TN17.1

Assessment of Level-2B wind errors resulting from realistic simulation of ISR/IRC/AUX_RBC calibration chain

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CHANGE LOG

Version	Date	Comment
1.0	08/06/2016	A first version.
1.1	16/08/2016	Finalising the Rayleigh calibration testing with an updated CoP and some comments from AGS.
1.2	16/01/2017	Update following L1B team comments (OR and DH). Update of Rayleigh calibration testing regarding the “tropical thick cloud” test case 6b using the CAL suite: 30 June 2016 + patches 1-3

Contents

1 Introduction

This technical note investigates the propagation of errors from the instrument response calibration files into the Aeolus Level-2B HLOS winds; that is, the calibrations linking instrument response to frequency and hence to the wind results. This work is a continuation of the investigations done for TN15.3 [RD4], but with an updated simulation and processing chain (as valid in early 2016) and importantly with the new ability to control the calibration processing steps so that our own testing of calibrations with realistic atmospheric scenarios can be performed.

To achieve this, the Aeolus Chain-of-Processors scripting system (henceforth referred to as CoP) has been updated with the ability to run the E2S and L1Bp in calibration modes and also to run the prototype Calibration Suite software as part of the chain. Therefore the L2B team can directly test our own calibration scenarios with various error sources, rather than relying on the L1B team to provide the calibration files.

This technical note also assesses the effect of E2S and L1Bp algorithm updates upon the L2B wind results.

This work is done for CCN5-6 WP2810 on "*Extended end-to-end testing: performance of L2Bp including calibration loops*".

In CCN5 it is written that WP2810 involves:

The chain-of-processors Python scripting system (developed by KNMI, which links together the atmospheric database, E2S, L1A, L1B and L2B processors, verification) will be updated to:

- *Allow the E2S calibration modes to be run automatically (via scripts) on a set of scenarios deemed to be suitable for producing realistic ISR, and IRC (RRC and MRC) procedures i.e. containing realistic noise sources and using realistic atmospheric scenes (e.g. the CALIPSO half-orbits in the KNMI database).*
- *Integrate the L1B team's prototype Calibration suite into the chain-of-processors (May 2014 delivery). That is the AUX_CSR updater and AUX_RBC generator software to allow the L2B team to produce realistic Rayleigh calibration products i.e. AUX_RBC (input to L2B processor) independently of the L1B team.*

Testing to be performed:

- *A plan will be produced of the required tests to produce a range of realistic calibration products. This will be done in consultation with the L1B team calibration experts. Effects such as ISR noise, RRC noise, RRC errors from particulate contaminated scenes, MRC errors due to imperfect ground returns, various étendue assumptions and AUX_MET data errors (as used in AUX_CSR updater). Several realisations of each noisy calibration will aid expectations for the effects of the potentially weekly IRC (and hence AUX_RBC file) up-dates.*
- *Testing should incorporate the most up-to-date E2S settings to ensure the simulated calibration and wind mode data has the most realistic possible error characteristics.*
- *A set of AUX_RBC and MRC files from the variety of scenarios will be generated. The calibration files can then be used in L2Bp wind mode test scenarios to determine the level of resultant systematic errors.*

Analysis of results:

- *The results of the investigation will be analysed in detail and shall be documented in a TN. If the results show that the biases are beyond the acceptable levels for positive NWP impact then recommendations to improve the calibration or make corrections in the L1B or L2B processors or in the L2/Met PF system will be documented.*

Output:

TN 17.1 "Investigations into the L2B product errors resulting from realistic calibration loops", including if necessary: "Recommendations for calibration improvements or ways to mitigate systematic errors from L2B products produced at the L2/Met PF"

Some of the work was extended into CCN6 due to unforeseen delays in obtaining a scientifically stable Calibration suite for integration into the CoP.

1.1 Documents

1.1.1 Applicable documents

	Title	Ref	Ver.	Date
[AD1]	Change Request No: 5, Aeolus Level 2B/C Enhancements and Launch Extension of ESA Contract No: 4200018555/04/NL/MM Development and Production of Aeolus Wind Data Products		1.1	24/01/2014

1.1.2 Reference documents

	Title	Ref	Ver.	Date
[RD1]	Correcting winds measured with a Rayleigh Doppler lidar from pressure and temperature effects, Dabas et al.	Tellus A, 60(2), 206–215, 2008	N/A	2008
[RD2]	E2S Issue 3/04 Software Release Note	ADM-RN-52-2890	3/04	Jun 13 2014
[RD3]	E2S modelling	AE-TN-DLR-E2S-001	1.3	31/7/2012
[RD4]	End-to-end testing of the continuous mode L2B processor	AE-TN-ECMWF-GS-153	3.1	19/3/2014
[RD5]	ADM-Aeolus level-2B algorithm theoretical baseline document	AE-TN-ECMWF-L2BP-0024	2.4	Dec 2012
[RD6]	B. Witschas, *'Analytical model for Rayleigh–Brillouin line shapes in air'* ,	APPLIED OPTICS / Vol. 50, No. 3 / 20 January 2011	N/A	2011
[RD7]	Generation and update of AUX_CSR	AE-TN-MFG-L2P-CAL-003	3.2	15/12/2015
[RD8]	Generation of the RBC Auxiliary file: Detailed Processing Model	AE-TN-MFG-GS-0001	3.2	15/12/2015
[RD9]	Advanced monitoring of Aeolus winds	AE-TN-ECMWF-GS-16	1.1	28/10/2015
[RD10]	Performance assessment of the Aeolus Doppler wind lidar prototype. PhD thesis by Ulrike Paffrath (DLR).		N/A	2006
[RD11]	Testing the behaviour of wind retrievals with new E2S simulation options	AE-TN-ECMWF-GS-173	1.1	6 Aug 2014
[RD12]	TN 2.1 Sensitivity Analysis	AE-TN-DLR-L1B-002		2007
[RD13]	The assimilation of horizontal line-of-sight wind information into the ECMWF data assimilation and forecasting system, part II: the impact of degraded wind observations. By András Horányi, Carla Cardinali, Michael Rennie and Lars Isaksen	Q.J.R. Meteorol. Soc., 141: 1233–1243. doi: 10.1002/qj.2551	N/A	2015
[RD14]	Witschas, B: Analytical model for Rayleigh–Brillouin line shapes in air	Applied Optics Vol. 50, No. 3, pp 267-270.	N/A	2011
[RD15]	Technical Note 51.2: Mie and Rayleigh Algorithm Performance Assessment (WP5100, Phase 2) by Karsten Schmidt, Oliver Reitebuch and Dorit Huber	AE.TN.DLR.5100.2.20151214	1.0_draft	2015
[RD16]	Technical Note Enhanced Performance Simulations	AE-TN-DLR-L1B-003	1.1	2007

1.2 Acronyms

ACCD	Accumulation Charge Coupled Device
AOCS	Attitude and Orbit Control System
ALADIN	Atmospheric Laser Doppler Instrument
ATBD	Algorithm Theoretical Baseline document
AUX	Auxiliary
BM	Burst mode
BRC	Basic Repeat Cycle
CM	Continuous mode
CoP	Chain-of-processors software
CSR	Corrected Spectral Registration
DA	Data assimilation
DEM	Digital Elevation Model
DWL	Doppler Wind Lidar
ECMWF	European Centre for Medium-Range Weather Forecasts
EGM	Earth Gravitational Model
ESTEC	European Space Research and Technology Centre (part of ESA)
FWHM	Full-width half maximum
HLOS	Horizontal Line Of Sight
IDL	Interactive Data Language
IODD	Processor Input/Output Data Definitions Interface Control Document
IRC	Instrument Response Calibration
ISR	Instrument Spectral Registration
KNMI	Royal Netherlands Meteorological Institute
LOS	Line of sight
L1B	Level-1B
L2B	Level-2B
L2Bp	L2B processor
LUT	Look-up table
N/A	Not applicable
NWP	Numerical weather prediction
PBL	Planetary Boundary Layer
PDGS	Payload Data Ground Segment
PRNU	Photo Response Non-Uniformity
QC	Quality control
RB	Rayleigh-Brillouin
RBC	Rayleigh-Brillouin correction
RMA	Reference model atmosphere
RR	Rayleigh response

RRC	Rayleigh response calibration
SNR	Signal to noise ratio
SRD	System requirements document
SZA	Solar zenith angle
TBD	To be determined
TN	Technical note
USR	Useful Spectral Range
VHAMP	Vertical and Horizontal Aeolus Measurement Positioning
WGS	World Geodetic System
WP	Work package
WVM	Wind velocity measurement[1]
XML	Extensible Markup Language
ZWC	Zero wind correction

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[1] This is a misnomer as Aeolus measures a component of the wind velocity along the line of sight

2 Methodology

2.1 Modified Chain-of-Processors with calibration steps

The Chain-of-Processors scripting system (CoP) is a tool developed by KNMI (in particular Jos de Kloe) to run the Aeolus E2S simulation software and the Level-0/1A/1B/2A/2B operational processors via Python scripts, with the ability to modify the settings of the processing steps easily via settings defined in "test case" files and to choose from a range of atmospheric scenarios. Previously the IRC (AUX_MRC_1B, AUX_RRC_1B) and AUX_RBC_L2 calibration files that were used within the CoP (i.e. in the L1B and L2B processors) were the default files provided with the L1B processor deliveries or from specific requests for "clean" or "perfect" calibration files from the L1B team. The L1B team also provided a limited set of AUX_RBC_L2 files with "imperfect" calibration testing as documented in TN15.3 (that document did not cover Mie calibration testing).

In late 2015, as part of WP2810, the CoP was updated by KNMI to include an important part of the Aeolus calibration chain i.e. the response versus frequency calibrations for the Mie and Rayleigh channels. The updated CoP includes the E2S simulation and the Level-1 processing to generate the ISR and IRC (RRC/MRC) calibration mode products. It also includes the ability to run the prototype Calibration (CAL) Suite software from these L1B calibration products to produce the AUX_CSR_1B, AUX_RBC_L2 and AUX_CAL products (note that AUX_CAL_L2 products are not needed by the L2B processor for this investigation).

The AUX_RBC_L2 is a required input to the L2B processing for the processing of Rayleigh wind mode data (WVM). The L2B Mie winds require part of the AUX_MRC_1B data, but this is passed to the L2Bp via the L1B WVM file. The CAL suite that is integrated into the CoP is the prototype version (written in MATLAB and provided by Météo-France, in particular Alain Dabas). An operational equivalent is being developed by contractors for ESA-ESRIN which will be used in the operational PDGS during the mission.

The CoP-generated calibration products can then be fed back into CoP WVM runs to produce L1B and L2B HLOS wind observation products. A WVM scenario can be processed many times from a sample of CoP-generated calibration products to see the effect on the L1B/L2B winds e.g. to assess wind biases resulting from imperfect calibration. The new CoP allows the calibration products to be produced with realistic scenarios (from the many available in the atmospheric database) and with realistic error sources to estimate the magnitude of realistic calibration (response vs. frequency) errors for Aeolus in the L2B HLOS wind products.

Figure 1 illustrates the connections between the processing steps in the new CoP. The atmospheric database has a large variety of atmospheric scenarios available for use in the CoP e.g. LITE scenarios, CALIPSO half-orbit scenarios with ECMWF winds, simple scenarios with RMA aerosol profiles and more recent additions of high resolution (16 and 9 km model grid) ECMWF model wind, temperature pressure and model cloud derived optical properties scenarios covering many orbits.

The CoP is not restricted to specific versions of the E2S, Level-1B/2B and CAL suite processors, however it is maintained to use the latest versions of the software and combining old and new processor versions is typically not permitted, since they will not interface correctly or could produce unexpected scientific results. Since the L2B team controls the CoP, we can, if necessary, use our latest ongoing development version of the L2B processor, rather than being restricted to specific versions delivered to ESA.

At ECMWF this verification of the L1B and L2B wind results resulting from CoP testing is produced using ECMWF's own IDL software tools, which will be referred to as "advanced monitoring"; the verification tools are described in [RD9].

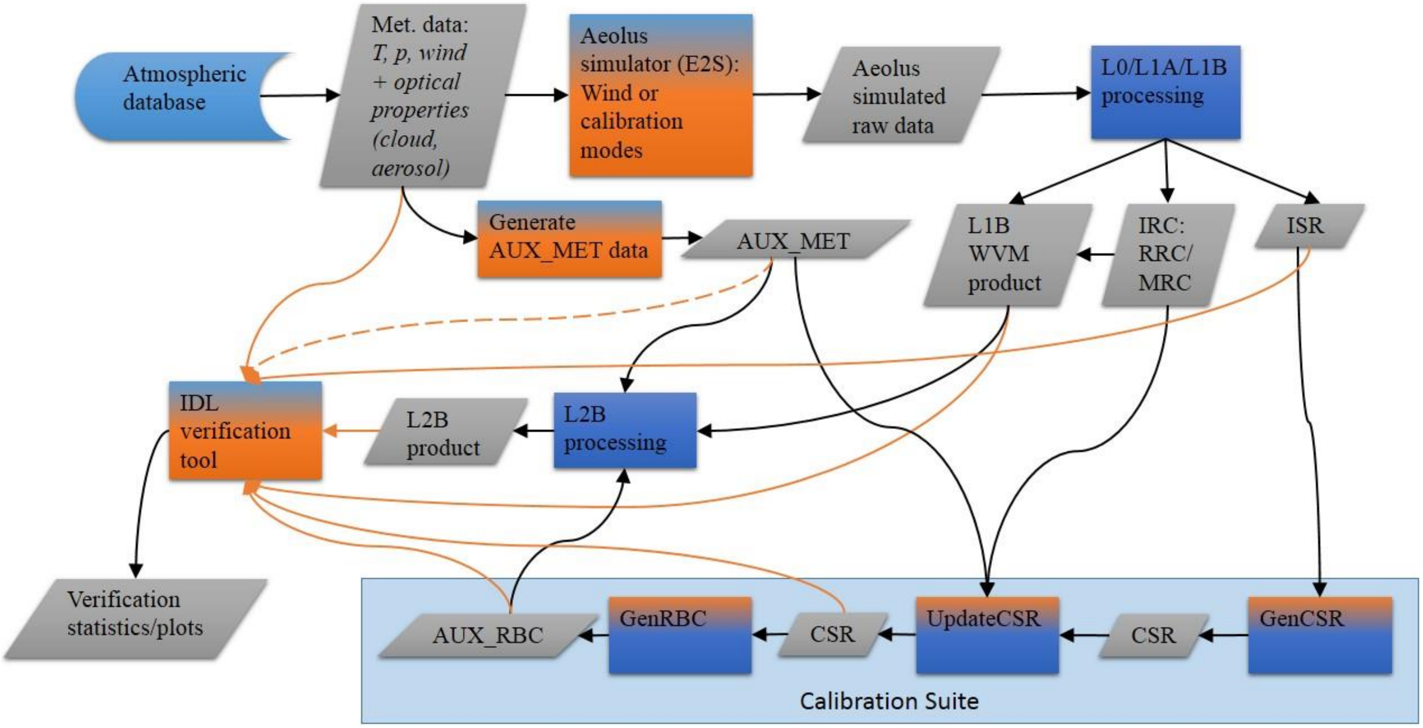

Figure 1. Flow diagram for the new CoP which interfaces to the Calibration Suite. A new feature is the ability to run the E2S and L1Bp in calibration modes (ISR/IRC) and to then input these products to the Calibration Suite. Data files are shown as parallelograms and processing steps as rectangles (operational processing software steps are shown in solid blue).

With the new calibration steps, the CoP has become an even more useful tool for pre-launch preparations and assessment of the operational processing chain; this functionality will also be very useful in the tests which will occur during the Commissioning Phase and CAL/VAL.

Note that the following internal Aeolus calibration modes are not tested in the new CoP: IAT (Instrument Auto Test), DCC (Dark Current Calibration), IDC (instrument defocus characterization), LCPA (Laser chopper mechanism phase adjustment), LDTA (Laser diode temperature adjustment). LBM (Laser beam monitoring) and DCMZ (Dark current in memory zone). Also, since the tools to generate the AUX_HBE (Harmonic Bias Estimation) and to accurately simulate the RDB (Range Dependent Bias) determination process were not available, they are not included in the CoP at this time.

The modified CoP including the calibration steps was implemented by KNMI and functionally tested with: E2S v3.05, L1Bp v6.04, CAL suite March 2015 (patch 1), and L2Bp v2.20+ (development version from Sep 2015). ECMWF then installed a copy of this CoP and confirmed it worked in their environment. ECMWF then updated the CoP to work with more recent combinations of the relevant processor components as will be described in the remainder of the TN.

2.2 CoP calibration steps

The first step in the CoP calibration steps is to produce an Instrument Spectral Registration (ISR) product. The ISR was designed for the spectral characterisation, and tuning of receiver and laser frequencies. However, it has since been adopted as part of the CAL Suite processing for the generation of the AUX_RBC_L2 product for the L2B processor's Rayleigh-Brillouin correction. The E2S can be run in ISR mode and the Level-0/1A/1B processing can then (with the appropriate Job Order files) process the AISP data from the E2S to an ISR file (AUX_ISR_1B). Since the ISR uses ALADIN's internal reference signals the specification of the E2S atmospheric scenario is scientifically irrelevant.

Similarly the E2S and Level-0/1A/LB processing can be controlled to run an Instrument Response Calibration (IRC) mode to produce the IRC products i.e. AUX_MRC_1B (Mie response calibration) and AUX_RRC_1B (Rayleigh response calibration) files. This mode involves the laser pointing in near-nadir and using atmospheric (for Rayleigh) and ground returns (for Mie) to obtain the response versus frequency calibrations. The IRC is made from response measurements over 40 frequency steps within the USR (Useful Spectral Range). It requires an 81 BRC atmospheric scenario to be defined as an input to E2S. Range bin settings for this mode are important to ensure a sufficient number of ground returns are available for the MRC to be deemed valid. The IRC is a critical calibration for obtaining the Doppler shift and hence the LOS wind observations.

With the appropriate Level-1B calibration products available, the next stage is to run the CAL suite with these files as inputs. From the L2B processing perspective the CAL suite is critical because it generates the Rayleigh-Brillouin calibration file (AUX_RBC_L2) which provides Rayleigh spectrometer atmospheric calibration curves as a function of temperature and pressure (as a look-up table). The AUX_RBC_L2 is necessary to derive temperature and pressure corrected L2B Rayleigh HLOS winds (see [RD1]); a correction that is unavailable in the L1B processing. Without any temperature and pressure correction Rayleigh wind biases of order 10 m/s are possible. The AUX_RBC_L2 also provides the internal (also known as "reference pulse") Rayleigh response curve which is derived within the CAL suite using the Rayleigh responses of the ISR for the direct and indirect channel.

Note that for the L2B Mie winds, the calibration information comes from the AUX_MRC_1B which is passed to the L2B processor via the L1B WVM file (which also means the L2Bp is currently[2] restricted to using the MRC that was applied in the L1Bp)

The steps of the CAL Suite which are relevant to the L2B Rayleigh winds are briefly explained below (see [RD7] and [RD8] for more in depth explanations).

1. **GenerateCSR**: Fits a model to the measured Rayleigh channel ISR transmission curves from the Fabry-Pérot (FP) direct and indirect receivers. This model assumes a function for the Fizeau reflection. This generates the initial CSR product which may be modified in point 2. The model fit is done with the aim of reducing the effects of noise in the ISR measurements.
2. **UpdateCSR**: Corrects the initial CSR for an atmospheric path étendue effect by a convolution of the original CSR with a tilted top-hat function, the parameters of which are found by fitting a predicted RRC to the measured atmospheric RRC produced from the IRC. The AUX_MET_12 file atmospheric temperature and pressure information and the MRC provided estimates of Mie channel scattering ratio are required by the UpdateCSR to predict the atmospheric RRC. Note that if the étendue effect is switched off in the E2S simulation then there is no étendue effect to

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[2] It is planned for the L2Bp to be able to directly read the AUX_MRC_1B in future to avoid this restriction.

correct for, hence this UpdateCSR step is not required (purely a simulation issue). This step has the option of accounting for the Rayleigh-Brillouin (varying with temperature and pressure) scattering or can just assume Rayleigh scattering (varying with temperature only); for real Aeolus data only the Rayleigh-Brillouin option should be chosen.

3. **GenerateRBC**: Generates the AUX_RBC_L2 look-up table for input to the L2B processor for Rayleigh wind processing (ILIAD correction scheme). This step has the option of accounting for the Rayleigh-Brillouin (varying with temperature and pressure) scattering or can just assume Rayleigh scattering (varying with temperature only); again for real Aeolus data only the Rayleigh-Brillouin option should be chosen.
4. **GenerateCAL**: Generates calibration coefficients which are used by the L2A processor and in future by the L2Bp optical properties code. This is not currently scientifically used by the L2B processor at the time of writing, therefore this step is unnecessary in this investigation.

Note that the AUX_MET_12 data required in the UpdateCSR (and the L2B processing) is generated by converting the E2S atmospheric inputs into an AUX_MET_12 file using a tool which is part of the L2B processing package. This differs from the operational method, whereby AUX_MET_12 will be generated from ECMWF model short-range forecast output directly.

2.3 Producing "perfect" calibration files

Before trying to understand the effects of realistic calibration on the L1B and L2B wind results, it is important to have the reference of "perfect" calibration files. By perfect we mean without errors and hence agreeing with the "true" calibration of the instrument. They can be used as inputs to WVM mode runs (at L1Bp/L2Bp stages) to generate "perfect" calibration wind results which can be compared with the "realistic" calibration wind results. Also, it is important to verify that the wind biases with "perfect" calibration are at the expected/acceptable levels to ensure that mistakes are not being made in the CoP settings (or with updates in the processors), particularly given the very large range of possible settings in the processing steps (many things can go wrong).

The following sections describe the settings which were found to be important to generate "perfect" calibration products. Note that they are only perfect if the corresponding WVM scenarios are simulated with consistent settings in the E2S simulation and processing steps (e.g. the E2S étendue settings).

2.3.1 E2S input atmosphere for the simulation of "perfect" ISR and IRC

- **ISR**: This is an internal reference calibration. Therefore the E2S atmospheric inputs are irrelevant. However, all noise sources should be switched off in the E2S to get "perfect" ISR results.
- **IRC**: This is only needed for testing Rayleigh-channel L2B calibration when the étendue is being simulated. It is needed for the Mie-channel L2B stage in all cases as the MRC data is necessary (via the L1B WVM product) for the L2B Mie winds. "Perfect" IRC results can be obtained with:
  - All noise sources switched off in the E2S
  - For the atmospheric inputs use a simple and idealistic atmosphere. We have chosen to use "**single_RMA_profile_midlat_winter_MF**" from the KNMI atmospheric database. This has the properties:

- The optical properties are constant horizontally for the 81 BRCs of the IRC.
- Vertically constant zero aerosol backscatter and extinction coefficients i.e. a clear atmosphere for the vertical range of the RRC (6-16 km) and only attenuation for the MRC due to molecular attenuation so strong ground returns are possible.
- Vertically variable standard molecular backscatter and extinction coefficient profile for mid-latitude winter atmosphere and corresponding representative temperature and pressure profile for mid-latitude winter. Horizontally constant.
- HLOS wind set to zero. Since pointing in near-nadir this may not be very important (depending on the near-nadir angle).
- Ground albedo set to a constant value of 0.8. This ensures good ground return signal levels for the MRC ground returns.
- The IRC is done over ocean, hence the ground Terrain Model has no influence. This in combination with the appropriate range-bin settings ensures good enough ground return signals for the MRC.
- Solar spectral irradiance set to zero i.e. no UV background noise. This is in effect a night-time calibration.

2.3.2 Recommended E2S and L1Bp settings for “perfect” ISR and IRC:

The default settings of E2S and L1Bp will be kept unless otherwise stated e.g. the laser pulse energy will be 80 mJ throughout the study. Some other recommended settings are:

- Switch the Rayleigh-Brillouin scattering “on” in E2S — this is important for testing the Rayleigh-Brillouin correction in the L2Bp (this uses the [RD14] approximation for the RB spectra). In the E2S input file `atmosphereProfileParameters.xml` set `<rayleighBrillouinFlag>true</rayleighBrillouinFlag>`
- The DCMZ should only be simulated in the E2S and its L1Bp correction applied (as is possible in L1Bp v6.05) if noise sources are “on” in the E2S. If DCMZ is “on” in E2S, then make sure that the E2S settings in `lidarInstrumentDetectorParameters.xml` for e.g. `<mieRmsNoiseRate unit="electrons/second/pixel">` and `<rayleighRmsNoiseRate unit="electrons/second/pixel">` are consistent with the settings for the L1Bp correction of DCMZ in `./aux/AE_TEST_AUX_DCMZ1B_*.EEF` (ask the L1B team for advice on this). Note that inconsistency of E2S DCMZ and L1Bp correction of DCMZ will introduce a HLOS wind dependent error (slope error).
- We recommend to switch-off the RDB[3] simulation in E2S (via the switch in `satelliteParameters.xml`) and switch-off any correction of this in the L1Bp because the L2Bp code (v2.20 and v2.30) does not yet correct for RDB. If RDB is simulated in the E2S and its L1Bp correction is applied, make sure the settings in the E2S

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[3] Note the a range-dependent bias correction is not available in the L2Bp at the time of writing, therefore it is important to switch it off in E2S for WVM runs of assessing L2B winds.

`lidarInstrumentLinkParameters.xml` of RDB coefficients match those for the L1Bp correction in `./aux/AE_TEST_AUX_RDB_1B_*.EEF`

- Switch vertical bin overlap off and spectrometer imperfections off in the E2S. Although the effects are interesting to investigate, for the reference "perfect" calibration it is best to avoid complicating things when the imperfections are not well defined on the real instrument yet. Or if the effects have to be "on" then make sure the imperfections are consistent between calibration modes and WVM modes E2S settings.
- Switch off AOCS errors in the E2S as there are no reliably estimated values to use in the simulation.
- For L1B processing of calibration modes, ensure that in the AUX_PAR_1B settings have:
    - The Mie Downhill simplex algorithm "on" in the IRC mode (to ensure the MRC will match with the L2Bp, which can only use Downhill simplex algorithm). That is, set: `<Mie_Core_Algorithm_Params>` `<DownHill_Simplex_On>TRUE</DownHill_Simplex_On>`
    - Switch-off ground (zero wind) corrections (unnecessary if AOCs error in E2S are off) via LOS_Velocity_Correct_Nadir in the AUX_PAR_1B set to FALSE. It is unclear if these values will be used in real calibration modes during the mission.

2.3.3 CAL suite settings for "perfect" AUX_RBC generation:

The following settings in the CAL suite were found to be important to ensure the "perfect" AUX_RBC_L2 file can be produced:

- Generate CSR; in AUX_PAR_CS:
    - Ensure `<Fiz_Reflec_Model>E2S</Fiz_Reflec_Model>` so that it matches the E2S simulation. This is only possible in CAL suite version December 2015 or later.
- Update CSR; in AUX_PAR_CS:
    - Ensure `<RBC_Spec_Model>TENTI</RBC_Spec_Model>` if Rayleigh-Brillouin scattering is being simulated in the E2S for the IRC and WVM modes. Note that in practice this setting ensures the simplified approximation (parameterised version[4]) to the Tenti model is used, see [RD14], rather than the full Tenti model.
    - Recommended to set `<Min_Freq_Steps_Valid>30</Min_Freq_Steps_Valid>`, rather than default value of 35, to give better chance of success in noisy IRC scenarios.
- RBC generation; in AUX_PAR_RB:
    - Ensure that `<RBC_Spec_Model>TENTI</RBC_Spec_Model>` if Rayleigh-Brillouin scattering is simulated in the E2S WVM runs which will use the AUX_RBC_L2 file. Note that this setting ensures the simplified approximation

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[4] N.B. the same parameterised version is used in the E2S simulation, so there should be no inconsistency with the CAL suite.

(parameterisation) to the Tenti model is used, see [RD14], rather than the full Tenti model.

2.4 The default WVM scenario for testing the use of calibration products: ECMWF_T1279

The effect on the HLOS wind systematic errors of various ISR/IRC/AUX_RBC calibration files generated needs to be tested with a WVM scenario that captures a broad range of atmospheric conditions to provide a large sample of HLOS wind values. Such a sample is needed to help assess e.g. the slope error, or any other factors that the errors may depend upon. Also the WVM scenario should have sufficient cloud/aerosol loading to produce a large and realistic sample of Mie winds.

The E2S input atmospheric scenario used for this will be referred to from this point as ECMWF_T1279. This is the most realistic scenario available in the database (at the time of writing) that can provide a sufficiently large enough sample of wind results. ECMWF_T1279 has the following properties:

- Atmospheric data was derived from ECMWF model output with a resolution of T1279 and L137 i.e. around 16 km grid-spacing and 137 vertical levels (up to around 80 km). Data derived in 2015.
- Has 9999 E2S segments[5] i.e. atmospheric profiles.
- The segments were sampled every 16 km, therefore providing roughly 4 orbits of data (this testing is done with the old orbit altitude characteristics). The data was extracted from an AUX_MET_12 product produced with the ECMWF L2/Met PF using an Aeolus predicted orbit file.
- The ECMWF model orography can be matched to the E2S DEM (digital elevation model) by choosing an appropriate start time and E2S orbit settings so that they align. This is more important for getting realistic ground returns.
- The particulate optical properties are derived from the model cloud fields (cloud liquid water content, cloud ice water content) using a parameterisation based on Mie theory to convert the cloud liquid/ice water content to extinction and backscatter coefficients, assuming a lidar ratio of 20 (the ratio between optical extinction and 180° backscatter), which is a reasonable estimate for various cloud types e.g. see [RD10] which references the RMA aerosol properties.
- There are no aerosol (non-hydrometeor) optical properties used in deriving the particulate optical properties; however this is thought to be of lesser importance than clouds which dominate the particulate scattering in most scenarios (particularly water clouds are highly attenuating). Also there are enough Mie results with clouds only to make conclusions on the systematic errors.[6] This will, however, lead to fewer valid Mie observations in the PBL from aerosol in otherwise cloud-free conditions and hence less valid statistics for the PBL performance in cloud-free conditions.
- The range-bins are defined to be WVM2 as shown in Figure 2.

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[5] This is currently the maximum allowed in the KNMI database format for the CoP. However, it should be reasonably straight-forward to modify the code to allow more segments.

[6] It may be possible in the future to include the aerosol 355 nm backscatter coefficients from the composition IFS (C-IFS) to improve the realism of the scenario.

- This ECMWF_T1279 scenario leads to around 31,000 L2B Rayleigh-wind results from the surface to 28 km, and around 6,000 Mie-cloudy wind results from surface to 15 km.
- The ECMWF_T1279 scenario E2S atmospheric inputs are plotted in Figure 3, Figure 4 and Figure 5.

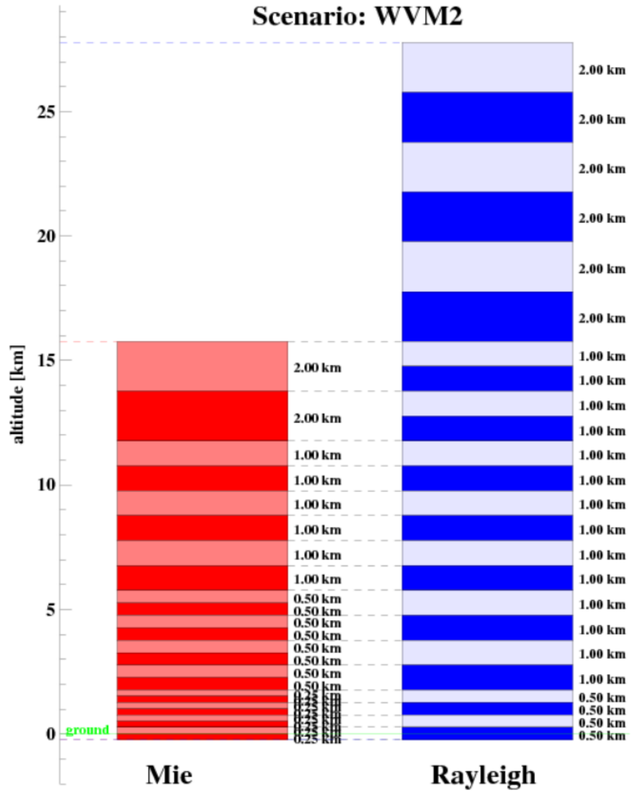

Figure 2. Range-bin definition named WVM2, used in ECMWF_T1279 scenario.

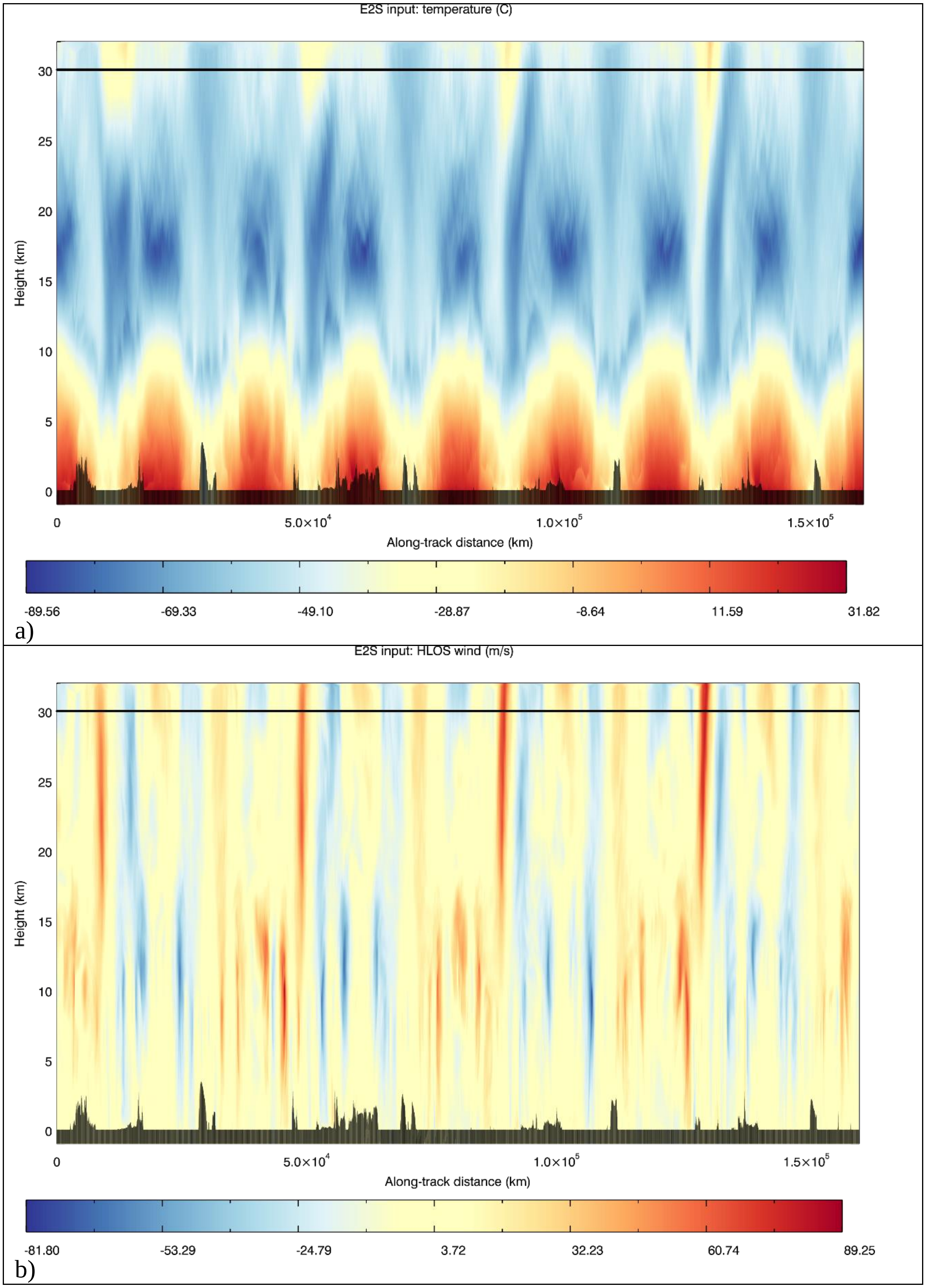

Figure 3. E2S inputs for the ECMWF_T1279 atmospheric scenario; a) temperature and b) HLOS wind component.

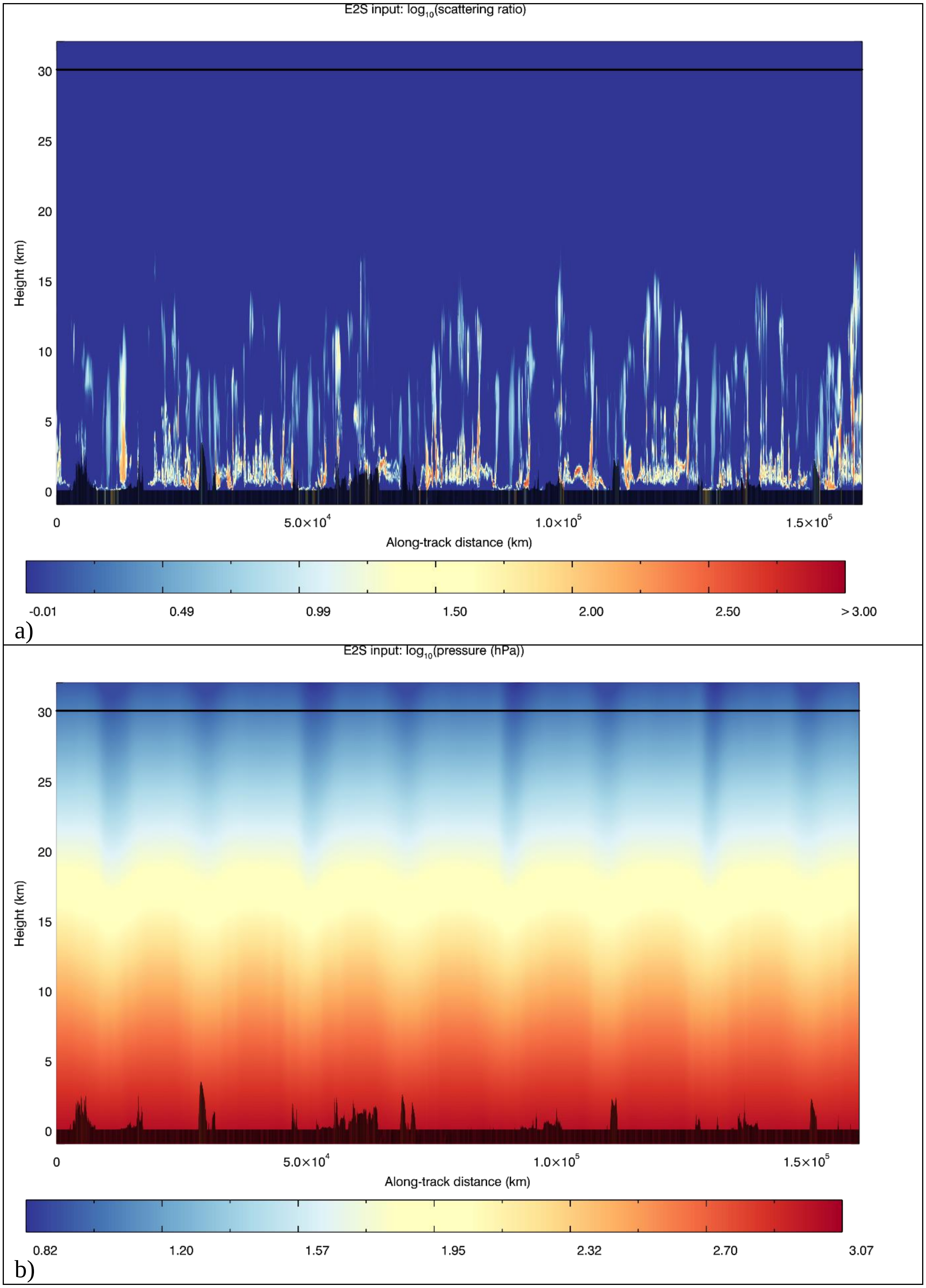

Figure 4. E2S inputs for the ECMWF_T1279 atmospheric scenario; log$_{10}$ of a) scattering ratio (derived) and b) pressure.

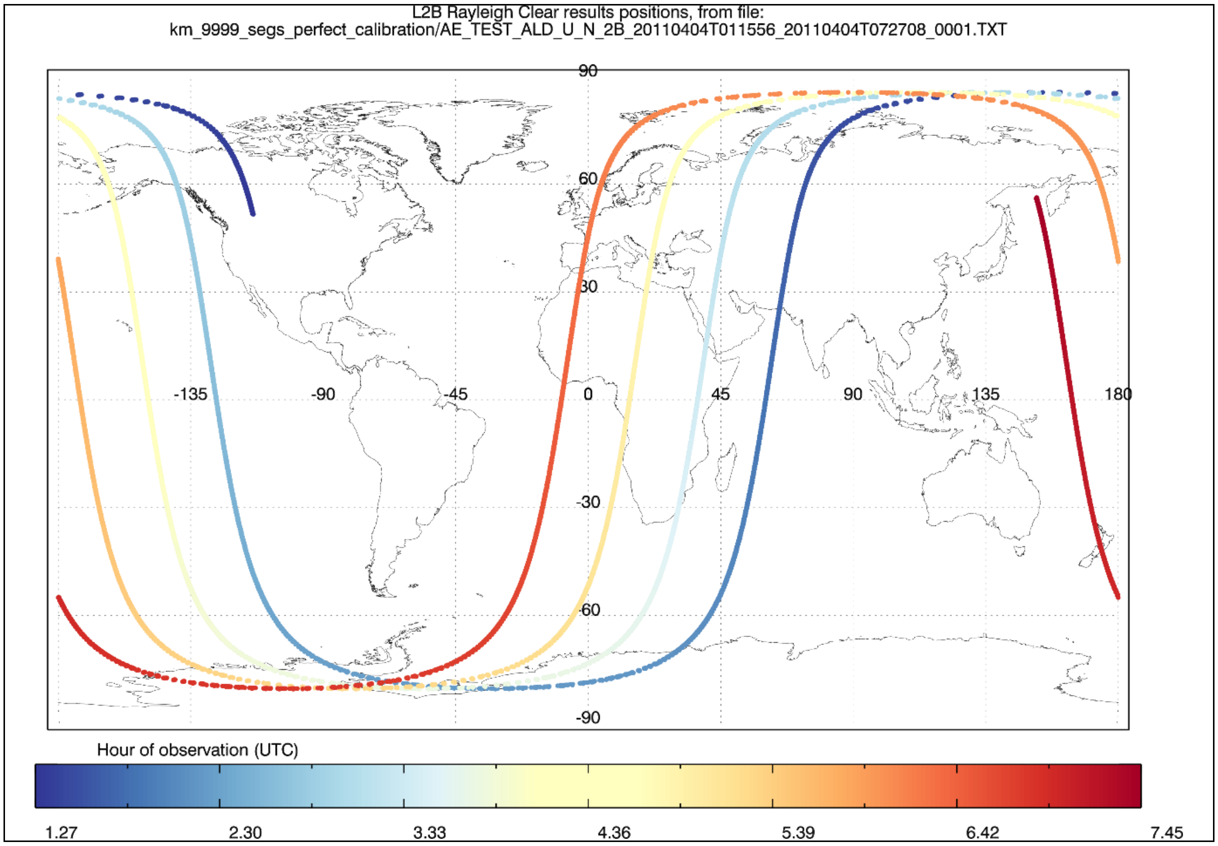

Figure 5. ECMWF_T1279, locations of L2B wind observations. Colour indicates the UTC hour of the L2B Rayleigh-clear observations. This shows that the scenario covers around 4 orbits.

When running a WVM scenario with the ECMWF_T1279 atmospheric inputs to E2S, the recommended settings for assessing systematic errors are:

- **E2S settings:**
  - The E2S settings should be consistent with those used in the generation of calibration mode products e.g. make sure the étendue effect is consistent in the WVM and calibration modes.
- **L1B settings:**
  - If verifying the L1B HLOS winds (as well as the usual assessment of L2B winds) make sure in the AUX_PAR_1B file that under `<WVM_Params>` that the `<Line_Of_Sight_Wind_Flag>FALSE</Line_Of_Sight_Wind_Flag>`. Otherwise any verification will show a large slope error of around 39% (due to comparing L1B LOS winds to E2S input HLOS winds!)
  - Ensure the same Mie core algorithm as used in the L1B IRC generation is applied.
  - Switch off ground (zero wind) corrections.
- The following are a selection of L2Bp settings that have been tuned to obtain good wind results with CoP combination E2S v3.04, L1Bp v6.03 and L2Bp v2.10 in the past:

  L2B settings:

- Use the classic grouping algorithm i.e. one BRC averaging. Note however that much smaller averaging lengths are possible for the Mie winds without degrading the quality e.g. 30 km averaging of measurements have been found in the past to give the most accurate random error results in previous testing. Note that large horizontal averaging e.g. > 200 km can introduce apparent slope error by averaging through horizontal wind gradients.).
- `<Line_of_Sight_Wind_Flag>false</Line_of_Sight_Wind_Flag>`. Important when assessing output HLOS winds against E2S input HLOS winds.
- A compromise Rayleigh height assignment factor, as suggested in TN15.3 is used to account for attenuated backscatter from molecules: `<Rayleigh_Height_Weight_Upper>0.49</Rayleigh_Height_Weight_Upper>`
- For ZWC, use L2B settings (rather than the L1B) and set all corrections to 0.0 — since there should not be any harmonic/mispointing biases being simulated in the E2S.
- Because the L1Bp measurement-level QC was found to be too strict in TN15.3, set: `<Ignore_Rayleigh_Meas_Invalid_Switch>True</Ignore_Rayleigh_Meas_Invalid_Switch>` and `<Ignore_Mie_Meas_Invalid_Switch>True</Ignore_Mie_Meas_Invalid_Switch>`
- Allow the use of non-linearities from the MRC: `<Skip_Mie_Non_Linearity_Correction>False</Skip_Mie_Non_Linearity_Correction>`
- Use the most accurate HLOS wind error estimation algorithms, which are: `<ErrorQuantMethod_Mie>ErrorQuantMethod_Mie_1Bweighted</ErrorQuantMethod_Mie>` `<ErrorQuantMethod_Rayleigh>ErrorQuantMethod_Ray_1Bweighted</ErrorQuantMethod_Rayleigh>`
- To obtain less-biased Rayleigh-clear winds, but on the downside increase the number of Mie-cloudy wind outliers (but this can be controlled by QC) set[7]: `<BackscatterRatio_Threshold>` `<Threshold_Value>1.15</Threshold_Value>`
- This should be done in combination with the more accurate L1B scattering ratio values i.e. "refined" which were found to be more accurate than "nominal" SR, particularly for low SR values: `<ScatRatio_Method>Scat_Ratio_from_L1B_refined</ScatRatio_Method>` `<ScatRatio_Method2>Scat_Ratio_One_If_No_Mie</ScatRatio_Method2>`

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[7] Note that work in CCN6 includes producing a separate Rayleigh and Mie threshold for the scattering ratio based classification into clear/cloudy.

- To avoid forcing the intercept of a calibration curve to be zero use[8]:
  `<Use_Ref_Pulse_Zero_Freq>True</Use_Ref_Pulse_Zero_Freq>`
  `<Use_Meas_Zero_Freq>True</Use_Meas_Zero_Freq>`

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[8] It is unclear why this option was provided in the first place.

3 Obtaining “perfect” calibration results as a reference

Given the many updates in the CoP since the last formal testing (which was done for TN17.3 see [RD11]), firstly we require a reference or baseline of good quality low bias results using “perfect” calibration files. The following sections describe the investigations that were performed to achieve this.

3.1 Testing “perfect” calibration with E2S v3.05 and L1Bp v6.04

ECMWF started with the CoP software from KNMI as described in section 2.1 and confirmed that it could run successfully in ECMWF’s computing environment (openSUSE 13.1 (Bottle) (x86_64)). Scientific testing could then begin, firstly with the “perfect” calibration files, to determine if L2B winds with sufficiently small biases could be obtained (relative to what was found in past testing e.g. TN15.3 and TN17.3) — this should be possible if all the settings are appropriate and there are no bugs in the processing chain. The systematic errors were compared to the CoP results obtained in September 2014. The September 2014 results were obtained using L1B team provided “perfect” calibration products (using E2S v3.04, L1Bp v6.03 and L2B v2.10).

It turned out to be a significant effort to achieve small biases with “perfect” calibration using the newer CoP processors as will be explained in the following paragraphs.

With the new CoP-generated “perfect” calibration products it was found that the L2B Rayleigh-clear winds are positively biased by around 0.5 m/s (result not shown) compared to the 2014 results for the ECMWF_T1279 test case. After some investigation, and after studying the progress reports from Alain Dabas (L1B team) about the CAL suite updates, the bias was determined to be due to differences between the Fizeau reflection model used in the March 2015 CAL suite’s GenerateCSR processor compared with the Fizeau reflection model simulated by the E2S. With a different model for the Fizeau reflection function the GenerateCSR can never perfectly fit the E2S simulated noise-free ISR. The mismatch led to imperfect atmospheric RRC curves in the AUX_RBC, which caused the bias change in the L2B Rayleigh-clear winds. Figure 6 shows the difference between a noise-free ISR and the March 2015 CAL suite CSR model fit to the ISR. These differences, particularly those close to the 0.0 GHz frequency offset (which is where the atmospheric return frequencies due to wind typically lie) are enough to cause the 0.5 m/s HLOS wind bias.

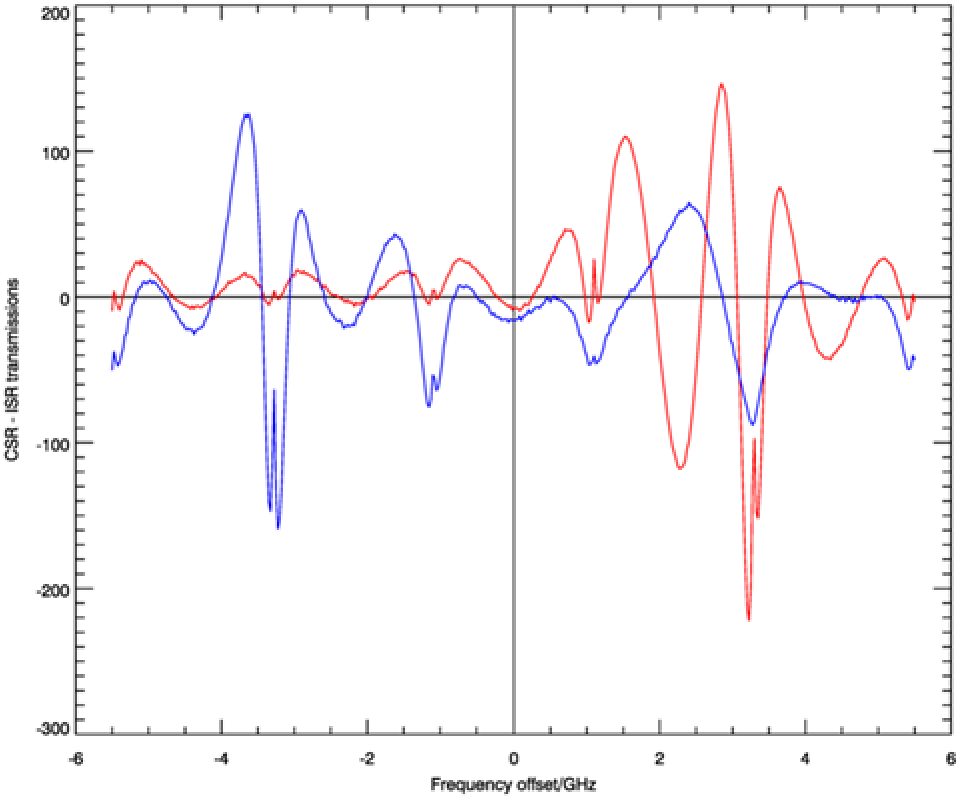

Figure 6. The difference, as a function of frequency offset, between the initial CSR model fit (March 2015 CAL suite) to the ISR Rayleigh T_A (red) and T_B (blue) and the E2S simulated noise-free ISR data.

A solution to this problem was provided by an updated CAL suite delivery, provided by Alain in December 2015. This version includes a switch to allow the use of the E2S or the DLR Fizeau reflection model in the GenerateCSR step.

R1: Differences between the E2S and DLR models of the Fizeau refection model cause a 0.5 m/s L2B Rayleigh HLOS wind bias. Therefore if possible a model for the real ALADIN Fizeau reflection function should be determined for use in the operational GenerateCSR.

The CoP was updated to integrate the Dec 2015 CAL suite (still in combination with E2S v3.05 and L1Bp v6.04). The new CAL suite's GenerateRBC step included an update in the AUX_RBC_L2 file format (to include some new variables; df, USR, FSR), therefore the L2Bp had to be updated to read the new file format[9]. A few problems were discovered in the new AUX_RBC_L2 (v3.2) file format, but these were fixed with our own patches to the CAL suite MATLAB code. Another problem was encountered with the new CAL suite: the new CSR updater step started using the AUX_MET_12 value for geoid undulation (height difference between EGM96 geoid and WGS84 ellipsoid), however this variable is set to a missing data indicator value in the L2B team generated AUX_MET_12 file (and cannot be filled correctly without a lot of effort). The incorrect use of the missing indicator value led to NaN values in the CSR updater output. ECMWF simply patched the MATLAB code to stop it from using the geoid undulation value; in practice for this testing the value should be zero, hence it will not

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[9] This was required to be done for the next L2Bp delivery anyway, version 2.30.

cause any consequences. The missing geoid undulation problem and the AUX_RBC v3.2 format issues were passed on to the L1B team (and will be addressed in the next CAL suite deliveries).

With the patched Dec 2015 CAL suite implemented in the CoP it was possible to get good L2B wind results using "perfect" calibration; the Rayleigh-clear and Mie-cloudy wind results are shown in Figure 7 to Figure 10. The verification statistics are presented in the style of [RD4] (which explains how the statistics are calculated). **Note that quality control (QC) is applied to reject any Rayleigh observations with L2Bp estimated errors (1-sigma) larger than 5 m/s and any Mie observations with estimated error larger than 3 m/s.** This type of QC was found to be very important in past verification studies to remove outliers which disproportionally affect non-robust metrics like the mean and standard deviation of the error; particularly for the Mie wind results.

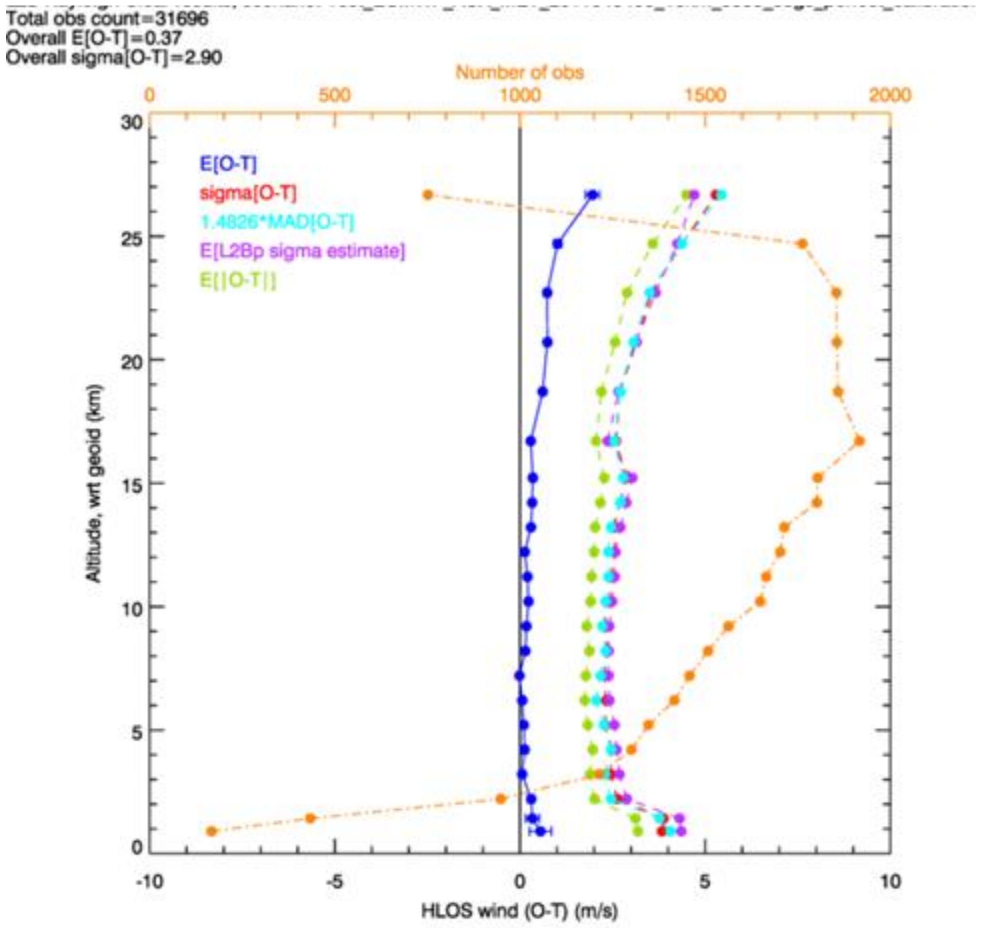

Figure 7. Verification statistics for L2B Rayleigh-clear HLOS wind results against E2S input "truth". For the ECMWF_T1279 scenario using "perfect" calibration files with the processors: E2Sv3.05/L1Bpv6.04/L2Bpv2.20+. AUX_RBC_L2 derived from Dec 2015 CAL suite.

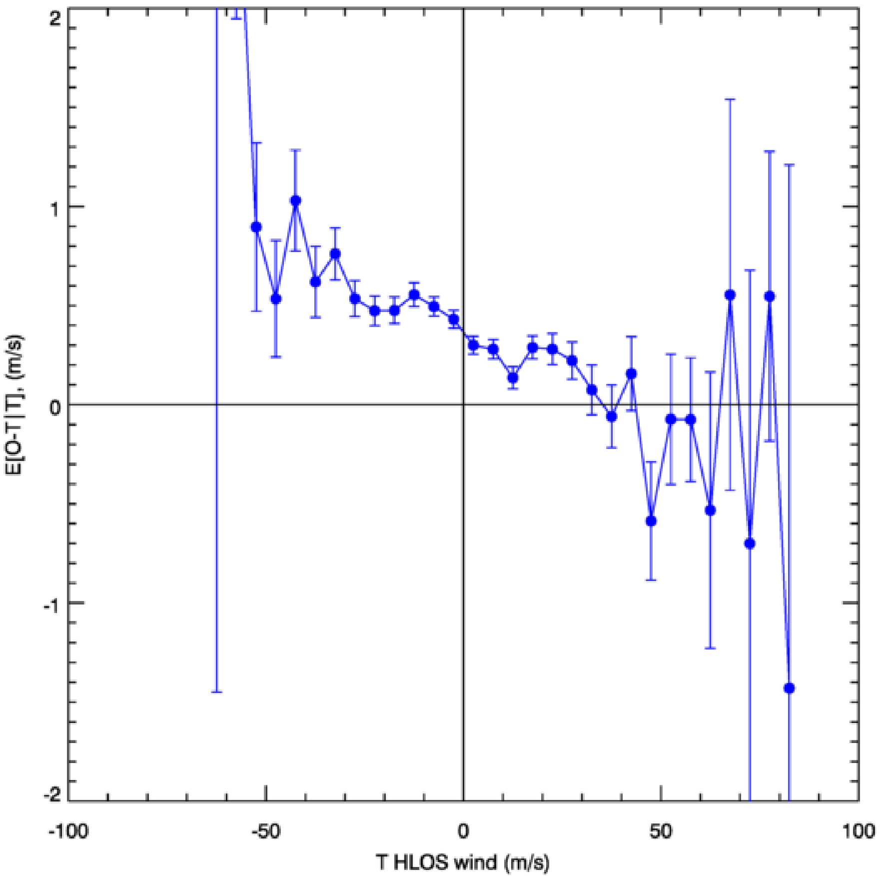

Figure 8. The L2B Rayleigh-clear HLOS wind, true (T) HLOS dependent bias (or slope error) for the same scenario as described in Figure 7. Although not linear there is ~1% slope error.

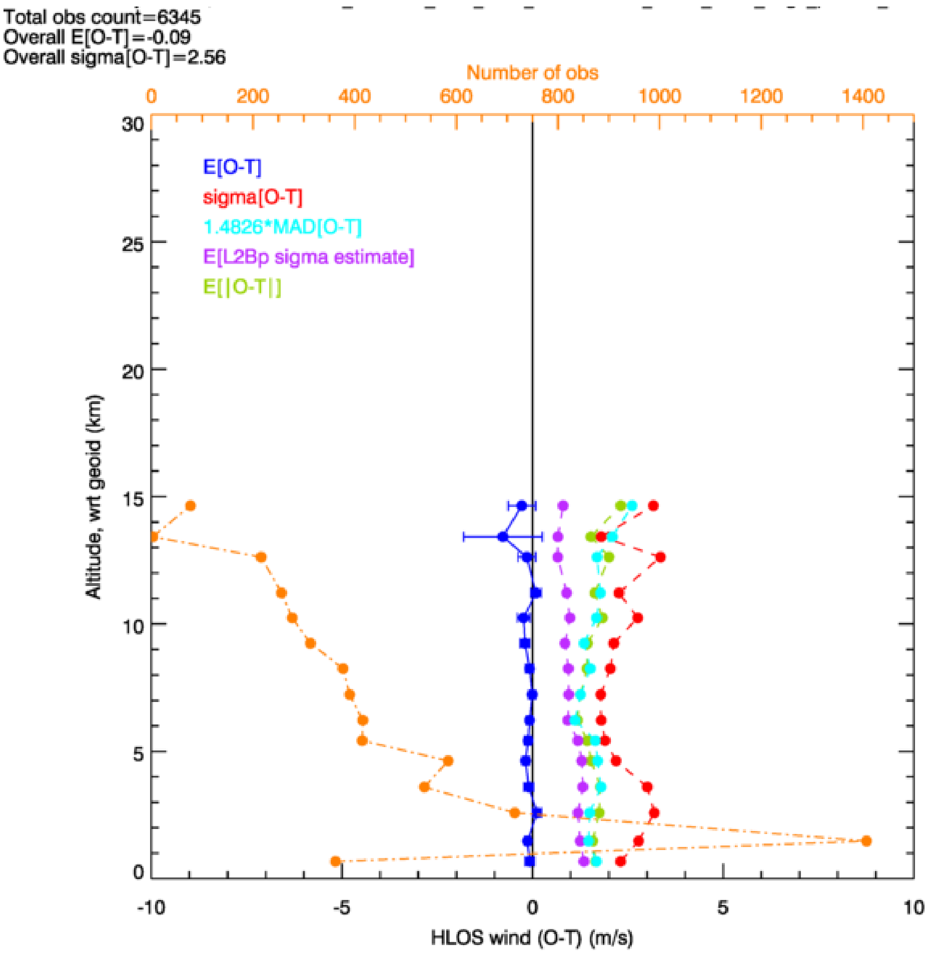

Figure 9. L2B Mie-cloudy HLOS wind result verification statistics for the ECMWF_T1279 scenario with "perfect" calibration: E2Sv3.05/L1Bpv6.04/L2Bpv2.20+. MRC derived from a simple clear atmosphere test case.

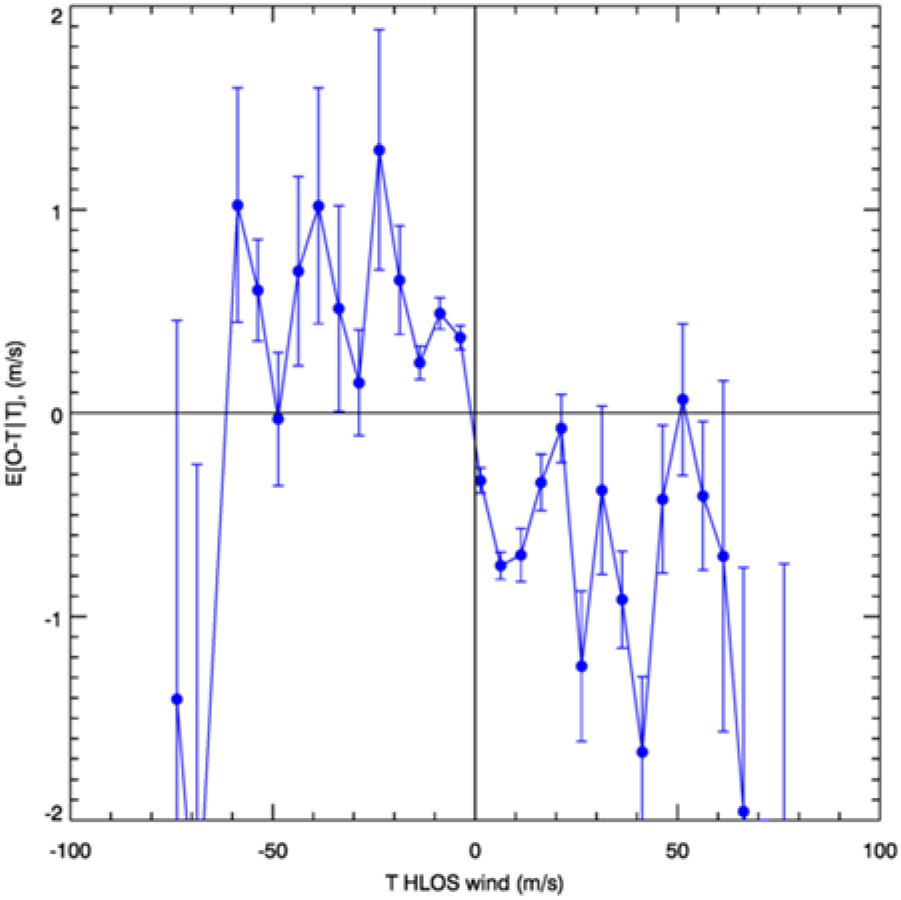

Figure 10. The L2B Mie-cloudy HLOS wind results, true (T) HLOS dependent bias (or slope error) for the same scenario as described in Figure 9.

Figure 11 and Figure 12 shows the L2B Rayleigh-clear and Mie-cloudy HLOS wind verification for the same atmospheric scenario, with the same L2Bp settings and with the same verification tool QC thresholds, but produced in September 2014 using E2S v3.04, L1Bp v6.03 and L2Bp v2.10. These can be compared to Figure 7 and Figure 9.

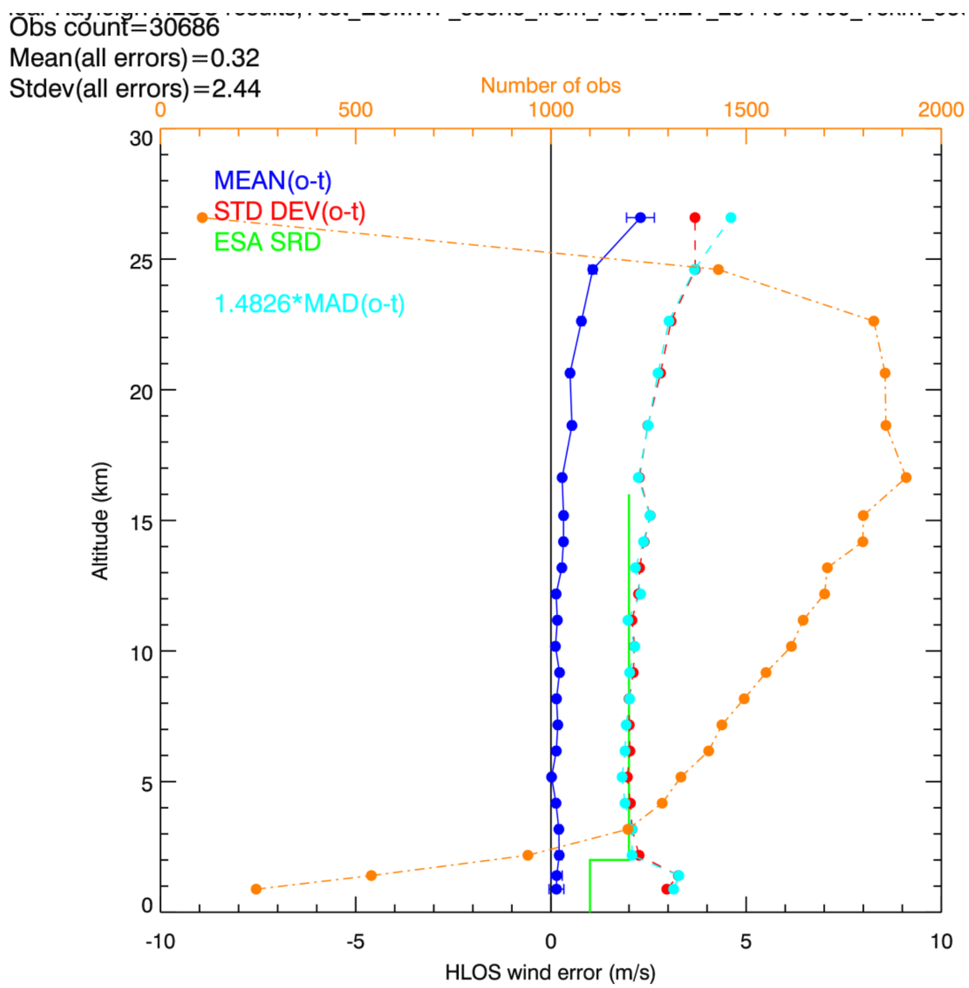

Figure 11. L2B Rayleigh-clear HLOS winds result verification from September 2014 using E2S v3.04/L1Bpv6.03/L2Bpv2.10 for the ECMWF_T1279 WVM scenario. With L1B team provided "perfect" calibration AUX_RBC.

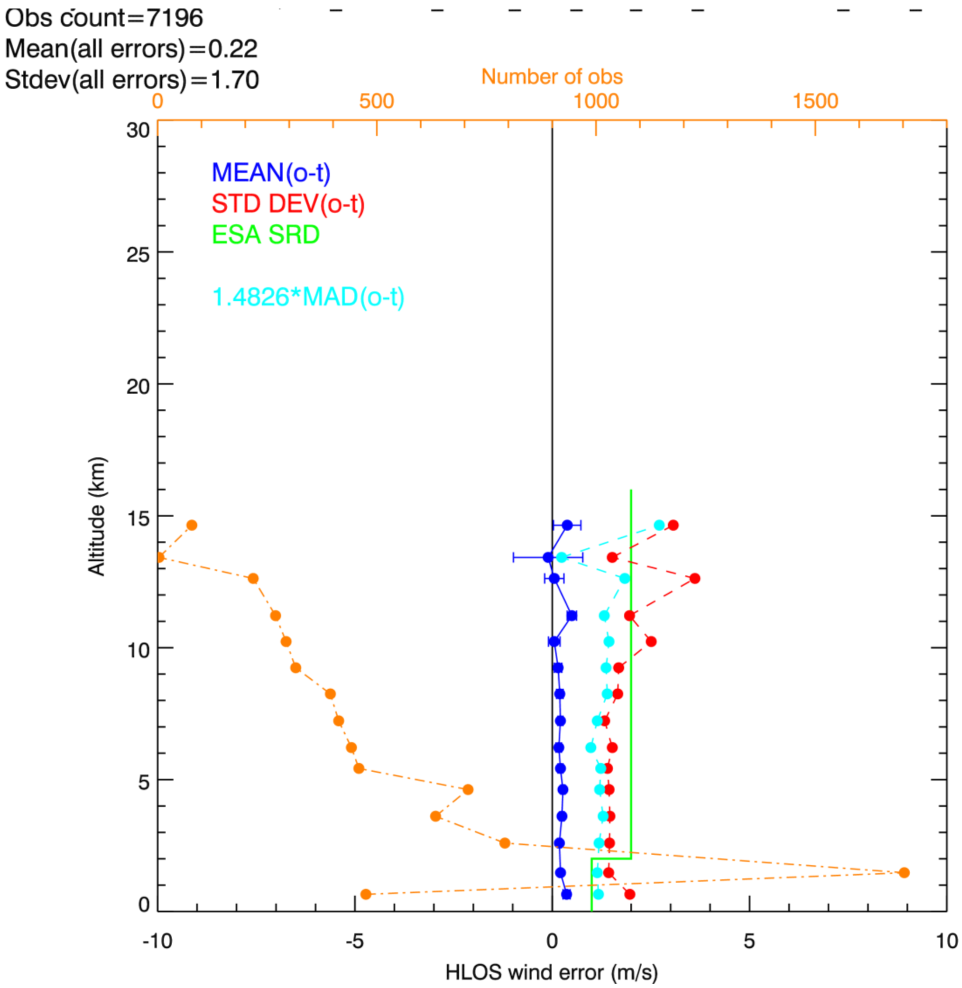

Figure 12. L2B Mie-cloudy winds result verification from September 2014 using E2S v3.04/L1Bpv6.03/L2Bpv2.10 for the ECMWF_T1279 WVM scenario. With L1B team provided "perfect" calibration MRC.

Bear in mind that the magnitude of the standard deviation of the error and the mean error are sensitive to the QC thresholds, particularly for the Mie results. When comparing the new CoP results to the September 2014 results, the following observations are made:

Rayleigh results:

- The standard deviation is 19% larger than in the earlier CoP. It is unclear if this a real increase in noise or a consequence of the QC changes because of changes in the L2B estimated error calculation, resulting from improvements in the L1B SNR estimates which are used in the L2B Rayleigh calculation.
- The bias is very similar to the old results, including the increase in bias at higher altitudes (and the 1% slope error). In the past this slope error was shown to be due to the DCMZ effect (and lack of correction in the L1Bp v6.03 and L1Bp v6.04).
- The number of observations is similar in both cases, as is the vertical sampling after QC.
- Note that the Rayleigh wind quality in the PBL is not compliant because a vertical sampling of 1 km (rather than the WVM2 500 m range bins) would be necessary and because the SRD (System Requirements document) PBL requirement is envisaged to be met by the Mie channel.

Mie results:

- The standard deviation is 50% larger than in the past. The QC interacting with changes in error estimates is not thought to be the reason for the change, it is believed to be genuinely noisier data because there are 12% fewer observations in the new results combined in combination with the higher standard deviation; this would not be possible with the same error distribution. It can be seen from Figure 9 that for the Mie-cloudy results the standard deviation (sigma[O-T]) is much larger than the 1.4826*MAD (1.4826 times the median absolute deviation) meaning that there are outliers causing the increase the standard deviation[10]; in the September 2014 results the two metrics are much closer. This tells us that the Mie-cloudy results have more outliers than in the earlier CoP testing. It is unclear what changed in the CoP processors to cause this. The L1B team results (personal communication with Karsten Schmidt, DLR) also reported such an increase in noise compared to older processing chains.

3.2 Testing “perfect” calibration with E2S v3.06 and L1Bp v6.05

In January 2016 the L1B team provided an E2S update (to v3.06 development version) and a L1Bp update (to v6.05 development version); official releases were not available at time of writing. A number of changes in the processors have large impacts on the accuracy of the L2B wind results, such as:

- Simulation of the Range-dependent bias (RDB) in the E2S and its correction in the L1B processing (with new AUX_RDB_1B file). Note however that because the RDB simulation and its L1Bp correction are switched off in this study (as explained in section 2.3.2) this will not matter.
- The correction of the Dark Current in Memory Zone (DCMZ) in the L1B processor for the Rayleigh channel (using the AUX_DCMZ1B file). The lack of correction of this effect in earlier L1B processors was shown in [RD4] to cause Rayleigh HLOS wind biases with a slope error type behaviour.
- E2S v3.06 more accurately simulates UV background noise which has been shown by the L1B team, see [RD15], to increase the noise levels in Rayleigh winds (in day-light conditions) significantly.
- Improvements in the L1Bp refined scattering ratio estimates for large scattering ratio values i.e. particularly for water clouds; see anomaly report AE-IPF-253 and associated reports.

Given these improvements in simulation and L1B processing it was decided to update the CoP to use the new E2S and L1Bp versions and to perform the remaining testing of WP2810 with this setup. Also, this update provides an appropriate test bed for the development of the next L2B processor delivery planned (at the time of writing) for summer 2016.

Therefore it was necessary to generate with the updated processors the “perfect” calibration products and to run the WVM scenario ECMWF_T1279 with the “perfect” calibration inputs and to compare the results to the previous CoP results before proceeding with more realistic calibration testing. Initial testing with the updated processor CoP led to the discovery of a bug in the E2S v3.06 (a problem

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[10] The expectation of 1.4826 times the MAD for large samples of normally distributed data is approximately equal to the population standard deviation.

simulating the DCMZ); this was reported to the L1B team who then promptly provided a patch for the issue.

The details of the processors to be used in the CoP for the testing in this technical note (**unless specified otherwise**) are given in Table 1.

Table 1. Processors in CoP for tests in this TN (unless specified otherwise)

Processor name	**Processor version**	**Purpose**
E2S	v3.06 development version (+ patch 1)	Simulate the Aeolus instrument signals in wind and calibration modes
L1Bp	v6.05 development version	Process the raw data to wind (WVM) and calibration products (e.g. ISR, IRC)
Calibration (CAL) suite	December 2015 release (+ ECMWF patch)	Generate the CSR file (and update if necessary), the AUX_RBC and the AUX_CAL files
L2Bp	v2.20+ (development version as of Jan 2016)	Produce the corrected HLOS wind observations

With the patched E2S v3.06 it was possible to get reasonable (but different to earlier processors) baseline wind results with the “perfect calibration” settings and the processors of Table 1. The verification results are shown in Figure 13 to Figure 17.

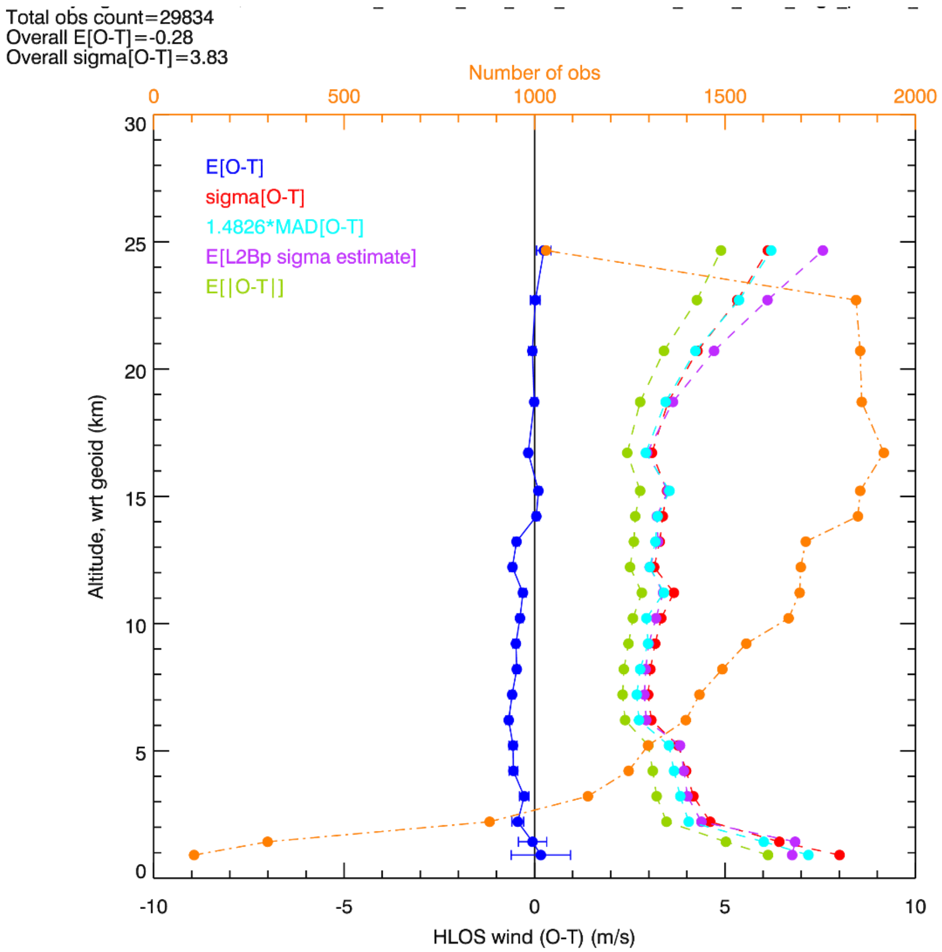

Figure 13 Verification statistics for L2B Rayleigh-clear HLOS wind results against E2S input "truth". For the ECMWF_T1279 scenario using "perfect" calibration with the processors listed in Table 1.

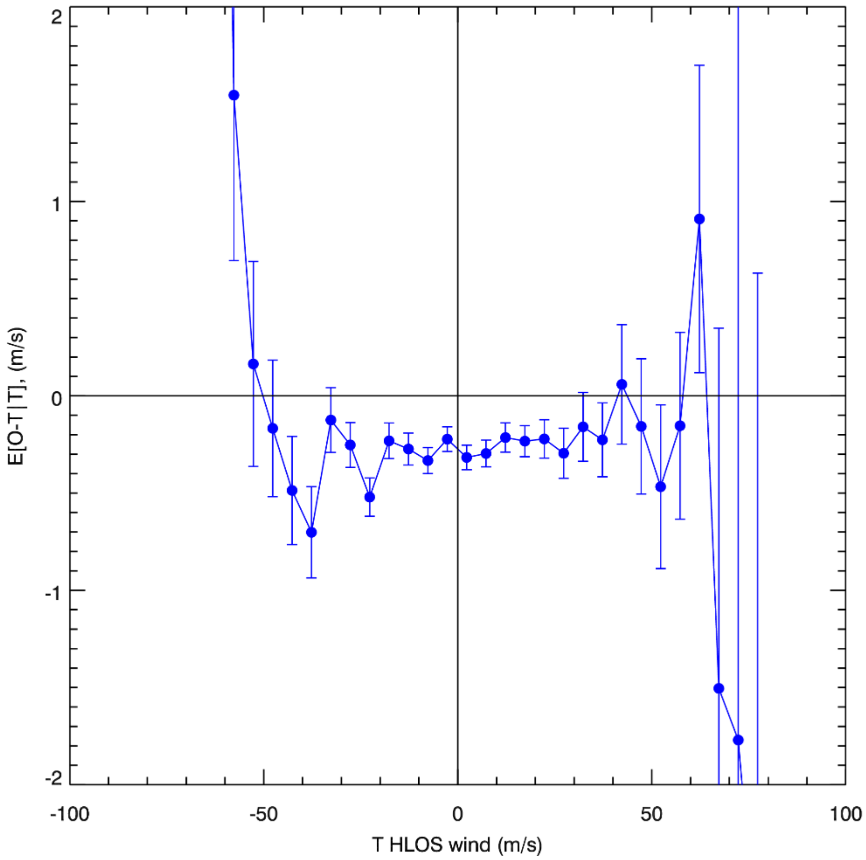

Figure 14. The true (T) HLOS wind dependence of the systematic error for same data as in Figure 13. The slope error is small (away from the extreme edges of the HLOS wind distribution).

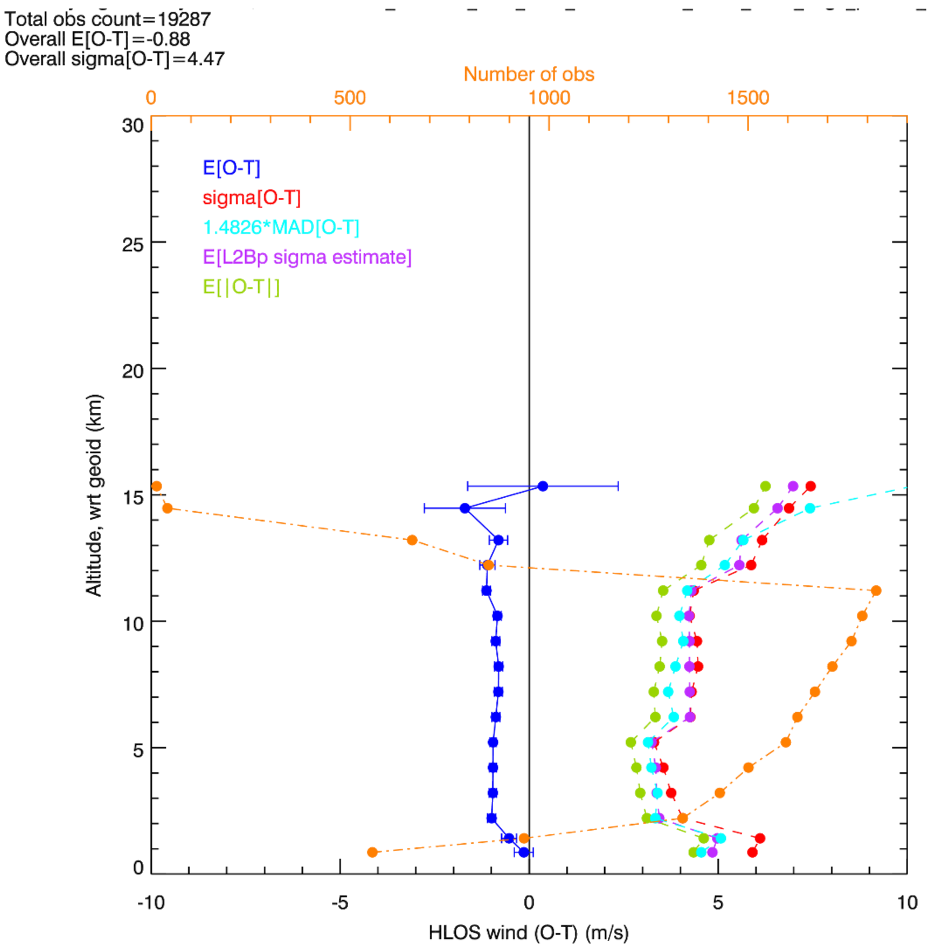

Figure 15. Verification statistics for L2B *Rayleigh-cloudy*[11] HLOS wind results against E2S input "truth". For the ECMWF_T1279 scenario using "perfect" calibration with the processors listed in Table 1.

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[11] L2B Rayleigh-cloudy HLOS wind results have tended not to be shown in the past because they were very biased, and probably not suitable for NWP.

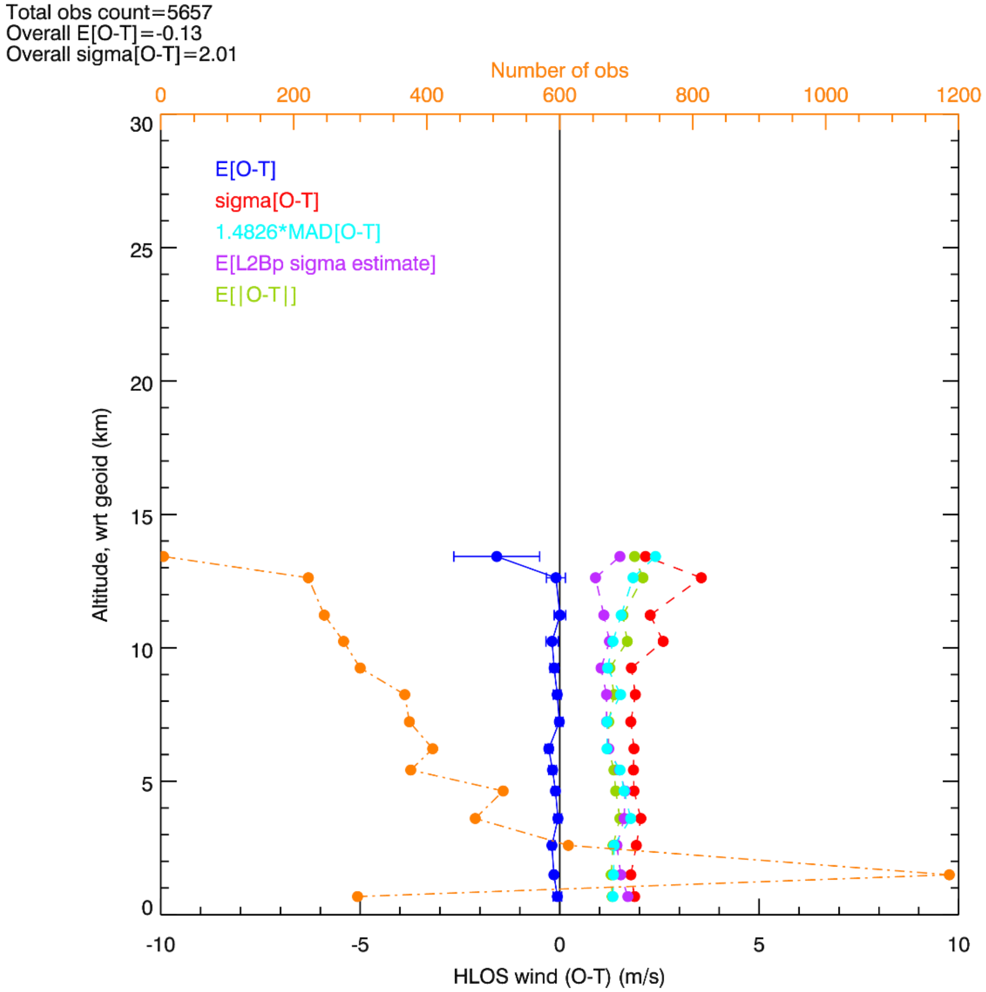

Figure 16. Verification statistics for L2B Mie-cloudy[12] HLOS wind results against E2S input "truth". For the ECMWF_T1279 scenario using "perfect" calibration with the processors listed in Table 1.

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[12] There are very few L2B Mie-clear wind results and hence the verification statistics are irrelevant.

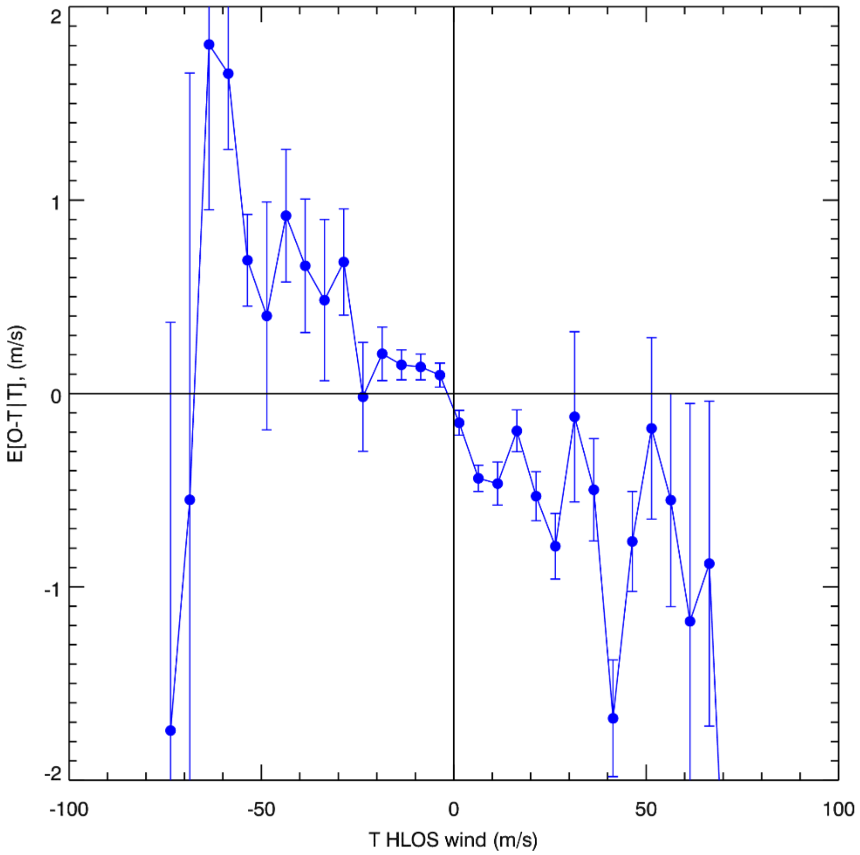

Figure 17. The true HLOS wind dependency of the systematic error for same L2B Mie cloudy data as in Figure 16. The slope error is ~1.6%.

Comparing the updated processor CoP results to the results obtained using E2S v3.05 and L1Bp v6.04 (as shown in section 3.1) the following differences are noted:

- **Degradations:**
  - Due to a large increase in noise for the L2B Rayleigh HLOS wind results, the verification QC for the Rayleigh winds (which uses the L2Bp estimated standard errors) had to be relaxed in order to obtain a similar number of wind results (whilst still trying to reject outliers which can distort non-robust statistics such as the mean and standard deviation).
    - For the L2B Rayleigh-clear winds the QC was relaxed from 5 m/s to 8 m/s.
    - After some testing the Mie QC value was increased from 3 m/s to 3.5 m/s to achieve a reasonable number of results whilst rejecting outliers.
  - With the above verification QC choices the **L2B Rayleigh-clear HLOS wind error standard deviation increased by 32%** to a profile average of 3.83 m/s. This came with a 6% decrease in the number of results (the number of results can be made more similar by relaxing the QC even further). The increase in noise is apparently because of the new UV background noise simulation (see Karsten Schmidt reference?) which increases the UV background noise by a factor of ~80. The default E2S v3.06 solar zenith angle settings of 75 degrees was used (which is the most representative value for the Aeolus orbit).

  - For the Mie winds it is difficult to judge if there has been a change in noisiness because the L2B estimated error has become more accurate[13], due to the use of a correct value of the Mie radiometric gain value (via the new L1B input). This interacts with the QC check. The Mie-cloudy HLOS wind dependent systematic error (slope error) has become a bit worse (at around 1.6%). It is unclear why; this should be investigated further.
  - The change in the L1B refined scattering ratio (SR) has interacted significantly with the L2B results. Section 3.2.1 explains in detail how the SR has changed and the consequences. It appears that an increase in the misclassification of actually “clear” measurements as “cloudy” when combined with a 1.15 clear/cloudy threshold has led to many more measurements entering the L2B Rayleigh-cloudy wind observations at the expense of the quality of the L2B Rayleigh-clear winds. There are 4.2 times as many Rayleigh-cloudy HLOS wind observations as in the previous CoP due to this.

- **Improvements:**
  - A significant improvement is seen for the L2B Rayleigh-clear HLOS wind slope error i.e. the pervious 1% slope error has gone. This is thought to be because of the DCMZ correction which has started to be applied with L1Bp v6.05 (N.B. using "perfect" coefficients to correct this effect). There is a reasonably small residual negative bias of -0.3 m/s (cause unknown). It is encouraging to see that the results of past CoP testing (i.e. showing the sensitivity of the slope error to DCMZ) have led to a real improvement in the L1B processing and hence the L2B results.
  - The Rayleigh-cloudy results are much improved, but this is an artefact of an increase in truly “clear” measurements entering the “cloudy” observations, which leads to better quality Rayleigh-cloudy winds i.e. the L2B classification of measurements is poorer than before.
  - The Mie L2B error estimate is more accurate than before due to the L2Bp using the correct value of radiometric gain being passed from the L1B input. The values have increased to be more in agreement with the error standard deviation (without outliers).

3.2.1 Assessment of the modified L1B measurement-level scattering ratio and the consequences on L2B winds

The change in L1B measurement-level scattering ratio (SR), in particular the refined SR, between E2S v3.05/L1Bp v6.04 and E2S v3.06/L1Bp v6.05 has a large effect on the L2B wind results. Particularly due to the interaction with the L2B classification algorithm. The effect on Mie cross-talk correction for Rayleigh wind observations is unclear.

Therefore some new verification statistics (as part of the “advanced monitoring” toolset) have been produced for assessing the accuracy of L1B measurement-level scattering ratio. The L1B refined scattering ratio (measurement-level) statistics are shown in Figure 18 for a) the previous CoP and b) the new CoP. In particular one should focus on the red line which shows the mean L1B refined scattering ratio as a function of the true scattering ratio (there is such an abundance of data for true SR=1 which makes the density plot not particularly useful). Note that we have defined the true SR as the E2S input

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[13] It was underestimated in earlier processing chains according to past verification statistics.

optical properties converted to SR at the centre of the measurement-bins[14].

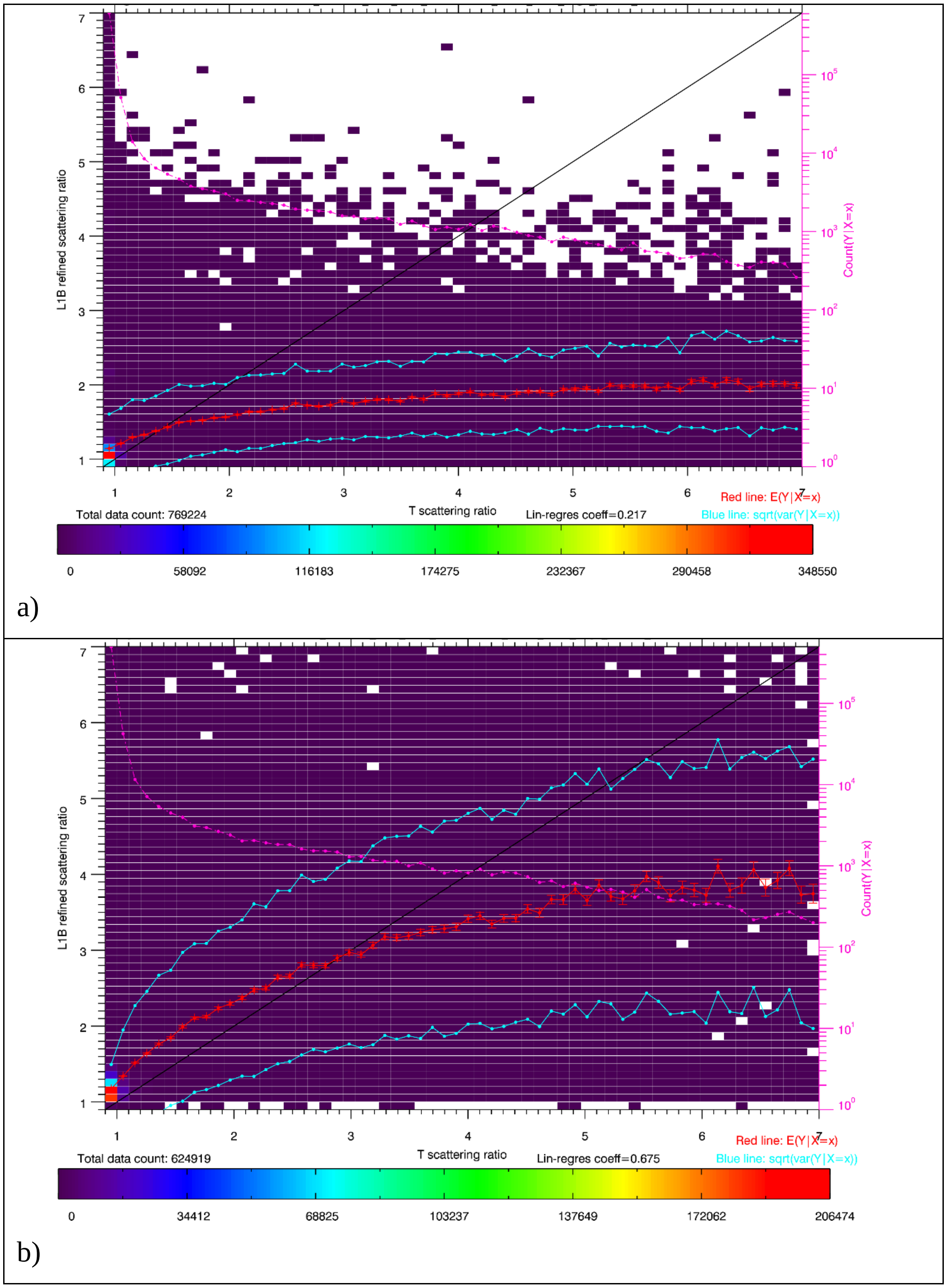

Figure 18. Verification statistics for the L1B measurement-level refined scattering ratio produced with a) E2S v3.05/L1Bp v6.04 and b) E2S v3.06/L1Bp v6.05. The E2S WVM scenario is ECMWF_T1279. The x-axis is the true (T) scattering ratio at the centre of the measurement-bin derived from the E2S input fields. The y-axis is the L1B refined scattering ratio. The mean of the L1B refined scattering conditioned on the true SR is shown by the red lines and the standard deviation either side of the mean is shown in light blue.

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[14] The sensitivity to using a vertical average of the truth over the bin made little difference to the statistics for the ECMWF cloud cases. The LITE scenarios showed more dependence due to their higher vertical resolution particle optical properties.

Figure 18 shows a large improvement in the SR bias for larger SR values with the new CoP compared to the old, however there is still a saturation of SR for larger true SRs i.e. SR~4 with new CoP, compared to SR=2 previously. The improvement is due to a bug fix in the L1B refined SR calculation as discussed in anomaly report: AE-IPF-255. However in the low SR range (around 1.5), which is important for the L2B processor classification and correction of Mie-contamination for Rayleigh winds, the SR has become more positively biased and is apparently noisier than before (note the blue standard deviation lines either side of the mean have increased).

This bias improvement and noise increase for the refined SR affects the L2Bp classification of measurements. With an applied SR threshold of 1.15 (as found to be useful in the past), the classification success rate (number of correctly classified bins/total number of bins) for this scenario decreased from 51% (old CoP) to 31% (new CoP) because more measurements are being classed as cloudy (SR> 1.15) with the new CoP when they are in fact truly clear. This leads to the factor 4.2 increase in the number of L2B Rayleigh-cloudy wind observations with the new processors (see Figure 15). This suggests a retuning of the SR classification threshold is required with the new CoP to improve the error statistics.

The L1B *nominal* scattering ratio verification is shown in Figure 19, but only for the new CoP; the statistics look quite similar for the old and new processing. The nominal SR has a very large positive bias at lower SRs (up to 1.5 units too large) and the large standard deviation. The massive SR bias at low SR values makes this more difficult to use for the L2B classification (without bias correction of some sort).

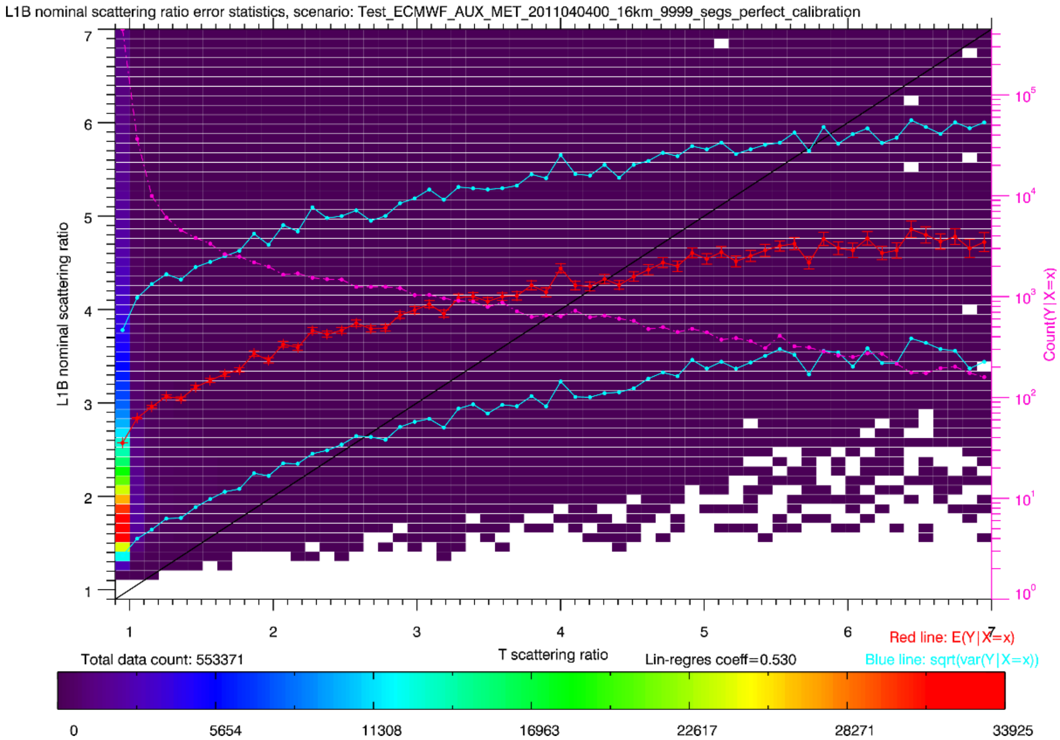

Figure 19. Verification statistics for the L1B *nominal* scattering ratio (measurement-level) produced with E2S v3.06/L1Bp v6.05. The E2S scenario is ECMWF_T1279.

In tests with a small, but realistic, optical properties scenario: LITE scene A (tropical cirrus, the true SR for this scenario is shown in Figure 24a)), it was noticed that the number of missing SR values increased from 16% to 30% with the new CoP compared to the old. Note that measurements with missing values for SR are given zero weight in L2B observations i.e. we throw away the information, which is a concern for the quality of L2B winds.

R2: It should be investigated if an improvement can be obtained in L2B winds by not throwing away measurements with missing L1B refined SR values e.g. setting the SR to 1 might be a good idea, since the missing values typical occur when there is a weak Mie signal.

It was noticed that the fraction of missing values (with the new CoP) depends to some extent on the UV background noise level; something that probably did not happen with previous CoP in which the E2S simulated much less UV background signal. This dependence on UV solar background noise for the LITE scene A case is shown in Table 2.

Table 2. Investigating the effect of solar zenith angle on the fraction of missing L1B refined scattering ratio values for a scenario= LITE scene A.

Solar zenith angle (degrees)	***cos*(SZA)**	**Percentage of missing SR values (%)**
10	0.98	45
60	0.50	37
75	0.25	33
90	0.00	30

There is an increase in the fraction of missing values with the increase in UV background noise levels. However note there are still 30% missing values with zero UV background noise (i.e. SZA=90 degrees).

The L1B SR calculations were investigated in more detail to understand the source of the missing values:

- The L1B nominal and refined SR are set to missing in the L1Bp v6.05 code if a value called `sortedSum` is negative. The `sortedSum` is the sum of the lowest 4 (a settable parameter) pixels in the useful range (3 to 18) after detection chain offset (DCO) subtraction and background noise subtraction (as estimated from row 25 of the LID data). The useful range values can be negative after subtracting these offsets due to Poisson noise in the estimates of the offsets in combination with Poisson noise in the signal. Figure 20b) shows an example of noisy measurement-level Mie signal from the E2S output (a cloudy scenario to show some Mie peaks). This can be compared to noise-free and large laser energy simulation in Figure 20a).
- After the DCO and background offsets are removed, the L1B refined SR determines a remaining offset level to estimate the RB signal (see a derivation of the L1Bp SR formula in the Appendix) using the Mie core algorithm 2. Note that the refined SR does not use the `sortedSum` value. After examining some L1B example data, it was clear that ignoring `sortedSum` will reduce the number of missing refined SR values. We tested such a code change for the SZA=10 degrees test case, and the number of missing refined SR values decreased from 45% to 9%. However, many of the new non-missing values were rather noisy estimates of the SR, which in hind-sight is not

surprising. However the classification success rate increased from 52% to 83% (when using a 1.8 SR threshold for partitioning in clear/cloudy) mainly due to the fewer missing values.

- Dorit Huber (L1B team) confirmed there is a need for the test on `sortedSum` for the refined SR, despite the value not being used directly in the calculation:
  …if the sum of these 4 lowest elements is negative, then the findPeakHeightAndOffset method that we have defined does not work properly, and returns an offset that is not correct. And then we us an incorrect initOffset value in the calculation of the SR. This is why I have added the check on the sortedSum even if it does not occur in the equation for the SR.

In previous CoPs it was predominantly the noisy DCO subtraction that led to negative sortedSum and hence missing values, but now due to larger UV background noise, the subtraction of this also affects the missing values. This UV background noise is also thought to account for the generally much noisier SR estimates seen in Figure 18 with the new CoP.

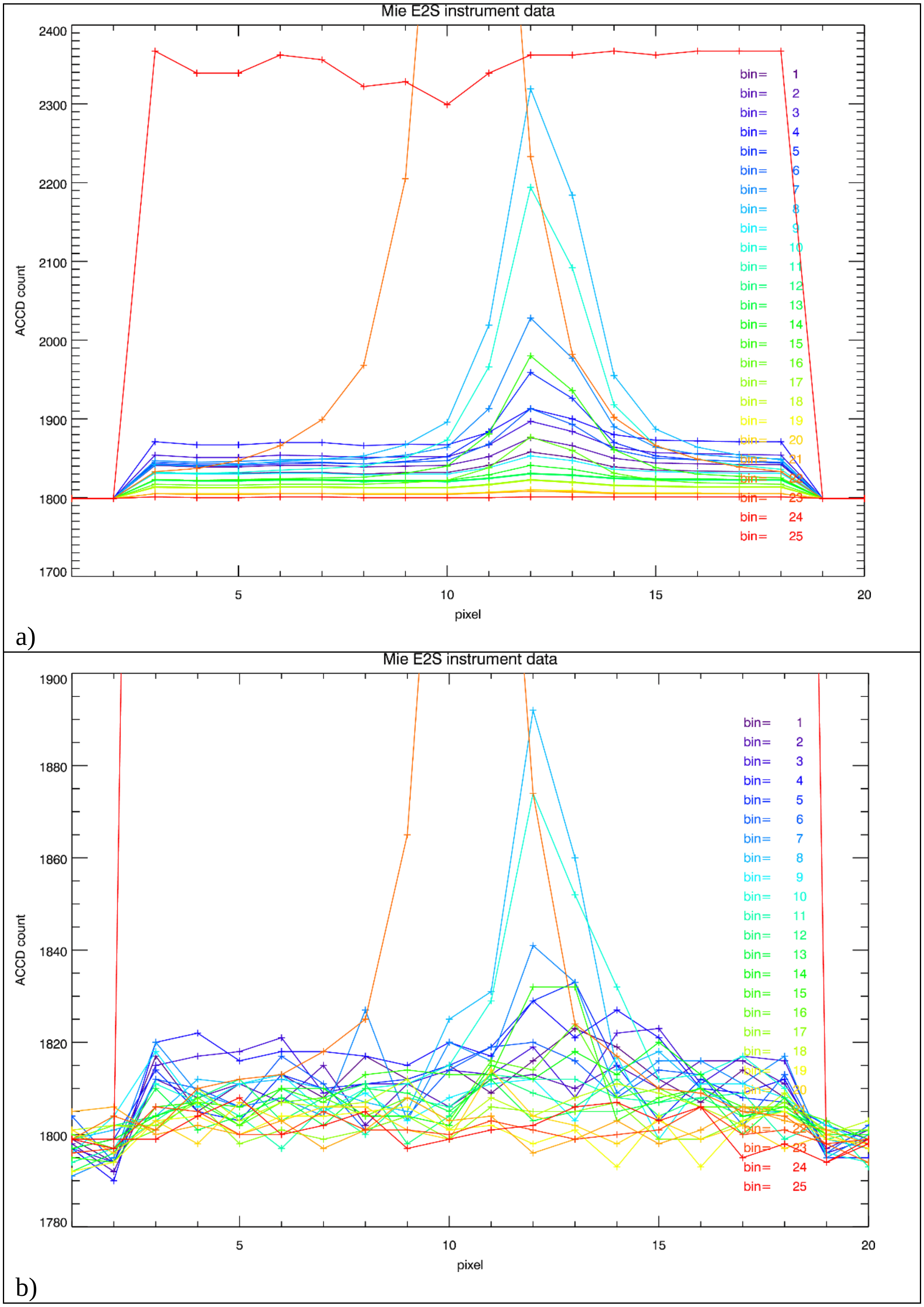

Figure 20. Mie channel ACCD read-outs from E2S simulated instrument data. This is for one measurement from a LITE scene C (a tropical cloud case) a) noise-free simulation with 1000 mJ laser pulse b) noisy simulation with 80 mJ

laser pulse. Bin 25 is the row of the LID data used for background noise estimates. Bin 1 is the highest altitude bin atmospheric return.

3.2.2 Reducing the refined SR bias for small SRs

A correction factor (given the symbol α) is used in the L1Bp SR calculation (see the Appendix 7.1). By definition α< 1.0, but it has been set to 1.0 in the default AUX_PAR_1B settings. This may partially account for the positive bias in the low SR estimates. The ECMWF_T1279 WVM test case verification of L1B refined SR was repeated with α=0.8, a value suggested by an old study [RD12]. This improves the situation for smaller SRs as shown in Figure 21; compare to Figure 18b). **Therefore the value of α=0.8 will be adopted for the L1Bp AUX_PAR_1B file from now on in this study.**

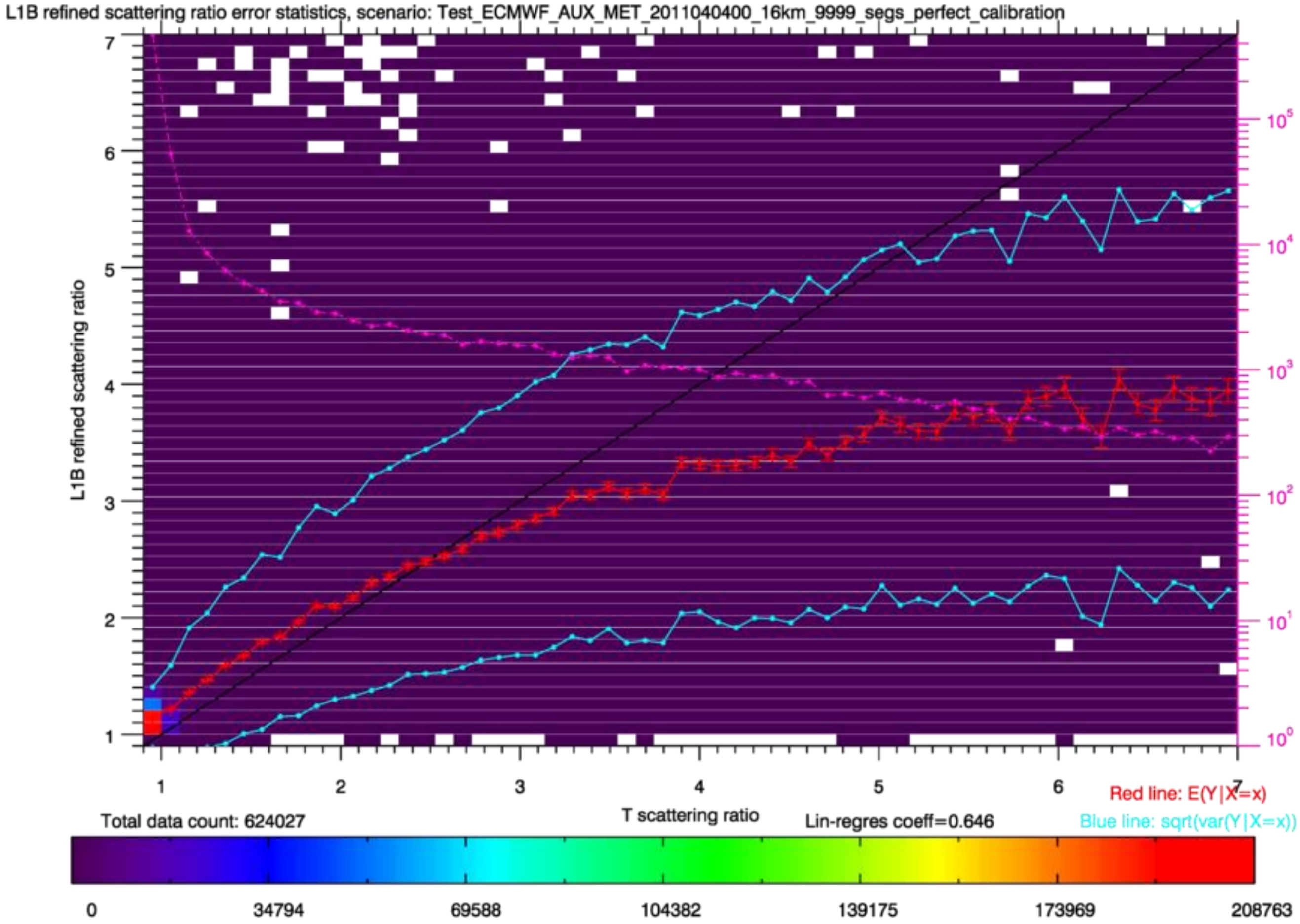

Figure 21. Same scenario as Figure 18b), but with the SR calculation α=0.8, rather than α=1.0

The effect on the L2B winds of using α=0.8 in combination with a newly tuned L2B SR threshold for classification (to try to take account of the positive bias in the low L1B refined SRs values) was assessed with the ECMWF_T1279 cloudy scenario.. The differences between the two cases are:

1. Old CoP settings: L1Bp α=1.0, L2B SR threshold=1.15
2. New suggested settings: L1Bp α=0.8, L2B SR threshold=1.8

The L2B wind results for the new suggested settings are shown in Figure 22 and Figure 23. This change led to a profile average decrease in HLOS wind error standard deviation of Rayleigh-clear winds by about 0.2 m/s; compare Figure 22a) to Figure 13. There was a clear improvement in the troposphere e.g. at 4 km altitude the L2B Rayleigh-clear HLOS wind error standard deviation was around 4 m/s with case 1., but reduces to 3 m/s with case 2., and are 8% more observations in case 2.

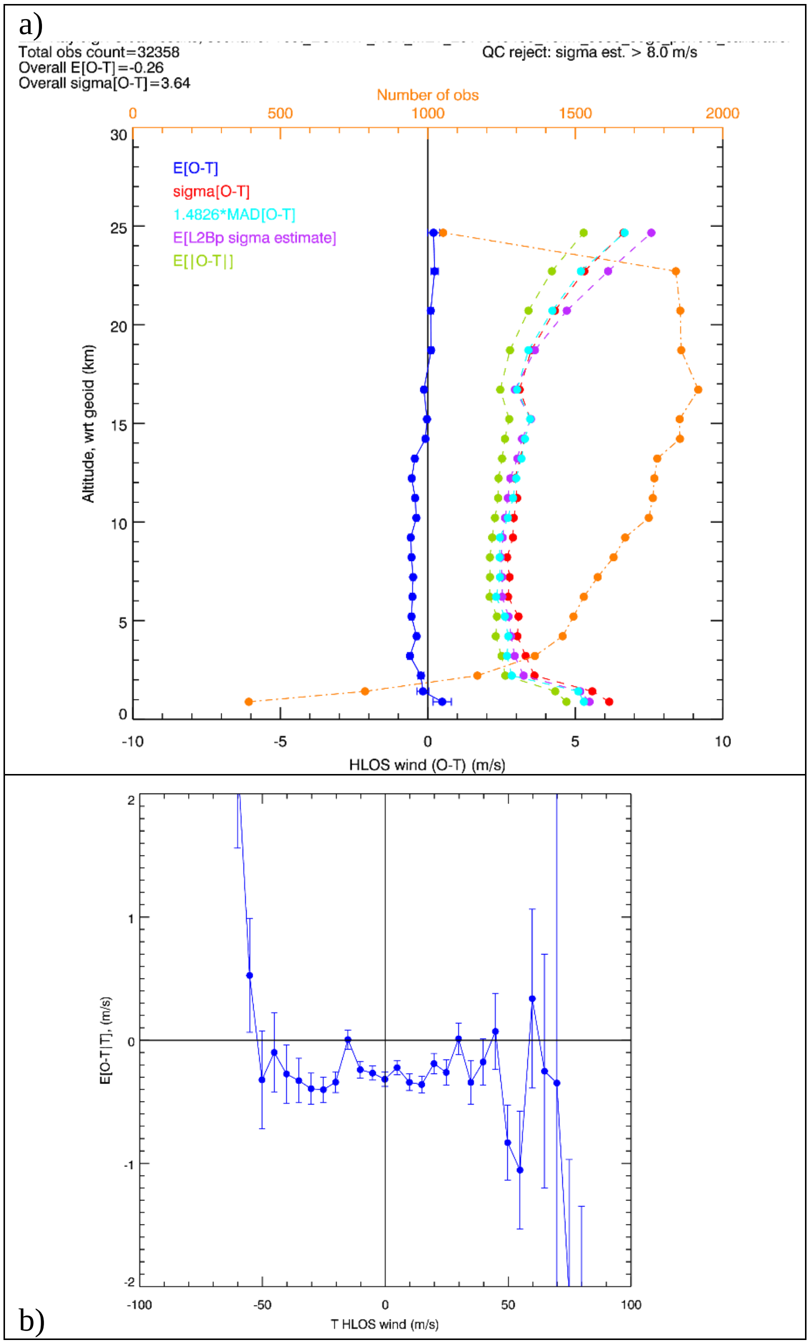

Figure 22. L2B Rayleigh-clear produced with SR threshold=1.8 and α=0.8. a) Verification as a function of altitude, b) mean error in HLOS wind versus true HLOS wind.

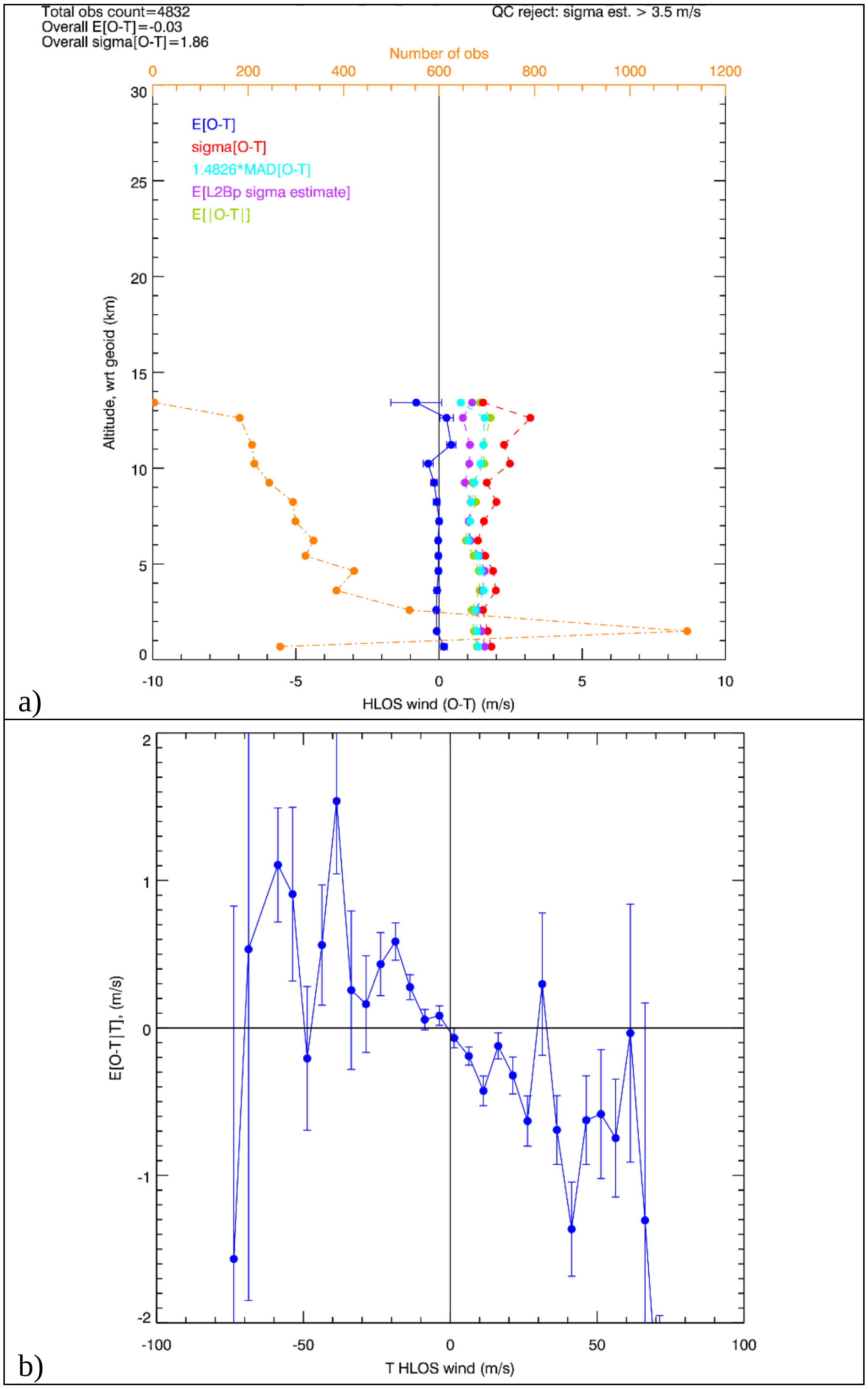

Figure 23. L2B Mie-cloudy winds produced with SR threshold=1.8 and α=0.8 and using "perfect" calibration a) Verification as a function of altitude, b) mean error in HLOS wind versus true HLOS wind.

There were fewer L2B Mie-cloudy results with case 2. (compare Figure 23a) to Figure 16), but the standard deviation is noticeably improved. This is because in effect the higher SR threshold is a type of QC allowing only stronger Mie returns for the Mie-cloudy results, so this is not surprising.

R3: A new L2Bp SR threshold of 1.8 in combination with L1Bp α= 0.8 is recommended and is adopted for the remaining test cases in this report.

3.2.3 Assessment of L1Bp modification to reduce the number of missing refined scattering ratio values

A change in the L1Bp code to reduce the number of missing refined SR values was implemented by editing the L1Bp v6.05 code and recompiling. This was done by removing the `sortedSum` check in `LBC_WVMProcessor.cc` for the refined scattering ratio calculation.[15]

First it was tested with the small LITE scene A scenario (tropical cirrus) with an unrealistically large amount of UV background noise for Aeolus by setting the SZA=10 degrees (with the default E2S value of solar irradiance i.e. 1100 $W/m^2/\mu m$) to produce more missing values (see Table 2).

The number of missing refined SR values decreased with the code change from 45% to 9%; this is shown via lidar cross-section plots in Figure 24 (going from b) to c)). However, many of the new non-missing values appear to be rather noisy estimates of the SR. This is thought to be because the missing values tend to occur in low Mie signal cases with larger noise in the DCO + solar background offsets. The classification success rate (for partitioning of clear/cloudy) increased from 52% to 83% in combination with a 1.8 SR threshold. N.B. most of this “improvement” is because a missing value for SR is classed as an incorrect classification in the statistics, therefore a non-missing value even if noisy can by chance be correctly classified.

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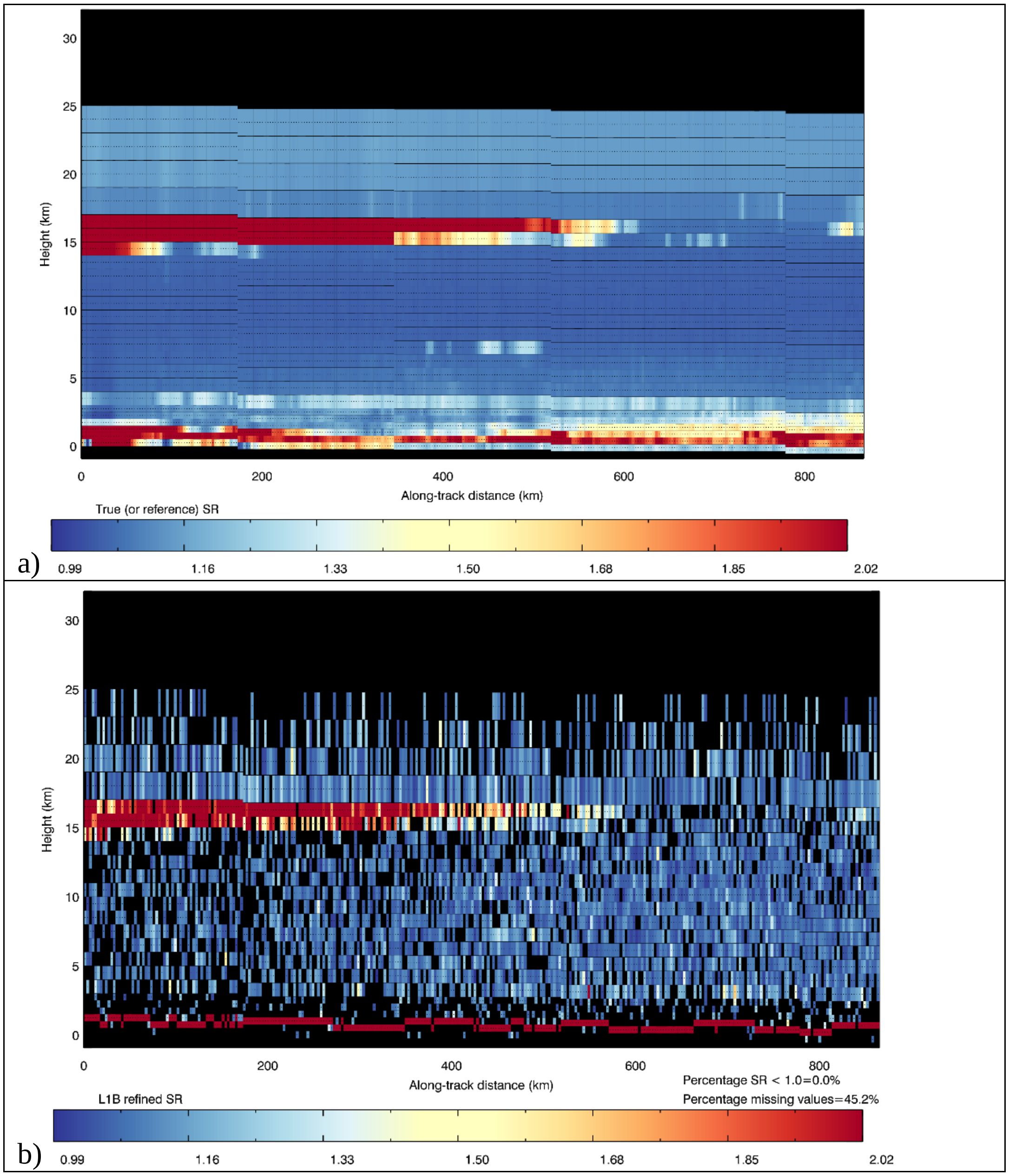
[15] Dorit Huber (L1B team) confirmed after this testing was performed that there was a good reason to keep the sortedSum check.


Height (km)
30
25
20
15
10
5
0
0
200
400
600
800
Along-track distance (km)
True (or reference) SR
0.99
1.16
1.33
1.50
1.68
1.85
2.02
a)
Height (km)
30
25
20
15
10
5
0
0
200
400
600
800
Along-track distance (km)
Percentage SR < 1.0=0.0%
Percentage missing values=45.2%
L1B refined SR
0.99
1.16
1.33
1.50
1.68
1.85
2.02
b)

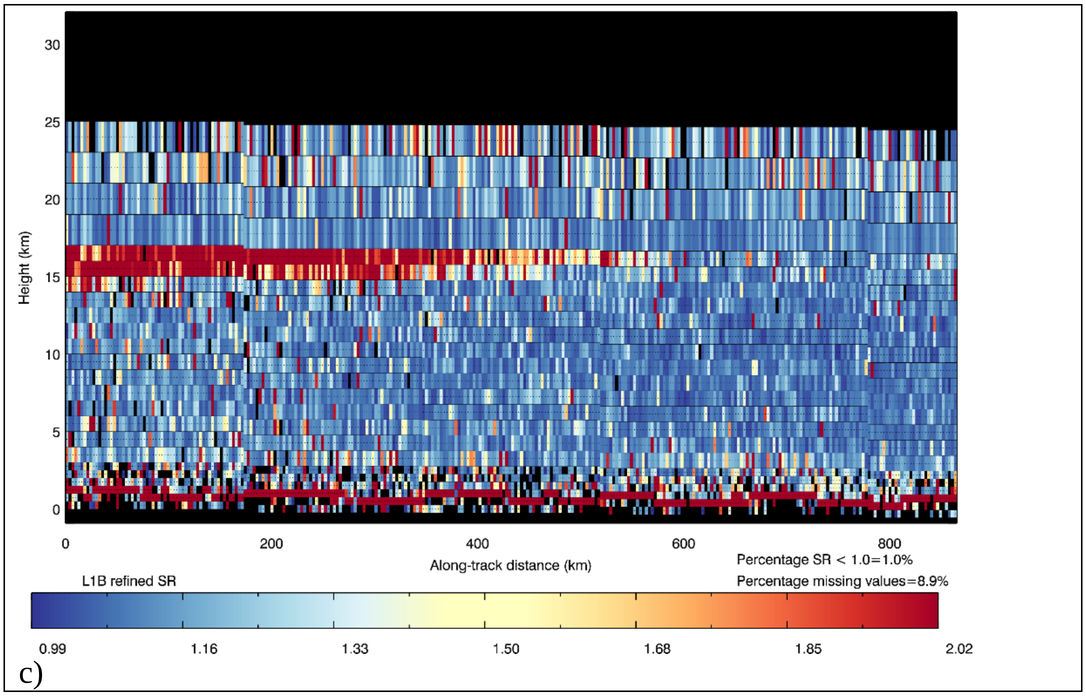


Figure 24. L1B measurement-level scattering ratio cross-section plots from LITE scene A scenario (0.5 km horizontal resolution E2S input). a) The true SR (derived from E2S input) on the Aeolus measurement grid b) the L1B measurement-level refined SR prior to the L1Bp fix for missing values c) with the L1Bp code modification.

Hence there are many more SR values, but they do not appear to be good quality estimates. Based on this LITE case it appears the L1Bp refined SR (at measurement level) is too noisy to detect true SR features of less than ~1.8; so it is unclear if we can ever do a reasonable job in correctly classifying smaller backscatter aerosol layers in the L2B processor. Some noise filtering techniques may help (such as those being investigated by KNMI, in particular Gert-Jan Marseille, as part of the Optical Properties retrieval work).

The impact on the L2B HLOS winds of the L1B SR code modification for missing values was also assessed using the ECMWF_T1279 cloudy 4 orbit scenario (with default E2S UV solar background noise levels). It was hoped that by using more measurements in the L2Bp, due to fewer missing values, the quality of the winds would improve. The number of missing SRs reduced from 49% to 29% in this scenario (with default E2S SZA). In practice, the Rayleigh-clear HLOS wind error improved only slightly i.e. a 0.07 m/s profile average reduction in error standard deviation (not shown). However, the bias became more negative, especially in troposphere by 0.1-0.2 m/s. This is thought to be because the new non-missing refined SR values entering the wind retrieval are noisier and more positively biased SR estimates; as shown in Figure 25 which plots the Rayleigh-clear HLOS wind error dependence on the error in SR (here the L2B SRs derived from the L1B refined SR at measurement-level). It can be seen in Figure 25 b) that there in an increase in the number of positively biased SR estimates and that these tend to induce negative HLOS wind bias. Therefore it seems that the use of biased and noisy scattering ratios in the Rayleigh wind Mie correction is counteracting the improvement in random error from extra measurements used in the observation, and that the positive bias in the extra SR values seem to produce negatively biased HLOS winds. The Rayleigh-cloudy winds are also noticeably more negatively biased (not shown).

Based on these results, we do not recommend the L1Bp refined SR code modification; this agrees with the L1B team assessment. However, as recommended earlier there may be better ways to use the measurements with missing SR values e.g. to set the SR to 1.

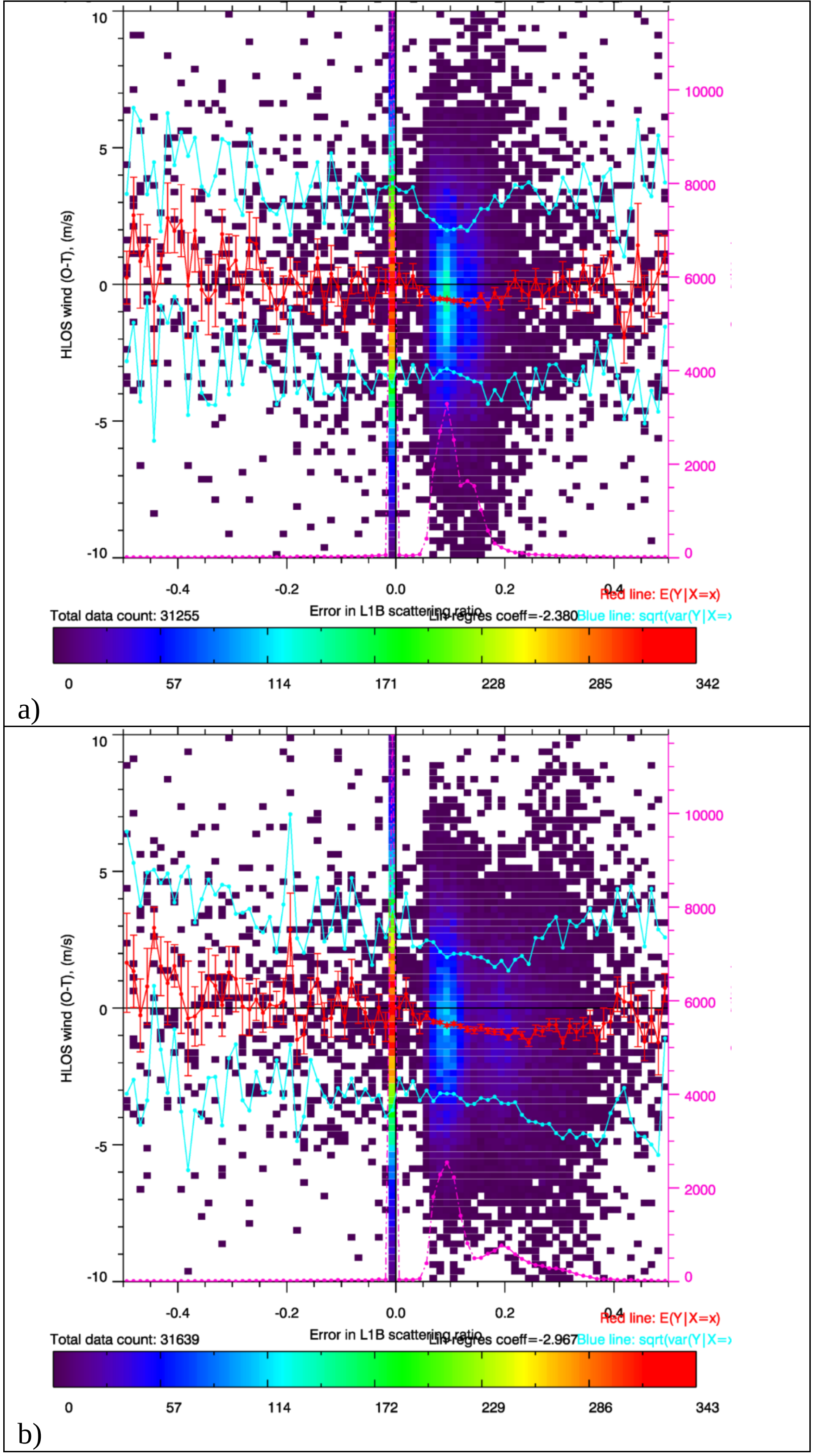


Figure 25. The dependence of the L2B Rayleigh-clear HLOS wind error upon the error in the L2B observation level scattering ratio (averages from L1B refined SR at measurement level). For a) before the L1Bp SR code modification (i.e. more missing values) and b) with the L1Bp SR code modification (fewer missing values)

4 The effects on L2B winds of imperfections in the calibration chain

We now move onto the main part of the TN which is to assess how imperfections in the calibration processing chain go on to influence the L2B wind systematic errors. Firstly the Rayleigh calibration chain will be assessed, then followed by the Mie.

4.1 Rayleigh calibration chain testing

There are many components to the Rayleigh channel calibration chain used to generate the AUX_RBC_L2 look-up table that is used by the L2B processor. Hence there are many possible choices when simulating the calibration in the E2S and running the L1B processing of the calibration mode followed by the CAL suite processing (i.e. the calibration part of the CoP). A diagram illustrating the choices that will be tested for this TN are shown in Figure 26. The test cases are numbered from 1 to 10. The final settings and combinations of processors as described earlier in Table 1 will be used for the testing in this Section.

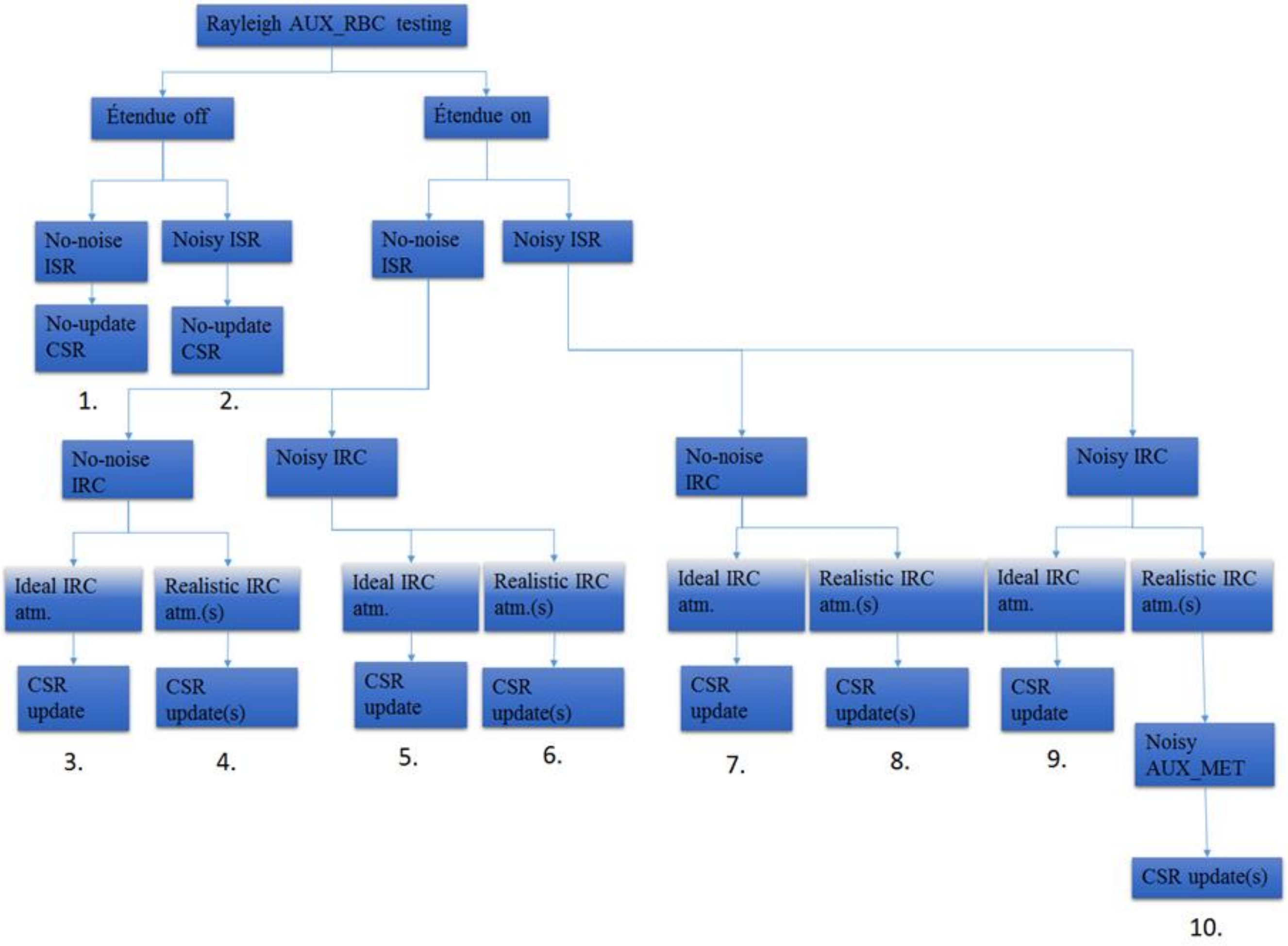


Figure 26. Diagram indicating the possible test cases for investigating the Rayleigh channel calibration errors and hence the effect on L2B winds.

Test case 1 is the simplest: a noise-free AUX_RBC_L2 file. It includes a noise-free ISR. Because the étendue effect is off in the E2S, it is unnecessary to run the IRC and the AUX_CSR updater to estimate the étendue effect from the RRC i.e. there is no effect to estimate. We have already produced and tested the AUX_RBC_L2 from this test case i.e. it is the "perfect" calibration case that has been extensively tested in Section 3.2 to produce the baseline "perfect" calibration ECMWF_T1279 WVM test case results for the Rayleigh channel.

Test case 2 includes an E2S simulation of a noisy ISR but otherwise it is similar to test case 1 in that it does not require the IRC and AUX_CSR updater since the étendue effect is switched off in the WVM run that uses the AUX_RBC_L2 file. Potentially the noise in the ISR will lead to a poorer function fit in the GenerateCSR step (that fits a model to the A and B transmission functions). The noisy ISR is also used to generate the internal Rayleigh response calibration curve that is stored in the AUX_RBC_L2 and needed in the L2B stage. Noise in the ISR was found to be a major source of bias in [RD4] due to the effect on the internal RRC; this will be tested again with the newer CoP (Table 1) here in test case 2 of this Section.

Test cases 3 to 10 have the étendue-effect switched on. The étendue-effect is expected to be important for the real ALADIN instrument Rayleigh channel atmospheric path, therefore it is important to check how well the CAL suite performs in the estimation of étendue parameters and how this influences L2B wind biases. Throughout we stick to a fixed set of étendue parameters i.e. width=500 MHz, tilt=1; values recommended by the L1B team. It may in future studies be of interest to investigate a range of parameters.

Test cases 3 to 10 have varying degrees of realism in terms of the inclusion or not of simulated noise and the realism of the atmospheric scenarios used for the IRC simulations that are input to the CSR updater. Test case 10 is the most realistic test case, involving all noise sources on in the calibration simulation in combination with the most realistic atmospheric scenario for the IRC (e.g. realistic cloud, winds, temperature and pressure fields from the ECMWF model). It may also incorporate errors in the AUX_MET_12 data used by the CSR updater.

Test case 3 is a no-noise simulation, but with the étendue effect on in the E2S simulation. This will assess the performance of the CSR updater in an idealistic no-noise and simple atmosphere scenario i.e. a scenario in which it is expected to perform very well. Test case 4, is similar to 3, but uses a more realistic scenario for the IRC atmosphere. Test cases 5 and 6 then introduce instrument noise into the IRC relative to the test case 4 setup. Test cases 7 to 10 incorporate the ISR noise also.

Each test case will generate an AUX_RBC_L2 file; assuming that each step of the CAL suite processing completes successfully. Each AUX_RBC_L2 will then be applied in an ECMWF_T1279 WVM test case, so that the calibration's effect on a large sample of winds can be assessed. Care will be taken so that the WVM test case matches the calibration settings e.g. étendue settings should match (it should be obvious if they do not, in terms of the wind bias it will generate). Default E2S noise sources will be switched on in the wind mode scenarios. The E2S WVM scenario only needs to be run twice, once with the étendue-effect "on" and once with it off. The use of a very large WVM sample leads to relatively stable L2B random error statistics. We are interested instead in the variability in the calibration products that are input to the L1B and L2B processors and how they affect the L2B HLOS winds systematically.

Each test case that involves random noise simulation as part of the calibration simulation will be repeated an appropriate number of times to generate a sample of possible calibration errors. Of course if random noise is not simulated (i.e. switched off in E2S) then the test case will only need to be run once (i.e. test cases 1, 3 and 4). The following sub-sections go through each test case.

Note that the L2B processor does not use the internal Rayleigh response as measured during the RRC; it instead derives it from the ISR as (T_A-T_B)/(T_A+T_B). This is then stored in the AUX_RBC_L2 file for use in the L2B processing.

4.1.1 Rayleigh test case 1: "perfect" calibration

As already discussed, this test case was generated already as part of the work in section 3.2. Since there is no noise simulated in this test case it only needs to be run once. The overall bias for the Rayleigh-clear HLOS winds came out as **-0.26 m/s** (see Figure 22). This is the reference bias with which the imperfect calibration tests will be compared to in the following test cases.

4.1.2 Rayleigh test case 2: the effect of noise in the ISR

This test case involves running the E2S with default noise settings before generating the ISR product (with the L1B processor). Since the E2S ISR simulation has random noise "on", the test case will be run five times to generate a sample of noise affected AUX_RBC_L2 files. Five samples seems a good compromise between assessing the biases and the time taken to run and analyse the tests.

Table 3 below provides the results. It shows theL2B Rayleigh-clear profile average bias after running the same ECMWF_T1279 WVM with the five realisations of the AUX_RBC_L2 files. We have defined the L2B HLOS wind bias to be relative to that obtained with "perfect" calibration in test case 1 i.e. The L2B Rayleigh-clear HLOS wind bias for test case *n* is:

$$HLOS\_bias\_n = \langle \varepsilon_{HLOS\_n} \rangle - \langle \varepsilon_{HLOS\_1} \rangle$$

The mean average uses all winds results which pass the QC (i.e. if estimated HLOS wind sigma > 8 m/s).

Table 3. Effect of noisy ISR on the L2B Rayleigh-clear wind bias (average over all data)

AUX_RBC_L2 run number	L2B Rayleigh-clear HLOS wind bias (m/s) relative to "perfect calibration"
1	-0.54
2	-0.76
3	-0.15
4	-0.53
5	+0.26

Assessing the behaviour of the bias with the "advanced monitoring" (not shown) confirms that the bias is a constant offset i.e. not varying as a function of the monitored variables (e.g. altitude, HLOS wind etc.). Table 3 informs us that fairly large L2B wind biases can result from noise in the ISR. The bias value changes with each realization of the ISR, with **the mean absolute bias of 0.44 m/s** (from this small sample).

The magnitude of the bias is similar in magnitude to that reported in the earlier study [RD4]. The reason for the bias is because the ISR noise propagates to a noisy internal RRC that is provided in the AUX_RBC_L2 file for the L2BP. For example, see in Figure 27 that the internal RR calculated from the noisy ISR has oscillations around a linear fit. Due to the extreme sensitivity (0.0034 GHz ≡ 1m/s HLOS wind) then these small noisy departures are a problem when the same (or very similar) internal response is measured repeatedly as it does in E2S simulations; which should also occur for the real mission.

A proposed solution is to use the DLR model fit to the ISR T_A and T_B to calculate the internal RR in the AUX_RBC _L2 file and hence reduce the noise, but this was not yet implemented in the CAL suite Dec 2015+ applied here (see Table 1). *However, this is tested in a newer CAL suite in Section 4.3.2.*

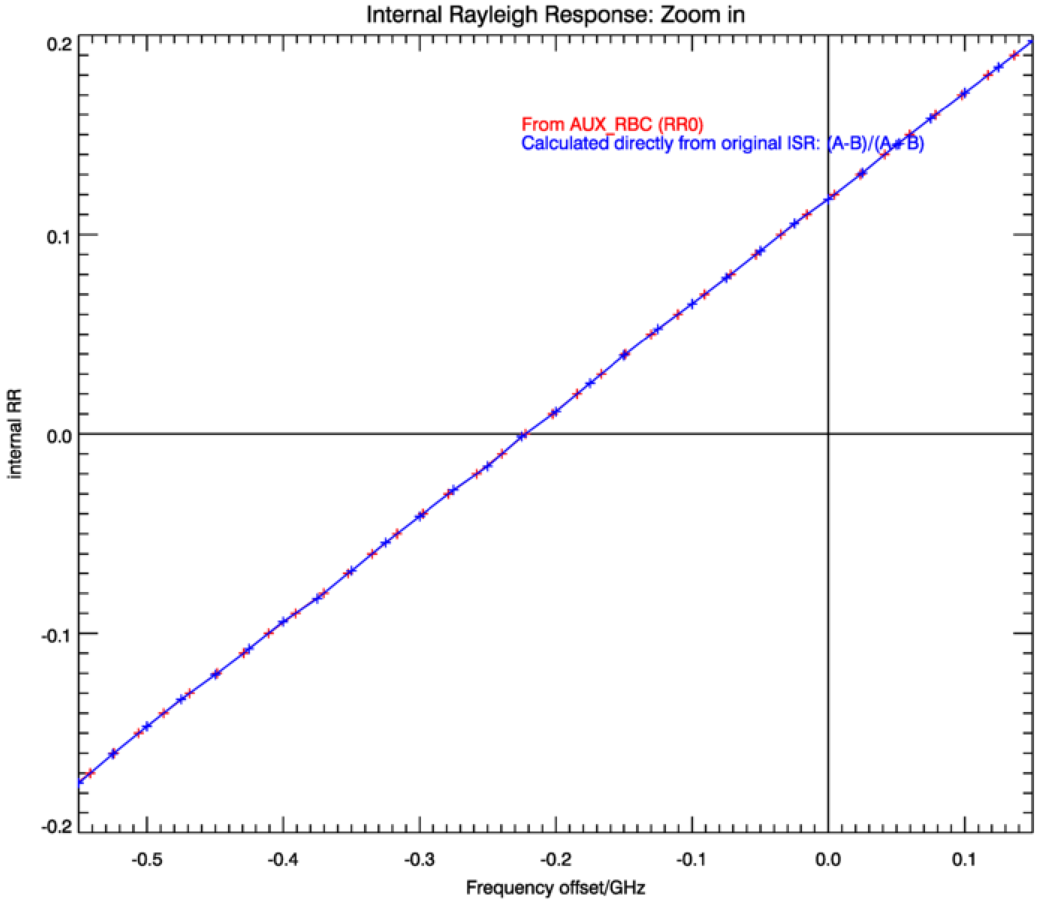


Figure 27. Plot of the internal RR curve as output in the AUX_RBC file and as derived directly from the ISR transmission curves. This is for an example noisy ISR.

R4: ISR noise leads to a significant L2B Rayleigh HLOS wind bias via the internal RR in the AUX_RBC_L2 file. This should be mitigated for the benefit of NWP impact if possible.

4.1.3 Rayleigh test case 3: Idealistic testing of the CSR updater (étendue fitting)

In this test case the E2S calibration modes are generated without noise. The difference with respect to test case 1 is that the étendue effect is switched on in the E2S with the tilted top-hat parameters set to width=500 MHz and tilt=1.0. These parameter values were suggested by the L1B team as appropriate for testing purposes.

Because the étendue effect is on the IRC step is necessary as part of the calibration chain processing. The IRC is an input for the CSR updater tool. The IRC is simulated in the E2S without noise (E2S NoiseFlag set to “off”) with a simplified atmosphere as input. The simplified atmosphere for the IRC simulation has the properties as was described in Section 2.3.1.

The L1Bp part of the IRC must be performed without the (relatively new feature of) DCMZ correction, by nullifying the coefficients in the input AUX_DCMZ file, since the E2S will not simulate DCMZ noise (when noise is switched off).

This test case assesses if the CSR updater method for determining the étendue effect is able to work correctly with idealistic inputs. Since there is no noise simulated, this test case is only required to run once.

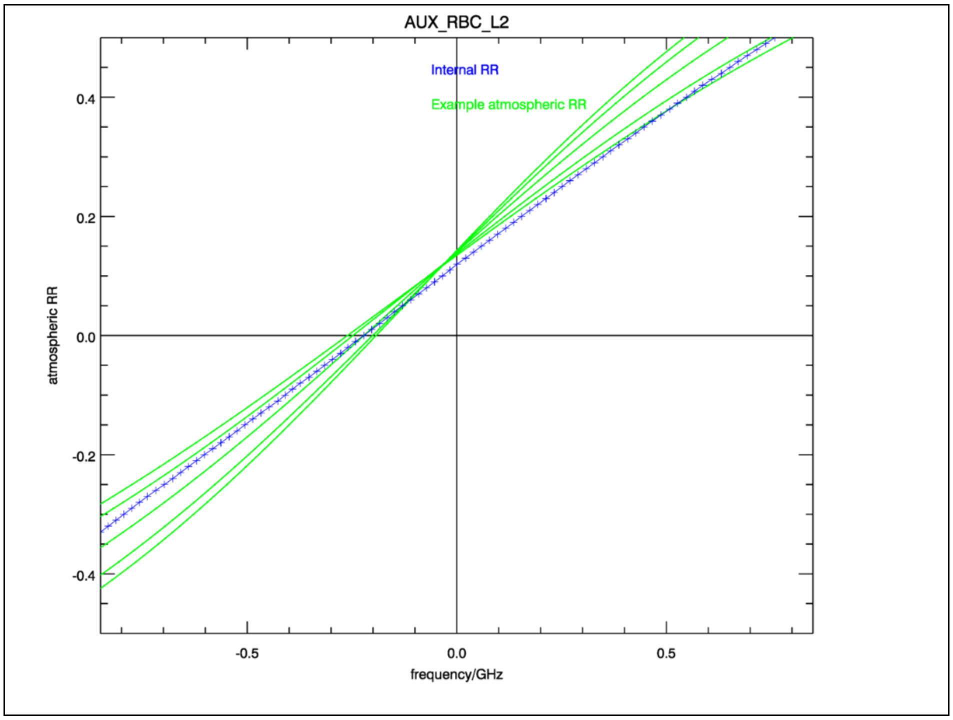
The UpdateCSR step of the calibration suite finished without error and estimated the étendue parameters to be:

Width = 468 MHz, Tilt = 1.2 and Dist = 0.000230

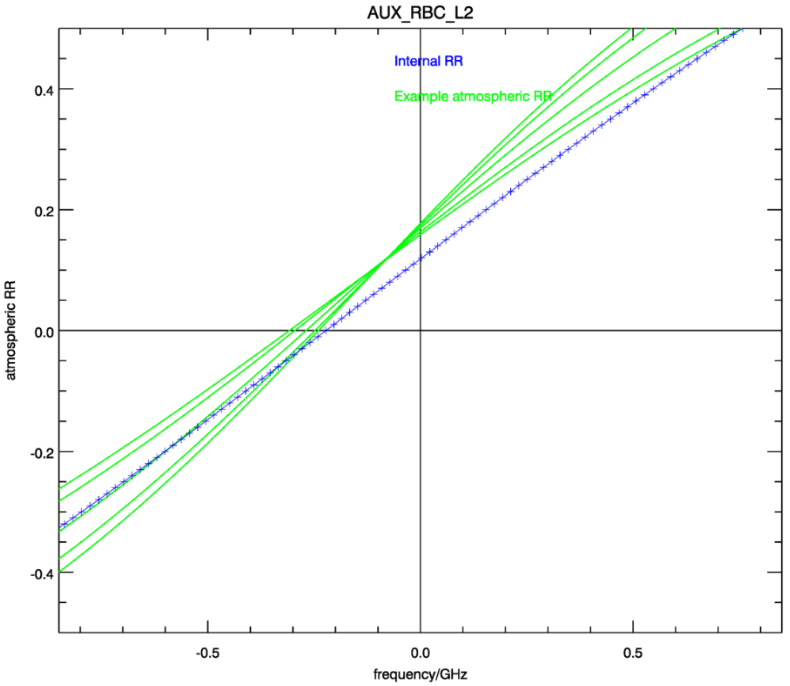
Dist is the distance between the measured RRC and the modelled RRC (like a cost function).

Therefore there is a reasonable correspondence of the estimated parameters to the simulation “true” étendue parameters, **but the result is far from perfect, which perhaps indicates that something is not quite consistent between the CAL suite and the E2S/L1B of Table 1.**

Note that the étendue effect leads to a large change in the AUX_RBC_L2 estimated atmospheric RRC curves as shown in Figure 28: compare a) without étendue effect (test case 2) to b) with étendue effect (test case 3); there is a significant positive shift in Rayleigh response curves (green lines). **Clearly the étendue cannot be neglected: in fact it leads to a 13 m/s HLOS wind bias if not accounted for.** This strong sensitivity is a concern for the real mission given that the top-hat model is only an approximation.



a)



b)

Figure 28. As extracted from the AUX_RBC_L2 file: example atmospheric RRC curves in green for various combinations of temperature and pressure s and the internal RRC shown in blue. a) For test case 2, run number 2 and b) for test case 3 with the étendue effect.

The effect on the L2B Rayleigh-clear HLOS wind bias using the AUX_RBC_L2 derived from the updated AUX_CSR file of test case 3 is an **overall bias of +-0.11 m/s** relative to the case with perfect calibration (test case 1). This is a fairly small bias if compared to the typical Rayleigh HLOS wind standard deviations of 3 m/s. The small bias must result from the imperfect estimates of the étendue parameters. The slope error remains fairly flat, just as in the ideal calibration without étendue test case 1 (as shown in Figure 22 b).

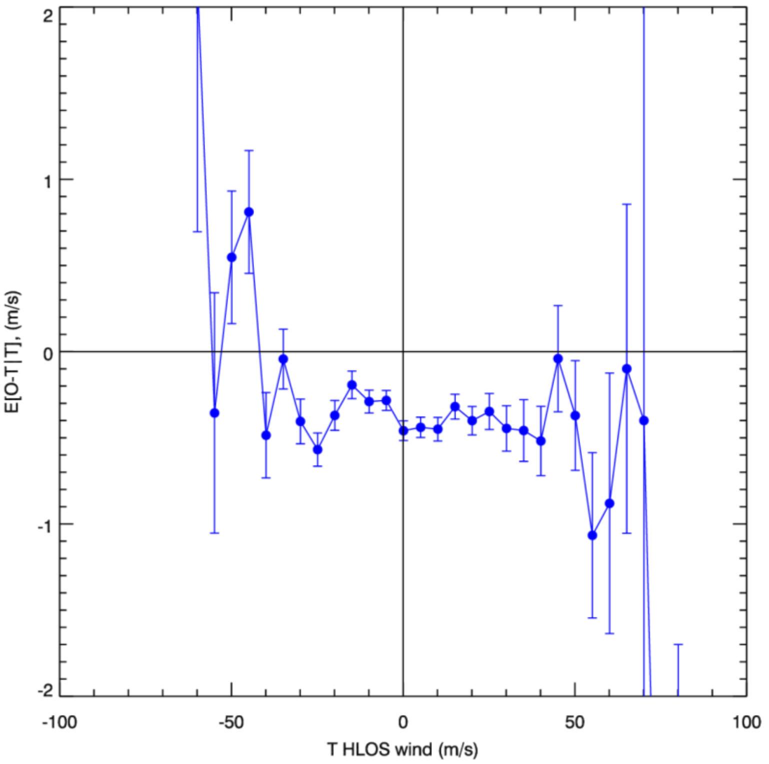


Figure 29. Rayleigh-clear HLOS wind mean error as a function of true HLOS wind for test case 3.

4.1.4 Rayleigh test case 4: Testing the CSR updater (étendue fitting) with a more realistic atmosphere for the IRC, but noise free

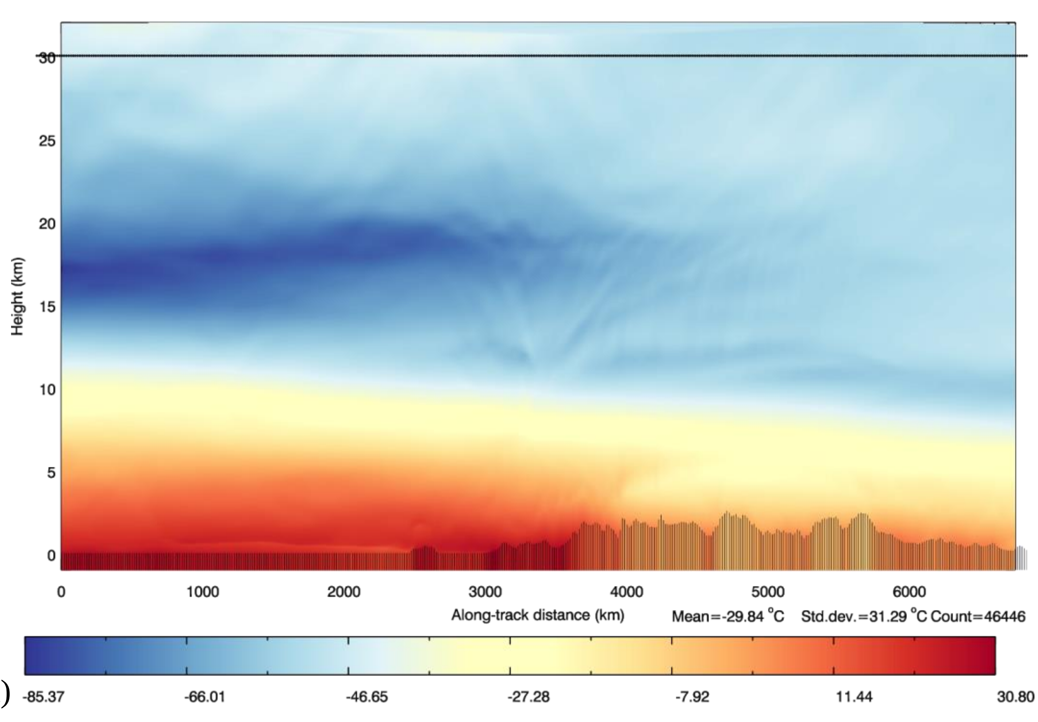
The difference relative to test case 3 is that this one uses a more realistic atmospheric scenario for the E2S inputs in IRC simulation. However, again this is a noise-free simulation of the calibrations. Being noise free the DCMZ will not be simulated in the E2S for the IRC and hence the L1Bp should comply by not correcting for DCMZ.

The IRC uses the realistic atmospheric fields of the first 81 BRCs (~7200 km along-track) from the ECMWF_T1279 scenario (which is also being used for the WVM run). A reminder, the ECMWF_T1279 scenario has:

- Realistic temperature and pressure fields and hence realistic molecular backscatter and extinction profiles derived from these fields. Also realistic in the sense ECMWF orography matches the Aeolus DEM (how this is achieved is described in the Appendix 7.4).
- Reasonably realistic optical properties for particulate scattering derived from ECWMF model cloud water and cloud ice fields. There are no aerosol optical properties considered.
- Realistic horizontal winds (of lesser importance since pointing in near-nadir during IRC mode)
- Constant ground albedo set to 0.8 (this simplification is of more relevance to the MRC results, but it can also influence the CSR updater which uses the MRC to estimate laser frequency offset drift).
- No UV background irradiance. This is in line with the no-noise E2S settings.

- Note that the E2S assumes zero vertical wind components, so we cannot test the calibration errors resulting from this assumption.

Some of the relevant atmospheric variability of the IRC scenario is shown in Figure 30. This cross-section covers the satellite track from near the equator to around 54 degrees north; hence notice the reducing tropopause height in the temperature field of Figure 30 a) with along-track distance. It can be seen that there are some clouds within the 6-16 km vertical range, which is the altitude range used in the RRC (as listed in the AUX_RRC_1B product), which can affect the RRC part of the IRC. However much of the scenario is clear air, perhaps making this particular test a bit too optimistic. There is cirrus cloud from about 5500 km along-tack at around 8 km altitude, which will interfere with the RRC and thus test the CSR updater's ability to account for cloudy scenes (by using scattering ratio estimates provided in the AUX_MRC_1B).



a)

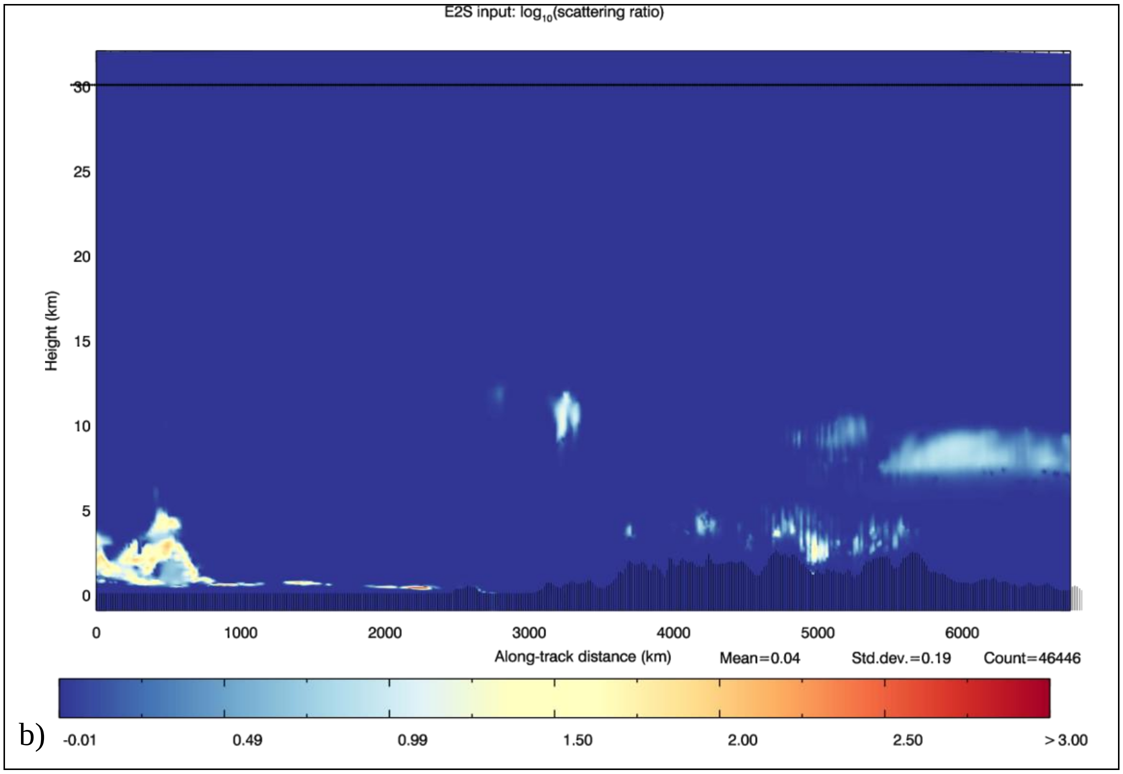


Figure 30. Atmospheric scenario derived from the first 81 BRCs of ECMWF_T1279 for test case 4. a) Temperature, b) $\log_{10}$ of scattering ratio. This is used in the IRC simulation of test case 4.

The UpdateCSR step of the calibration suite estimated the étendue parameters to be:

Width = 367 MHz, Tilt = 1.5 and Dist = 0.000192

These estimated parameters are distinctly worse than those from test case 3 (the simple clear atmosphere).

The WVM ran into problems with NaN values in the Rayleigh ground correction that propagated to become missing L2B wind results. The L2B processor applied settings chose not to apply the L1B ground correction. However the values are still used but with a zero weighting, which still causes the L2B processing problems. After asking, the L1B team reported that this problem has been fixed in more recent processor deliveries (L1Bp v6.06). The L2BP handling of NaN values has improved in more recent versions of the code (NaN values should never appear in EE products). Therefore, this more realistic calibration testing of the Rayleigh channel cannot proceed with the CoP processor combination listed in Table 1.

Also, problems for the CAL suite were encountered for other realistic test cases in which invalid frequency steps were not handled correctly. These issues have been resolved in a more up-to-date CAL suite (30 June 2016, patch 1), which works in combination with a more up-to-date E2S (v3.07) and L1Bp (v6.06). Therefore the more realistic testing of the Rayleigh calibration had to be postponed until a later section i.e. Section 4.3 with updated processors.

4.1.5 Rayleigh test case 5: Testing the CSR updater (étendue fitting) in

combination with a noisy, but idealistic atmosphere, IRC

This is the same as Rayleigh test case 3 except that noise is switched on the IRC simulation step i.e. testing the AUX_CSR updater performance for an idealistic IRC atmosphere, but with noise sources on. This means that the E2S will simulate the DCMZ in the IRC and therefore L1Bp should apply the DCMZ correction.

The results of the CSR updater tool are shown in the table below. The truth parameters for the étendue top-hat are width = 500 MHz and Tilt = 1.0.

Table 4. Results of the CSR updater for test case 5.

Run number	**Width (MHz)**	**Width error (MHz)**	**Tilt**	**Tilt error**	**Distance**
1	571	71	1.0	0.0	0.001146
2	542	42	1.0	0.0	0.001175
3	449	-51	1.2	0.2	0.000797
4	391	-109	1.4	0.4	0.001035
5	477	-23	1.1	0.1	0.001218
	Mean(absolute(error))	59		0.14	

The results are reasonable, however due to processor problems encountered (as described in Rayleigh test case 4) it was decided to postpone this testing and update the CoP to more recent processors so that progress could be made (see Section 4.3). Despite the described problems, the Mie calibration testing could be completed with the same processors as given in Table 1. The Mie testing is presented in Section 4.2.

4.2 Mie calibration chain testing

Despite the problems encountered with the Rayleigh calibration testing, the Mie calibration testing could proceed with the CoP combination as listed in Table 1.

There are relatively few steps needed to generate the Mie response calibration for use in L2B processing compared to that for the L2B Rayleigh channel processing. The steps are the IRC followed by the L1B processing of the IRC raw data to generate the AUX_MRC_1B file. The relevant parts of the AUX_MRC_1B result are written to the L1B WVM product, which is then read by the L2B processor and hence applied in the Mie wind retrievals. In particular the L2Bp needs the MRC linear fit coefficients i.e. the gradient and intercept of the response versus frequency-offset function and also the non-linearity information i.e. the difference between the linear fit and the raw response.

The L1B MRC data should be generated with the Mie core algorithm 2 (Downhill simplex) in the L1Bp to match the algorithm used in the L2Bp (only the Mie core 2 algorithm is available in the L2Bp). Also the same algorithm settings should be used by the L2B processor as used in the L1Bp for consistency. An early investigation of the Mie channel processing options [RD10] showed that there can be a great sensitivity of the Mie calibration response to the assumed values for the Fizeau filter transmission spectral width or specifically the FWHM, hence the importance of having matching settings.

There is not an option to simulate the étendue effect for the Mie channel in the E2S for the IRC nor in the corresponding WVM run. Oliver Reitebuch (DLR, L1B team) explained the Mie étendue effect:

The étendue describes essentially the different illumination between the internal and the atmospheric path. Certainly there is an effect for both the Rayleigh and the Mie channels. This results in slightly different slopes and different intercepts for Mie internal and atmospheric path, which has been observed for the A2D. It is not modelled in the E2S, which is a simplification. But it is also not necessary to take it into account, because the responses from the Mie ground return (as obtained from the MRC) can be used to determine the slope and intercept. And these slope/intercept can be used in the Mie wind retrieval. I would expect from real in-orbit data that these slopes/intercept for the internal and ground-returns are slightly different – in the current E2S implementation there should be actually no difference for internal/atmospheric path. There is no need for a Temperature/Pressure/Mie contamination correction for Mie as for the Rayleigh winds, which is the reason for the AUX_RBC and the need to estimate the Rayleigh channel étendue. In addition the étendue effect for Mie is more complicated, because one needs also to take into account Fizeau imperfections (in the horizontal, and not as currently implemented in the vertical) and also ACCD pixel-response non-uniformity PRNU (Photo Response Non-Uniformity), which could be several %.

The measurement response of the MRC is obtained using ground return signals. This can be done because with negligible thermal Doppler broadening for the Mie peak the ground returns have the same spectral width as the atmospheric returns and the internal reference. The ground returns have the advantage of providing stronger and more reliable signals than particulate atmospheric returns (although one could imagine using e.g. stratocumulus clouds which in some parts of the Earth are reliably placed, however this may introduce non-negligible vertical wind velocities). The ground returns give a zero wind reference, since of course wind is the movement of the atmosphere relative to the fixed earth. Oceans may be unsuitable due to e.g. currents, vertical motions of the water and also relatively low albedo.

Therefore for assessing L2B Mie wind systematic errors resulting from errors in the MRC it is of interest to investigate the effect of realistic atmospheric and ground albedo conditions in combination with instrument noise (which also affects the internal reference calibration).

For testing the MRC sensitivity to errors, we can test:

- The effects of realistic instrument noise simulation in the E2S simulation upon the measurement and internal MRC.
- The effects of realistic cloud distributions within the IRC scenario which may strongly (or totally) attenuate the lidar signal leading to weaker (or missing) ground returns and hence response values may be missing for certain frequency ranges during the calibration. This will increase the noise in the MRC which will lead to systematic errors when the calibration is applied in L1B or L2Bp wind retrievals.
- The effects of realistic albedo simulation (available by the ADAM database as input to the E2S) which affects ground return signal strength.

Figure 31 gives an overview of the type of test cases to be run for the Mie calibration investigations.

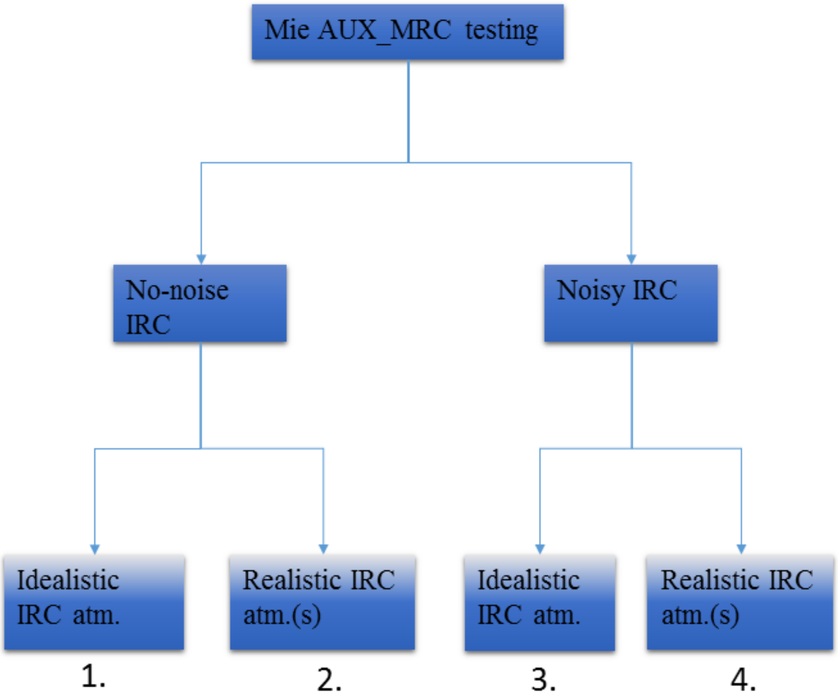


Figure 31. The proposed test cases for investigating the Mie-channel calibration errors.

4.2.1 Mie test case 1: “perfect” calibration

The atmospheric scenario used for the IRC part of this test case has already been described i.e. it is the idealistic IRC atmospheric scenario for “perfect” calibration results from Section 2.3.1. Since there is no noise simulated in the IRC for this test case, then it only needs to be run once to produce a reference of “perfect” calibration.

For verifying the L2B HLOS winds we run the WVM with noise simulation on using the large sample ECMWF_T1279 scenario as described in Section 2.4. Given that there is noise in the WVM mode and that Mie wind results are not as numerous as the Rayleigh then the HLOS wind systematic error estimates can vary somewhat due to sample size being too small i.e. despite simulating 4 orbits of data, there can still be sampling error (there are around ~7000 Mie wind results). For example, the overall bias for the Mie-cloudy HLOS winds came out as -0.03 m/s (as already shown in Figure 23), however upon rerunning the WVM test case (including the noisy E2S step) **a bias of -0.13 m/s was produced** (all the same settings were applied in the CoP). We will use this second run of the E2S WVM scenario as the reference for comparison with the stochastic tests of the IRC in the other test cases. This is the reference bias with which the imperfect calibration tests will be compared to in the following sections.

The MRC results for this test case are shown in Figure 32. The response values for all 40 frequency steps are present and valid and in the MRC file the maximum number of 60 measurements are valid per frequency step (each of which lasts for 2 BRCs). The data appears to be very well modelled by a linear fit at the scale shown. Note that the linear fit coefficients for the atmospheric and internal MRCs are in close agreement (see the linear fit parameters in the top left of the figure); i.e. the red and blue lines appear to be on top of each other — this agreement between atmospheric and internal response is expected due to the lack of étendue effect simulation in the E2S for the Mie channel.

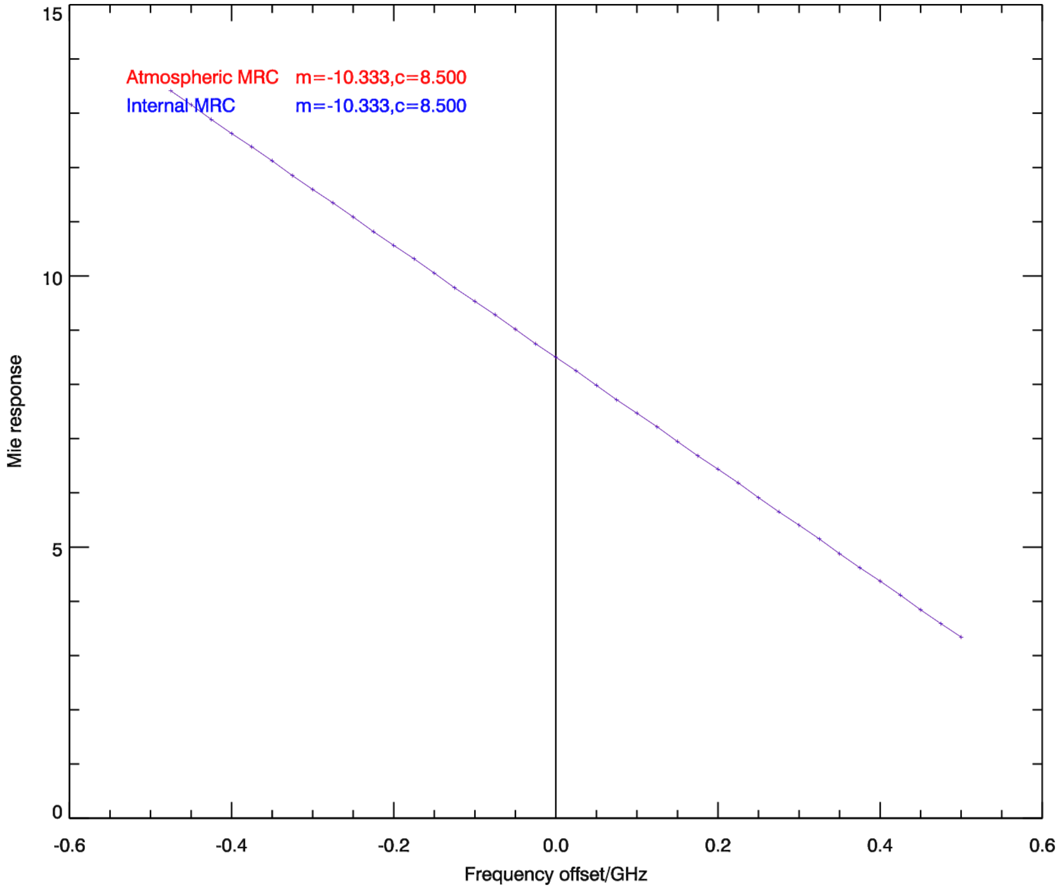


Figure 32. The results of the MRC for Mie test case 1; "perfect" calibration. The Mie response (pixel number) as a function of frequency offset.

However, the difference of the atmospheric (measurement) and internal MRC from the corresponding linear fits shows small amplitude oscillations, as shown in Figure 33.

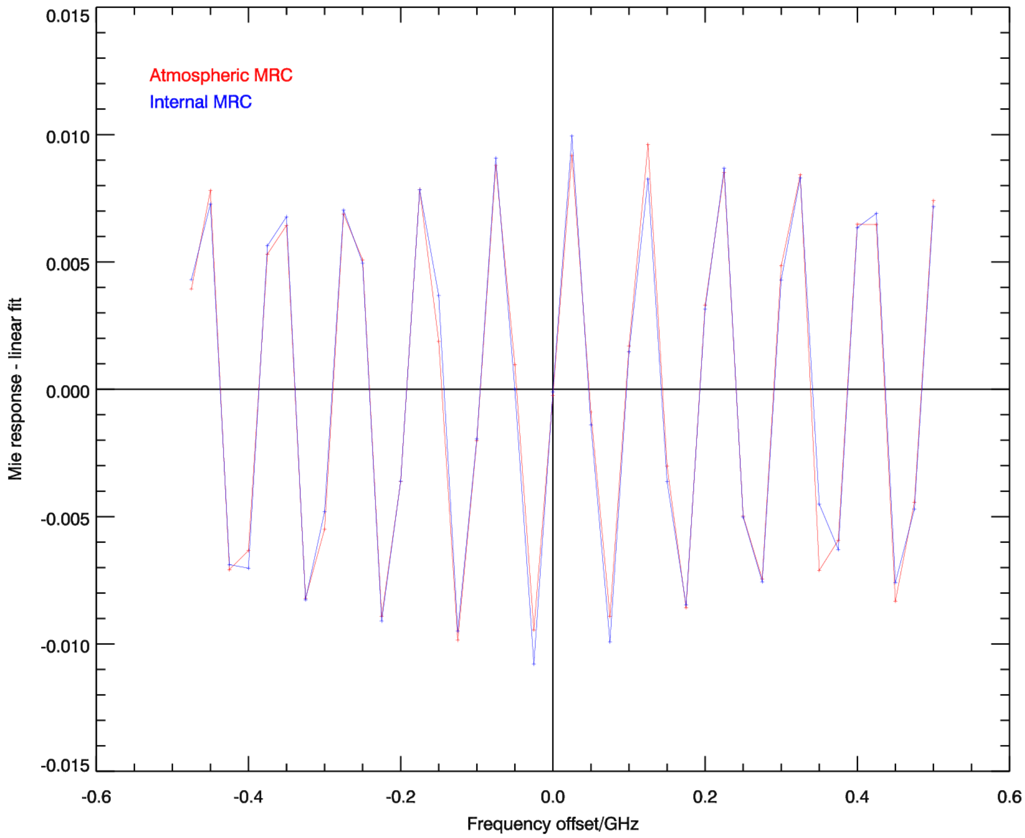


Figure 33. Deviation between the Mie test case 1 (“perfect” calibration) MRC data and the linear fit (provided in the MRC).

The raw response clearly oscillates about the linear fit, but with a small amplitude <1% of a pixel. The oscillation occurs due to the discretization of the signal onto the 16 ACCD pixels (in frequency space) and has been investigated in [RD10, see section 4.1]. The oscillation is very similar for the atmospheric and internal MRC, although not identical (perhaps due to quantization issues). If one applied only the linear fit coefficients from the MRC in the L2B processing (i.e. did not perform the Mie non-linearity correction), then this 0.01 pixel difference would lead to errors in the frequency estimate (and hence Doppler shift and HLOS wind speed) as follows:

$$\frac{\partial R}{\partial f} = -10.333\ GHz^{-1}$$

$$\Delta f = \frac{\Delta R}{-10.333} = \frac{0.01}{-10.333} = 0.97 MHz \equiv 0.28\ ms^{-1}\ HLOS$$

In the absence of other sources of HLOS wind bias, a lack of non-linearity correction would produce a bias that oscillates with true HLOS wind (assuming the internal reference response is constant, in WVM E2S simulations it is almost constant at 10.50 pixels) with amplitude ~0.2 m/s; which is a fairly large bias. Note that the real Mie channel non-linearity could be much larger in amplitude and more non-uniform than shown in Figure 33, due to Fizeau imperfections and ACCD PRNU. So these simulations are somewhat optimistic regarding the effects of Mie non-linearity upon the L2B HLOS systematic errors.

Note that the L2Bp includes a switch in the AUX_PAR_2B to control the application of the Mie non-linearity correction and this has been (and will continue to be) switched on by default in tests so far.

Switching off the Mie non-linearity correction in the L2Bp was tested (not shown). It led to only a small change in the overall profile average bias (by 0.01 m/s), but there was increased oscillation in the bias as a function of true HLOS wind speed on the same order as the estimate i.e. 0.2 m/s, but these oscillations are fairly small compared to the overall HLOS wind dependent bias structure found for this "perfect" calibration as shown in Figure 34.

It appears that sources of bias other than non-linearity are dominating the HLOS wind dependence of the L2B Mie-cloudy HLOS winds; there is a slope error of order 1-2% even with an idealistic noise-free MRC. The source of much of the slope error is thought to be a geophysical one: it is related to the height assignment of Mie winds within thick range-bins (see WVM2 range-bins, they are 1-2 km at 10-15 km altitude) with strong vertical wind shear; this is explained in the Appendix 7.3. Therefore the slope error will change depending on the specific details of the range-bins and the atmosphere being sampled.

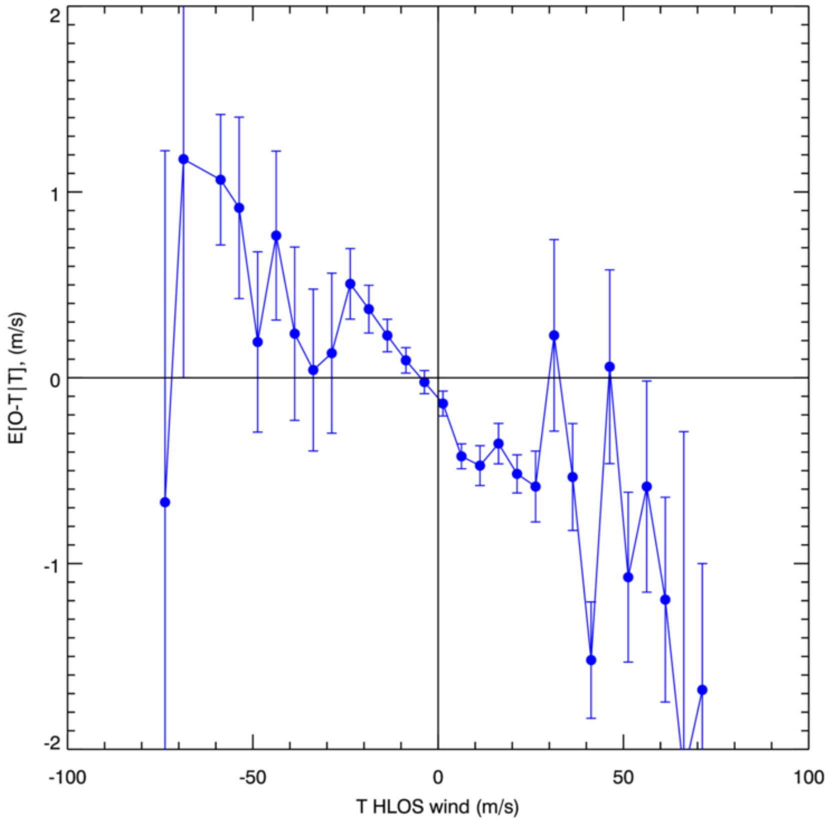


Figure 34. The reference L2B Mie-cloudy HLOS wind bias as a function of true HLOS wind from test case 1.

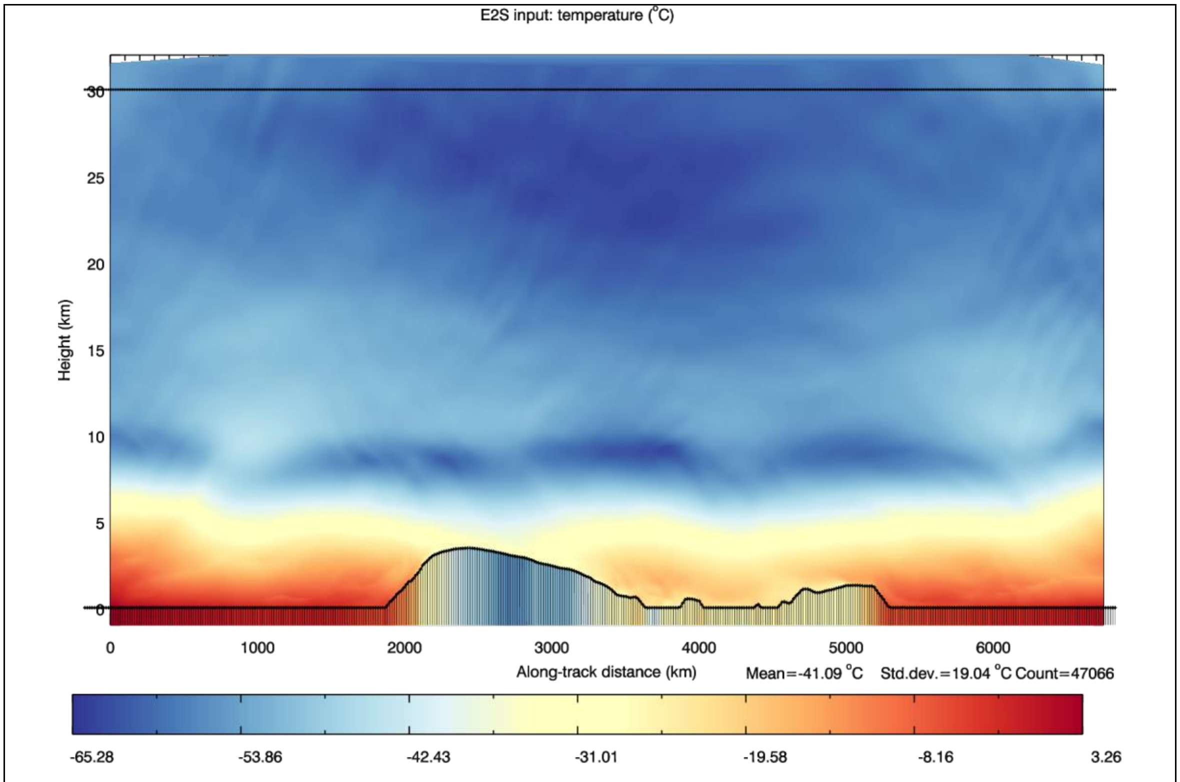
4.2.2 Mie test case 2: No-noise IRC simulation using realistic atmosphere and ground properties

This test case involves the simulation of a noise-free IRC using a realistic atmosphere and realistic ground albedo scenario. It is has been suggested that the Aeolus' IRC should be performed over polar ice areas to improve the signal to noise of the ground returns for the MRC, due to the high albedo of ice. Therefore we have generated an Antarctic IRC simulation which has the following properties:

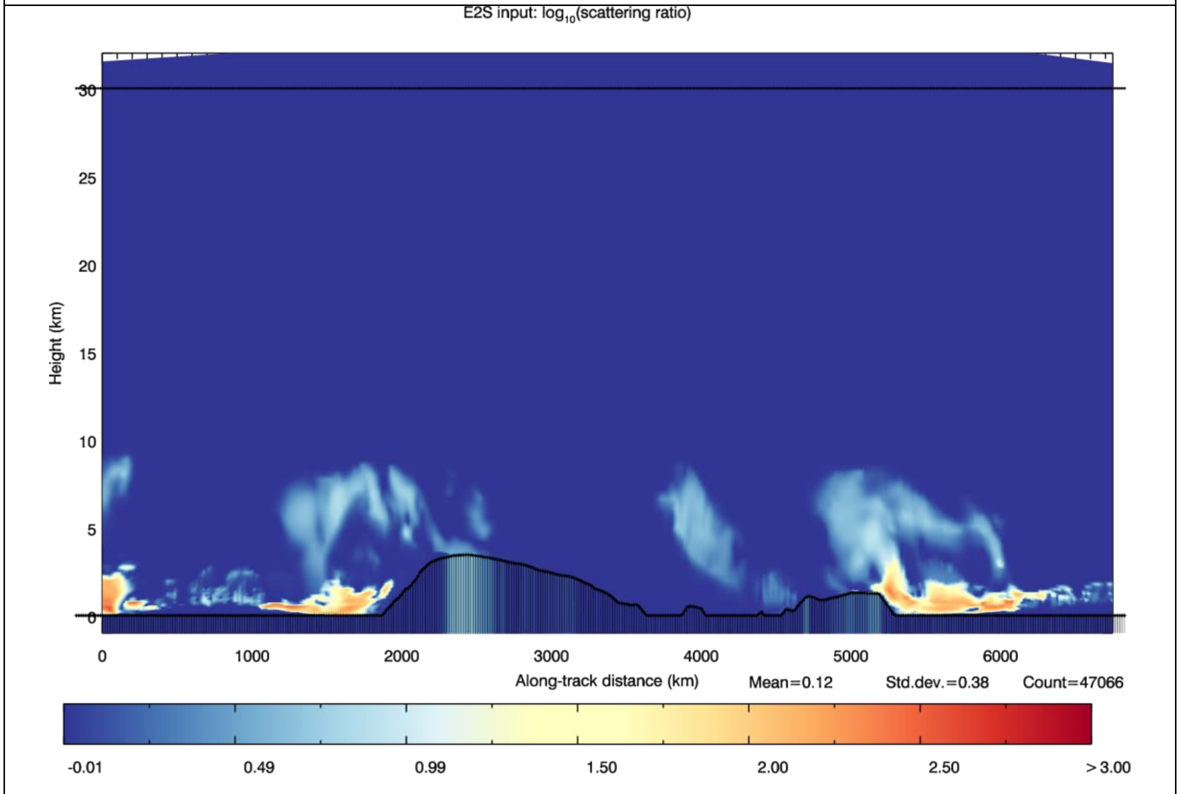
- The atmospheric inputs are derived from a one IRC-long portion (i.e. 81 BRCs) of the ECMWF_T1279 scenario for a model forecast valid on 04/04/2011 (an arbitrary date). The IRC extends from around 54 °S, crosses part of Antarctica and goes back to 54 °S. The reasonably realistic ECMWF model cloud fields have been converted to backscatter and extinction coefficient profiles using a parameterization (as already described in Section 2.4). Realistic cloud optical properties are important to simulate realistic ground return signal levels. Also important is to make sure the orography of the ECMWF model is aligned to agree with the Aeolus DEM, which was ensured in this test case (see Appendix 7.4 for how this is achieved), so that realistic ground returns are possible. The atmospheric conditions are shown along-track in Figure 35.

- The IRC starts over the Southern Ocean, then heads south over Antarctica before heading back north into the Southern Ocean. The elevation of Antarctica (up to 3-4 km) is evident from Figure 35b) (black line). The elevation is from the lowest altitude in the E2S input scenario data, which is from the ECMWF model output (the ECMWF model levels are terrain following). Also shown are the cloud conditions, as displayed using the scattering ratio, along the IRC. There is optically thick low-level cloud in parts of the scenario, but there are clear conditions over much of the Antarctic land-mass offering the possibility for good ground returns. It has not been investigated how representative these one off IRC cloud conditions are i.e. if we are being too optimistic for the IRC. Aerosol (non-cloud particulates) optical properties are not input to the simulation, which will make the results too optimistic by a small extent, due to less attenuation of the ground return signal.

- The ground albedo conditions are also thought to be realistic due to setting the E2S to use maps of surface reflectance. The maps vary globally and change with each month of the year in a much more realistic manner than a constant value of 0.8 (i.e. the ADAM (A surface reflectance Database for ESA’s EO Missions) surface reflectance maps); see Figure 36 for the conditions applied for April. Very high surface reflectance values exist over the Antarctic ice-sheet.


E2S input: temperature (°C)
Height (km)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
Along-track distance (km)
Mean=-41.09 °C Std.dev.=19.04 °C Count=47066
-65.28
-53.86
-42.43
-31.01
-19.58
-8.16
3.26

a)


E2S input: log$_{10}$(scattering ratio)
Height (km)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
Along-track distance (km)
Mean=0.12
Std.dev.=0.38
Count=47066
-0.01
0.49
0.99
1.50
2.00
2.50
> 3.00

b)

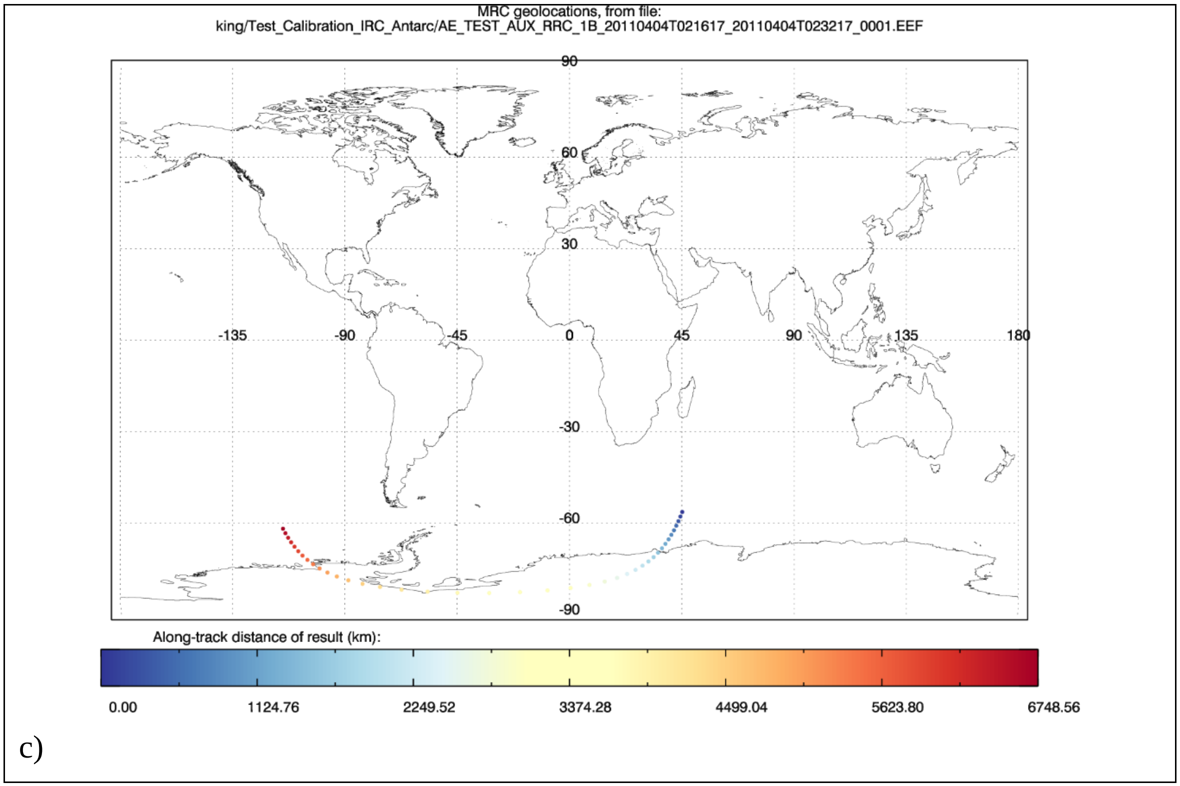


Figure 35. IRC test case over Antarctica on 4th April 2011. a) The E2S input temperature; b) $\log_{10}$ of the scattering ratio (highlights particulate scattering shown due to clouds) and c) map of MRC result geolocations. The E2S ground elevation height is also shown (black line).

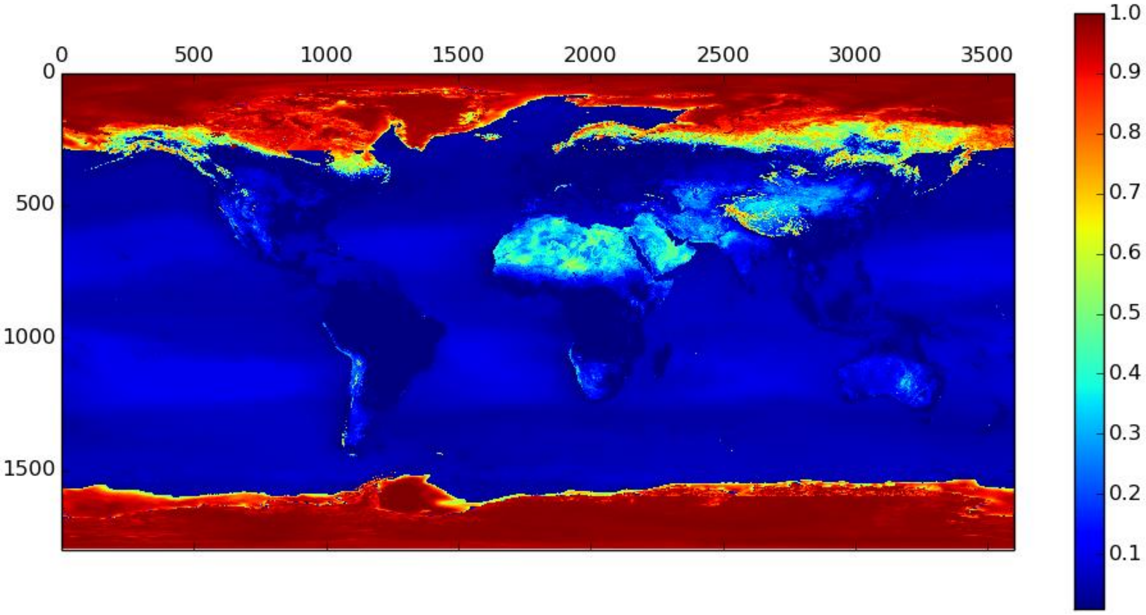


Figure 36. Plot of the map of surface reflectance values for the end of April from ADAM. Image courtesy of T. Kanitz (ESA-ESTEC).

The resultant MRC data are shown in Figure 37. Invalid atmospheric and internal MRC values[16]

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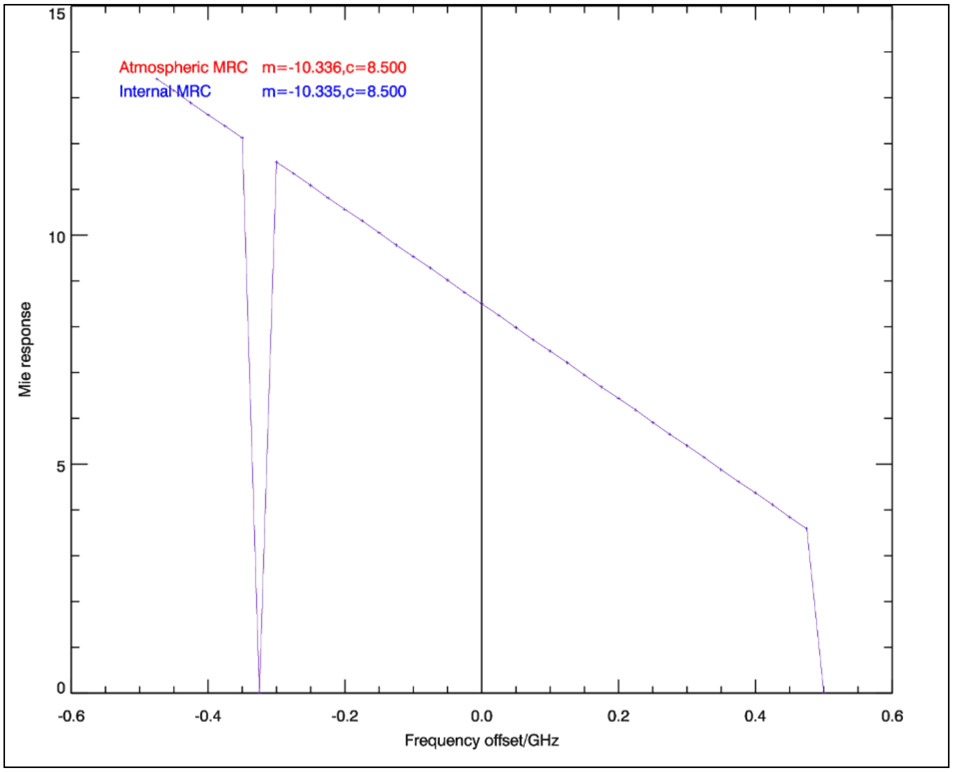
[16] Invalid values are flagged in the MRC, and the invalid response values are set to 0.0. It is unclear why the corresponding

occurred for frequency offset values of -0.325 GHz and 0.5 GHz, however the overall validity of the MRC is OK. Frequency offset of 0.5 GHz is the first frequency step of the IRC, lasting for the first two BRCs (60 measurements) or around 170 km horizontally. You can see there is a particularly strongly scattering (and hence attenuating, with assumed lidar ratio of 20) cloud at the start of the scenario (see Figure 35 b) which covers the first 170 km. This frequency step is over the sea (without ice) so the surface reflectance is low also (< 0.3). These effects combine resulting in no detected ground echo and hence an invalid frequency step. The -0.325 GHz frequency step should be the 33rd step, and will correspond to roughly 5600 km into the scenario. You can see there is also thick cloud between 5000 and 6000 km along-track from the figure combined with also being over the sea with the lower surface reflectance.

The number of valid measurements (which detected a ground echo) per frequency step (out of 60 possible measurements) varies a lot throughout the scene, with many providing the full 60 valid measurements, two with 0 valid measurements (the invalid steps as already discussed) and the rest with values between.

The difference between the linear fit and the MRC data is similar to test case 1 as shown in Figure 33 (apart from the missing values). This is expected since there is no noise simulated in this test case, so the non-linearity is due to the pixilation effect. Note that the internal MRC has a different linear fit parameter from the "perfect" by 0.002 GHz^{-1} presumably because the 2 missing data points in the calibration when combined with the small non-linear oscillations causes a different linear gradient estimate. The atmospheric MRC linear fit gradient differs from the "perfect" by 0.003 GHz^{-1} for similar reasons, but such a change should be negligible in terms of influence on HLOS wind errors as calculated in Section 7.2 in the Appendix.



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internal MRC should also have missing values (this has been reported as an anomaly in AE-IPF-276).

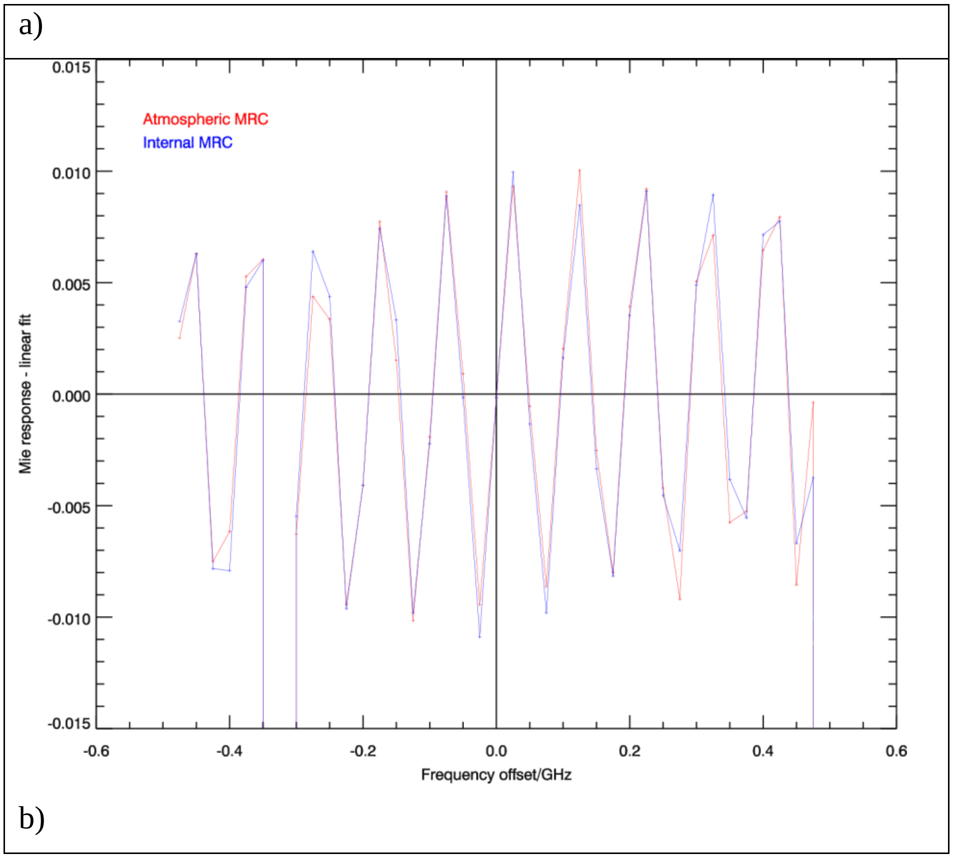


Figure 37. Mie test case 2: MRC data from Antarctica scenario. a) The MRC data b) difference between MRC and linear fit.

The impact on the L2B Mie-cloudy HLOS wind bias for this test case is -0.29 m/s overall bias i.e. **-0.16 m/s relative to the "perfect" calibration of test case 1**. The HLOS wind dependence of the mean error (see Figure 38) differs from test case 1 in the detail, but there is still about the same level of slope error. Since the only change between test case 1 and test case 2 in terms of the WVM results is the MRC file then some effect from the atmospheric/ground return scenario over Antarctica is causing the differing bias. Despite simulating with no noise, the clouds and varying ground albedo will mean the Mie signals will be lower compared to the detection chain offset. It may be that the Mie response which is determined by the Mie core algorithm varies with the signal strength (despite having the same centroid frequency). Or perhaps it is an effect resulting from the invalid frequency steps.

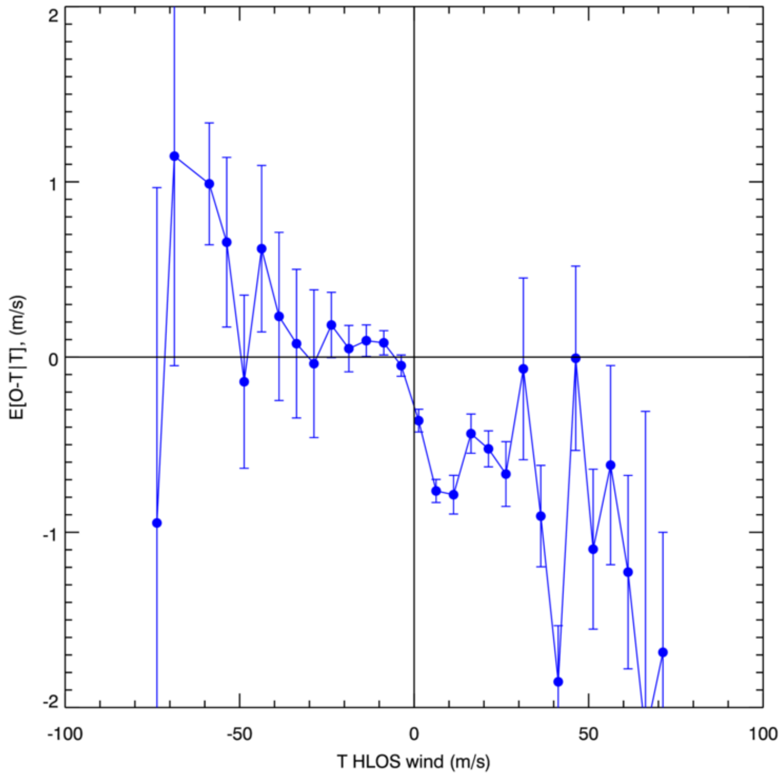


Figure 38. L2B Mie-cloudy HLOS wind bias as a function of true HLOS wind for test case 2.

4.2.3 Mie test case 3: Idealistic atmosphere IRC with noise

This test case uses the same IRC atmospheric scenario as Mie test case 1 i.e. a simple atmosphere with no clouds nor aerosol. The difference is that the default noise sources in the E2S have been switched “on”; therefore the IRC is run five times to get a sample of possible errors.

In terms of assessing the bias in L2B Mie-cloudy HLOS winds, we shall use the one realization of the WVM ECMWF_T1279 scenario as used in test case 1. Note that the L1B/L2B processing steps are rerun for each run of the IRC to ensure the MRC information is passed from the L1B to L2B processing.

As in test case 1, all 60 measurements of each frequency step are found to be valid. The systematic error results of the five runs are given in Table 5.

Table 5. Effect of noise in IRC on measurement MRC for an idealistic atmosphere and ground albedo

AUX_MRC_1B run number	Measurement MRC: m (GHz^{-1})	Measurement MRC: c	L2B Mie-cloudy HLOS wind bias (m/s)	Bias relative to test case 1 (m/s)
1	-10.332268	8.500028	-0.09	0.04
2	-10.332993	8.500509	-0.13	0.00

3	-10.331594	8.500296	-0.18	-0.05
4	-10.334615	8.500072	-0.15	-0.02
5	-10.335270	8.500449	-0.15	-0.02
Standard deviation	0.0016	0.00022	0.03	**Mean(absolute(bias))**=0.03

In terms of the overall profile bias compared to the "perfect" calibration results of test case 1, the **biases are small: less than 0.05 m/s**. The variability of the bias as a function of the true HLOS wind is displayed in Figure 39 (the five results are superimposed). There is small variability as a function of true HLOS up to around 0.2 m/s bias. Therefore overall errors in the MRC due to noise with a perfect atmosphere and ground albedo are fairly small and not over concern to NWP users.

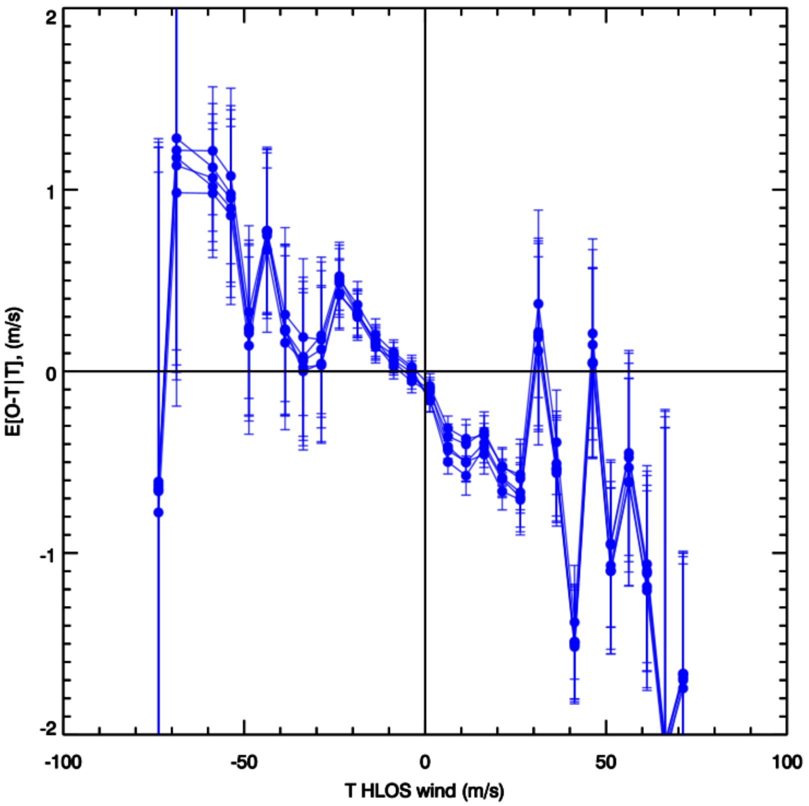


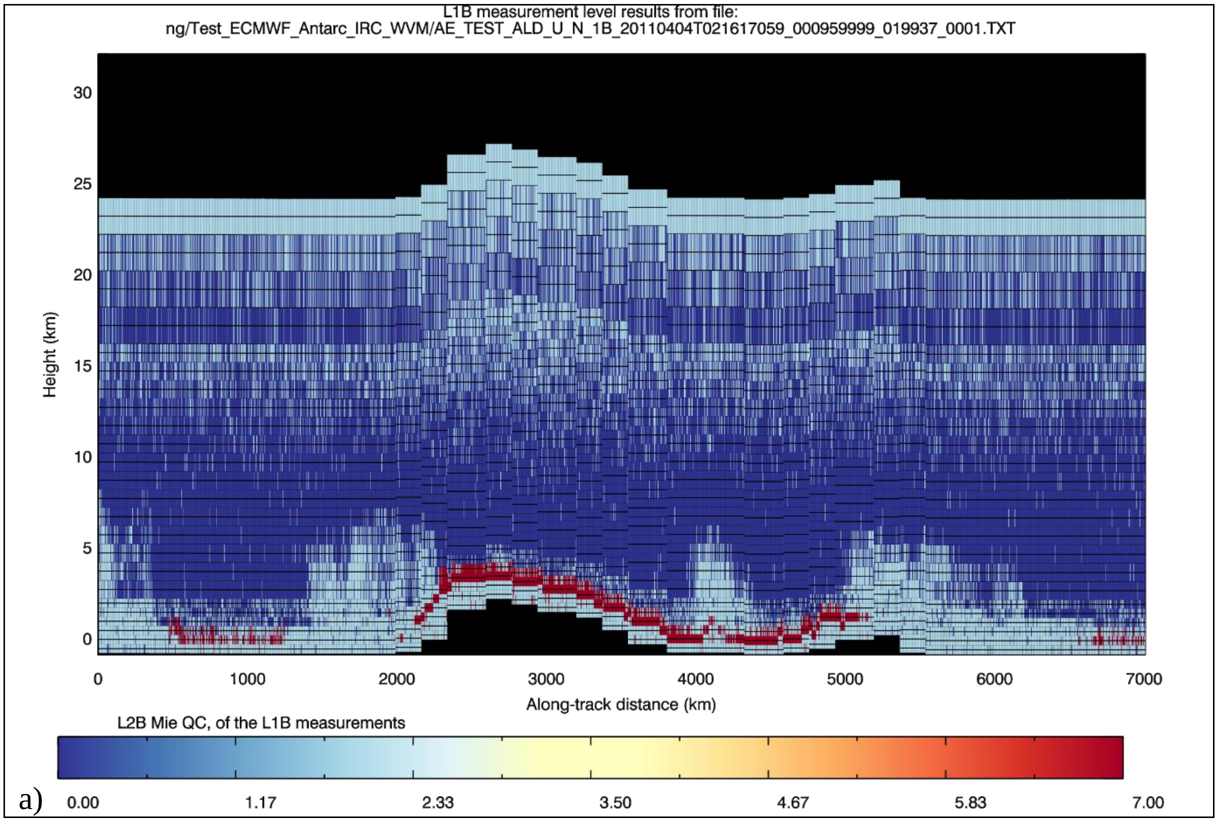
Figure 39. L2B Mie-cloudy HLOS wind bias as a function of truth HLOS wind. The plot overlays the 5 realisations of case 3.

4.2.4 Mie test case 4: Realistic atmospheres with noisy IRC simulations

This test case uses the same IRC atmospheric and surface reflectance scenario as Mie test case 2; but with noise simulated in the E2S. This test case is the most realistic simulation of MRC errors in this TN. Given that noise sources are on, then the IRC was run five times to determine a range of possible calibration errors.

In terms of assessing the bias in the L2B Mie-cloudy HLOS winds, we shall use the one realisation of the E2S noise for the WVM ECMWF_T1279 scenario as used in test case 1. Note that the L1B/L2B processing steps will have to rerun for each noisy IRC available.

The atmospheric and surface reflectance scenario has already been described for Mie test case 2. To get an impression of where ground returns are obtained it was necessary to run the same Antarctic atmospheric/surface scenario in WVM with the same IRC range-bins and to extract the L1B measurement-level QC results (advanced monitoring tools are available to extract this information from WVM runs). These are shown in Figure 40: a) shows the Mie QC flags, the red colour indicates that ground return is found, it can be seen there are regions where red colour is absent (there may be the odd few measurements which are enough to give a valid frequency step, but this is hard to see given the scale of this plot). The lack of ground returns below clouds and in areas with low surface reflectance as shown in Figure 35 and Figure 36 is apparent. Figure 40b) shows the Mie useful signals and it is seen that the strongest ground returns are occurring over the Antarctica where, in this case, there is no cloud and strong surface reflectance.



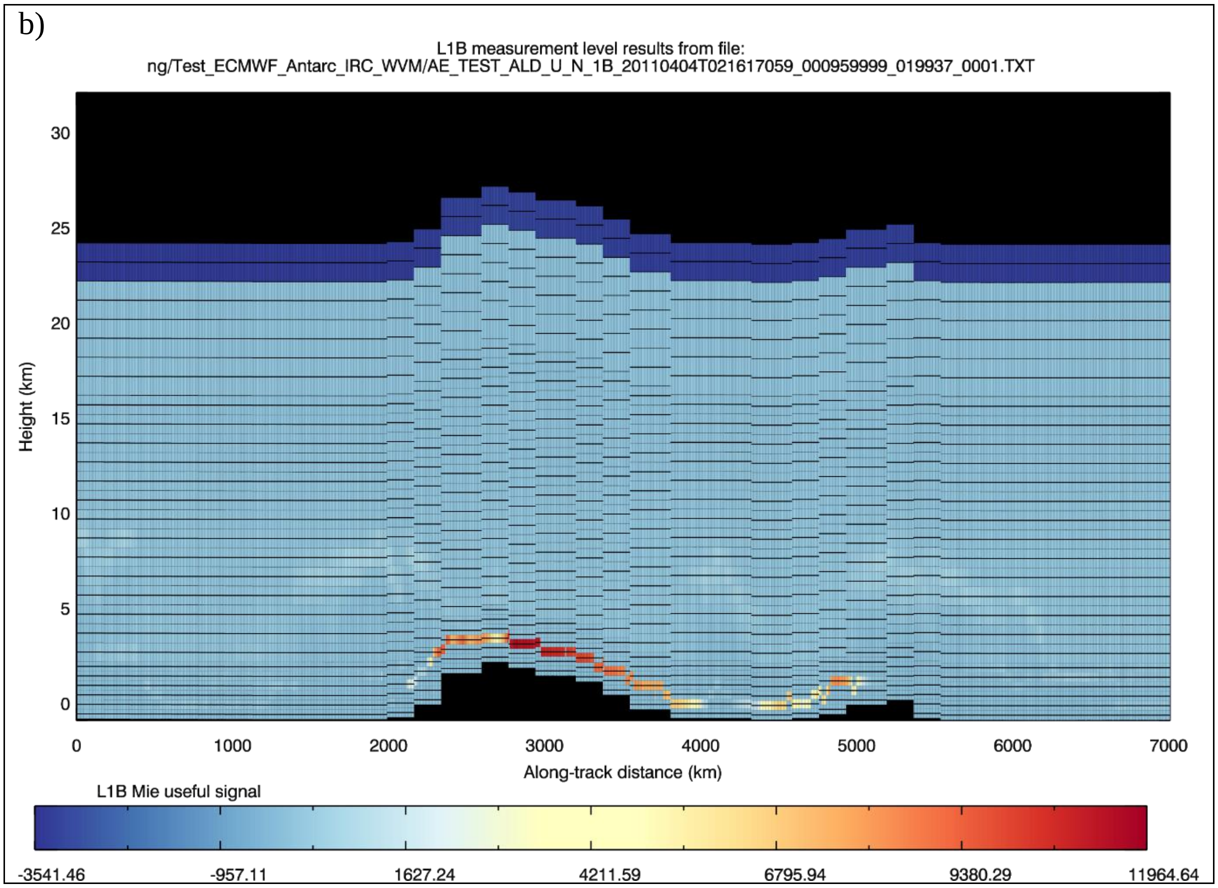


Figure 40. L1B measurement-level results for the Mie channel a) Mie QC flags b) Mie useful signal. Obtained from a WVM run but using the Antarctica atmospheric and ground properties.

MRC data results for an example run are shown in Figure 41. The frequency steps -0.325 GHz and 0.5 GHz are invalid just as they were in the noise-free simulation of test case 2. Comparing the MRC data to test case 2 it was noted that the number of valid measurements per frequency step is lower in this test case with noise on, which is expected. The difference between the linear fit and the MRC data in Figure 41b) has increased variation in comparison to the noise-free Figure 37b). The noise is larger in the atmospheric (measurement) response compared to the internal response which is expected. The internal reference response noise is not negligible either however. The linear fit parameters deviate from the ideal of test case 1.

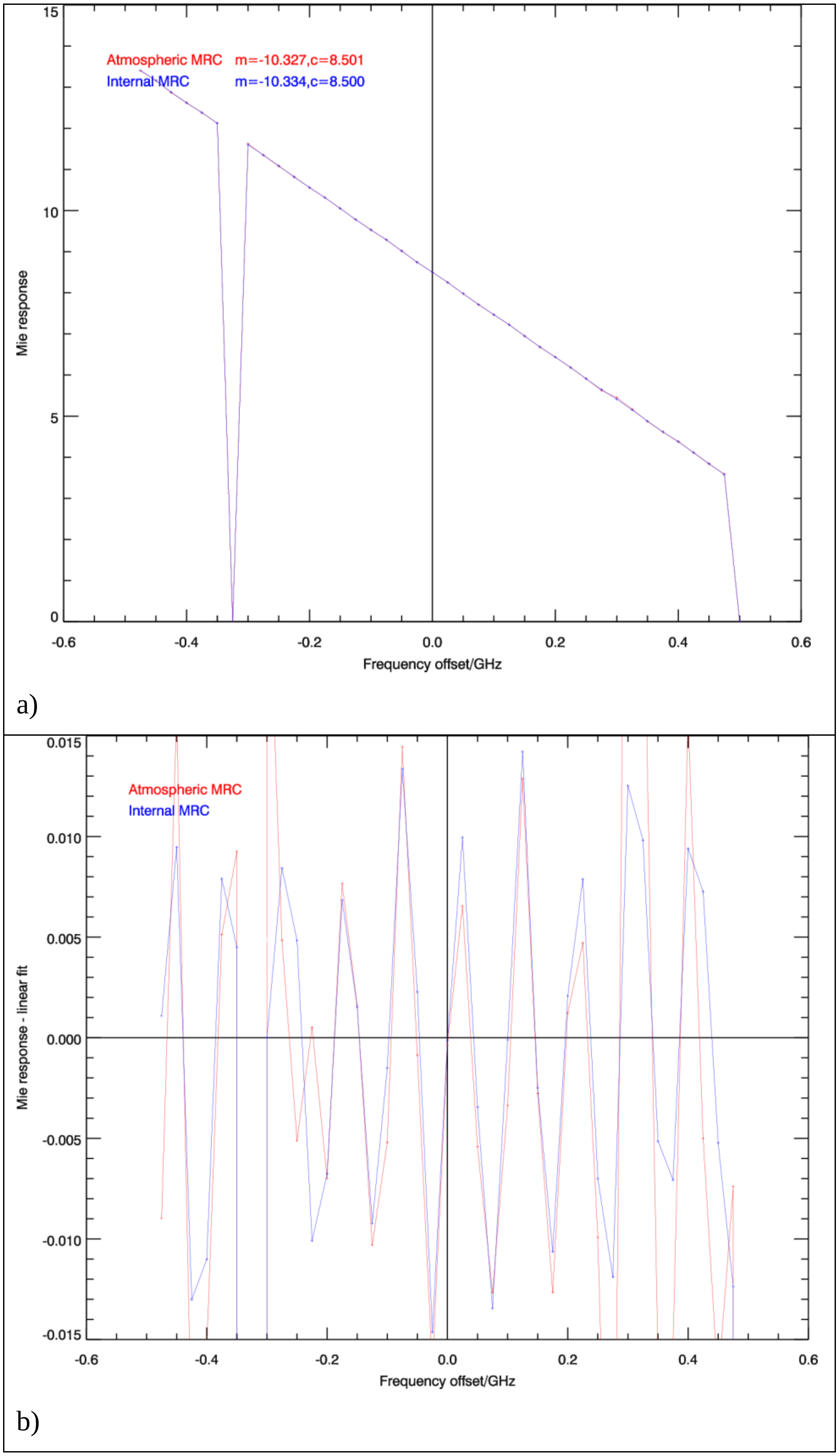


Figure 41. Example data from Mie test case 4: MRC data from Antarctica scenario with noise simulation. a) The MRC data and b) difference between MRC and linear fit.

The results from the five runs of the noisy IRC are given in Table 6.

Table 6. Effect of noise in IRC on measurement MRC for a realistic atmosphere and ground albedo

AUX_MRC_1B run number	Measurement MRC: m (GHz^{-1})	Measurement MRC: c	L2B Mie-cloudy HLOS wind bias (m/s)	Bias relative to test case 1 (m/s)
1	-10.353489	8.499644	-0.37	-0.24
2	-10.331432	8.502249	-0.39	-0.26
3	-10.322572	8.502218	-0.31	-0.18
4	-10.331877	8.503367	-0.06	0.07
5	-10.333596	8.501023	-0.36	-0.23
Standard deviation	0.0114	0.00141	0.14	**Mean(absolute(bias))=**0.20

Based on the standard deviation of *m* and *c* alone, we would expect HLOS wind biases on order of 0.1 m/s; see the Appendix Section 7.2. The actual standard deviation of profile average L2B Mie-cloudy HLOS wind bias is 0.14 m/s HLOS wind in this test case (mostly due to run 4 being an outlier). Typical values of **profile average bias tend to be around 0.2 m/s**; which is still a reasonably small overall bias level for NWP users for this realistic simulation.

Figure 42 shows the HLOS dependence of the bias of the five runs by superimposing the five curves in one plot. The impression is that the slope-error type dependence of the error is fairly stable amongst the five runs, however the offset can vary as shown by run 4 which is around ~0.3 m/s more positively biased than the rest. By comparing Figure 42 to Figure 39 (from test case 3) it is seen that the shape of HLOS dependence has altered systematically, again like test case 2; see Figure 38. This must be because of the realistic atmosphere and surface reflectance have some systematic effect on the responses. Therefore we can expect a unique “signature” bias for each atmospheric scenario that an MRC is performed upon. However, the magnitude of the fluctuations in bias is not too worrying for NWP applications.

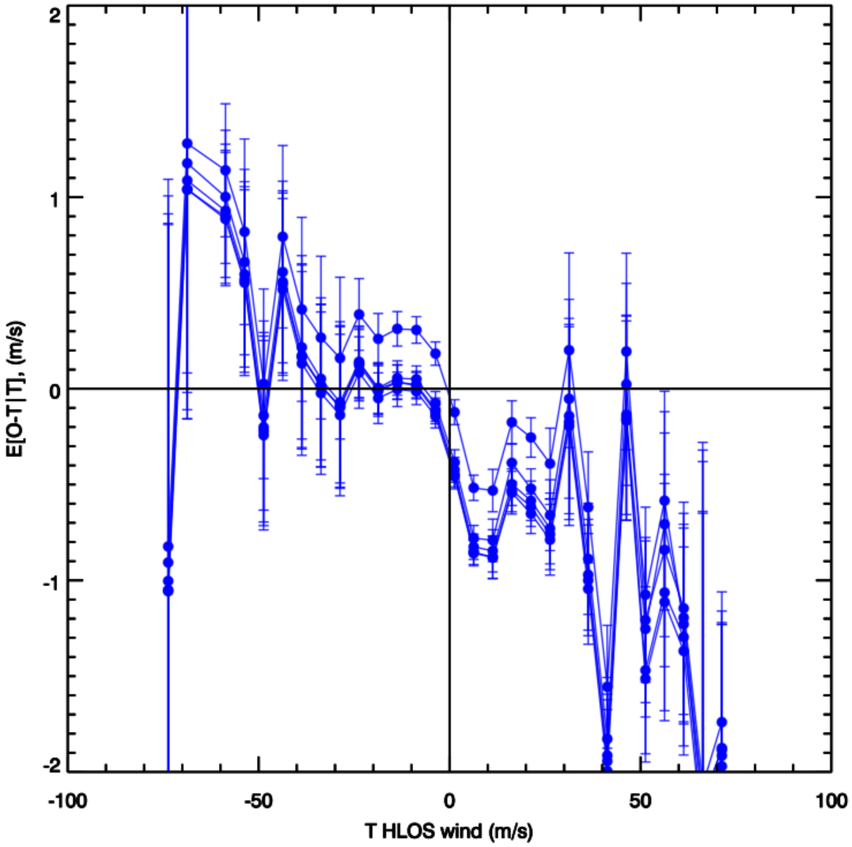


Figure 42. L2B Mie-cloudy HLOS wind bias as a function of truth HLOS wind. The plot overlays the five realisations of test case 4.

The constant offset difference of run number 4 compared to the others is thought to be due to the internal reference calibration. Since the E2S is simulating an almost constant internal reference response of around 10.5 pixels, then by chance the MRC data near 10.5 pixels may have a larger error for run number 4. Hence in the WVM the internal response will systematically apply the error leading to a constant offset bias over the HLOS dynamic range. Similar behaviour has been observed for the Rayleigh internal reference calibration as explained in Section 4.1.2.

A method to reduce the noise and atmospheric variability effects should be considered e.g. averaging over a number of MRC realisations from different conditions. However given the IRC is scheduled to take place weekly, it is unclear if it will be appropriate to average MRCs separated in time during which the instrument characteristics may have drifted.

R4: In simulations, the internal reference calibration is almost identical to the measurement calibration for “perfect” calibration. This is an unrealistic simulation by the E2S; it should be investigated if more realistic simulation is required.

R5: It may be worth investigating if the Mie non-linearity correction would be better modelled as a function rather than interpolating the potentially noisy non-linear correction data to the raw response values.

It seems unnecessary to investigate different realistic cloud conditions in that similar behaviour will be found i.e. some frequency steps will not have sufficient ground return signal, and some will be more strongly affected by noise than others. Determining the climatology of MRC related Mie HLOS wind biases is beyond the scope of this TN.

4.2.5 Summary of Mie calibration testing

Here is a summary of the main points from the Mie calibration testing:

- Using the “perfect” Mie Response Calibration in combination with a realistic atmosphere WVM runs leads to L2B Mie-cloudy HLOS winds with a fairly substantial slope error (of order 1-2%).
- It has been found that the overall slope error is not particularly sensitive to noise processes in the IRC simulation.
- The majority of the slope error is thought to be caused by geophysical issues related to Mie range-bin vertical size in combination with vertical wind shear as seen in realistic atmosphere in WVM (see Appendix Section 5.3).
- It has been found that with realistic atmospheric/ground albedo scenarios including noise that biases of order 0.2 m/s HLOS wind occur due to noise in the MRC. This is on top of the geophysical source of slope error.
- It is expected that the MRC noise induced biases could be reduced significantly if several MRCs could be produced (in a short period of time) and an average taken.
- The MRC noise induced systematic errors (if these simulations are realistic enough) are much less of a concern for NWP use than the overall slope error.
- The amount of non-linearity in the MRC is likely to be underestimated in the E2S simulations, hence the systematic errors are likely to be underestimated compared to reality.

4.3 Rayleigh calibration testing with an updated processing chain

Due to a number of problems encountered with the CAL suite of Dec 2015 (e.g. the CSR updater tool did not work with an RRC which has some invalid frequency steps and an issue in the L1B processor related to NaN values for ground return values) in August 2016 it was decided to update the whole processing chain (CoP) software to new versions of the processors to resolve the issues. Therefore the Rayleigh channel calibration testing in this Section used the newer processor versions as listed in Table 7 below.

Table 7. CoP processor version combination used in this Section for Rayleigh calibration testing

Processor name	Processor version	Date of release
E2S	v3.07	June 2016
L1Bp	v6.06	June 2016
Calibration (CAL) suite	30 June 2016 + patch 1	Patch provided later than main release
L2Bp	v2.30	July 2016

The test cases performed Rayleigh calibration testing are already defined in Section 4.1, but with the new processor versions of course.

Another difference is the change of the WVM scenario used for testing the resulting AUX_RBC_L2 file upon the L2B winds. This has changed from ECMWF_T1279 to an updated version that will be referred to as ECMWF_TcO_1279_2015 from now on. The new scenario uses of higher-resolution and more realistic ECMWF model output as meteorological input to the E2S and also the more recent date is more convenient more general testing purposes in the ECMWF data assimilation system.

This ECMWF_TcO_1279_2015 scenario has the following properties:

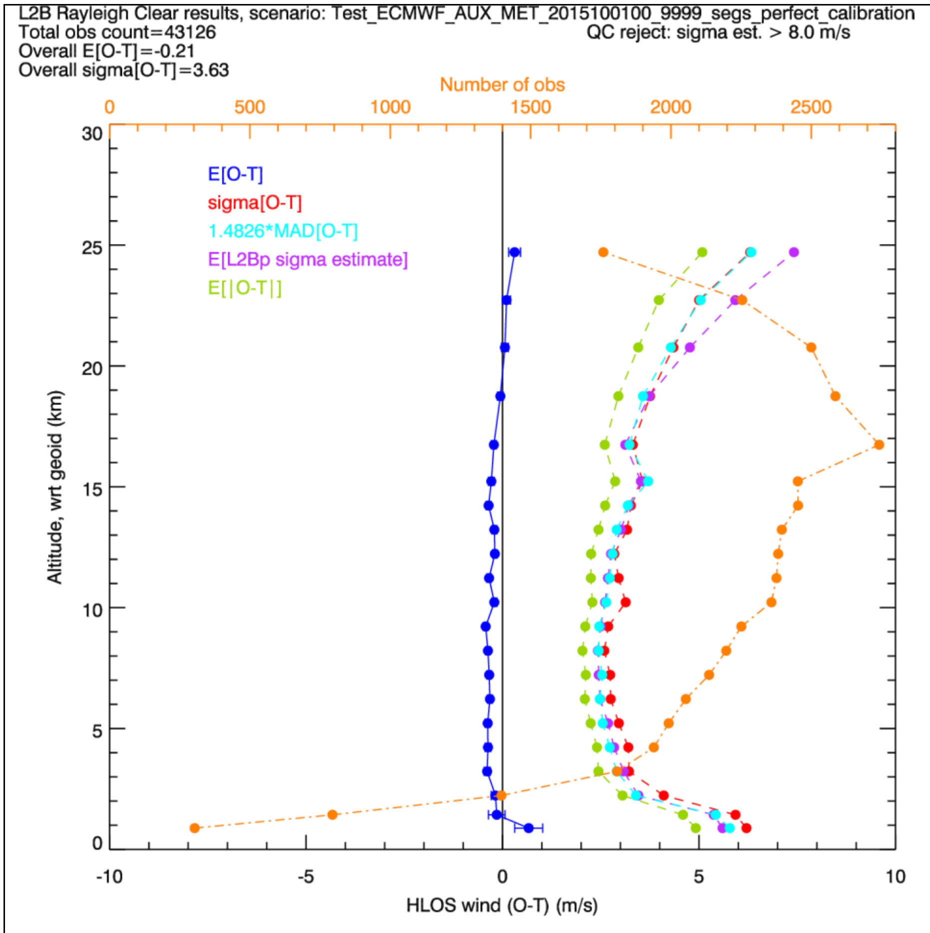
- 9999 segments (a current limitation of the KNMI atmospheric database format) every 3 seconds (~21 km) along track
- Meteorological data from the new ECMWF model output at TcO1279 (9 km horizontal resolution, cubic octahedral grid) for the date of 1/10/2015. Subjectively there is more variability in the small-scale winds for this model data than with the T1279 data. The scenario is valid for around 8 hours from 1 AM, covering about 5.5 orbits. The implemented E2S remains on the "old" Aeolus orbit settings despite E2S 3.07 having the option for the new lower orbit. A larger sample of winds is possible with the ECMWF_TcO_1279_2015 scenario compared to ECMWF_T1279 due to more orbits being simulated.

The L2Bp v2.30 processor settings are the same as those optimized for the first attempt at Rayleigh calibration testing in Section 4.1. A list of the processor updates can be found in the relevant software release notes.

4.3.1 Rayleigh test case 1: Perfect calibration results with updated processors

This test case uses “perfect” calibration i.e. no noise ISR, no étendue effect (therefore no IRC and update CSR required). It has already been described in Section 4.1.1.

The resultant AUX_RBC_L2 file was applied in the L2Bp for the WVM scenario ECMWT_TcO1279_2015 and the L2B Rayleigh-clear HLOS wind error statistics are presented in Figure 43 below. They can be compared to the error statistics with the previous CoP combination with ECMWF_T1279 shown in Figure 22 — the error statistics are similar as expected since the E2S, L1B and L2B processors have not changed very much with the update. There are some differences due to sampling of different meteorological conditions with the new WVM scenario (note there are 34% more wind results in the new scenario due to the increase in orbits). The similarity of the results compared to the old CoP shows that no anomalies have occurred in the new CoP and therefore further calibration testing can proceed. The tendency for a small negative bias in the L2B Rayleigh winds is not yet understood.



a)

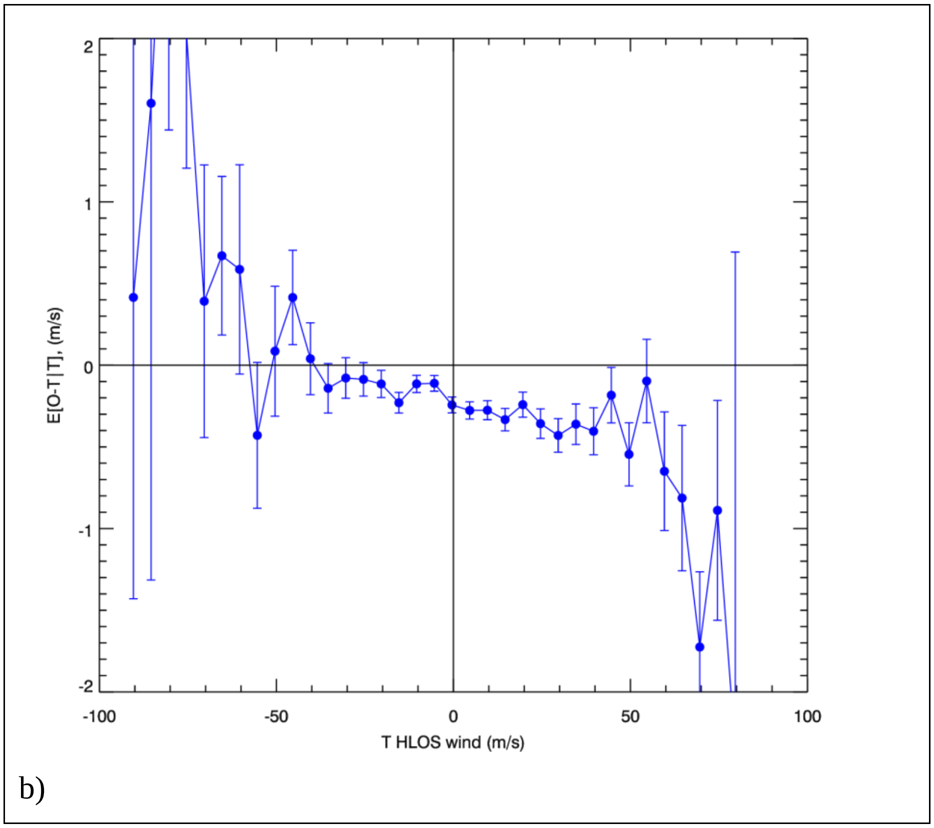


Figure 43. L2B Rayleigh-clear HLOS wind error statistics for ECMWF_TcO1279_2015 using the perfect calibration AUX_RBC file. a) Statistics versus altitude b) Dependence of bias upon true HLOS wind.

The **overall bias is -0.21 m/s** (as shown in Figure 43a) for the L2B Rayleigh-clear HLOS winds and there is a small slope error (from -50 to +50 m/s; the extremes outside this range are considered outliers) as shown in Figure 43b), despite DCMZ being corrected for the WVM. This test case provides the reference Rayleigh-clear HLOS wind systematic error (bias) against which the following imperfect calibration test cases will be assessed.

4.3.2 Rayleigh test case 2: The effect of noise in the ISR

It is particularly important to rerun this test case involving noise in the ISR with the new CoP because the new CAL suite includes an update which should improve the earlier results; N.B. fairly significant biases were found in Section 4.1.2 due to ISR noise.

In the new CAL suite, the DLR model fit to the ISR transmission functions (as part of GenCSR; uses the “E2S” version of the Fizeau reflection) is used for the internal reference RRC (as provided in the AUX_RBC_L2 file), rather than using the raw and hence noisy ISR data. This model fit should reduce the ISR noise and hence lead to a reduction in the fairly large biases found in the tests of Section 4.1.2.

An indication of the improvement is, on rather close inspection, visible in Figure 44, which shows that the internal RR stored in the AUX_RBC_L2 (red line) is now a smoother function than when previously calculated directly from the noisy ISR transmission data i.e. the blue line which is the internal RR calculated directly from the noisy ISR data.

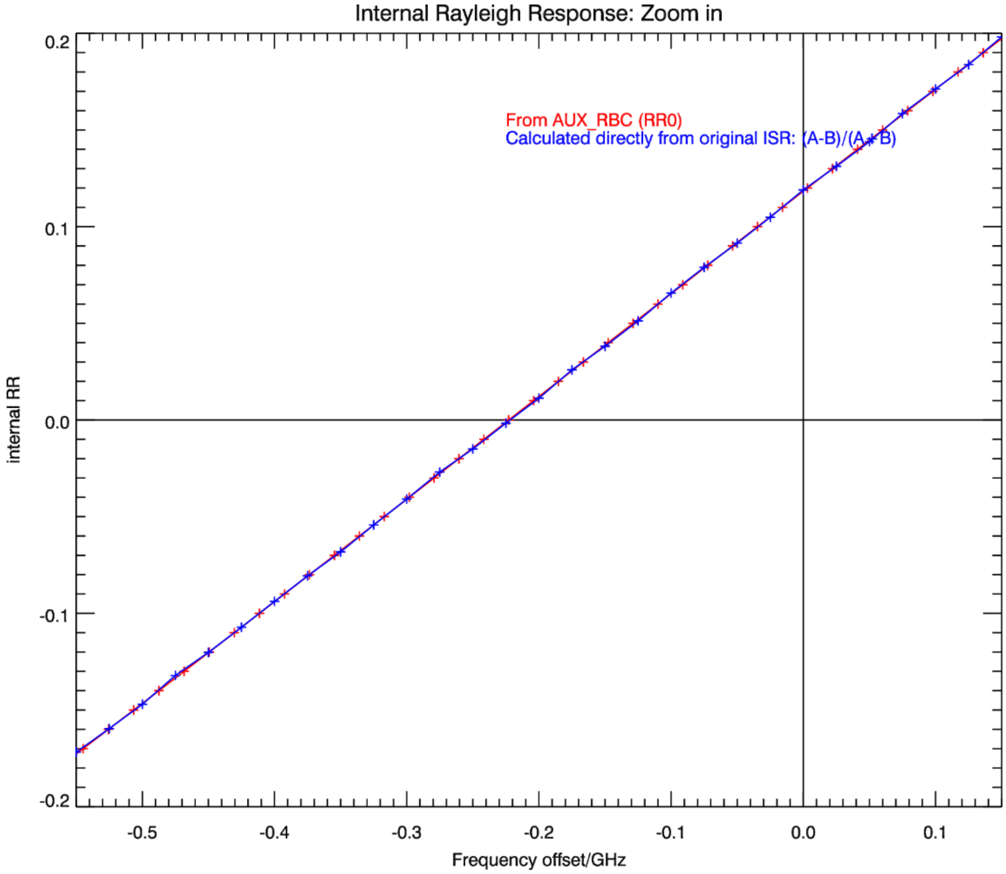


Figure 44. The internal RR from the new AUX_RBC_L2 is shown in red and that calculated directly from the raw ISR data in blue. It appears that the small oscillations in the blue curve (due to noise) have been removed in the red curve.

The systematic errors introduced with five realisations of the ISR (and hence of the AUX_RBC_L2) relative to the “perfect” calibration of test case 1 are listed in Table 8 below.

Table 8. Effect of noise in the ISR on the L2B Rayleigh-clear wind bias (average over all data) with new CAL suite

AUX_RBC_L2 run number	**L2B Rayleigh-clear HLOS wind bias (m/s) relative to “perfect” calibration**
1	-0.10
2	-0.11
3	-0.14
4	0.18
5	-0.03
Mean(absolute(bias))	0.11

Note that the biases appear as a constant offset i.e. not varying as a function of e.g. HLOS wind speed. The level of bias resulting from the new “filtered” internal RRC is much smaller than in the earlier CAL suite. **The mean absolute bias is now 0.11 m/s which is a quarter of the magnitude before the CAL**

suite improvement. This useful improvement demonstrates the benefit of testing the calibration chain and finding such issues so they can be corrected for in processing software updates.

4.3.3 Rayleigh test case 3: Testing the CSR updater (étendue detection) with idealistic IRC conditions

The set-up for this test case has already been described in Section 4.1.3. In summary this test case regards testing the ability to detect étendue parameters in the CSR updater when there is no noise in the simulation and using a simple atmosphere (no horizontal variability or clouds) in the IRC.

With the new CoP the CSR updater successfully produced a modified ISR matching the actual RRC with the following parameters:
Width = 0.542GHz Tilt = 1.0 Dist = 0.000281
i.e. a width error of 42 GHz and a tilt error of zero (the E2S input width = 500 MHz and the tilt=1.0).

This CSR updater result is an improvement relative to the previous CAL suite for the tilt parameter (there was a 0.2 tilt error with old CAL suite), but still it is 42 MHz from the truth for the top-hat width, whereas the error was 32 MHz with the old CAL suite (width=468 MHz).

The WVM scenario ECMWF_TcO1279_2015 was run with the same étendue effect on (i.e. same input parameters for width and tilt), applying the AUX_RBC_L2 file generated using the appropriate updated CSR file. In terms of the effect on the L2B Rayleigh-clear winds results, there **is zero (0.0 m/s) bias relative to the "perfect" calibration** result of test case 1. Therefore this result appears to be a successful demonstration of the CSR updater performance in ideal noiseless and simple atmosphere conditions.

4.3.4 Rayleigh test case 3b: Effect of biased AUX_MET_12 data on CSR updater for test case 3 setup

This test was not listed in the original test cases, but is a possible source of bias that should be investigated. Using the same set-up as test case 3, in this test case we investigate the effect of temperature and pressure errors in the AUX_MET_12 used by the CSR updater and how this propagates to the L2B Rayleigh wind errors.

Five runs were performed with varying levels of temperature and pressure *systematic errors* in the AUX_MET_12 data. This was done by modifying the `ConvertKnmiAscToAMD` tool (which is part of the L2B software package) to have the optional inputs of temperature and pressure bias parameters. The bias is added to the KNMI database meteorological profiles before writing to the AUX_MET_12 EE file. The imperfect AUX_MET is then applied in the UpdateCSR step, and the GENRBC step is run on with the updated CSR file.

It was decided to test a variety of systematic errors rather than random errors because:

- Systematic T and p errors are simpler to implement than realistic random errors. It would be a lot of work to implement random realisations of the ECMWF background error covariance matrix for temperature and pressure.
- A constant error is like a random realisation of the B matrix but with very long correlation length scales; say over much of the horizontal extent of the IRC.
- Also systematic errors assess the maximum effect that could occur; random errors without spatial correlations are expected not to effect the CSR updater.

The temperature bias is simply a constant offset value added to every AUX_MET_12 temperature value. The pressure bias is a multiplicative factor on the pressure i.e. the pressures can be increased or decreased by the factor; this is because pressure changes by many orders of magnitude with altitude so a constant bias is inappropriate.

The CSR updater test results are given in Table 9 below.

Table 9. Test case 3b results for the CSR updater with various combinations of AUX_MET_12 temperature and pressure bias

Run number	Temperature bias (K)	Pressure bias (%)	Width (MHz)	Width error (MHz)	Tilt	Tilt error	Distance	HLOS L2B wind bias relative to test case 1 (m/s)
1	2.0	2.0	331	-169	1.7	0.7	0.000281	+0.08
2	2.0	0.0	298	-202	1.8	0.8	0.000281	+0.09
3	0.0	2.0	560	60	1.0	0.0	0.000281	-0.01
4	-2.0	0.0	707	207	0.8	-0.2	0.000280	-0.08
5	0.1	0.0	532	32	1.0	0.0	0.000281	N/A

A constant 2 K temperature and +2% pressure bias over the whole IRC (7200 km along-track) is used in run number 1 to test the sensitivity of the CSR updater. It is debatable whether the ECMWF produced AUX_MET_12 data will contain errors analogous to this.

The difference between ECMWF EDA (Ensemble data assimilation) member forecasts (from an arbitrary forecast) is a proxy for the short-range forecast error magnitude and structure that should be similar to that possible in an AUX_MET_12 file; see Figure 45. For temperature at 200 hPa (~10 km), Figure 45 a), the difference values reach ~2-3 K, however this should be divided by √2 if both members have the same error statistics. So the magnitude of error of 2 K is a reasonable assumption. The temperature error correlation length scales are fairly short relative to the IRC distance (based on the oscillations in the plot), so the assumption that the error is constant over the whole IRC is too pessimistic it would seem.

Mean sea-level pressure differences of 3 hPa occur (~0.3% error) in Figure 45 b) so the 2% relative error assumption is too large; however the horizontal correlation scales are a larger fraction of the IRC distance (more coherent structure) than the temperature errors hence the constant error assumption is reasonable.

The vertical error correlation scales have not been assessed, but will typically be on the order of one kilometre for temperature and much deeper for pressure; so the assumption of constant temperature error in the vertical is not a realistic one, but it is a more realistic assumption for pressure.

In summary the assumed errors for run number 1 are fairly pessimistic and real AUX_MET_12 errors should lead to a smaller effect.

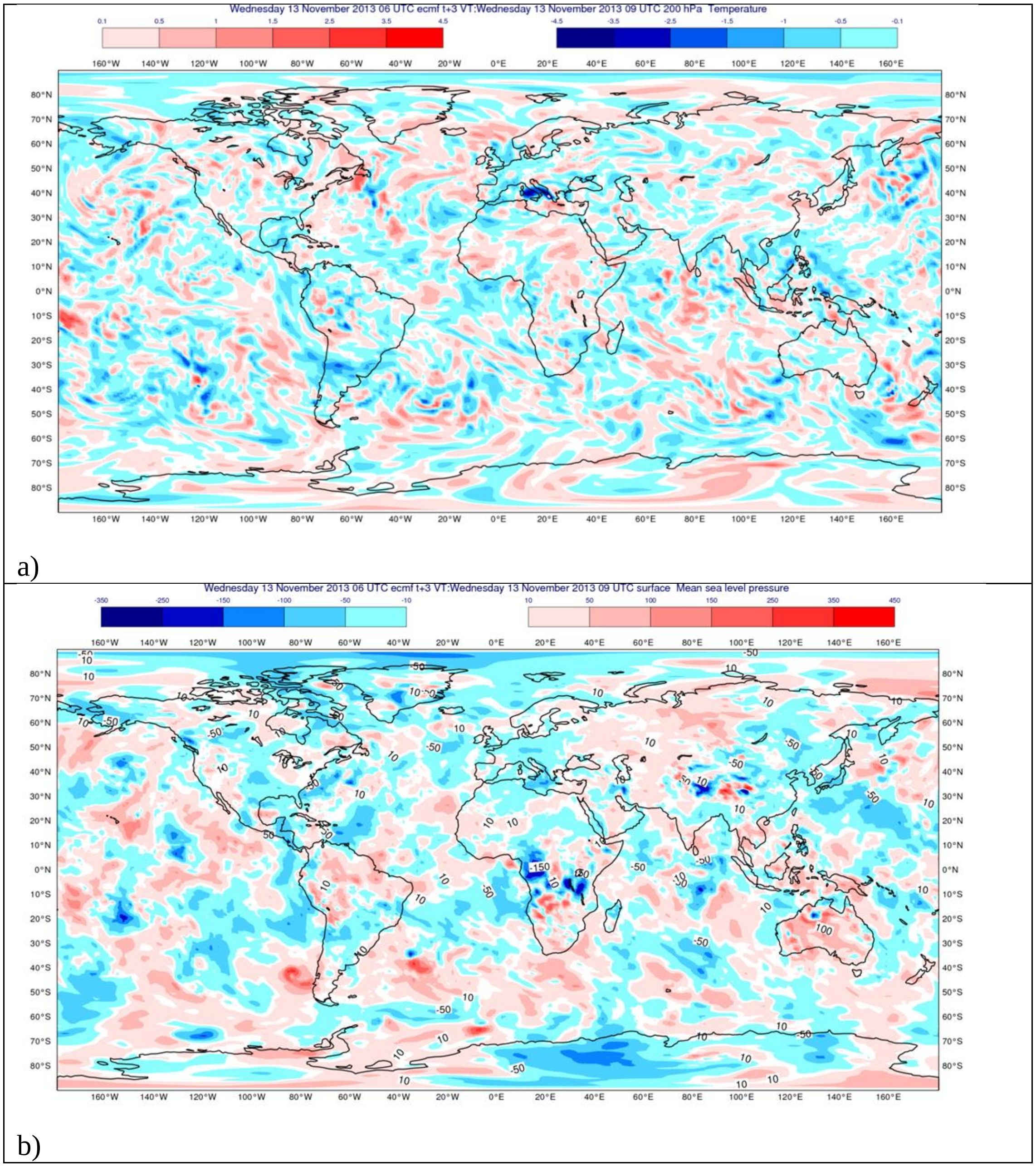


Figure 45. Difference between ECMWF EDA members for a) temperature (units: K) at 200 hPa and b) for mean sea level pressure (units: Pa) for an arbitrary cycle run in November 2013.

Run number 1 led to substantial errors in the retrieved étendue parameters. However, the resultant L2B Rayleigh-clear HLOS wind bias overall bias was surprisingly small at +0.08 m/s relative to “perfect” calibration; however the slope error did increase slightly (not shown). It appears that the opposite sign errors of the width and tilt are compensating each other to leave a small HLOS wind bias.

By removing the pressure bias, but keeping the 2 K temperature bias the parameter errors increased; suggesting the pressure bias was mitigating for the temperature bias; perhaps by increasing both pressure and temperature the effective density profile (and hence molecular backscatter signal) is kept similar (since in hydrostatic equilibrium density is proportional to pressure/temperature). However overall L2B HLOS wind bias is only 0.09 m/s and the slope error is very similar to run number 1.

Positive temperature bias leads to a negative width error (and positive tilt error) and negative temperature bias leads to a positive width error (and negative tilt error). The CSR updater appears to be trying to compensate for the RB spectrum being too wide due to positive temperature bias by decreasing the top-hat width, and too thin with negative temperature bias by increasing the top-hat width. The -2 K bias leads to similar magnitude L2B wind bias as the +2 K bias, but of opposite sign.

The 2% pressure bias by itself led to rather small parameter errors. This must be because the Rayleigh-Brillouin spectrum has a relatively small sensitivity to pressure errors for small pressures (which will be case in the 6-16 km altitude range, around 500 hPa to 100 hPa, of the RRC). The resultant L2B HLOS wind errors are negligible. So it seems that AUX_MET_12 pressure errors are not a concern for the CAL suite CSR updater and hence the L2B Rayleigh wind calibration strategy.

Finally, the long term and global average temperature biases in the ECMWF model output are ~0.1 K according to global radiosonde O-B statistics. Such a bias leads to rather small parameter errors and hence negligible L2B wind errors.

4.3.5 Rayleigh test case 4: Testing the CSR updater (étendue detection) with a more realistic atmosphere for the IRC, but noise free

Details of the IRC scenario for this test case were already described in Section 4.1.4; i.e. this test uses the first 81 BRCs of the ECMWF_T1279 scenario to generate a realistic atmosphere IRC. Given that there is no noise simulated in the IRC then the test needs only to run the calibration processing steps once.

The CSR updater resulted in a modified ISR to match the actual RRC with the following parameters:

Width = 0.657 GHz Tilt = 0.8 Dist = 0.000183

That is a width error of 157 MHz and a tilt error of -0.2. Compared to the results of the previous CoP (Width = 367 MHz and Tilt = 1.5 i.e. width error=-133 MHz, tilt error=0.5), the tilt error has improved, however the width error is a bit worse.

In terms of the effect on the L2B Rayleigh-clear winds results, there **is -0.15 m/s bias relative to the “perfect” calibration results** of test case 1, with no significant increase in slope error. This is a promising result, demonstrating that the CSR updater method of accounting for étendue apparently works sufficiently well for a realistic IRC scenario with some cloud (but without noise), so not as to induce significant bias in L2B winds i.e. the ability to use the L1B MRC scattering ratio in the forward model of the RRC in the CAL suite must be working reasonably well.

4.3.6 Rayleigh test case 5: Testing the CSR updater (étendue detection) with a simple IRC atmosphere, but with noise

This test case is similar to test case 3, but with noise processes on in the E2S IRC simulation. Therefore the L1Bp needs to correct for the DCMZ. This testing is the same as that from 4.1.5 except it uses the newer CoP. The results of the CSR updater step and L2B winds are given in Table 10; this can be compared to the results found with the previous CoP provided in Table 4.

Table 10. Test case 5 results for the CSR updater and resultant L2B Rayleigh-clear wind bias

Run number	Width (MHz)	Width error (MHz)	Tilt	Tilt error	Distance	HLOS L2B wind bias relative to test case 1	Comment
1	462	-38	1.2	0.2	0.001077	-0.01	
2	593	93	0.9	-0.1	0.001145	-0.01	Slight change in slope error relative to run 1
3	664	164	0.8	-0.2	0.001091	0.05	
4	620	120	0.9	-0.1	0.001242	-0.11	
5	585	85	0.9	-0.1	0.001153	-0.02	
	Mean(absolute(error))	100		0.14		0.04	

The CSR updater error has a mean absolute error of 100 MHz for the width and 0.14 for the tilt. The errors are the same order of magnitude as in the old CoP. The errors are worse than the noise-free equivalent of test case 3.

The resultant bias in L2B Rayleigh-clear HLOS winds are pretty small **with mean absolute bias of 0.04 m/s** — it would appear there is some compensation between the width (typically over-estimated) and tilt (typically underestimated) errors which means the RBC generated RRC curves are still a reasonable match with the truth RRC curves.

4.3.7 Rayleigh test case 6: Testing the CSR updater (étendue detection) with a more realistic atmosphere for the IRC and with IRC noise

The first test of this section (which will shall call test case 6 a) is same as test case 4 but with noise sources on in the E2S simulation of the IRC. Due to noise the test is repeated five times to sample the errors. Test case 6a is done with the realistic IRC atmosphere from the first 81 BRCs of scenario ECMWF_T1279. The results of the test case are presented in Table 11 below.

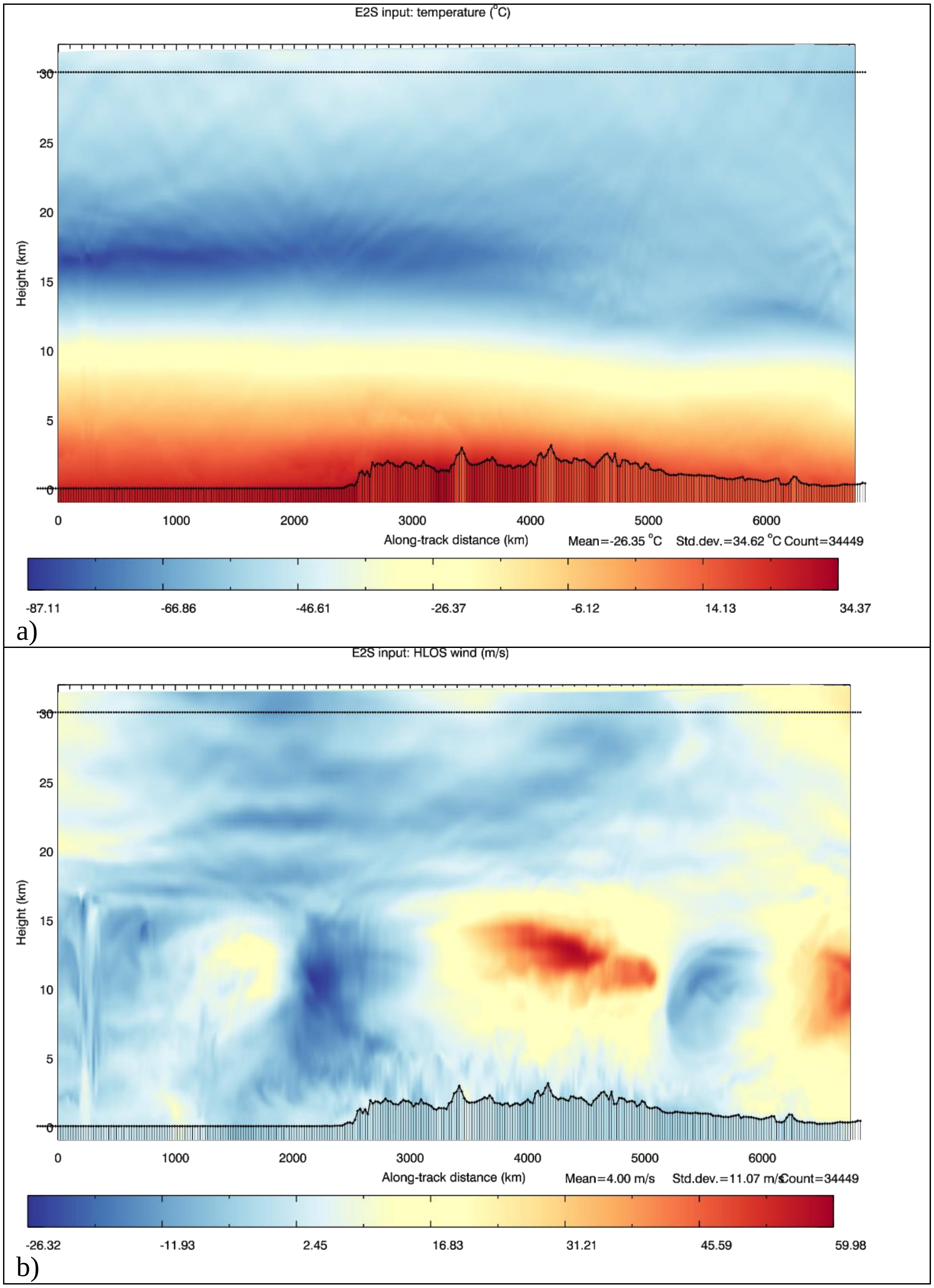
Table 11. Test case 6a results for the CSR updater and L2B Rayleigh-clear wind bias

Run number	Width (MHz)	Width error (MHz)	Tilt	Tilt error	Distance	HLOS wind bias relative to test case 1	Comment
1	640	140	0.8	-0.2	0.001068	-0.28	
2	580	80	0.9	-0.1	0.001116	-0.38	Small slope change compared to run 1
3	696	196	0.8	-0.2	0.001103	-0.29	
4	638	138	0.9	-0.1	0.001259	-0.21	
5	554	54	1.0	0.0	0.000979	-0.38	
	Mean(absolute(error))	122		0.12		0.31	

The CSR updater finished correctly i.e. reached its criteria for all five runs. The top-hat width errors are similar to the equivalent test case without noise (test case 4) and a bit worse than the equivalent test case with an idealistic IRC atmosphere (test case 5). **The resultant L2B HLOS wind biases have a mean absolute bias of 0.31 m/s. This is large enough to be a concern for NWP use.**

It is unclear why the L2B biases are significantly worse than test case 5 given that the width and tilt errors are not that much worse.

Another test with a different realistic atmosphere for the IRC was tested; which we will refer to as test case 6b. This particular atmosphere had much more cloud than test case 6a (in particular thick tropical convective cloud at the start). It is derived from the first 81 BRCs of ECMWF_TcO_1279_2015 model output; Figure 46 shows the relevant atmospheric conditions. It also including realistically varying ground albedo maps (from ADAM). The location of the IRC starting in the tropics and heading north towards North America was not a deliberate choice, rather it just happened to be first 81 BRCs of the ECMWF scenario used. This will most likely not be a chosen location to perform an IRC; the poles are more favourable due to higher albedo over ice for the MRC.


E2S input: temperature (°C)
Height (km)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
Along-track distance (km)
Mean=-26.35 °C
Std.dev.=34.62 °C
Count=34449
-87.11
-66.86
-46.61
-26.37
-6.12
14.13
34.37
a)
E2S input: HLOS wind (m/s)
Height (km)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
Along-track distance (km)
Mean=4.00 m/s
Std.dev.=11.07 m/s
Count=34449
-26.32
-11.93
2.45
16.83
31.21
45.59
59.98
b)

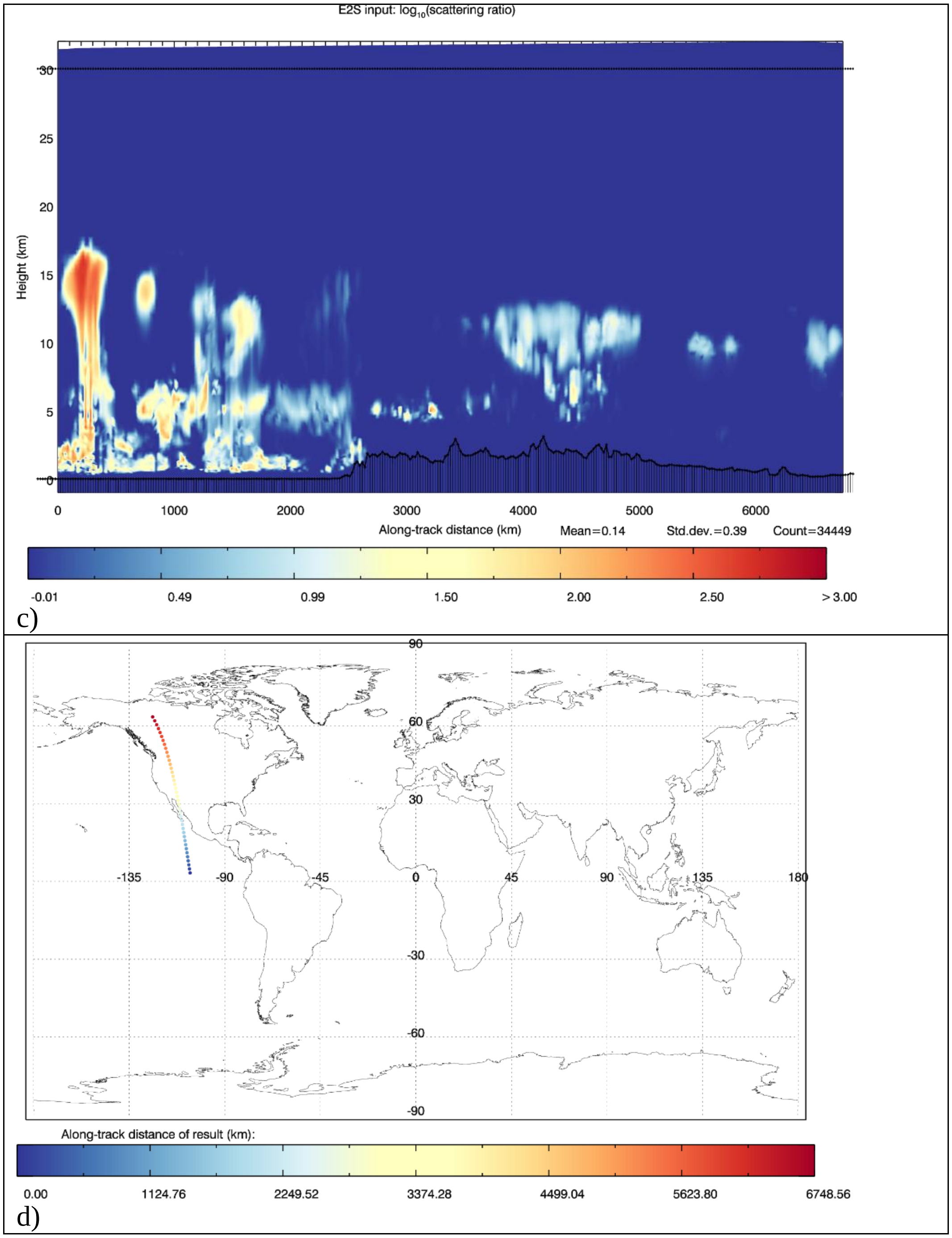


Figure 46. Plot of the atmosphere for the IRC scenario used for the second part of Rayleigh test case 6b. a) Temperature b) HLOS wind speed, c) scattering ratio and d) a map of where the IRC took place.

The RRC encountered some problems in the first few frequency steps because of the optically thick tropical convective cloud (see Figure 46c). Figure 47 shows the RRC result from one run of the scenario.

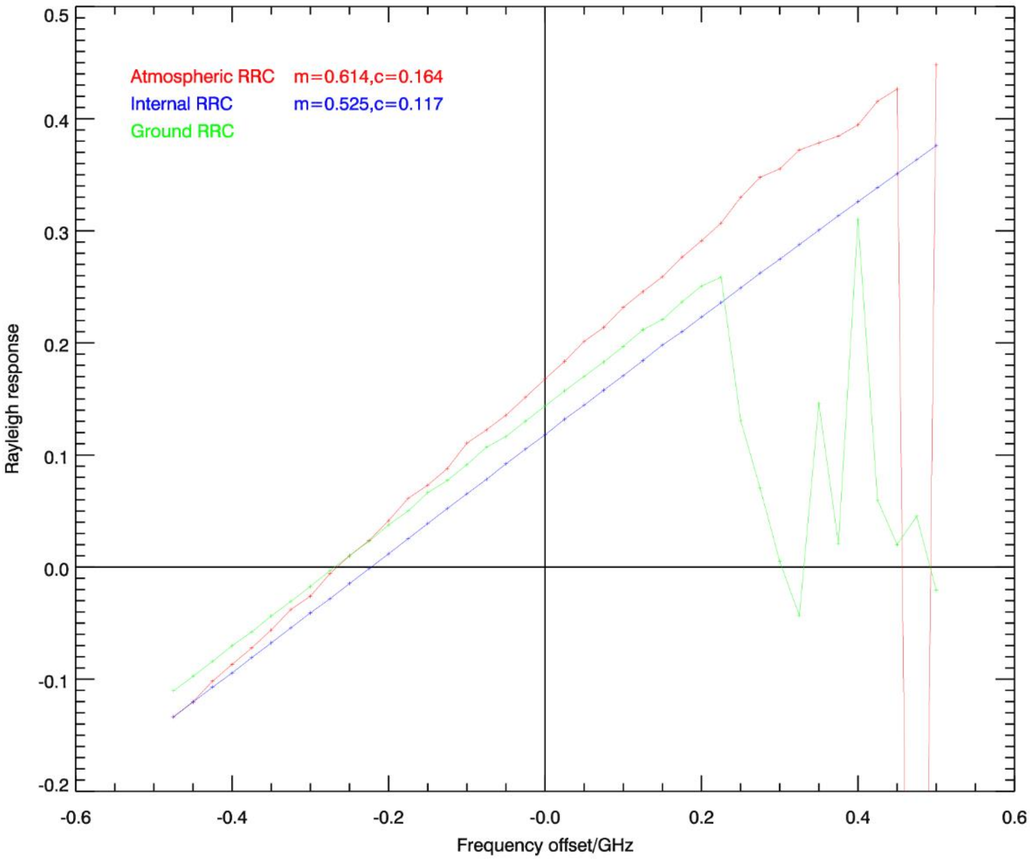


Figure 47. RRC result for an example run of test case 6b. There is a missing result for the atmospheric RRC (red line) at Frequency offset = 0.475 GHz which is as a result of the strong convective cloud at the start of the RRC (note the RRC starts at 0.5 GHz and steps down to -0.5 GHz). The ground RRC (green) is strongly affected by the cloud attenuation in the range 0.25-0.5 GHz.

The results of five realisations of the CSR updater are given in Table 12 below.

Table 12. Test case 6b results for the CSR updater and L2B Rayleigh-clear wind bias

Run number	**Width (MHz)**	**Width error (MHz)**	**Tilt**	**Tilt error**	**Distance**	**HLOS wind bias relative to test case 1**	**Comment**	**Num_Valid_Frequency_Steps**
1	299	-201	2.0	1.0	0.023071	N/A	CSR did not reach validity criterion	39
2	1290	790	0.4	-0.6	0.013736	N/A	CSR did not reach validity criterion	39

3	284	-216	2.0	1.0	0.008006	N/A	CSR did not reach validity criterion	38
4	313	-187	2.0	1.0	0.032787	N/A	CSR did not reach validity criterion	39
5	727	227	0.8	-0.2	0.006205	0.35		38
	Mean(absolute(value))	324		0.76				

Unfortunately the CSR updater did not reach the validity criterion for four of the five runs. The width and tilt values shown above are that of the final iteration. The estimates of width and tilt are far from the truth and hence convergence was not possible. Only run number 5 succeeded in providing an updated CSR file; and this lead to 0.35 m/s L2B wind bias.

If the CSR updater does not complete, then the RBC generation uses a non-updated CSR i.e. without the étendue (transmission functions straight from the model fit to the ISR). This leads to very large biases in the L2B winds, on the order of 13 m/s (effectively the L2B results are not applicable) when the étendue is simulated. If this failure of the CSR updater happens for the Aeolus mission then one would have to conclude that the IRC was invalid and should be repeated in more favourable atmospheric conditions i.e. less cloud contamination to hopefully get the CSR updater to work.

The failure to reach the validity criterion was despite the threshold in the AUX_PAR_CS file being increased to have an offset of 0.3 m/s (from the default of 0.1 m/s).

As an aside, note that the CSR updater was tested from an official ECMWF AUX_MET_12 file which contained the ECMWF_TcO_1279_2015 data. The prototype CSR updater was able to correctly read the file (although it was very slow reading the 30 hour AUX_MET_12 file) and perform the CSR updater process.

The poor performance in this test case was investigated by the L1B team. Resultant improvements in the CAL suite is covered in an additional chapter 4.3.10.

4.3.8 Rayleigh test cases 7, 8 and 9

These cases have not been run, because they only add a noisy ISR into the calibration chain, and the effect of this has already been demonstrated to be only on the internal RR calibration curves. Therefore if the test cases had been run we will have seen bias typically around 0.14 m/s added to the results of test cases 3, 4 and 5.

4.3.9 Rayleigh test 10: All noise sources included for a realistic atmosphere

The setup is the same as test case 6a, except that ISR noise is now included in the calibration chain. That is, this is the most realistic test case. There are separate realisations of ISR and IRC noise for each of the five runs. The results are presented in Table 13.

Table 13. Test case 10 results for the CSR updater and L2B Rayleigh-clear wind bias

Run number	Width (MHz)	Width error (MHz)	Tilt	Tilt error	Distance	HLOS wind bias relative to test case 1	Comment
1	667	167	0.8	-0.2	0.001092	-0.31	
2	662	162	0.8	-0.2	0.001038	-0.47	
3	590	90	0.9	-0.1	0.001187	-0.26	
4	662	162	0.8	-0.2	0.001182	-0.47	
5	664	164	0.8	-0.2	0.001308	-0.31	
	Mean(absolute(error))	149		0.18		0.36	

There is a clear trend towards overestimating the width and underestimating the tilt. The results are a little bit worse than the similar test case 6a with a **mean absolute HLOS wind bias of 0.36 m/s.**

Given that so many of the CSR update steps failed in the rather cloudy scenario of Test 6b, there is no point combining that with ISR noise, since things will not improve.

4.3.10 *Additional chapter:* Repeat of Rayleigh test case 6b after further fixes to the CAL suite

After reporting the instability in the CAL suite performance for the “thick tropical cloud” scenario (test case 6b) to the L1B team (in particular Alain Dabas), progress has been made. In particular there were a number of bugs in CAL suite which were discovered related to not rejecting missing frequency steps in the IRC. Patches to the CAL suite were subsequently provided (in January 2017) by Alain. We shall refer to this updated CAL suite as version: 30 June 2016 + patches 1-3.

Rerunning test case 6b with this patched CAL suite produced a much more stable CSR updater performance; 10 runs of test case 6b (with different realisations of the noise) gave the following output:

Table 14. Rerun of test case 6b CSR updater with CAL suite: 30 June 2016 + patches 1-3

Run number	Width (MHz)	Width error (MHz)	Tilt	Tilt error	Distance	Comment
1	577	77	0.9	-0.1	0.002097	A modified ISR matching actual RRC has been found
2	605	105	0.9	-0.1	0.001842	“”
3	648	148	0.8	-0.2	0.003173	“”
4	582	82	0.9	-0.1	0.002614	“”

5	452	-48	1.2	0.2	0.001497	“”
6	633	133	0.8	-0.2	0.001651	“”
7	661	161	0.8	-0.2	0.002185	“”
8	569	69	1.0	0.0	0.002479	“”
9	599	99	0.9	-0.1	0.002287	“”
10	531	31	1.0	0.0	0.002562	“”
	Mean(absolute(value))	95		0.1		

The test case 6b errors in width and tilt are similar in magnitude (actually a little smaller) than the earlier results of test case 6a (the much less cloudy, realistic case) which itself led to 0.3 m/s HLOS wind bias. Therefore if the WVM scenario was run with the example AUX_RBC_L2 files resulting from the 10 runs in Table 14, then one would expect a similar level of L2B Rayleigh-clear wind bias i.e. around 0.3 m/s. This result is a great improvement for the CSR updater in optically thick clouds, suggesting a more optimistic tone can be taken forward regarding the L2B Rayleigh calibration strategy.

4.3.11 Summary of Rayleigh calibration testing

Here are the highlights from the Rayleigh calibration testing:

- L2B wind systematic errors resulting from noise in the ISR propagating to the internal RR in the AUX_RBC_L2 file is now much less with the updated CAL suite — the biases are now on the order of 0.14 m/s.
- The CSR updater using the worst case AUX_MET_12 temperature errors resulted in L2B Rayleigh-clear HLOS wind bias of magnitude 0.1 m/s with a slight increase in slope error. Pressure errors have a negligible effect.
- The CSR updater performed reasonably well in noisy conditions with a realistic atmosphere with a limited amount of cloud (not particularly optically thick). L2B Rayleigh-clear HLOS wind systematic errors ~0.3-0.4 m/s were found, which is within the boundary of acceptable for NWP use.
- The CSR updater step often failed in a scenario which has optically thick clouds within the 6-16 km vertical range of RRC. After an investigation into this scenario the L1B team found some bugs in the CAL suite which when fixed rectified the performance such that ~0.3-0.4 m/s L2B Rayleigh-clear wind bias can be achieved in such cloudy IRC scenarios.

5 Conclusions

Improvements in the E2S and L1B processing over the past two years have led to some notable changes in the L2B HLOS wind observation error statistics compared to earlier chain-of-processors verification e.g. in [RD4], for example:

- 19% larger standard deviation of Rayleigh wind errors due to a more accurate UV solar background simulation (for the most representative value of solar zenith angle). Related to this there are significantly noisier L1B measurement-level scattering ratio estimates.
- Rayleigh slope error improved thanks to DCMZ correction.
- Changes in the L1B refined scattering ratio biases and noise (some degradation for small SRs, some improvements for large SRs) meant a retuning of the L2Bp classification algorithm scattering ratio threshold settings was required.
- The increase in the number of options in the E2S and L1B leads to increased difficulty in trying to avoid unwanted effects in the simulation and processing.

The calibration testing of this TN has demonstrated that the Rayleigh response calibration chain used for Level-2B winds will, in our most realistic atmospheric simulations, result in HLOS wind systematic errors of around 0.4 m/s relative to the "perfect" calibration case (this can increase to 0.5 m/s if including the effect of worst case AUX_MET_12 temperature errors upon the calibration). For the Mie response calibration chain we found L2B HLOS systematic errors of around 0.2 m/s relative to those obtained with "perfect" calibration. However, the Mie systematic errors are believed to be optimistic because the E2S does not simulate the Mie non-linearity realistically; it is found to be much larger in practice e.g. A2D data.

Unsurprisingly, the calibration results for both channels can be significantly poorer if the IRC is performed in very cloudy conditions such that the amount of valid data is reduced i.e. in terms of the MRC ground returns and the near-clear measurements in the RRC.

The magnitudes of L2B HLOS wind bias from these simulations (~0.5 m/s) are fairly promising for the impact of Aeolus HLOS wind observations in NWP. HLOS wind assimilation studies [RD13] demonstrated that biases above 1 m/s (for HLOS winds with random error standard deviation 1.5-3 m/s) are particularly damaging to the NWP impact. However, there will very likely be additional sources of biases not considered in this TN e.g. the testing did not consider the systematic errors resulting from imperfect harmonic bias correction, imperfect range dependent bias correction and as already mentioned larger than simulated Mie calibration non-linearity. These additional sources of bias may add constructively to the existing biases leading to larger and more complex overall biases. However it seems plausible based on these TN results for Aeolus to achieve L2B HLOS wind biases less than 1 m/s.

A list of recommendations made during the investigation is listed here:

1. Differences between the E2S and DLR models of the Fizeau reflection model cause a 0.5 m/s L2B Rayleigh HLOS wind bias. Therefore it is recommended that a model for the true ALADIN Fizeau reflection function is determined for use in the operational CAL suite (GenerateCSR).
2. It should be investigated if an improvement can be obtained in L2B winds by not discarding measurements with missing L1B refined scattering ratio values e.g. setting the scattering ratio to 1 in such situations might be a good idea, since the missing values typical occur when there is a weak Mie signal.

3. A new L2Bp scattering ratio threshold of 1.8 in combination with L1Bp α= 0.8 is recommended with the most recently tested CoP.
4. For Mie calibration: In simulations the internal reference calibration is almost identical to the measurement calibration for “perfect” calibration. This is an unrealistic simulation by the E2S; it should be investigated if a more realistic simulation is required.
5. For Mie calibration: It may be worth investigating if the Mie non-linearity correction is better modelled as a function rather than interpolating the potentially noisy non-linear correction data to the raw response values.

6 Acknowledgments

Thanks to Alain Dabas (L1B team) for advice on the CAL suite. Thanks to Dorit Huber and Oliver Reitebuch (both L1B team) for advice on a number of issues encountered during the testing and for the review. Thanks to Anne Grete Straume (ESTEC) for the review and suggestions.

7 Appendix

7.1 Derivation of L1B scattering ratio formula

The L1B processor scattering ratio formula is provided in the L1B MAD and DPM, but its derivation could not be found, and it is not obvious. Therefore we attempted our own derivation to see if the final formula matches that written in the documents.

The scattering ratio, which is what we are trying to determine, is given by:

$$SR = \frac{\beta_p + \beta_m}{\beta_m} = \frac{\beta_p}{\beta_m} + 1$$

Where β are the backscatter coefficients for p=particles and m=molecules.

Assuming that the Mie signal is proportional to the particle backscatter coefficient and the Rayleigh-Brillouin (RB) signal is proportional to the molecular backscatter coefficient, then we can use the Mie channel readings to estimate the scattering ratio. For the Mie channel signal for a given atmospheric range-bin consists of detection chain offset (DCO), plus broadband UV background noise, plus the Rayleigh-Brillouin signal, plus the Mie signal (if there is any), see Figure 48 for a schematic of this. The DCO and background signal are subtracted from noisy estimated values. If the RB signal level can be estimated, then the ratio of the total signal to the RB part gives:

$$signal\_ratio = \frac{total\ signal}{estimate\ of\ fraction\ of\ RB\ signal} = \frac{\rho_p + \propto \rho_m}{\propto \rho_m} = \frac{\rho_p}{\propto \rho_m} + 1$$

Where α indicates the fraction of the total RB signal that is sampled in the Mie channel.

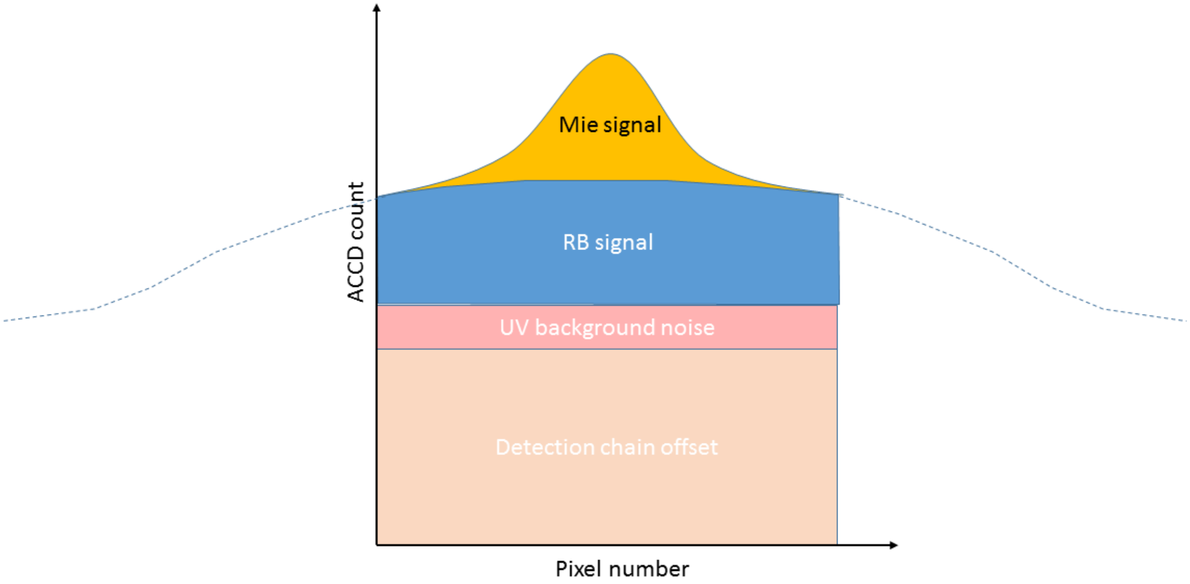


Figure 48. Schematic of the Mie signal.

The RB signal fraction can be estimated by assuming the RB signal is a flat function (i.e. an offset) and the Mie signal is a Lorenztian function on top of this. The refined scattering ratio uses the Mie core algorithm 2 to estimate the offset, whereas the nominal scattering ratio uses the four lowest ACCD counts (scaled).

By comparing the two equations it is possible to calculate the true SR from the *signal_ratio* to as follows:

$$SR = \alpha(signal\_ratio - 1) + 1$$

This agrees with the formula in the L1Bp MAD and DPM documents.

It is apparent that α should be less than 1, because only a fraction of the RB spectrum is sampled by the Mie channel (as indicated in Figure 48 as the dashed line outside the ACCD). It is unclear what α should be theoretically appears, therefore it can be tuned to minimize the bias in L1B SR estimates. An old L1B document [RD16] found that the best value of alpha=0.8. [RD16] also provides an explanation of the saturation of SR estimates for large true SR values. This is because for large SR values the Mie signal accounts for a significant fraction of all pixels, therefore it cannot be assumed that the offset is due to only RB signal. Therefore the RB signal is overestimated, leading to too small SRs. These biases for large SR are not much a concern for the L2B processing however.

7.2 An estimate biases in HLOS wind from MRC errors

The MRC response versus frequency is approximately linear when viewed over the whole USR. Based on the typical deviations of the linear fit parameters from the “perfect” calibration parameters (from the CoP runs of the IRC with various conditions as presented in Section 4.2) we can estimate, without the need to run WVM simulations, the biases that will result in L1B and L2B Mie HLOS wind results. This assumes that the L2B processor uses only the gradient and intercept information of the MRC and does not attempt to use the non-linear deviations around the linear fit.

The Mie channel response as a function of frequency can be written:

$$R = mf + c$$

Where *R*=response (pixel number), *f*=offset frequency, *m*=gradient of line and *c*=intercept of line.

Since we are interested in errors in the resultant frequency estimation and hence HLOS wind estimation, we rearrange for *f*:

$$f = \frac{R - c}{m}$$

The propagation of uncertainty formulation leads to the variance of frequency error formula:

$$\sigma_f^2 = \frac{(c - R)^2}{m^4}\sigma_m^2 + \frac{\sigma_c^2}{m^2}$$

With “perfect” calibration settings the CoP results gave an MRC with linear fit parameters of:

$$m = -10.333\ GHz^{-1}, c = 8.500$$

Inserting these values into the frequency error variance formula we approximately have:

$$\sigma_f^2 \approx \frac{(8.5 - R)^2}{11400}\sigma_m^2 + \frac{\sigma_c^2}{107}$$

In CoP testing of the MRC with noise, realistic clouds and realistic ground returns in Section 4.2 we typically found for the atmospheric calibration:

$$\sigma_m = 0.01\, GHz^{-1}, \sigma_c = 0.002$$

Ignoring the first term of the frequency error variance involving the error in the gradient, we find that the error in HLOS wind comes out as:

$$\sigma_f \approx 0.19\, MHz \ \equiv 0.06\, m/s$$

This would be a constant offset (not varying with HLOS wind value). This is small bias and will be hard to detect given the noise of the Mie HLOS wind observations (standard deviation around 2 m/s).

Ignoring the 2nd term of the frequency error variance formula; clearly the frequency error due to the gradient error is zero at *R*=8.5, but at the frequency extremities of the calibration e.g. R=13, this slope error can lead to values of:

$$\sigma_f \approx 0.4\, MHz \ \equiv 0.13\, m/s$$

This again is a fairly small bias, but will show up as a small slope error (~0.1%). In the worst case that the gradient and offset add, we could get bias of order 0.2 m/s for the largest HLOS winds. Note we have not considered the internal reference systematic errors resulting from noise because these are much smaller and therefore relatively unimportant.

Therefore it appears that Mie HLOS wind systematic errors due to the noise processes simulated in the E2S for the MRC will not be a major concern for Aeolus. However note that there are other sources of systematic error already present in the "perfect" calibration results leading to slope error of ~ %. Also the non-linearity is found in practice (with A2D data) to be much larger than simulated in the E2S. The non-linearity interacting with noise and limited MRC validity (i.e. some frequency steps missing) will pose a greater systematic error risk than the above simple arguments based on E2S simulations.

7.3 An explanation for the Mie slope error in the ECMWF model atmosphere

In Section 4.2.1 a significant dependence of mean HLOS wind error upon the true HLOS wind value for L2B Mie-cloudy results was found, even with "perfect" calibration. Evidence will be presented in this Section that supports the hypothesis that this slope error is related to strong vertical wind shear combined with vertically sharp cloud/aerosol features coinciding with the mid-rangebin height assignment for larger Mie range-bins.

The hypothesis is that:

- Jet streams (e.g. polar jet) have large magnitude HLOS winds and also HLOS wind vertical gradients (shear)
- Mie wind observations with thick range-bins (e.g. 1-2 km) in strong HLOS wind vertical shear may have unrepresentative altitudes if assigned at the middle of the range-bin if the scatterers are distributed in a thin layer giving an effective HLOS wind error, as illustrated in Figure 49.

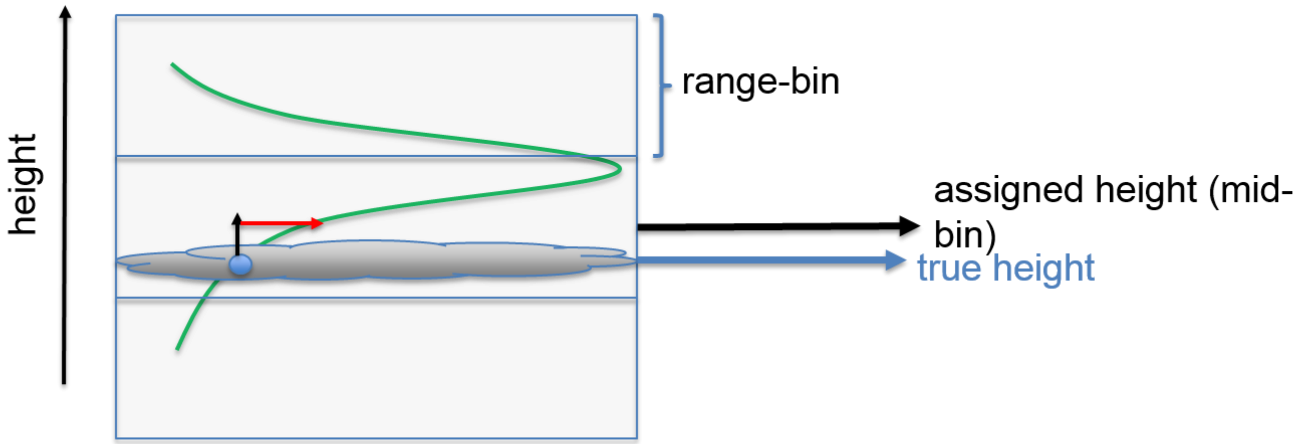


Figure 49. Cartoon illustrating how the middle of range-bin height assignment of Mie winds can lead to wind errors in strong vertical wind shear with thin scattering layer conditions. The wind result would ideally have been assigned the height of the blue dot, not the middle of the range-bin, however the true cloud distribution within the bin is unknown

There is some evidence from the advanced monitoring for this behavior for the ECMWF_T1279 scenario as applied in Section 4.2.1. This is shown in Figure 50 below: there is a small negative correlation between HLOS wind mean error and the HLOS wind vertical shear value in the left plot; with bias up to 2 m/s for the extreme HLOS vertical wind shear of magnitude 15 m/s/km.

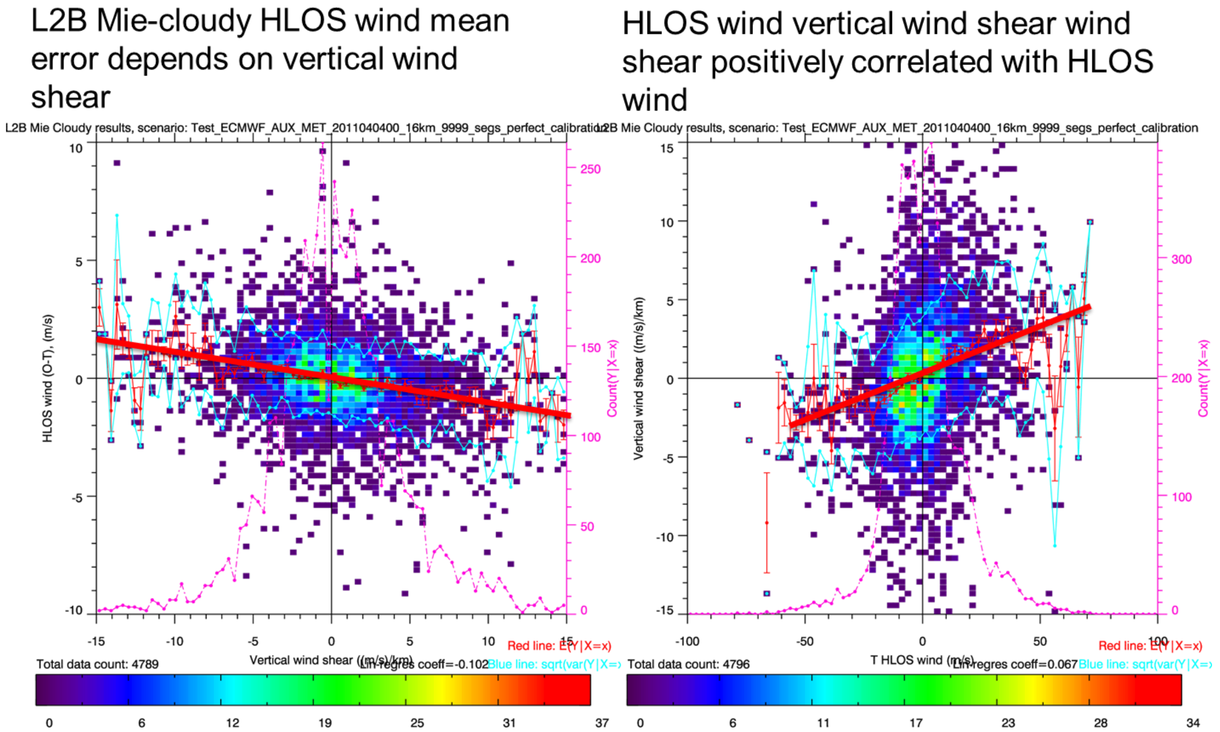
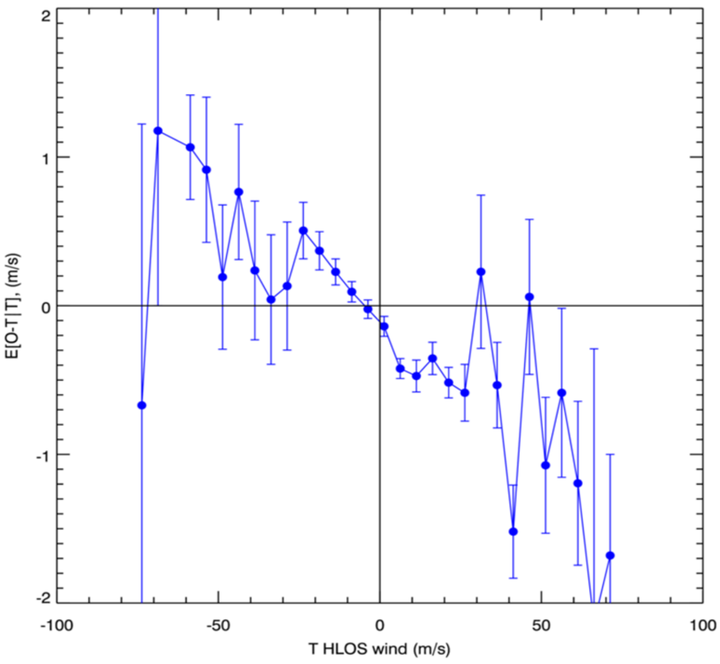


Figure 50. Some evidence in the monitoring for the dependence of mean error upon HLOS wind vertical shear, and the positive correlation of HLOS wind vertical shear with HLOS wind. These are L2B Mie-cloudy HLOS wind results.

In addition the HLOS wind vertical shear is positively correlated with the HLOS wind (right plot), giving an apparent dependence of the vertical shear induced error upon the HLOS wind. The reason for the positive correlation between HLOS vertical wind shear and HLOS wind may be because the satellite orbit samples jet streams (typically westerlies in the extra tropics) as a positive HLOS wind jet with e.g. positive vertical shear on ascending orbits and as a negative HLOS wind jet with negative vertical shear on descending orbits; hence the dependence seen. Also the jet streams will be almost constant in location over the few hours of the scenario, as will be the Mie range-bin definitions, which could account for the systematic nature of the errors. It is yet to be confirmed if clouds are systematically positioned relative to the jet stream in this scenario.

To test the hypothesis the same optical properties (clouds, i.e. giving rise to Mie wind results) from the ECMWF_T1279 scenario are applied but with a simplified wind field that is horizontally constant for periods of the test case and with zero HLOS vertical wind shear. The results comparing the original HLOS wind mean error dependence on HLOS wind (a) to the result with zero vertical wind shear (b) are shown in Figure 51. It can be seen that the slope error is indeed reduced for the zero vertical wind shear case, which supports the above hypothesis. However, there is some residual slope error, suggesting additional causes for the slope error.



a)

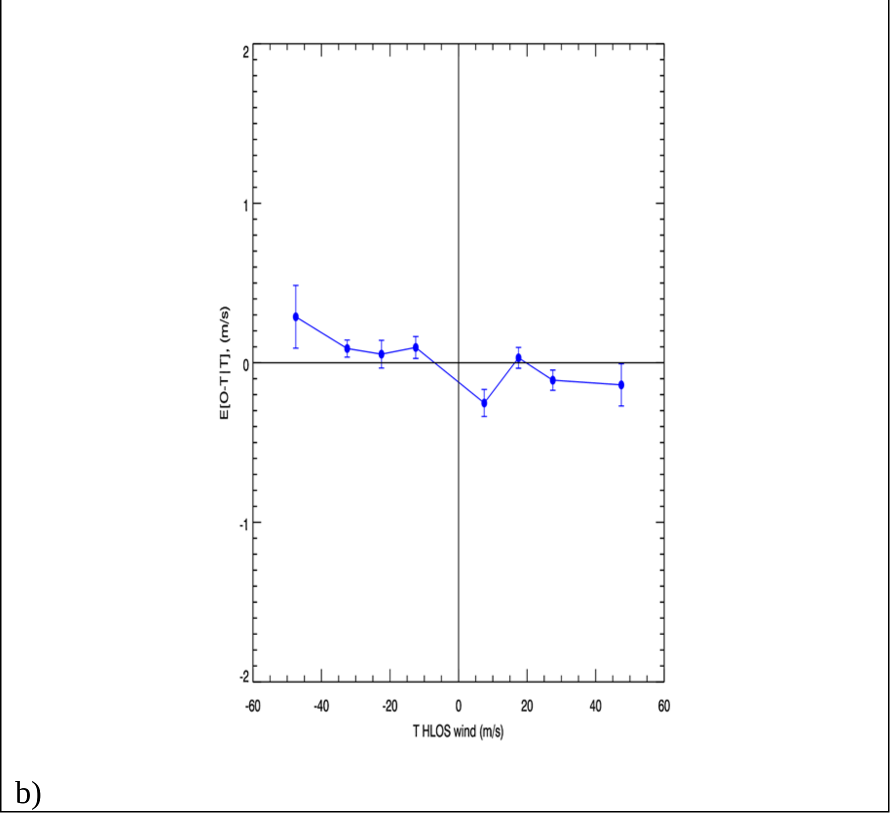


Figure 51. L2B Mie-cloudy HLOS wind mean error versus true HLOS wind for a) ECMWF_T1279 atmosphere b) Same atmosphere as ECMWF_T1279 expect wind field modified to have zero vertical wind shear.

Similar behavior i.e. slope error depending on HLOS wind shear is found to be absent for the Rayleigh winds (not shown here), presumably because the scatterers for Rayleigh (i.e. molecular scattering) given a far more even backscatter profile throughout the vertical extent of the range-bin, therefore it is more of a vertical average wind across the range-bin, meaning near mid range-bin height assignment is usually adequate.

The Mie slope error can be reduced by reducing the vertical range-bin thickness of the upper Mie bins, however this will mean (given the restriction to 24 range-bins) a much lower top altitude for Mie results e.g. if all set to 0.25 km thickness, then maximum altitude would be 6 km, therefore missing out on upper tropospheric winds which can have a large NWP impact. Also, without the upper Mie range-bins the L2Bp would not have the L1Bp scattering ratio estimates needed for classification.

7.4 How to generate realistic ECMWF model E2S scenarios with orography that matches the Aeolus DEM

The method used to generate E2S simulation scenarios with meteorological and orographic conditions that match reality is done with the following steps:

1. Obtain or generate a GRND_TRACK file (an Aeolus predicted orbit ground-track geolocations file for one repeat cycle) with times that match the date of the meteorological conditions that you want

to extract. E.g. may have an example GRND_TRACK file labelled in October 2007, but can modify the date to that of interest.

2. Generate an ECMWF model AUX_MET file using the GRND_TRACK file using the prototype L2/Met PF tool with the appropriate ECMWF model data assimilation cycle date-time to match the modified GRND_TRACK.
3. Convert the AUX_MET EE file to KNMI ASCII using L2Bp tools. Use only the off-nadir AUX_MET profiles only if interested in simulating the WVM or nadir if interested in simulating the IRC.
4. Create a new atmospheric database directory in the CoP packages directories with the ASCII file and give it a sensible name.
5. Modify the ASCII file so that there are an appropriate number of profiles as inputs for the E2S simulation e.g. 9999 (max allowed in CoP at present) and ensure the starting profile and the time stepping is correct in the associated settings file to match the sampling of the AUX_MET file. To select the first profile, inspect the GRND_TRACK file to find the first ANX crossing time and the longitude of the data point. Make sure the first profile in the ASCII is at a time later than this.
6. Set the E2S orbitScenario.xml and terrainmodelLUT.xml to have ANX details that match the above selected ANX crossing (the nadir values). Note that longitude of ANX is defined with 0 to 360 degrees from Greenwich meridian.
7. In the E2S (WVM or IRC) scenario parameters make sure the start time is that of the first profile in the ASCII of the atmospheric database.
8. If when running the E2S scenario there are problems with the CFI software related to the orbit, then try subtracting an integer number of orbit repeat cycles (e.g. 7 days) off the ANX date time; until you find a combination that works.