Overview of Instrument Response Calibrations

U. Marksteiner[1], O. Lux[1], O. Reitebuch[1], J. de Kloe[2], G.-J. Marseille[2], M. Rennie[3]

[1] DLR German Aerospace Center, Institute of Atmospheric Physics, Oberpfaffenhofen, 82234 Weßling, Germany

[2] Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

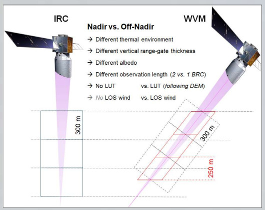
[3] European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK

Motivation

The **Instrument Response Calibration (IRC)** constitutes a fundamental part of the Aeolus processing chain and the basis for accurate and precise wind information provided to the global user community. The IRC is a crucial instrument mode for the wind measurement and has, hence, been extensively investigated with the ALADIN Airborne Demonstrator[(a)] already before launch of the Aeolus satellite.

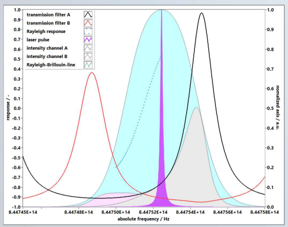
IRCs are used to determine the **relationship between** the Doppler **frequency shift** on the backscattered light, i.e. the wind speed, **and the frequency response** of the **Rayleigh** and **Mie** spectrometers. This is achieved by sampling a frequency range of **1 GHz** in steps of **25 MHz** around the nominal laser frequency for the wind measurement.

Whereas Aeolus wind measurements (WVM) are obtained under an off-nadir viewing angle of 35°, IRCs are performed in viewing nadir mode, thereby trying to avoid the atmospheric horizontal wind component along the line-of-sight as well as the component of the satellite velocity. The special importance of the IRC mode has changed with time caused by the experiences gained after the launch of Aeolus.



Left: Comparison of IRC and 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.

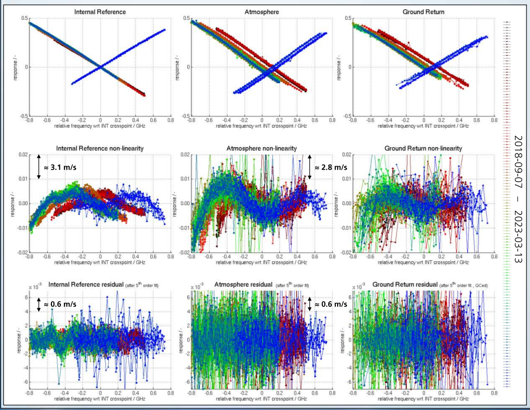


(a) Marksteiner, U., Lemmerz, C., Lux, O., Rahm, S., Schäfler, A., Witschas, B. & Reitebuch, O. (2018) Calibrations and Wind Observations of an Airborne Direct-Detection Wind LiDAR Supporting ESA's Aeolus Mission. *Remote Sensing*, Vol. 10, No. 12. Available from: https://doi.org/10.3390/rs10122056

Rayleigh response calibration curves

The curves are separated into basically four chunks caused by the operation of the laser on four different base frequencies during the mission related to four of the switch-offs of the instrument:

1. on 2019-06-24 for the switch from laser FM-A to FM-B
2. on 2021-03-22 due to a switch to survival mode (*frequency step error*)
3. on 2022-10-11 for the switch back from laser FM-B to FM-A

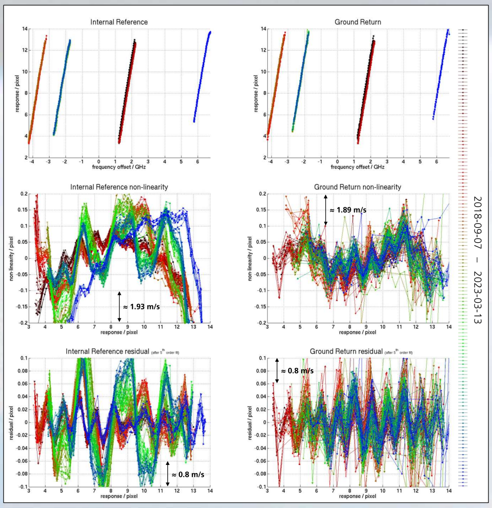


Response curves (top row), non-linearities (middle row) and residuals after subtraction of a 5th order polynomial fit (bottom row) for all 132 Rayleigh response calibration curves from the internal reference path (left column), the atmospheric molecular return (middle column) and the ground return (right column).

For the atmospheric and internal (similar for ground) non-linearities small arrows indicate the relation between response and wind speed.

During the mission the laser was operated at basically four different base frequencies. To have a common reference, all curves are shown with respect their filter crosspoint frequency.

Mie response calibration curves



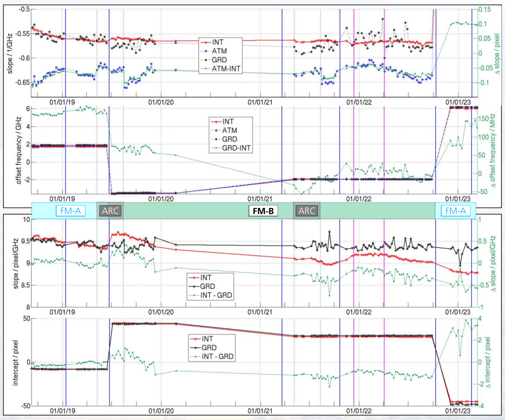
The response curves in the top row are shown with respect to the actual **laser operation frequency** to allow a separate view onto the four different periods divided by the laser switch-offs.

The non-linearities and residuals are given with respect to **pixel position 8.5** to have a common reference.

Response curves (top), non-linearities (middle) and residuals after subtraction of a 5th order polynomial fit (bottom) for all 132 Rayleigh response calibration curves from the internal reference path (left column) and the ground return (right column).

Timelines of Rayleigh and Mie response calibration characteristics

From **linear fits** through the Mie and Rayleigh response curves we derive the **slope**, the **intercept** (y-axis) and the **offset frequency** (intersection with x-axis) to characterize the instrument and to recognize potential drifts (*e.g. in illumination*) that could point to changes in the environment of the satellite or the condition of the spectrometer and laser (*optics*).



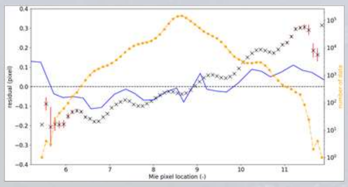
Slope (top) and offset frequency (bottom) of the Rayleigh response calibration curves for the internal reference path (red), the atmospheric return (blue) and the ground return (black). The two periods during which the IRCs were performed over the Arctic (ARC) instead of over Antarctica are marked as grey areas. The slopes for the 2nd FM-A period are positive (and flatter) due to operation at the opposite filter crosspoint.

Slope (top) and intercept (bottom) of the Mie response calibration curves for the internal reference path (INT, red) and the ground return (GRD, black) via the so-called atmospheric path of the instrument. The differences are indicated as green lines. The two phases during which the FM-A laser was operated are marked as light blue areas. Vertical blue and pink lines indicate "switch-offs" of Aeolus and a change in P/N settings, respectively.

Alternative Correction Methods

After the launch of Aeolus, unexpected and **varying wind speed biases** were observed that could **neither** be addressed by a readily developed **Harmonic Bias Estimator nor** by **IRCs**. Instead, it required the introduction of a **new correction method** which considers the temperature gradients across Aeolus' primary telescope mirror [(b)]. This method **implicitly** also performed a part of the **bias correction** for which the IRC mode was initially implemented for. The impossibility to disentangle the effects of an IRC and the alternative bias correction renders an analysis about the detailed impact of IRCs onto the wind speed errors along the mission very challenging and could only be answered by reprocessing activities.

Furthermore, the monitoring of Aeolus winds against winds from the European Centre for Medium-Range Weather Forecasts (ECMWF) revealed **systematic errors in the Mie channel** winds pointing to imperfections in the calibration data that is used as input to the wind retrieval. It was found that, by making use of **winds from the numerical weather prediction model**, these systematic errors could be **reduced** as part of the Level 2B wind processing since July 2021 [(c)].



The blue line denotes the Mie non-linearity as a function of Mie centroid location derived directly from the measured IRC #48 from 2019-09-16.

The black crosses denote the Mie non-linearity obtained from a NWP calibration procedure [(c)] and was derived on the basis of one month (December 2019) of Aeolus L2B wind data.

Orange dots indicate the number of L2B wind data points available within the 0.1 pixel sized bins.

The red error bars shall reflect the standard deviation of the mean value (std. dev. of values within these bins divided by sqrt of number of data). The size of the error bar is negligible for most pixel bins.

(b) Weiler, F., Rennie, M., Kanitz, T., Isaksen, L., Checa, E., de Kloe, J., Okunde, N. & Reitebuch, O. (2021) Correction of wind bias for the lidar on-board Aeolus using telescope temperatures. *Atmospheric Measurement Techniques*, 14, 7167–7185, Available from: https://doi.org/10.5194/amt-14-7167-2021

(c) Marseille, G.-J., de Kloe, J., Marksteiner, U., Reitebuch, O., Rennie, M. & de Haan, S. (2022) NWP calibration applied to Aeolus Mie channel winds. *Quarterly Journal of the Royal Meteorological Society*, 1–15. Available from: https:// doi.org/10.1002/qj.4244

Summary and Conclusions

- During the Aeolus mission a total of **133 IRCs** were performed, from which **5 have been used in Near-Real-Time processing** to adapt to the different laser conditions.
- **Dataset**:
  1. IRCs #001 - #036 are taken from the 3rd reprocessing campaign (FM-A-1)
  2. IRCs #037 - #061 are taken from the 2nd reprocessing campaign (FM-B)
  3. IRCs #062 - #063 have been reprocessed separately (FM-B)
  4. IRCs #064 - #121 are take as NRT version with 1B11 – 1B15 (FM-B)
  5. IRCs #122 - #133 have been reprocessed separately (FM-A-2)
- The **monitoring of IRC related parameters** supported the continuous general assessment of the stability and performance of the Aeolus instrument.
- The **influence of different instrument parameters** (laser frequency stability, alignment) on the IRC results was studied.
- Not shown here: The IRC related parameters slope, intercept and offset have been compared to those of **IRONICs** (**I**nstrument **R**esponse **O**ff**N**ad**I**r **C**alibration). After the suspension of IRCs in Feb. 2020 this newly implemented mode was deemed to be a way to partly take over the role of the IRCs. Clear difference in the characteristics of the response curves of both modes were found which are most probably related to different temperature environments of the satellite in nadir and off-nadir mode.
- No obvious influence of the change in P/N settings was found.
- With the IRCs it was not possible to correct for the unexpectedly observed wind speed **biases that varied on timescales shorter than anticipated**. Instead, a so called "**M1 bias correction method**" was developed using temperature information about the primary mirror and wind speeds from the numerical weather prediction.
- The **experience gained** from the application of Aeolus' IRC mode is of significant relevance **for** the preparation of the **Aeolus-2** mission.