by a factor sin(37.5)/sin(20.0)=1.78, or to convert the results to LOS winds requires multiplication by sin(37.5)=0.61; such modifications could only be performed in post-processing (outside the L2Bp). The figures showing the L2bP retrieved winds in the remainder of this document do not contain these post-processing steps, but this limitation is considered in the discussion of the results.

The L1B product appears to report the correct azimuth angle (e.g. ~309 degrees for the Greenland coast flight and ~167 degrees for the Iceland to Norway flight, which agrees with the plotted flight direction in [RD10]), so this should be adequate for calculating NWP model HLOS (or LOS) wind equivalents if necessary.

3.4 Calibration for the flights

As discussed in section 3.1, the L1B processed A2D data (both flights) examined in this chapter used the calibration referred to as A2D_CAL2 (calibration 2) for the Mie processing. The L1B IRC data (i.e. RRC and MRC) of A2D_CAL2 is plotted in Figure 20 and Figure 21 respectively, along with the (assumed to be) same calibrations from [RD10]. The AUX_PAR_1B file indicates for the RRC that the height bins between 1 km and 5 km were co-added in atmospheric RRC production. UM had a comment about this:

"I wonder about the 1 km, because the A2D calibrations were performed over Greenland with ground at about 2 km or more, so 1 km should be below the surface."

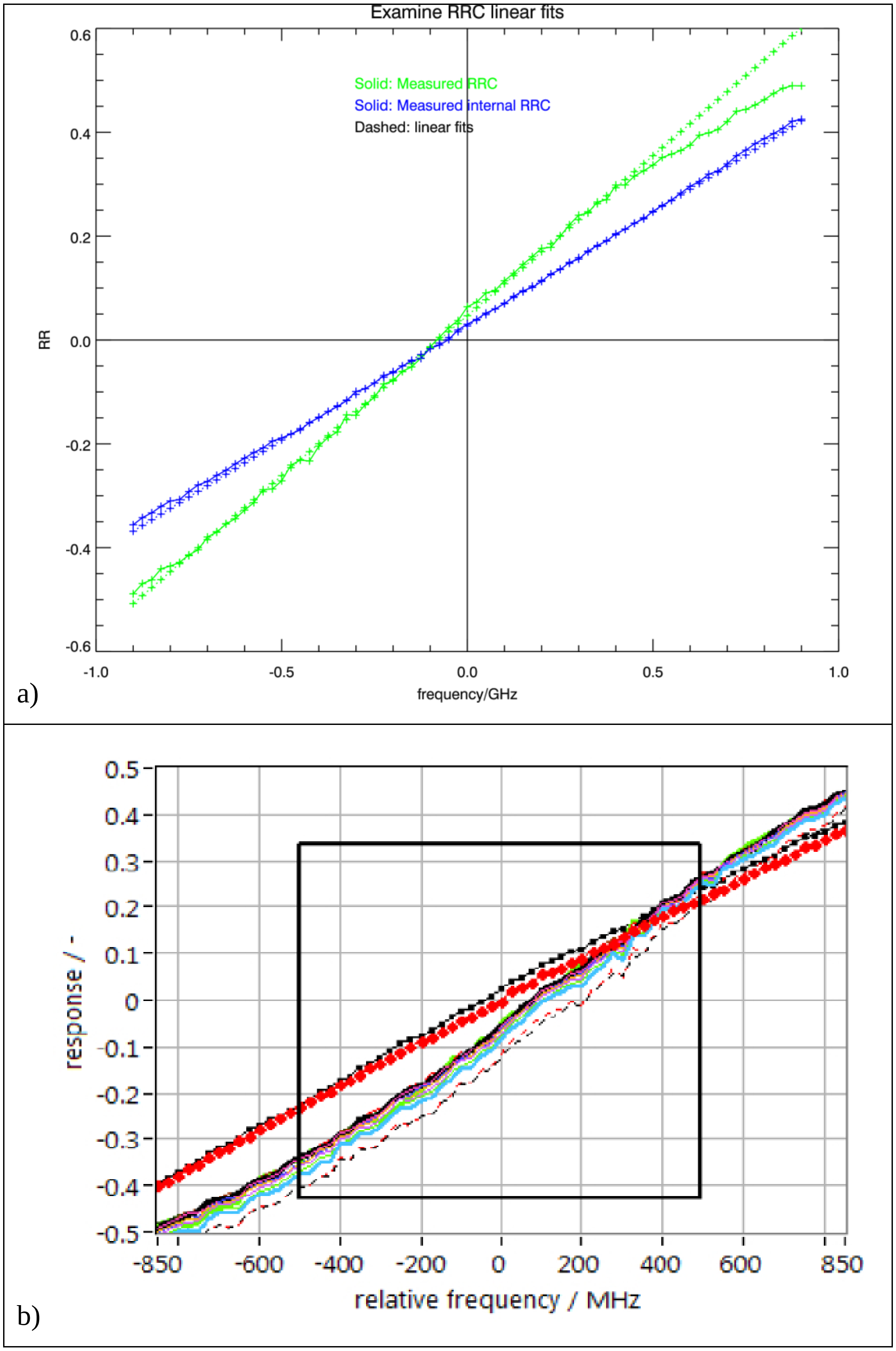


Figure 20. A2D_CAL2 Rayleigh response calibration (RRC) data from L1B product in a). The green lines are the measured (or atmospheric) RRC values, both the measurements and the linear fit. The blue lines are the internal reference calibration. DLR RRC from calibration 2 in b), courtesy of UM [RD10]. Red dots is internal reference. The band of curves lower down are atmospheric RRC for different range-bins.

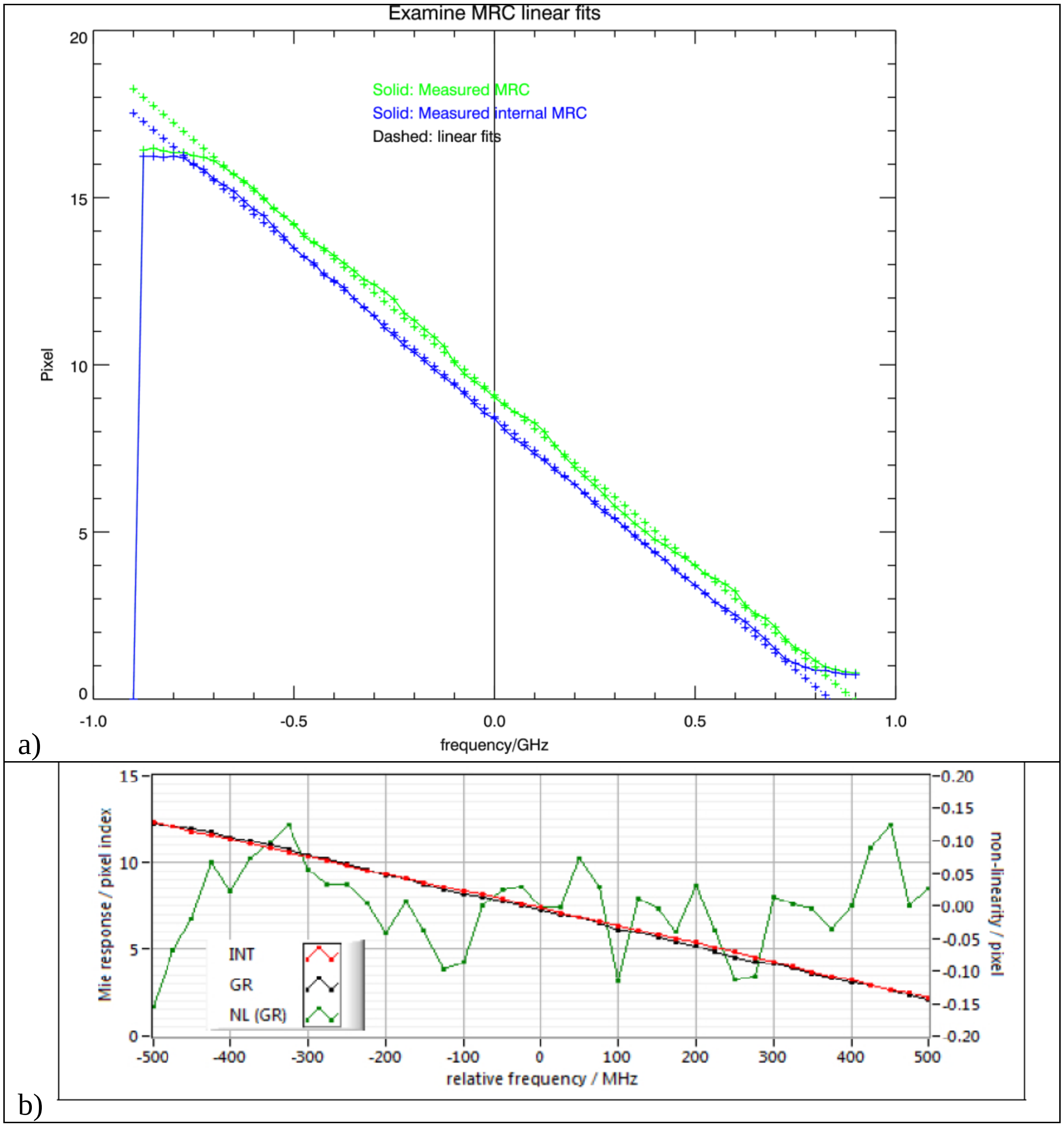


Figure 21. A2D_CAL2 Mie response calibration (MRC) data as in the L1B product in a). Similar definitions of lines to Figure 20. The A2D DLR equivalent is shown in b), courtesy of UM [RD10].

Some features of the AUX_RRC and AUX_MRC L1B products are discussed below:

- It would appear that the A2D calibration data is fairly noisy compared to what is typically seen for "noise-on" E2S simulations of ALADIN.
- The wobbles relative to the linear fit for the MRC look to have coherent deviations over hundreds of MHz. OR explained this: *100 MHz corresponds to 1 pixel. The 100 MHz oscillation is resulting from the* ***Mie non-linearity due to pixel non-linearity and Mie fringe non-linearity over the useful spectral range****. Thus it is not noise, but rather the result from the characterization of the MRC.* ***These types of non-linearities are present also for ALADIN but not simulated within the E2S.*** *Another contributor to the oscillation, which is only visible on*

the atmospheric measurements is the ***aircraft ground speed which has not been corrected*** *in this calibration data.*

- Some discrepancies between the A2D L1B calibration data and the same calibrations as processed by DLR (shown in [RD10]) exist:
  - The L1B product AUX_RRC from calibration 2 has a different offset value (a positive value) compared to the DLR derived curves from apparently the same calibration (which has a negative intercept), compare Figure 20 a) and b).
    - The L1B RRC (A2D calibration 2) has:

      <Measurement_Zero_Frequency unit="AU">0.046790</Measurement_Zero_Frequency>

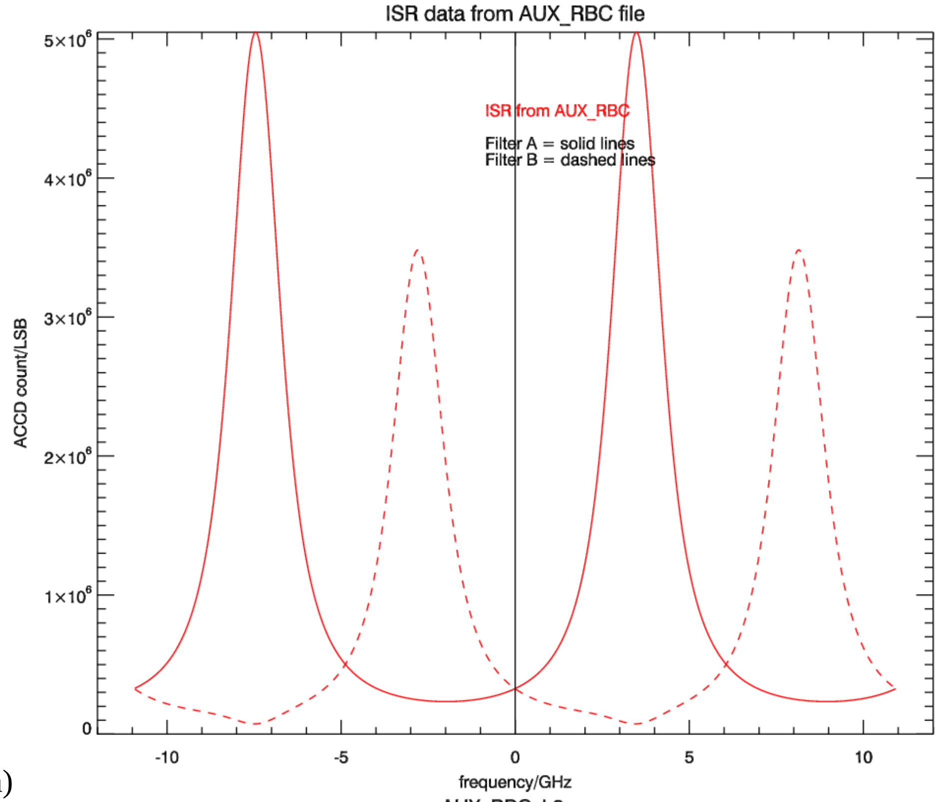
      whereas (the uncorrected) offsets in Fig 3.16 of [RD10] varies between around -0.05 to -0.12. These differences correspond to LOS wind errors of ~36 m/s.

      OR commented that:

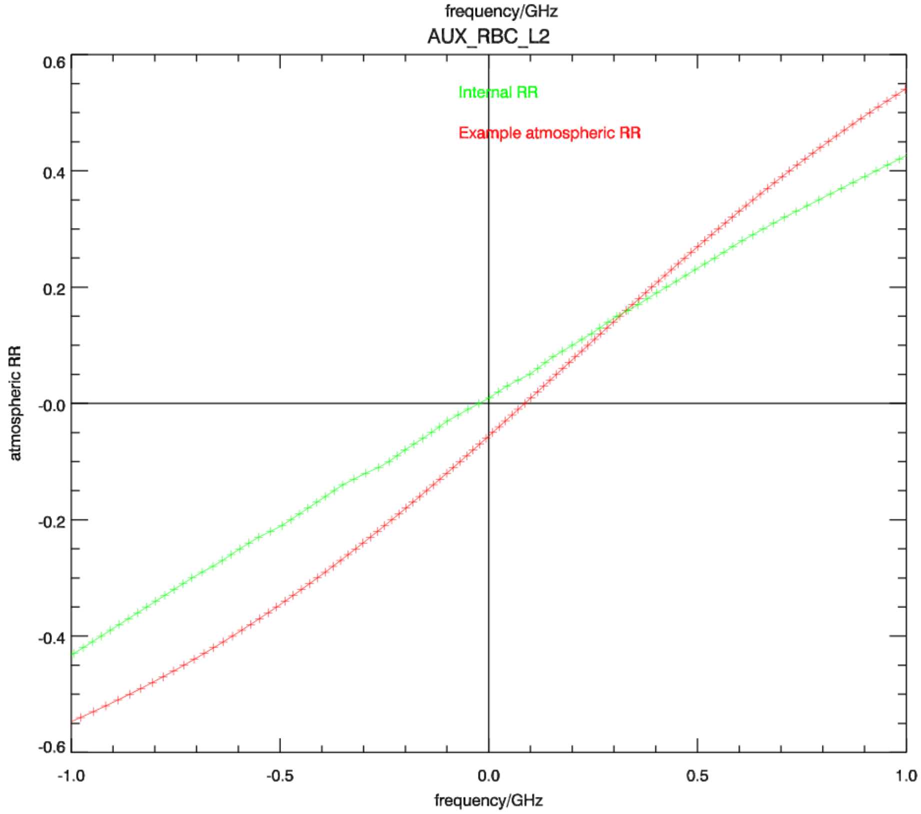
      "*The different offsets visible in* Figure 20 *top/bottom are due to the different definition of the 0-MHz frequency (reference frequency). If you would shift the 0-MHz to negative frequencies, so that the internal reference R=0, then it is more comparable. Even with that frequency shift, the blue curve is not around -0.1 as in fig. b), which is due to the aircraft ground speed on the LOS Doppler shift.*"
    - The L1B product MRC from calibration 2 has a large difference in the offset value (by about 0.66 pixels) of the internal reference and the atmospheric (ground) MRC curves, see Figure 21 a). This is not seen in the DLR processed calibration data: see Figure 21 b), where the offset is very similar. OR commented:

      "*This could be due to the fact that different range-bins are used for ground (sum of 2 for DLR´s processing see Fig. 3.12 from RD10). Also both the shift of atmospheric measurement response curves could be explained by the contribution of the aircraft ground speed (between 9-13 m/s) during the response calibration, which is corrected for in DLR´s processing (see p. 79/80, and Fig. 3.23 from RD10), but not corrected in the L1B data.*"
    - Such inconsistencies in the calibration will lead to large biases in L1B/L2B winds compared to DLR processed winds.

As discussed in section 3.4, for Rayleigh wind processing the L2B processor requires an AUX_RBC_L2 calibration file for use in the Rayleigh-Brillouin correction of temperature and pressure effects. An example of the contents of AUX_RBC_L2 file derived from A2D ISR 1 is shown in Figure 22.



a)



b)

Figure 22. a) Fitted transmission functions (A and B) for A2D ISR 1. b) The internal RR curve and an example atmospheric RR curve for an arbitrary temperature and pressure combination from the AUX_RBC_L2 file.

The simulated atmospheric/internal RR curves from the AUX_RBC_L2 derived from ISR 1 (Figure 22

b)) have a similar response cross-over value to A2D measured curves in Figure 20 b) from DLR processed calibration data i.e. between 0.1-0.2 response units. This disagrees with the cross-over response in Figure 20 a) from the L1B RRC file. OR had a comment on this:
"*This sustains my argument regarding the aircraft ground speed. The L1B RRC is not correcting for the aircraft ground speed (and thus has an offset), while the ISR -> RBC chain is not affected by aircraft ground speed (if no étendue correction is performed).*"
Note also that the AUX_RBC_L2 derived from ISR 4 is fairly similar to that derived from ISR 1 (not shown here).

The ISR 1 data was measured under different conditions to the A2D wind datasets in this section. It was performed for the BRAINS campaign on Zugspitze, in January 2009. ISR 4 was performed on the ground at Keflavik airport in Iceland on the 22/09/2009 during the A2D campaign, and therefore is the ISR closest in time to the flights, but the conditions (RSP and MSP temperatures) were different.

An important issue for the L2B calibration strategy was noticed when investigating the A2D calibrations**: For the L2B calibration strategy, the calibration suite assumes the reference frequency (i.e. the 0 MHz on the frequency axis) corresponds to the same absolute frequency for both the ISR and IRC modes. If it is not, RRC results (as part of AUX_CSR updater) cannot be predicted from the ISR and potential étendue effects on the response of the double FP cannot be corrected.** The reference frequency of the A2D ISR is unlikely to match that of the A2D IRC, since they were performed at different times and in different conditions. This assumption (that reference frequencies match) is not valid for the Aeolus mission either since it is not planned (at least at the moment) to schedule the ISR with the IRC, there will be a significant time delay between the ISR and IRC, during which the reference laser frequency can drift by e.g. 60 MHz (peak-to-valley requirement for drift of absolute laser frequency during 1 week). **Therefore a new strategy for the calibration suite to assure that the ISR matches the reference frequency of the IRC is needed.**

Note that the A2D ISR, when extracted to L1B format, had the relative frequency zero point shift such that the zero frequency lies at the A and B transmission cross-point. DH reported in an email that:
"*The ISR A2D data comes with reference to absolute frequency. But this is not what we use in our Aeolus processing chain: for the Aeolus satellite the ISR file is determined against frequency offsets, offsets to the nominal laser frequency. Usually the 0MHz offset is the offset close to the cross-over point of the filter curves A and B. And I have assumed that also for the A2D the nominal laser frequency is the one closest to the cross-over point. So I have set the 0MHz offset step to that frequency, that was closest to the cross over in the particular A2D ISR measurement.*"

Note that the zero frequency reference has to be equivalent for the atmospheric and internal reference calibrations for a correct frequency change (Doppler shift) to be calculated. This is not necessarily a problem in the AUX_RBC_L2 generation (or for the use of this file) for the A2D data, since the internal reference and atmospheric responses were generated from the same ISR, and so the absolute frequency offsets will cancel out irrespective of the where the zero frequency is placed. **It would only be a problem if the CSR updater step is performed to assess the étendue effect, which requires matching the simulated RR to the actual measured RRC. The choice of the zero frequency reference by DH also explains why the L1B file versions of ISR 1 and ISR 4 are fairly similar, and hence why the resultant AUX_RBC_L2 files are similar.**

3.5 Greenland coast flight

A2D wind measurements were made on the flight between Keflavik (Iceland) and Kangerlussuaq (Greenland) between 11:50-12:29 UTC on 26/09/2009 when located off the east coast of Greenland (details can be found in [RD10], see page 105). The L1B files required for L2B processing were provided in the e-room directory: A2D_GREENLAND_COAST. The L1B dataset was processed successfully to L2B products given the steps employed in section 3.2.

The wind conditions during the flight are described in [RD10]. They are also shown in Figure 23, which is the ECMWF 3 hour forecast winds for two model levels near the top and bottom of the scene. The wind is generally blowing towards the A2D instrument (which was pointing to the right of the aircraft), and therefore positive LOS winds are expected (see section 3.5.2). The wind speed is fairly strong at 8 km altitude (around 40 m/s) and is in the range 16-24 m/s at 850 hPa in the vicinity of the flight path. Given the elevation angle of the A2D laser the LOS winds should be sin(20 deg)=0.34 multiplied by the horizontal wind speed values, i.e. 14 m/s and 7 m/s LOS winds for the two levels respectively. These values are in the same range as the DLR processed A2D and 2 micron LOS winds as shown in Figure 24 (which is a copy of the results from [RD10]).

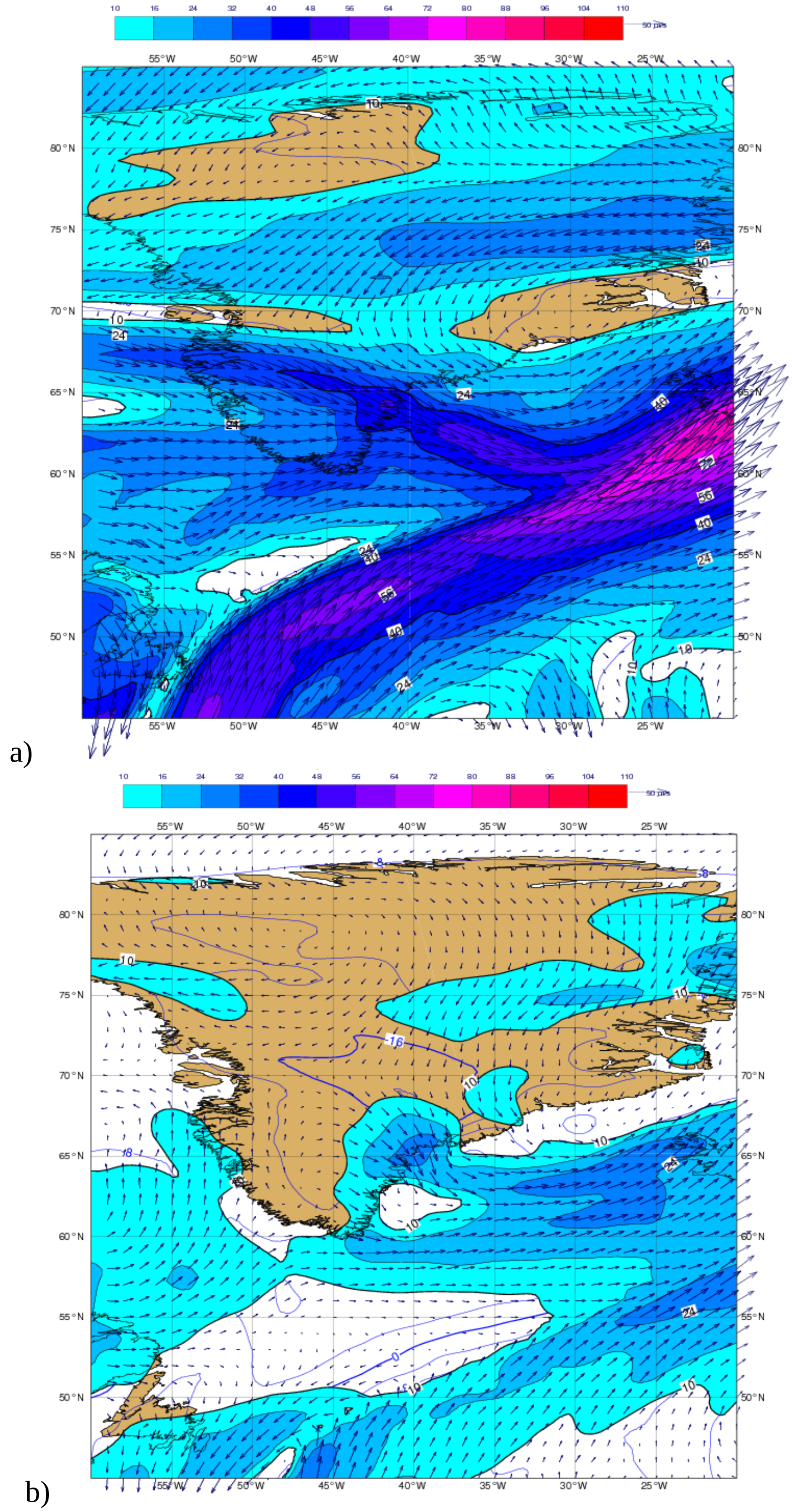


Figure 23. ECMWF model forecast (3 hours) winds (arrows and isotachs) on 26/09/2009 at 12 UTC at level a) 300 hPa (~8 km above mean sea level) and b) 850 hPa (~2 km above mean sea level). Shaded contours indicate wind speed (m/s) > 10 m/s.

3.5.1 DLR processed results

For comparison to the L2B processed A2D results, the results generated by DLR are reproduced below.

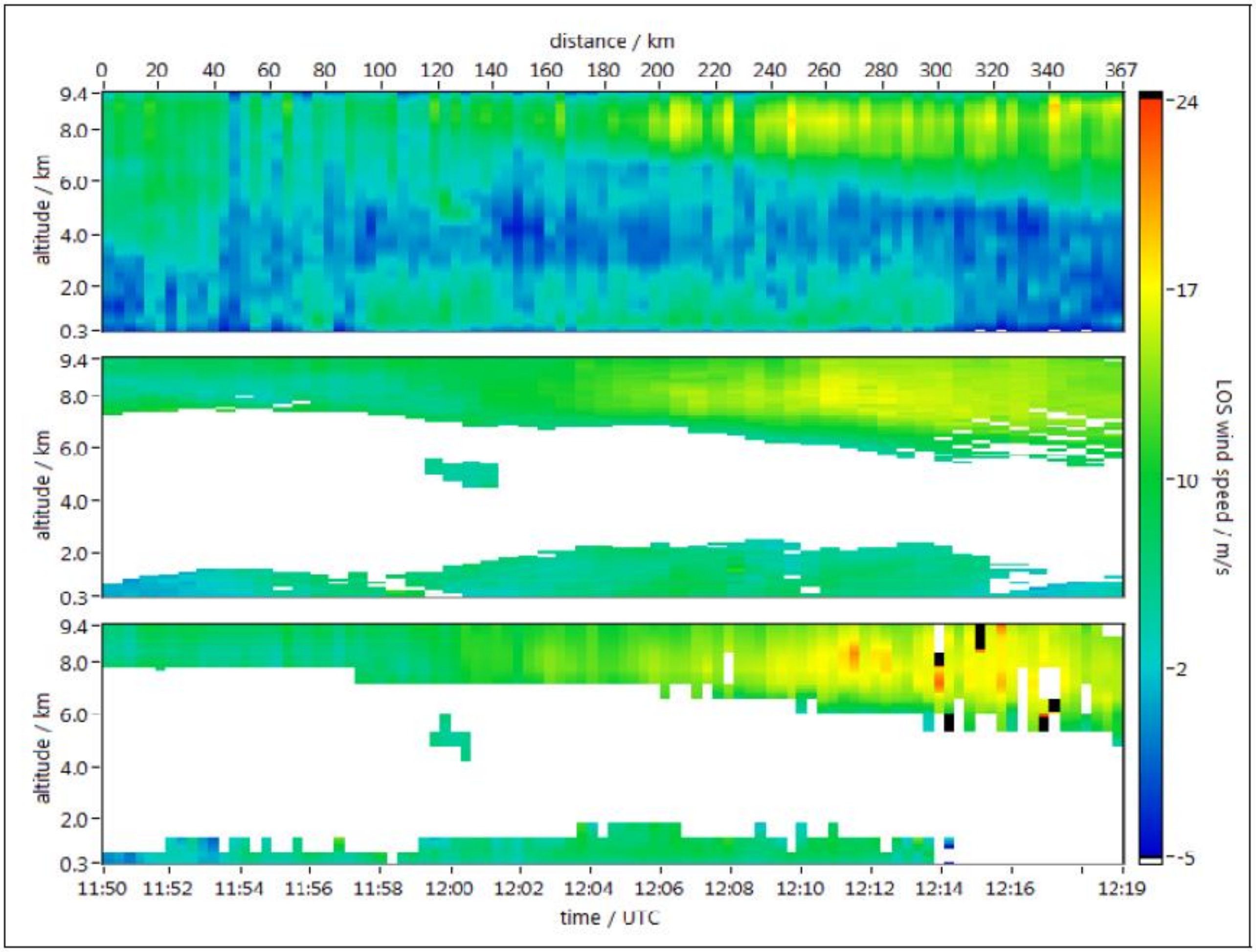


Figure 4.7.: LOS wind speed as measured on 2009/09/26 between 11:50 - 12:19 UTC from A2D Rayleigh channel (top), A2D Mie channel (bottom) and 2-µm Lidar (middle). A2D winds are interpolated onto a 100 m vertical grid. Valid Mie and 2-µm winds are present between 2 km to ground and 6 km - 10 km. White colour and black bins represent invalid winds due to low aerosol signal. Measured LOS wind speed ranges from minimum -5 m/s to maximum 24 m/s.

Figure 24. A copy of the DLR processed A2D results from the Greenland cost flight from [RD10]. Courtesy of UM [RD10]

3.5.2 L1B and L2B processed Mie results

Upon first inspection, the L2B Mie results, see Figure 25 b, from this A2D flight appear physically plausible. That is for parts of the scene at least the L2B processing must have functioned OK. Note that these type of **plots show all wind results, irrespective of L2Bp or post-processing QC decisions**.

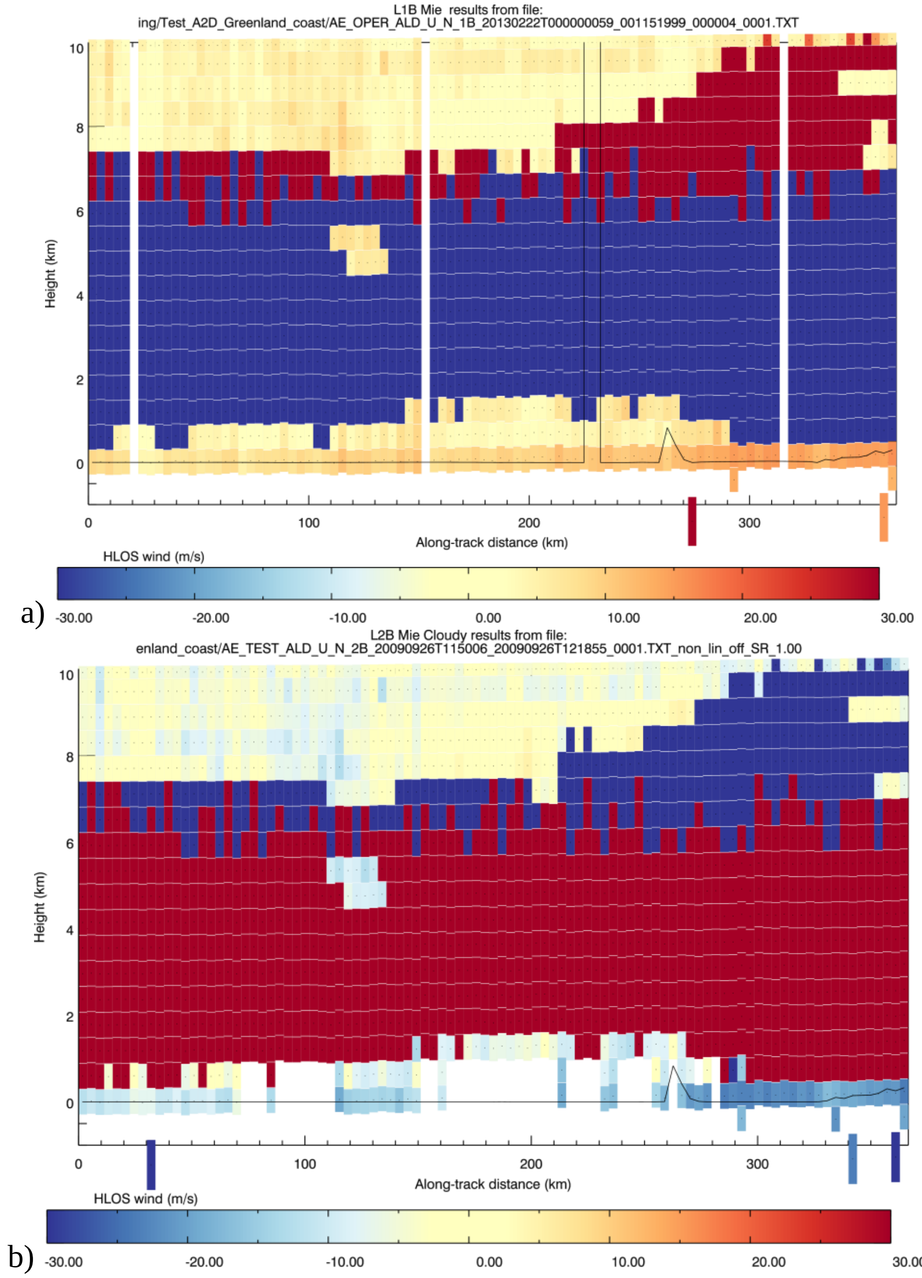


Figure 25. Mie wind observations for the A2D Greenland coast case a) L1B and b) L2B Mie-cloudy. All non-missing wind results shown i.e. disregarding QC.

Also the winds agree to some extent with the A2D DLR processed Mie results (bottom plot of Figure 24). Some features of the L2B Mie results in common with the DLR processed winds are:

- The katabatic winds near the ocean surface are more negative than the winds at 8-10 km
- The agreement on the absence of valid winds from 1-8 km (there appear to be gross errors in this range), except from a small area of cloud around 120 km along the track at 5 km altitude. Some discussion on the invalid winds comes later.

However there are some noticeable disagreements between the L2B Mie winds and DLR's:

- The L2B Mie winds appear to be negatively biased relative to the DLR winds by around 10 m/s. However note that the L2B Mie observations are HLOS winds (and calculated using the wrong elevation angle). So multiplying the L2B results by sin(37.5)=0.61 to make them LOS winds which may improve the bias relative to the A2D DLR results. However, the bias seems to be more of an offset issue rather than a multiplicative factor. This bias may be due to the difference in offsets of the internal and atmospheric calibration of the L1B MRC seen in Figure 21, compared to the DLR MRC. The offset difference is around 0.66 pixels, which roughly translates to 0.66 pixel*98 MHz/pixel=64 MHz = 11 m/s LOS wind, so pretty close.
- There are many extreme values (< -30 and > 30 m/s), which are obviously gross errors in L2B and L1B results, where the A2D DLR results are absent (missing values, due to QC of A2D Mie winds in the DLR processor with a SNR threshold, Fig. 3.31 [RD10]). These L2B wind "observations" are actually being produced from basically no signal and a judgement is needed as to whether these results should be included in the product: see section 3.6.2 for a more detailed explanation of what happened for these invalid winds (the same issue occurred for the Iceland to Norway flight). Note again that the L2bP QC is ignored in these types of along track versus altitude plots, so that all non-missing wind results can be assessed.
- An area of positive LOS winds in the A2D DLR results at near 8 km for the final quarter of the scene seems to be absent from the L2B and L1B Mie results (or at least occupied by gross errors). OR had no explanation for this. UM said that the SNR was very low for this area (~3); **this leads to the question of what is it the DLR algorithm doing that allowed sensible winds to be retrieved, whereas the L1B and L2B processors produced gross errors.**

The L2B Mie winds can also be compared to the L1B Mie winds which are given in Figure 25 a). There is an obvious disagreement with the L1B Mie Results: a sign mismatch. There is an anti-correlation between the L1B and L2B Mie winds i.e. more positive L2B winds coincide with more negative L1B Mie winds, and the L2B winds tend to agree more (in terms of horizontal shear) with the DLR results. The source of this mismatch was investigated further as explained in the following paragraphs.

Firstly, the L2B Mie core algorithm was confirmed to be using the same MRC information as the L1B processor, from A2D_CAL2 L1B MRC file. The atmospheric calibration sensitivity and offset were found to be also similar to those values reported in [RD10] (although not a perfect match). Various L2B settings were teseted to see if the L1B results could be matched. In the process, it was discovered that the L2Bp AUX_PAR_2B setting switch called *skip_Mie_nonlin_correction* had no effect on the results because although the setting was read correctly, it had no effect in the L2B code, as the **setting was hardcoded to `.FALSE.`; a bug which has now been fixed**. After the fix it was noted that the non-linearities (which are seen in Figure 21 a) of the A2D MRC can make a large difference to the A2D L2B Mie results (and it was therefore switched off, so at least it is comparable to the L1B settings). But this did not explain the sign error.

After consulting with the L1B team it was discovered the sign mismatch between L1B and L2B Mie winds is related to definitions of the LOS wind. The sign of the LOS wind calculation can be defined to be either:

1. $\frac{\lambda}{2}(f_{meas} - f_{ref})$ or 2. $-\frac{\lambda}{2}(f_{meas} - f_{ref})$

The L1B and L2B processors apply formula 2, which agrees with the definition of the LOS wind for Aeolus ALADIN defined in the L1B MAD: "*... assume that a positive wind velocity is one where the wind is directed away from an observer on the spacecraft*". DLR states that for A2D: "*A wind blowing towards the laser as positive",* and [RD10] applied formula 1. Therefore the Aeolus satellite and A2D definitions of LOS wind disagree on the sign convention.

But this does not explain why the L2B winds match the sign of the DLR winds (more than L1B) given their formulae disagree. The L1B processor settings (AUX_PAR_1B) had <data_source>A2D</data_source> for this case. DH said that this switches the sign of the frequency shift calculation to agree with the A2D DLR's definition, but confusingly this has made the L1B winds disagree with the A2D DLR results of Figure 4.7 of [RD10]. It was confirmed that if the A2D L1B product is re-processed with an AUX_PAR_1B with <data_source>E2S</data_source> then the L1B and L2B Mie winds agree in terms of the sign with each other and with the DLR A2D results. The same issue occurs for the Iceland-Norway flight which is discussed in section 3.6. **As to why the A2D DLR winds agree best with the L1B when the <data_source> set to E2S is an unresolved issue.**

Due to a lack of L2B Mie-cloudy results when using the original L2B settings, the SR threshold was reduced from 1.15 to 1.05. This gave many more Mie-cloudy results (i.e. measurements with SR > 1.05), and gave a greater spatial coverage more in line with the L1B results.

In conclusion, the L2B processed A2D Mie results have some agreement with the DLR results in terms of wind shear (i.e. how the winds change both horizontally and vertically), but they are negatively biased by around 10 m/s which is apparently because of a calibration problem in the L1B MRC (calibration 2) file. Until such biases can be resolved, it is not worth doing more quantitative verification against DLR results or NWP model equivalents. OR commented:

"Another source of bias for both the Mie and Rayleigh processed winds, is the correction with aircraft ground speed (on the LOS) in the wind mode, which was between 4 to -4 m/s (for 26/09) see Fig. 5.6 (RD 9). But I agree to your conclusion, that the 10 m/s bias arises probably from the L1B MRC."

3.5.3 L2B processed Rayleigh results

Upon the first inspection of the Rayleigh L2B HLOS wind results, an absence of Rayleigh-clear winds and the abundance of Rayleigh-cloudy winds was noticed. For the classification into clear/cloudy a SR threshold of 1.15 was initially used. The lack of Rayleigh-clear winds resulted from very few L1B measurements having a refined SR less than 1.15 (i.e. what we define as clear). The L1B refined SR, rather than the L1B nominal SR is used for classification because it has smaller bias (at least with E2S simulations, see [RD11]). This was resolved by changing the SR threshold to 2.0, which produced a full set of Rayleigh-clear winds. **A mismatch between the SR thresholds for obtaining good Mie-cloudy (previous section) and good Rayleigh-clear results may need to be addressed in future processors versions, e.g. by having separate settings for each channel.**

The first processed results were produced with an AUX_RBC_L2 file derived from an E2S simulated calibration. The HLOS winds were found to be very biased compared to the DLR processed results which are shown in Figure 24 (top plot). It was therefore assumed that a more appropriate calibration for A2D was required; therefore an AUX_RBC_L2 file derived from the A2D_ISR4 as provided by AD was tried instead (see the discussion of section 3.4). However using this A2D derived calibration made the results worse: mostly the HLOS winds were less than -30 m/s or missing.

To fill some gaps which were found in the wind results cross-section (i.e. where missing values for wind were reported), some adjustments to the L2Bp QC thresholds were required. To increase the number of valid Rayleigh wind results required a change in the allowed threshold on `dRR_drho_max` (maximum allowed gradient of Rayleigh response with respect to scattering ratio) from 5.0 to 7.0. Also it was found that the threshold value in screening of the measurement Rayleigh response had to be adjusted, from -0.4 to -0.92. These changes were needed because the FP transmission function positioning on the relative frequency axis has changed considerably compared to the nominal settings for E2S simulated ALADIN. **These thresholds are hard-coded; therefore for flexibility it is recommended to move such settings to the AUX_PAR_2B file in future releases.**

The A2D_ISR1 derived AUX_RBC_L2 file provided by Alain was tried instead, however the results were quite similar to A2D_ISR4; the L2B Rayleigh-clear HLOS wind results are shown in Figure 26 b). This implies that the relative frequency difference between the internal and atmospheric Rayleigh responses from both AUX_RBC_L2 files (A2D_ISR_1 and A2D_ISR_4) must be similar (the absolute frequency differences cancel in the atmospheric minus internal calculation).

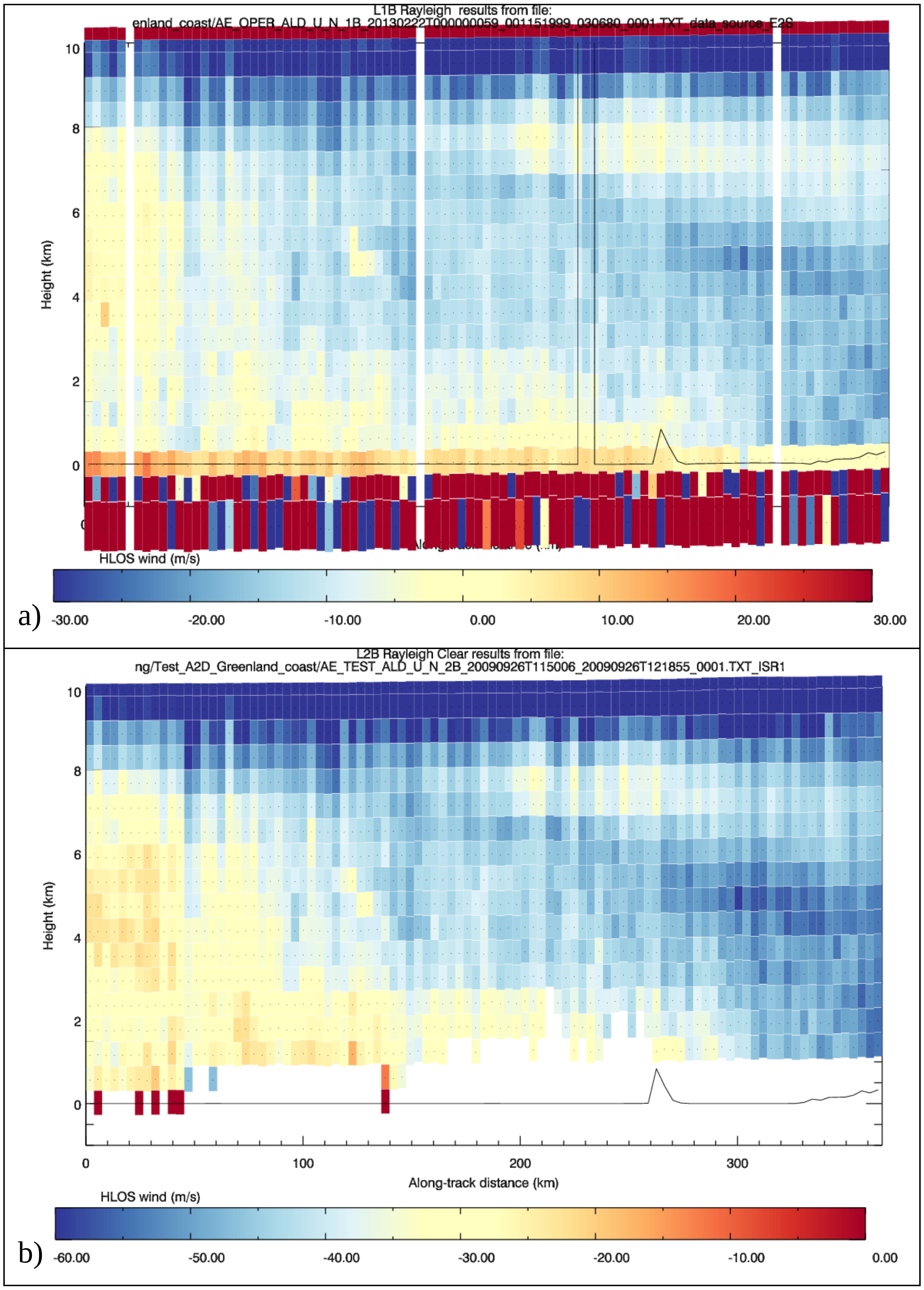


Figure 26. Rayleigh wind results for A2D Greenland coast case. a) L1B processed Rayleigh HLOS winds (data source set to E2S) b) L2B processed Rayleigh-clear HLOS winds. Note that the HLOS wind colour scale is shifted by - 30 m/s in b) relative to a). All non-missing wind results shown, irrespective of QC decisions.

For comparison to the L2B results, the L1B processed Rayleigh HLOS winds are shown in Figure 26 a). Note that the HLOS wind scale is -30 to +30 m/s in a) and -60 to -30 m/s in b), this was needed because the **L2B winds are biased by roughly -30 m/s relative to the L1B**. This is due to inconsistencies in the A2D L1B RRC and the AUX_RBC_L2 calibrations. **Note that the L1B HLOS winds used the RRC of Figure 20 a) i.e. A2D calibration (IRC) 2. Also, the L1B settings had data_source set to E2S, which explains why the L1B sign agrees with the L2B winds**. The L2B wind observation results have filtered out the ground returns better than the L1B observations, since the L2Bp rejects measurements affected by suspected ground return signals (N.B. the L2Bp uses the L1Bp measurement-level QC regarding ground-return contamination).

Despite the bias between L1B and L2B, there is a clear correlation in the HLOS winds, in terms of the vertical and horizontal gradients in wind. When comparing the L1B/L2B results to the DLR processed winds of Figure 24 (top plot), the first impression is that there is not much correspondence between the results at all, however on closer inspection some of horizontal wind gradients are similar.

The reason for the mismatch to the DLR winds in the vertical shear is thought to be because the A2D Rayleigh winds have a range dependent bias (resultant from sensitivity to angular incidence of RSP, which varies with range). The A2D Rayleigh calibration in Figure 3.16 of [RD10] demonstrates this effect; the offset becomes more negative with increased altitude, which creates a 15 m/s LOS (24 m/s HLOS with Aeolus elevation angles) difference in the wind between 3 km and 9 km altitude if not corrected for. This range dependent bias (and hence induced vertical wind shear) is not corrected for in the L1B and L2B processing at the time of writing. The levels of the range dependent bias are unique to A2D; a range-dependent bias exists for the Aeolus satellite but of different magnitudes/properties.

The bias (~30 m/s) of L2B relative to L1B winds is assumed to be due to inconsistencies in the A2D L1B RRC file and the AUX_RBC_L2 calibrations which were noted in section 3.4. However it is not understood why the L1B RRC calibration is apparently better (compared to DLR results) given that the AUX_RBC_L2 calibration curves appear to match the DLR calibration better. It may be coincidence due to lack of aircraft LOS velocity correction in the A2D RRC data and in the A2D wind mode data.

Other sources of disagreement may be the lack of étendue correction of the A2D ISR on generating the AUX_RBC_L2 file. Also the AUX_MET_12 file applied in L2Bp used does not have valid atmospheric profiles for the geolocations of the A2D flight and so the AUX_MET match-up method was set to “Dummy” to ensure a profile is provided for each BRC (even if not the correct T, p information). The A2D L2B wind results would need to be more accurate to justify generating an AUX_MET_12 file that matches the A2D geolocations. Using an appropriate AUX_MET_12 would give modest bias improvements of around 4 m/s compared to the overall bias of order 30 m/s.

In conclusion, the L2B Rayleigh winds correspond to the DLR results in the horizontal wind shear, but **the main obstacles to producing an accurate Rayleigh wind dataset is the calibration, the range dependent bias and lack of aircraft induced velocity correction**. Given the large biases it was decided not to compare the results to NWP equivalents or performing any data assimilation experiments.

3.6 Iceland to Norway flight

Another dataset of wind measurements was made on the flight between Keflavik in Iceland flying toward the Norwegian coast between 09:35-10:39 UTC on 1/10/2009 (details can be found in [RD10], e.g. on page 126). The scene has more than twice as many BRCs as the Greenland coast dataset.

The required L1B files for L2B processing were provided in the e-room directory: A2D_ICELAND_NORWAY. The dataset was processed successfully to L2B given the steps employed in section 3.2.

This scene included cloudier conditions than the Greenland coast flight and therefore should provide more Mie results for analysis. There was some high cirrus associated with a jet stream and low level convective cloud due to northerly flow over a relatively warm ocean, see Figure 27 and Figure 28 for the synoptic situation.

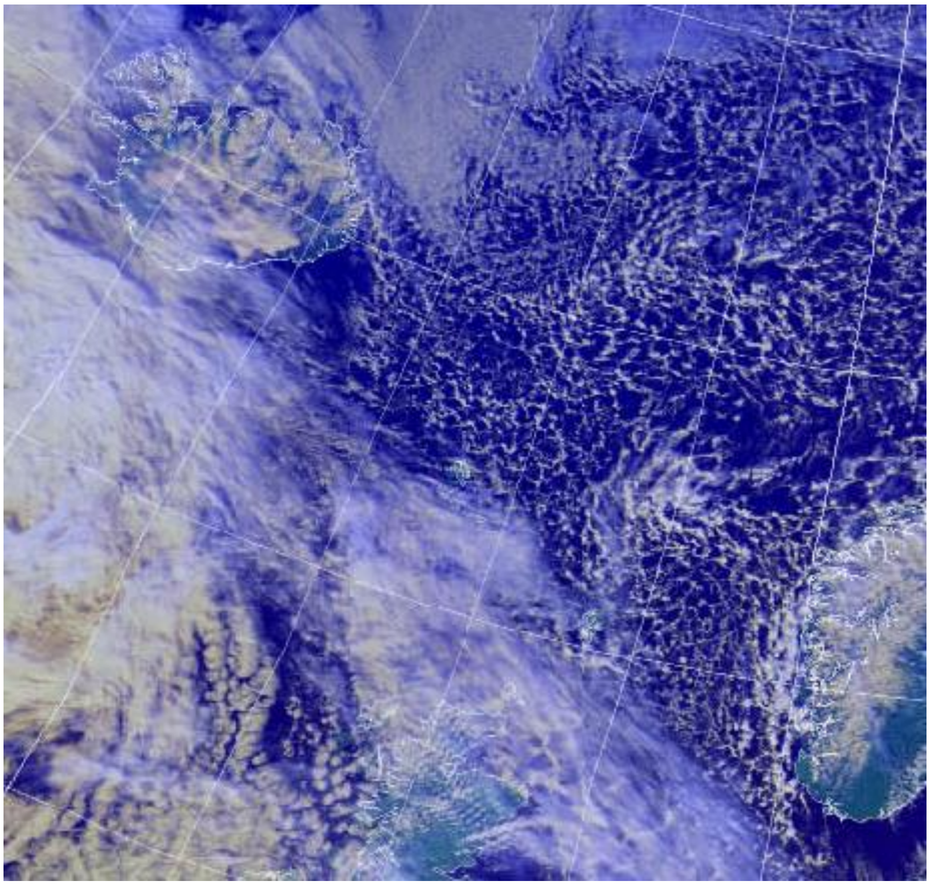


Figure 27. NOAA-19 satellite imagery at 13:10 UTC on 1/10/2009.

Figure 28 shows the synoptic situation (the UK Met Office analysis) at the surface, 9 hours before the measurements were taken - there is a north/north-westerly flow at the surface between Iceland and Norway.

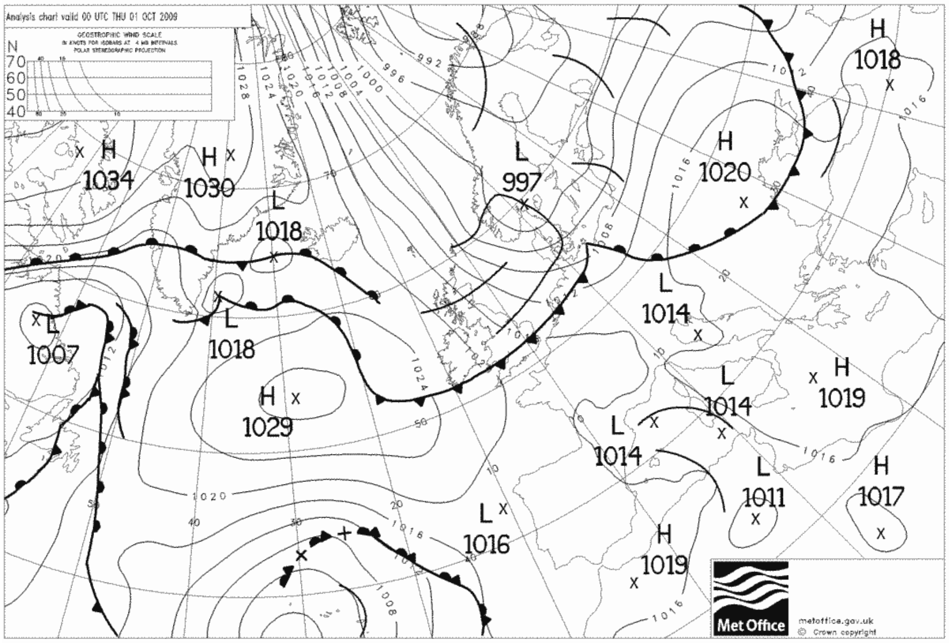
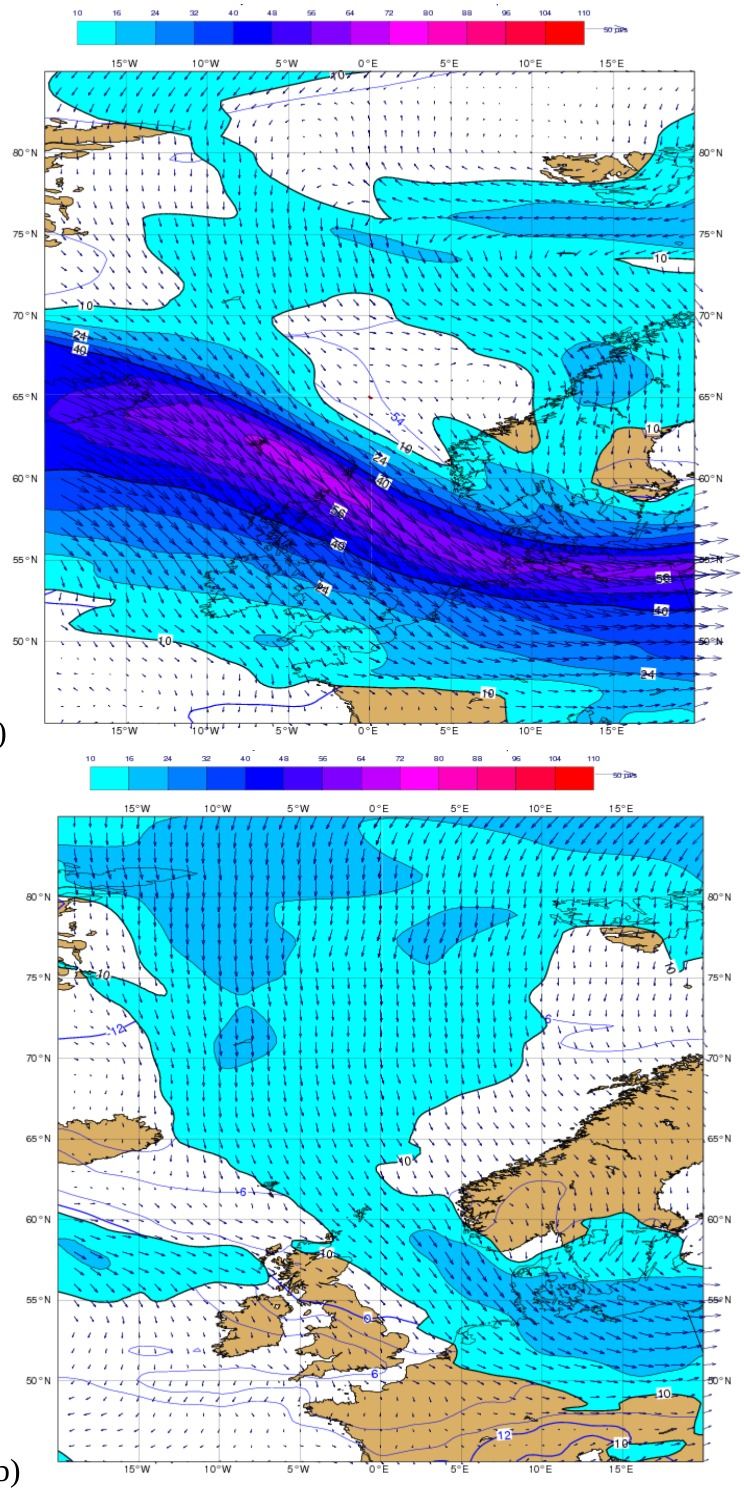


Figure 28. Surface pressure analysis chart for 00 UTC 1/10/2009. Courtesy of Met Office.

The 300 and 850 hPa ECMWF forecast wind at 12 UTC is shown in Figure 29. There is a north-westerly polar jet stream at 300 hPa directed from Iceland towards Norway i.e. approximately parallel to the aircraft flight direction.



a) b)

Figure 29. ECMWF model forecast (3 hours) winds on 1/10/2009 at 12 UTC at level a) 300 hPa (~8 km) and b) 850 hPa (~2 km above mean sea level). Shaded contours show wind speed; > 10 m/s.

Some clouds are present as indicated in the A2D L1B measurement level scattering ratio estimates as plotted along the flight track in Figure 30: there is a large SR feature (very likely to be cloud) at 8 km at the start of the scene (which might be associated with the jet stream near Iceland) and also at 5 km at 250 km along-track. Also there are highly variable optically thick cloud signals lower in the lower atmosphere (2-4 km), presumably the convective clouds that are seen in Figure 27. The L1B scattering ratio values are found to be adequate for L2B processor classification into clear and cloudy measurements, but the measurement level results seem fairly noisy compared to noise levels typically observed in E2S ALADIN simulations. A couple of possible explanations are: the A2D scene genuinely had low levels of aerosol leading to SRs slightly above 1.0, or the E2S simulation is missing sources of noise (quite likely). Occasionally the signals penetrate to the surface range bin, which would provide opportunity for a Zero Wind Correction. However, ZWC over the ocean is likely to be biased by vertical motion of surface waves [RD12].

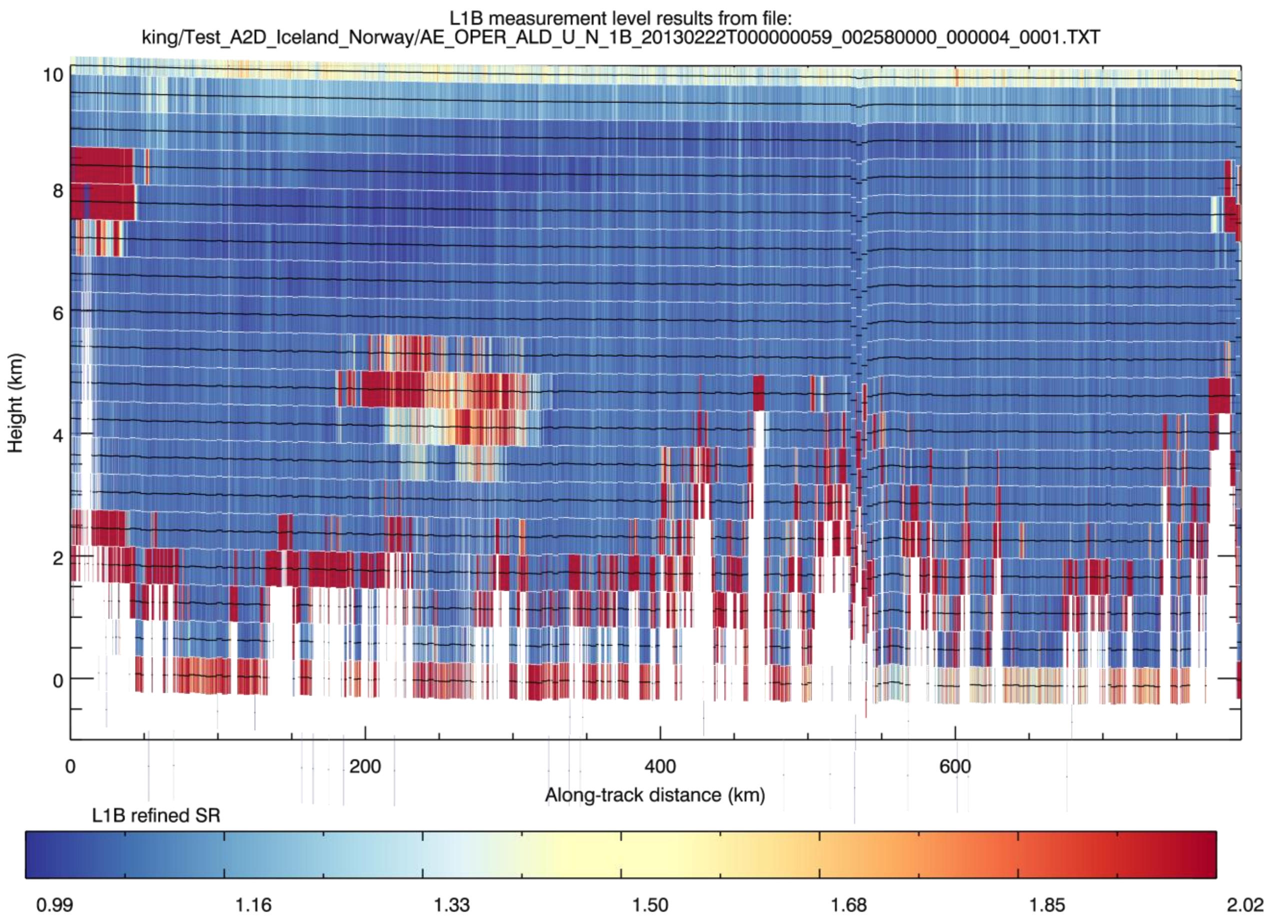


Figure 30. L1B measurement-level refined scattering ratio values from the A2D measurements on an Iceland to Norway flight. Such values are used in the L2Bp classification algorithm to distinguish cloudy and clear scenes. All non-missing results are plotted.

3.6.1 DLR processed results

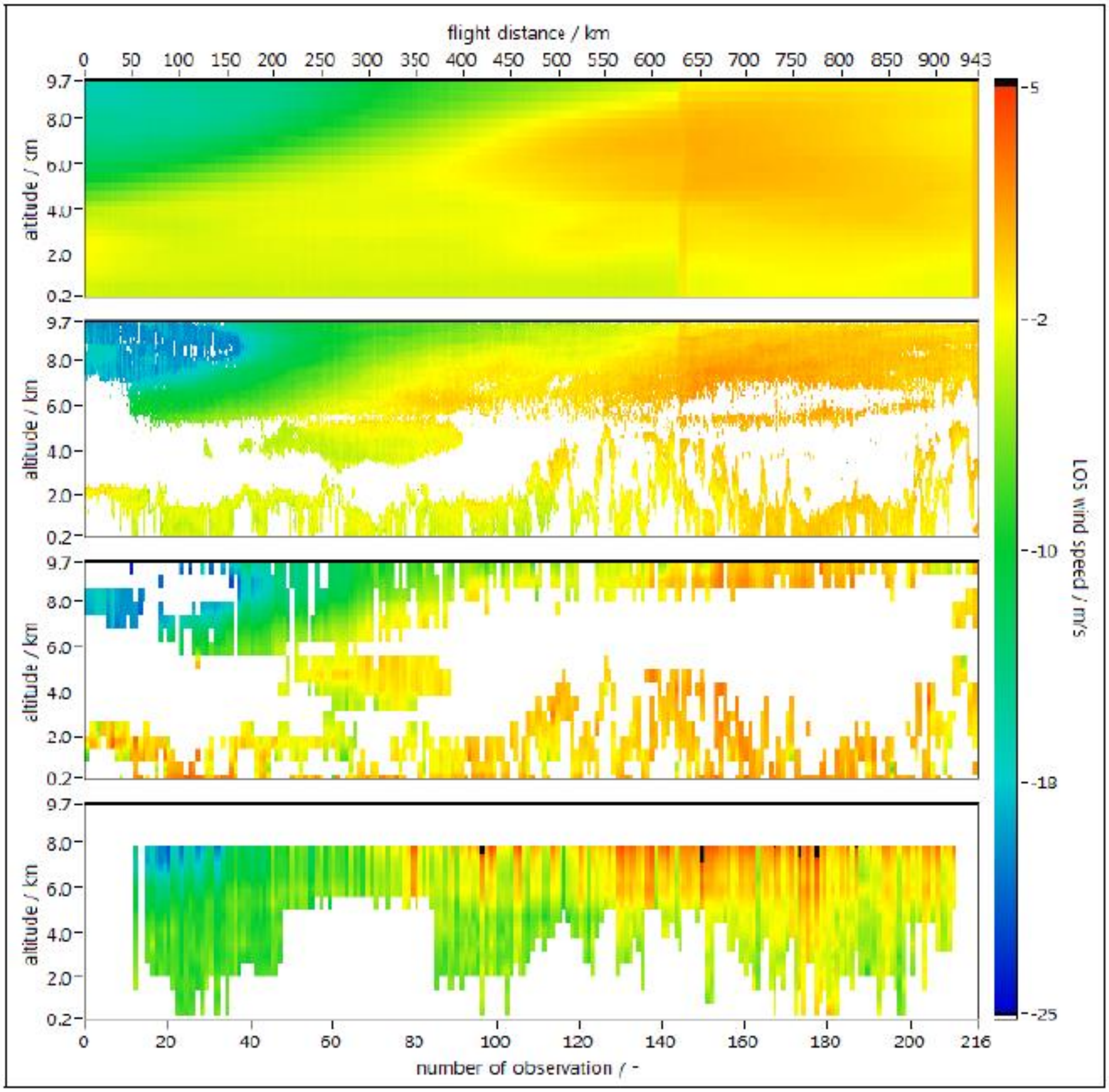


Figure 4.19.: LOS wind speeds as obtained on 2009/10/01 from ECMWF analyses (top) and measurements of the 2 µm Lidar (2nd from top), the A2D Mie channel (3rd from top) and the A2D Rayleigh channel (bottom). The altitudes of 9.7 km and 0.2 km approximately correspond to the upper/lower borders of the A2D range-gates #6 / #21, respectively. White colour represents invalid winds due to low aerosol signal (Mie channel) or to exclusion below clouds and in the region of the telescope overlap (Rayleigh channel). Measured LOS wind speed ranges from minimum -25 m/s to maximum more than 20 m/s (black, Rayleigh channel).

Figure 31. A copy of the DLR processed results for the Iceland-Norway flight from [RD10]. Courtesy of UM [RD10].

3.6.2 L2B processed Mie results

The L2B Mie-cloudy HLOS wind results are shown in Figure 32. These observations are based on a measurement classification using a 1.05 SR threshold (i.e. measurement bins with L1B refined SR greater than this value are used in retrieving the L2B Mie-cloudy observations). This low SR threshold was chosen to produce more observations near the aircraft (which have low aerosol loading, but large SNR). This setting produces results more comparable with the L1B and DLR processed Mie results (which do not attempt to partition measurements in cloudy/clear conditions). The Mie winds appear to be reasonably consistent with those of [RD10] (also shown in Figure 31, third from top) apart from the many gross-outliers (seen as dark red and dark blue colours, which also occurred for the Greenland coast case L2B results). Areas with gross errors are QC'ed (and hence missing) from the A2D DLR results. Note that the same issue with the L1B winds being anti-correlated with the L2B winds (and A2D DLR results) was seen in this case (as explained in section 3.5.2). The L1B wind results are not shown here.

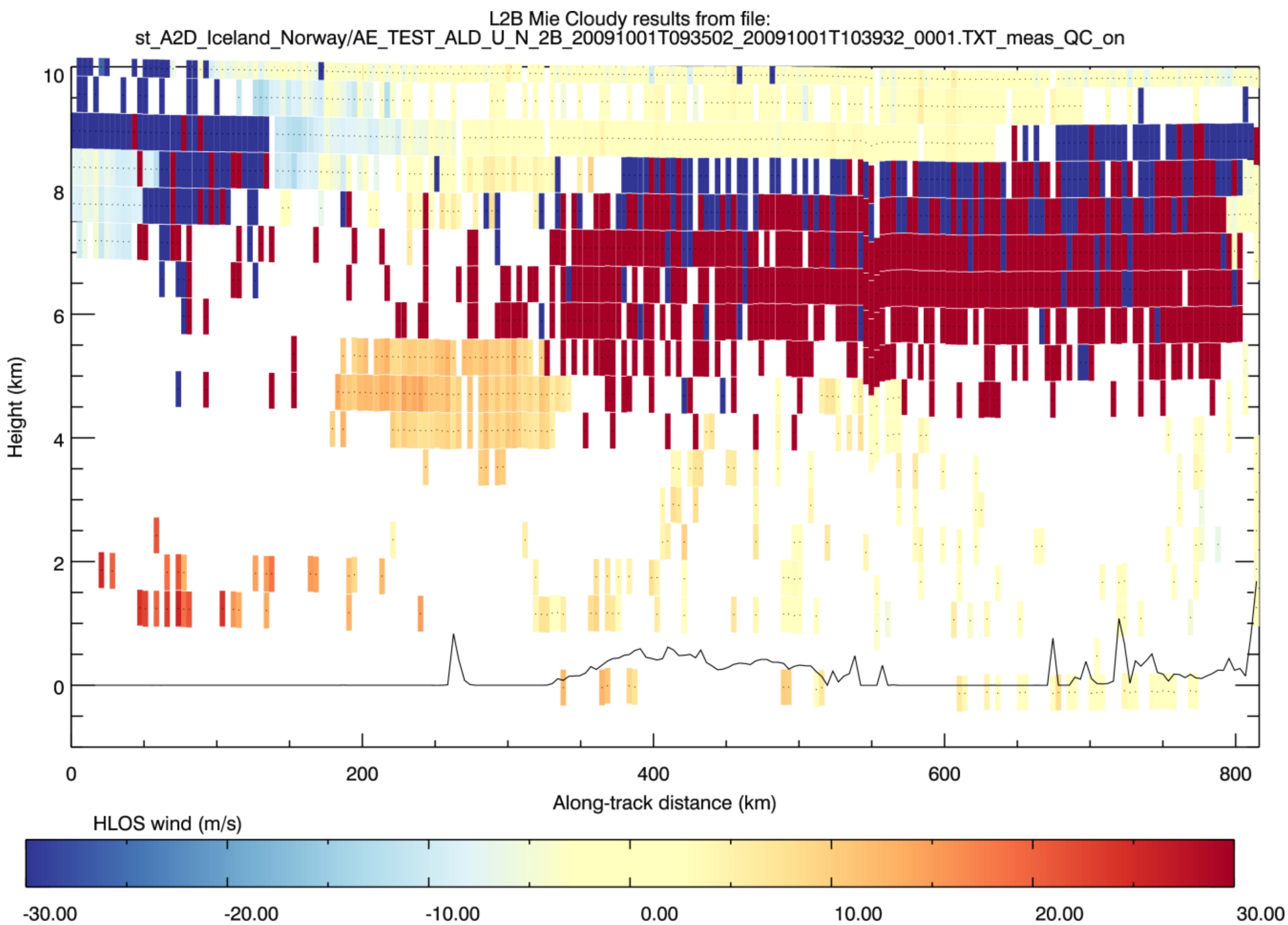


Figure 32. L2B Mie-cloudy HLOS wind results for the Iceland to Norway A2D flight. All non-missing results shown, irrespective of QC flags.

The L2B winds at around 8-9 km altitude can be seen to change from blue hues (i.e. negative HLOS) to smaller negative (yellow) values along the flight track, which is somewhat similar to the DLR processed A2D Mie winds (third plot down in Figure 31). These results agree with the flight path being more perpendicular to the jet stream (and hence the laser is more parallel) at the start position (hence winds are blowing away from sensor, i.e. negative LOS winds in A2D convention), and becoming less negative along the flight path as the aircraft moves away from strongest part of the jet stream.

The L2B winds from the cloud backscatter at 5 km (and ~250 km along-track) are around 5-15 m/s HLOS, whereas they are closer to 0 m/s in [RD10]. It is unclear why the L2B results are biased positively, the bias is inconsistent in sign with that of the Greenland coast case, which was negative by 10 m/s. Again, this is not helped by the L2B results being HLOS winds, whereas [RD10] are LOS winds. Therefore the L2B winds of Figure 32 should be multiplied by sin(37.5 deg)=0.61 to get the LOS winds. Despite these biases and hence most likely calibration issues (A2D calibration 2 has been used), qualitatively the results look reasonable from the L2B processing. OR commented that: *Another source of bias for both the Mie and Rayleigh processed winds, is the correction with aircraft ground speed (on the LOS). In addition a zero-wind correction was applied for this flight (p. 84ff of RD10), as you already mentioned. Note also that the zero wind correction for the Mie and Rayleigh channels were found to be different (m/s) in the A2D data analysis.*

There are many gross-outlier L2B wind results (as also seen in the Greenland coast results of Figure 25 b)) that are outside the normal colour scale of Figure 32. **These results were found to have negative values of observation level "refined SNR" due to the offset value (as estimated in Downhill simplex algorithm) being larger than the Lorentzian peak estimate**. This means there was no Mie peak to fit, and hence the data is simply noise. The L2B Mie QC *flags3* flagged these results because the SNR value is below the acceptable threshold (which was set to be around 10-17, varying with height). Also the L2B Mie QC *flags1* was set due to the Lorentzian peak height being lower than the allowed threshold from the AUX_PAR_2B settings. This goes on to trigger the *Overall Mie_validity_flag* to be set invalid (N.B. the SNR check does not influence this, which should be fixed). Perhaps if the SNR value is unphysical e.g. negative, then the HLOS wind should be set to missing in the L2B processor.

Perhaps these gross outlier Mie results are occurring because the SR was sufficiently noisy to be classed as cloudy measurements, when in fact there is no "real" Mie peak, however they do also occur in the L1B results which has no classification.

Some points worth noting about the L2B Mie QC flags:

- The currently chosen SNR threshold (10-17) is a little too strict i.e. some "good" Mie winds at the edge of the clouds are flagged for having too low a SNR. This is easily changed in the AUX_PAR_2B settings. The SNR is only good enough in clouds or very close to the aircraft to produce valid winds.
- The *internal* reference Offset value was always estimated to be a negative number e.g. -123 when the amplitude is rather large e.g. 11377. I do not know if this is a problem. The internal reference data is never flagged as "bad", which is not a surprise given the large signals.

The *Overall Mie_validity_flag* for the wind should be paid attention to by users, see **Error! Reference source not found.**, as this flags many of the gross-outliers. Another method to remove the gross-errors in the L2B wind results is to use QC based on the HLOS error estimate value as shown in **Error! Reference source not found.**. For example, if we reject any observation with error estimate >2 m/s then this would eliminate many of the gross-outliers mentioned earlier. Note that a rather low threshold of 2 m/s is needed because the Mie error estimator calculation currently neglects the radiometric gain factor.

3.6.3 L2B processed Rayleigh results

The L2B Rayleigh-clear HLOS wind results for the Iceland-Norway flight are shown in Figure 33. The calibration was the AUX_RBC_L2 derived from A2D ISR 1. The wind results look physically plausible, however they have only minor correspondence with the DLR processed wind results (and ECMWF winds) of Figure 31 from a visual comparison. Note that the results are very negatively biased compared to the DLR results, hence the scale is from -60 to 10 m/s.

The largest discrepancy in spatial pattern (wind shear) is seen between the relatively positive area below 6 km altitude, for the first 200 km along track for the L2B results, whereas this feature does not appear in the DLR results in Figure 31. The spatial pattern of the L1B Rayleigh HLOS winds is very similar to the L2B, except the L1B is positively biased by ~10-20 m/s compared the L2B results. **The A2D DLR results are corrected for a ZWC of 5.4 m/s**, but this does not account for the discrepancy as it is a constant correction. Again these L2B results should be multiplied by 0.61 to be LOS winds and hence more comparable with the DLR results.

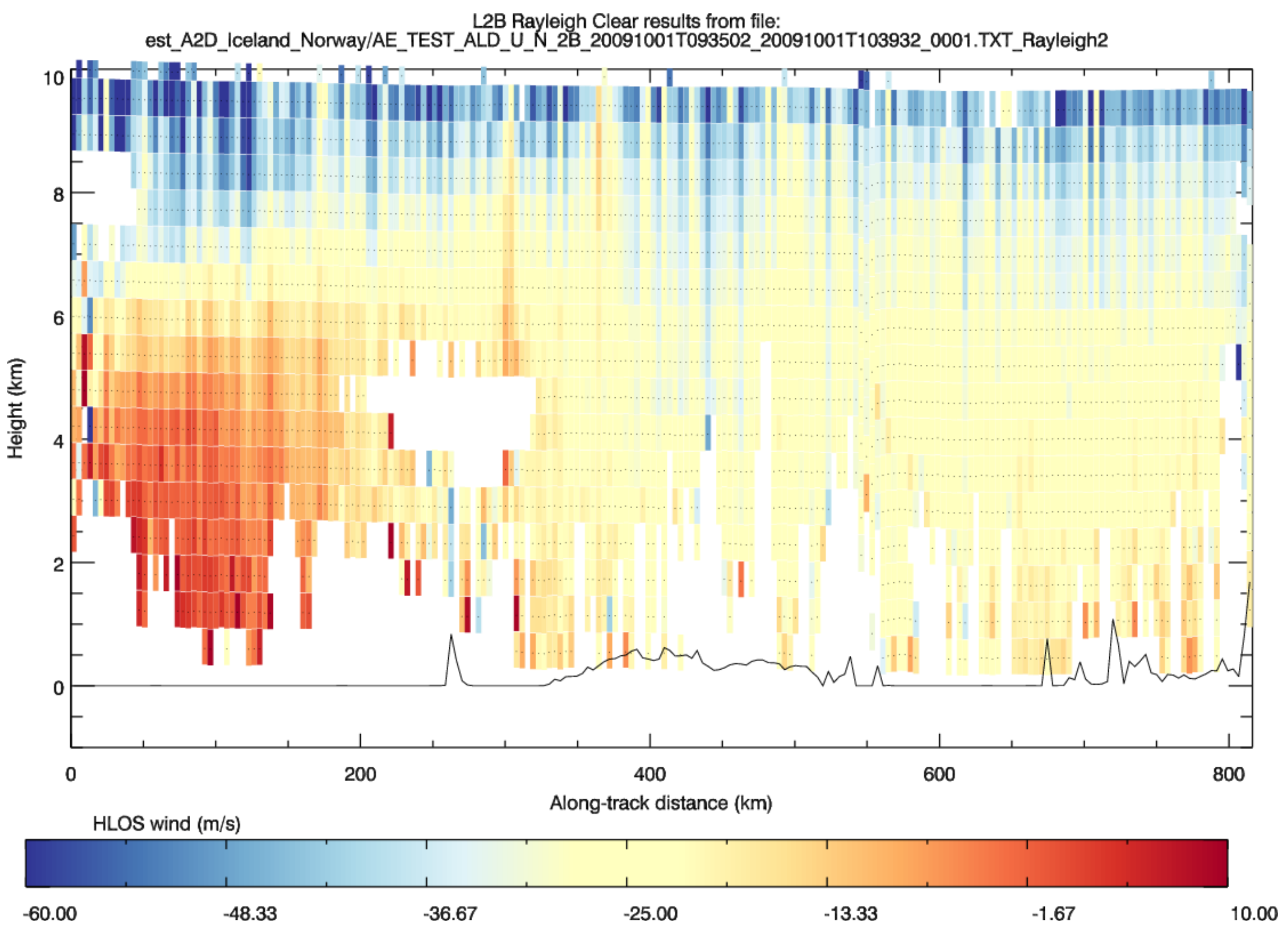


Figure 33. L2B Rayleigh-clear HLOS winds from the Iceland-Norway flight.

There does appear to be some vertical correlation (vertical stripes) in the results which is also seen for the DLR processed A2D Rayleigh winds. OR commented that: *These vertical stripes arise from*

vertical correlated errors due to the range-dependent bias RDB. ***For the A2D the cause of the RDB is the co-alignment between transmit-receive path, which introduces these stripes****. The co-alignment varies from observation to observation and thus introduces different range-dependent biases, which are not corrected in the DLR processing (at least at the moment).*
The lack of correction of the range dependent bias, like for the Greenland coast will in effect be destroying the vertical wind shear.

The error estimates of Figure 34 provide an indication of which observations can be trusted (in terms of random error at least). The gap in the DLR Rayleigh winds for the first 50 km is due to the lack of signal below a cloud, which they must have quality controlled in their processing. OR commented: *Rayleigh winds within clouds and below clouds are excluded with the DLR QC by using a cloud mask, see Fig. 3.8 and discussion on p. 128 in RD10. This is due to the fact, that DLR is not applying a Mie contamination correction for Rayleigh winds (at the moment).*

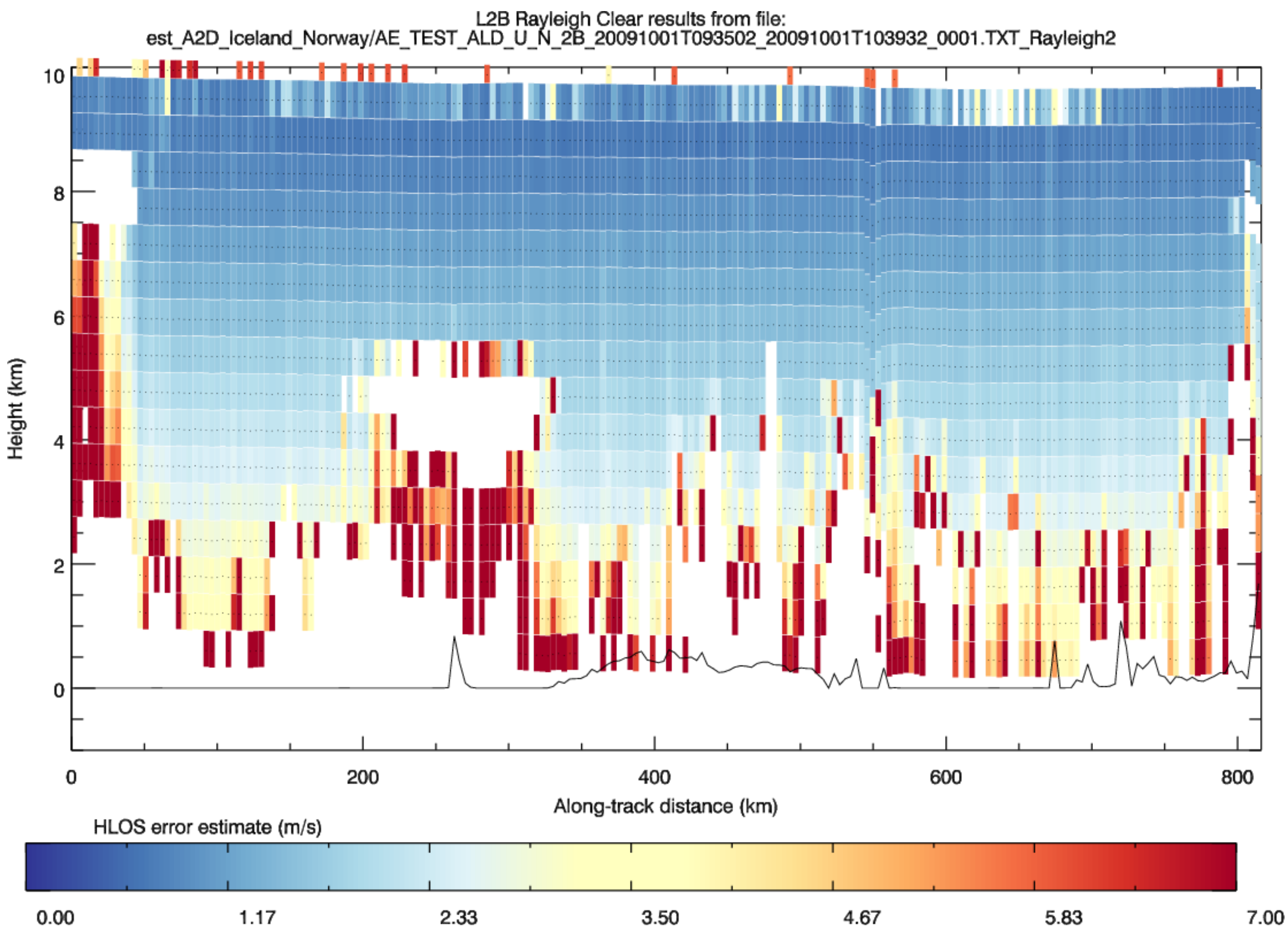


Figure 34. L2B Rayleigh-clear HLOS wind random error standard deviation estimates. White areas indicate an absence of results.

3.7 Aircraft LOS velocity

After the investigation was completed, UM confirmed that:

"*The A2D data set provided for conversion to L1B does not contain any information about the aircraft LOS velocity (for calibration and wind measurements) nor any ZWC information (for wind measurements on 29.09. along Iceland east coast). Thus, DH could not include reasonable LOS parameters in the L1B. Consequently, you didn't have the chance to get your winds matching the ones of the A2D. I'm sorry for that.*"

Therefore much of the bias seen in the L2B winds is due to the lack of aircraft LOS velocity corrections and ZWC. This could be improved upon in any future provisions of A2D data for conversion to L1B data.

3.8 Conclusions on A2D extended dataset L2B processing

A general conclusion on the extended A2D dataset L2B processing is that this real data (extracted to L1B format) can be processed with relatively little intervention in the code and that reasonable results can be obtained in terms of the horizontal wind shear (and vertical wind shear for the Mie) when compared qualitatively to the DLR results. The original intention prior to the investigation was to hopefully obtain L2B A2D winds sufficiently accurate to be passed through the ECMWF data assimilation system to perform verification against the ECMWF model winds. However the uncorrected effects in the provided A2D calibration and wind mode data (e.g. aircraft LOS velocity, ZWC, mismatch in ISR and IRC reference frequency and range/pointing dependent bias) is a significant obstacle to obtaining L2B A2D wind results which are sufficiently unbiased to even consider making quantitative comparisons against the DLR results or the NWP model equivalents.

Some recommendations:

- A recommendation for the **ALADIN calibration suite** is that the consequences of an absolute frequency drift between ISR and IRC (e.g. by 25 MHz, up to 60 MHz) should be investigated and that strategies need to be developed to cope with it. If uncorrected, this will lead to significant biases for winds produced by the L2B Rayleigh calibration strategy (i.e. the Rayleigh-Brillouin correction method).
- With respect to the provision of A2D data (from ISR mode, from IRC and from wind mode) for future airborne campaigns to be useful to test the L1B - L2 Calibration L2B processing chain are provided:
    - Ensure the A2D ISR mode is as consistent as possible with the IRC i.e. perform at a similar time and under similar conditions of the RSP.
    - One of the main sources of bias in the L2B results that could be corrected for in the L1B data (both calibration and wind mode) is due to the **aircraft ground speed**. The A2D atmospheric calibration results should be provided with the aircraft LOS velocity information for extraction to L1B calibration products; the same applies for A2D wind mode data. Both of these corrections can be done in a similar manner to the satellite LOS velocity correction for ALADIN data, done in the L1B and L2B processors.
    - Provide the real A2D Rayleigh and Mie ZWC if possible.
    - The range/pointing dependent bias in the A2D L2B Rayleigh wind retrieval is an issue that cannot obviously be corrected in the L1B/L2B processing, since it is different to the satellite RDB effect (i.e. varying from observation to observation). The recommendation is that a solution to this is investigated.
    - Include the correct A2D LOS elevation angle in the L1B data, so that HLOS winds can

be correctly calculated in L1B/L2B processing.

If similar (initially unknown) biases to the L2B processing occurs for the real Aeolus satellite mission, then it will take a considerable effort to understand and correct these effects, just as it has for DLR to do the corrections in the processing of the A2D data (which took 1-2 years according to OR).

This investigation has been a useful process in finding a number of L2Bp bugs and also to help improve the understanding of the ALADIN calibration. Hence some recommendations for the L2B processor:

- The thresholds for QC of RBC related parameters should be moved to the AUX_PAR_2B settings for the convenience of changing values outside the code.
- The L2Bp should be updated to allow calculation of both LOS and HLOS winds.
- Investigate whether the L2Bp should produce wind results when the SNR is unphysical e.g. negative.
- Fix the *skip_Mie_nonlin_correction* switch, so that Mie non-linearity can be switched on or off.
- A mismatch between the SR thresholds was required for obtaining good Mie-cloudy (previous section) and good Rayleigh-clear results. This may need to be addressed in future processors e.g. having separate thresholds for each channel.
- To understand why the DLR Mie algorithm allows retrieval of sensible winds for low SNR for part of the Greenland coast flight, whereas the L1B and L2B processors produced gross errors.

Recommendations for L1B processing:

- Investigate why the setting <data_source>A2D</data_source> seems to have the wrong sign effect on the winds i.e. wind sign is opposite to that of DLR A2D.

4 Acknowledgments

Thanks to Dorit Huber and Uwe Marksteiner of DLR for providing the L1B A2D data. Thanks to Alain Dabas for providing the A2D AUX_RBC_L2 files. Thanks to Oliver Reitebuch, Uwe Marksteiner, Anne Grete Straume and Thomas Kanitz for reviewing it and providing many useful comments.