Aeolus' Response Calibration

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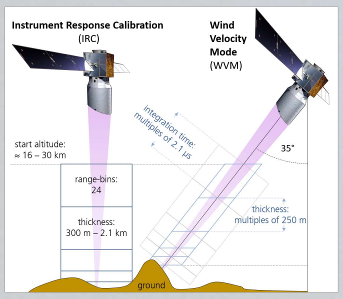
The Aeolus mission

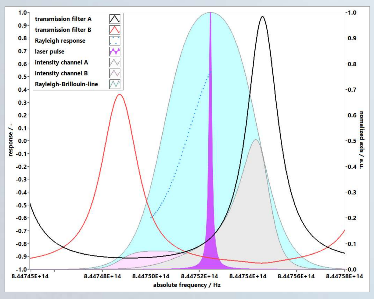
- Launch of the satellite on 22 August 2018 and first-of-its-kind assisted reentry in July 2023
- Orbit: polar, sun-synchronous dusk-dawn, mean altitude of 320 km, 1 week repeat cycle
- 1st European lidar and 1st Doppler Wind Lidar (DWL) in space [1-3]
- Single payload: ALADIN (Atmospheric LAser Doppler INstrument), equipped with two frequency tunable flight model (FM) lasers FM-A and FM-B
- Direct-detection approach utilizing high-resolution interferometry → Allows for the analysis of narrowband Mie (particles) and broadband Rayleigh (molecular) spectra
- Frequency shift can be associated with the position of an intensity maximum on a suitable detector (Mie) and the change in the intensity transmitted through the filters (Rayleigh)
- → Benefit: Large vertical coverage due to reliable backscatter at all altitudes [4]



Figures:

Left: Measurement geometry during Instrument Response Calibration (IRC) and Wind Velocity Mode (WVM).

Right: Principle of the Rayleigh response calibration: By shifting the laser to defined frequencies on both sides of the operating point the effect of wind speed is simulated.



[1] European Space Agency ESA, "ADM-Aeolus Science Report", ESA SP-1311, 121 pp, (2008).

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[3] O. Reitebuch, C. Lemmerz, O. Lux, U. Marksteiner, S. Rahm, F. Weiler, B. Witschas, M. Meringer, K. Schmidt, D. Huber, I. Nikolaus, A. Geiss, M. Vaughan, A. Dabas, T. Flament, H. Stieglitz, L. Isaksen, M. Rennie, J. de Kloe, G.-J. Marseille, A. Stoffelen, D. Wernham, T. Kanitz, A.-G. Straume, T. Fehr, J. von Bismarck, R. Floberghagen, T. Parrinello, „Initial assessment of the performance of the first wind lidar in space on Aeolus", 29th Int. Laser Radar Conference ILRC, June 24-28, 2019 Hefei, China, EPJ Web Conferences 237, 01010 (2020).

[4] M. Rennie, L. Isaksen, F. Weiler, J. de Kloe, T. Kanitz, O. Reitebuch, "The impact of Aeolus wind retrievals on ECMWF global weather forecasts", QJRMS, Volume 147, Issue 740, pp. 3555-3586, (2021).

The ALADIN instrument

- Wind velocity measurements are performed under 35° off-nadir angle along the line-of-sight (LOS) and across-track, obtaining only one component of the wind vector.
- Laser pulses emitted in the ultra-violet (UV) at 354.8 nm (thereby profiting from the λ^{-4} – dependence of the effective scattering cross-section of molecules), with a repetition frequency of 50.5 Hz, a linewidth of ≈50 MHz, a frequency stability of mostly 7 MHz [5] and reported pulse energies of 40 mJ – 101 mJ (nominal mission).
- Interferometers: Fizeau for Mie signal and Double-Fabry-Pérot for Rayleigh signal
- Mie response = Fringe position on Accumulation Charge Coupled Device (ACCD)
- Rayleigh response (R_R) = Contrast ratio of the signal sum of each of the two spots A and B on the ACCD: $R_R(f) = (A(f) - B(f))/(A(f) + B(f))$
- Considerable effort was put into an End-to-End simulator and the ALADIN Airborne Demonstrator with ground-based and airborne campaigns before launch to investigate the overall performance of such a wind lidar system, to validate the measurement principle and to optimize the retrieval algorithms [6,7].

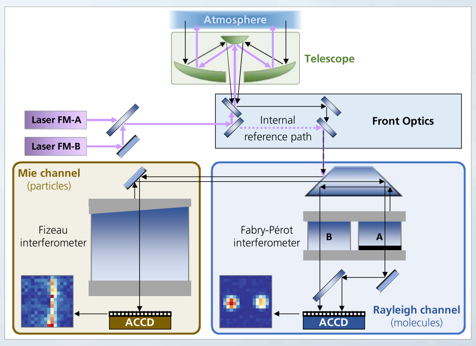

Figure: Schematic of the direct-detection Doppler wind lidar ALADIN on-board Aeolus

[5] O. Lux, D. Wernham, P. Bravetti, P. McGoldrick, O. Lecrenier, W. Riede, A. D'Ottavi, V. De Sanctis, M. Schillinger, J. Lochard, J. Marshall, C. Lemmerz, F. Weiler, L. Mondin, A. Ciapponi, T. Kanitz, A. Elfving, T. Parrinello, and O. Reitebuch, "High-power and frequency-stable ultraviolet laser performance in space for the wind lidar on Aeolus", Optics Letters, Vol. 45, Iss. 6, pp. 1443-1446, (2020).

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The Instrument Response Calibration

A calibration is required to establish a relation between the measured responses and the frequency of the backscattered light. From the beginning the IRC was seen as a crucial contribution to the strategy for the correction of instrumental drifts, e.g. to the spectral characterization of the instrument using internal measurements and to the correction of remaining linear and harmonic biases in the wind speed using ground-return velocities.

- 40 steps of 25 MHz → 1 GHz (± 90 m/s) around laser frequency f_0 used for measuring wind
- Nadir pointing excludes influence of wind speed (vertical component neglected)
- High albedo of ice + snow → high SNR for ground returns → required for atmospheric Mie response curve → important for measuring relative velocity of earth surface (0 m/s expected)

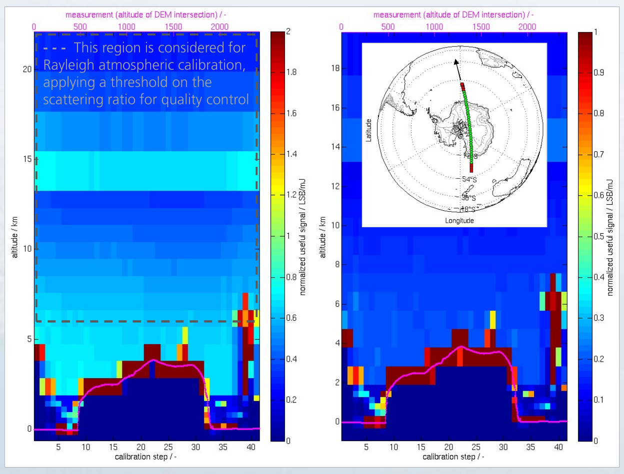


Figure:

Rayleigh (left) and Mie (right) normalized (to emit laser energy) useful signal in units of LSB/mJ (LSB = least significant bit) per frequency step from Aeolus' IRC #016 conducted on 2018-12-17 and reprocessed during the 4th reprocessing campaign in 2024. It provides very good ground visibility and, hence, a high number of valid ground returns along a ground track starting south of New Zealand, crossing Antarctica and ending in the Southern Atlantic. High signals (dark red) that follow the Digital Elevation Model (DEM, pink) are considered as ground returns. Features with enhanced signal deviating from the DEM are considered as clouds or aerosol. The signal jump at 14 km and 15 km in the Mie and Rayleigh channel, respectively, is caused by an increase in the integration time, i.e. the range-gate thickness from 0.95 km to 2.21 km.

Response calibration curves

- Curves for ground and internal reference differ remarkably despite both having a spectrally narrow signal. These differences vary with time → illumination conditions of the interferometers on the two optical paths [8].
- Linear fits provide:
  - slope = sensitivity
  - intercept = intersection point with y-axis
  - offset frequency = intersection point with x-axis
- Slope and intercept values are the only IRC-related L1B information forwarded to the L2B processor, whose wind retrieval is additionally based on a method using another type of internal reference calibration data [9].
- Non-linear dependency between frequency Doppler shift & response → taken into account to reduce the systematic & random error on the wind speeds v_{LOS} in the wind retrieval algorithm:

$$v_{LOS} = \frac{c}{2} \cdot \frac{f_{ATM} - f_{INT}}{f_0}$$

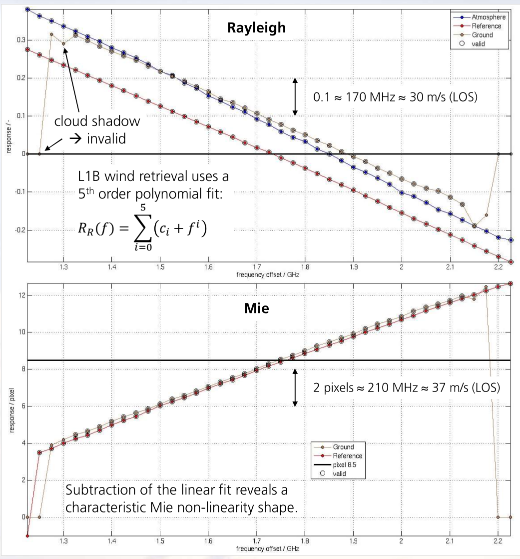


Figure: *Rayleigh (top) and Mie (bottom) response calibration curves for internal reference (red), atmospheric return (blue) and ground return (brown) of IRC #016.*

[8] U. Marksteiner, O. Lux, O. Reitebuch, J. de Kloe, G.-J. Marseille and M. Rennie, "Overview of Instrument Response Calibrations", Aeolus Science Conference, 22-26 May 2023, Rhodes, Greece, (2023).

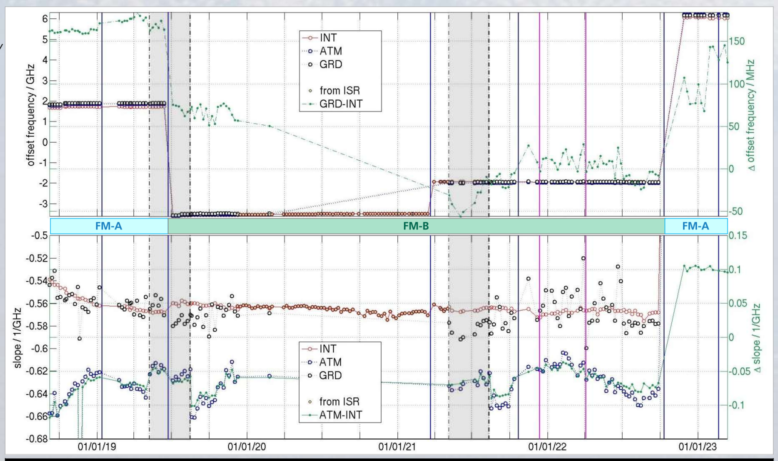
[9] A. Dabas, M. L. Denneulin, P. Flamant, C. Loth, A. Garnier, and A. Dolfi-Bouteyre, "Correcting winds measured with a Rayleigh Doppler lidar from pressure and temperature effects". Tellus A, 60(2):206-215, (2008).

Timelines of response calibration characteristics

As drifts of instrumental characteristics can be induced, for example, by slowly changing angles of the light incident on the spectrometers, IRCs are used not only to calibrate Level-1B winds, but also to monitor the state of the involved parts of the system.

Figure:

Offset frequency (top) and slope (bottom) of the Rayleigh response calibration curves for the reference path (INT), the atmospheric return (ATM) and the ground return (GRD). Performances over the Arctic are marked as grey areas. Vertical lines mark "switch-offs" of Aeolus (blue) and setting changes (pink).



Data set:

Mode	Number	Laser	Baseline	Comment
IRC	001 – 036	FM-A	16	from the 4th reprocessing campaign preparations
IRC	037 – 061	FM-B	11	from the 2nd reprocessing campaign
IRC	062 – 063	FM-B	12	reprocessed manually with L1B v.7.10
IRC	064 – 121	FM-B	12 – 15	near real-time versions
IRC	122 – 133	FM-A	15	reprocessed manually with L1B v.7.13
ISR	2019/12/09 – 2021/05/03	FM-B	11	68 files (**I**nstrument **S**pectral **R**egistration) for reference

Refinement of the calibration approach based on real data

- Following the launch of Aeolus, **unexpected and varying biases** in wind speed were observed. These biases could not be effectively addressed using existing methods such as the IRCs. A new correction method was introduced to the L2B wind processor, taking into account **temperature gradients** across Aeolus' primary telescope mirror [10] .
- Additionally, comparisons of Aeolus winds against winds from the European Centre for Medium-Range Weather Forecasts revealed **systematic errors in the Mie channel winds**, indicating imperfect calibration data [11] .
- Following a temporary suspension of IRCs in February 2020, a new calibration mode was implemented: Instrument Response Off-Nadir Calibration (**IRONIC**). With a similar setup of the actual procedure but performed under the 35° off-nadir pointing, IRONICs were thought to partly take over the role of **IRCs**. However, the characteristics of the response curves of **both modes differ** slightly but systematically. This raises the question whether or not IRCs in the implemented form are actually suitable for deriving wind speed with low systematic error, considering the **mission requirement of a maximum bias of 0.7 m/s on horizontal LOS winds** [12] .
- Consequently, one focus during the preparation of the upcoming **Aeolus-2** mission is on **improving** the thermal stability of the satellite **structure**, the **telescope**, the **lasers** and the **receivers** in combination with a **refined method for the IRC** taking into account the **lessons-learnt from Aeolus**.

Acknowledgements:

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