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DLR

Verification of different peak centroid analysis algorithms based on airborne wind lidar data in support of ESA's Aeolus mission

B. Witschas[1], J. M. Vaughan[2], O. Lux[1], C. Lemmerz[1], I. Nikolaus[3] and O. Reitebuch[1]

[1] German Aerospace Center (DLR), Institute of Atmospheric Physics, Oberpfaffenhofen 82234, Germany
[2] Optical & Lidar Associates (OLA), Buckinghamshire, HP14 3PF, United Kingdom
[3] University of Applied Sciences Munich, Germany

Introduction

Measurement principle for "Mie winds" – The fringe imaging technique

The measurement of Aeolus **Mie cloudy winds** is based on the **fringe-imaging** technique. It relies on determining **the spatial location of** a linear **interference pattern (fringe)** due to multiple interference in a Fizeau spectrometer. This fringe is vertically imaged onto the Mie-channel detector. The accuracy of Mie cloudy winds thus depends on several pre- and post-detection factors.

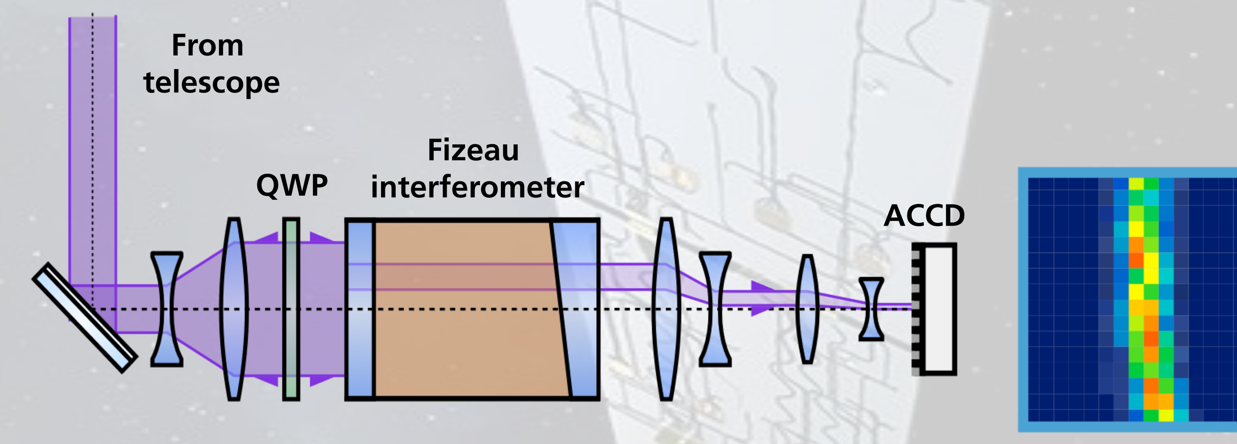

Fig. 1: Simplified sketch of the A2D Mie channel setup. QWP: quarter wave plate, ACCD: accumulation charge-coupled device.

Peak centroid algorithms for Aeolus "Mie wind" retrieval

In the Aeolus Level 1 B (L1B) processor, the centroid location, and the width of the Fizeau fringes are usually analyzed by the **Mie core 2 algorithm**, which applies a downhill simplex fit routine of a Lorentzian peak function $\mathcal{L}(x)$ to the measurement data.

$$\mathcal{L}(x) = I_{\mathcal{L}} \cdot \frac{(\Gamma_{\mathcal{L}})^2}{4(x-x_0)^2 + (\Gamma_{\mathcal{L}})^2}$$

where $I_{\mathcal{L}}$ is the peak height, $\Gamma_{\mathcal{L}}$ is the FWHM of the peak profile, and x_0 is the center position.

Based on **atmospheric ground return and internal reference signals** it was demonstrated that the Mie fringe profile is better described by a **pseudo-Voigt function** $\mathcal{V}(x)$ → A Voigt fit was implemented in the L1B processor in 2022 as the **Mie core 3 algorithm** for an improved retrieval of the **scattering ratio** and is currently implemented **for the Mie wind retrieval.**
In addition, **a novel, non-fit-based algorithm** was developed and reduces computation time significantly (by a factor of 700).

$$\mathcal{V}(x) = I_{\mathcal{V}} \cdot (\eta \mathcal{G}^*(x) + (1-\eta)\mathcal{L}^*(x)) + \mathcal{O}$$

$$\mathcal{L}^*(x) = \frac{2}{\pi} \frac{\Gamma_{\mathcal{V}}}{4(x-x_0)^2 + (\Gamma_{\mathcal{V}})^2}$$

$$\mathcal{G}^*(x) = \frac{\sqrt{4\ln 2}}{\sqrt{\pi}\Gamma_{\mathcal{V}}} \exp\left(-\frac{4\ln 2}{(\Gamma_{\mathcal{V}})^2}\left((x-x_0)^2\right)\right)$$

$\mathcal{V}(x)$ is a linear combination of $\mathcal{L}^*(x)$ and $\mathcal{G}^*(x)$, normalized to unit area. $I_{\mathcal{V}}$ is the area below the peak, η is varying from 0 to 1 and $\mathcal{O}$ is an offset.

Goal of this study

The goal of this study was to **investigate the performance of different existing Mie core algorithms** (Lorentzian and pseudo-Voigt) as well as to **develop a new, non-fit-based, and very fast algorithm** for the Fizeau fringe analysis.

An peak centroid algorithm for Fizeau-fringe analysis algorithm – The 4-channel ratio R_4

Simulated Fizeau fringe profiles

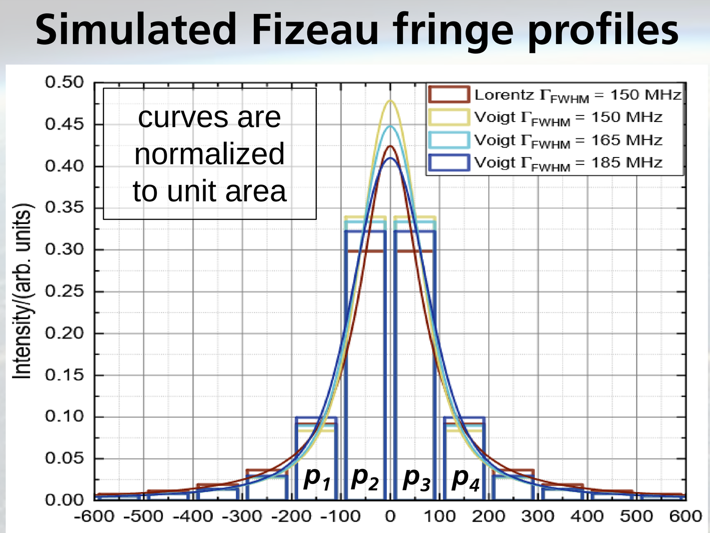

Fig. 2: Fizeau fringe profiles simulated by different model functions (Lorentzian and pseudo-Voigt) and different widths (see label) for a spectral pixel width of 100 MHz (bars).

- About **85%** of the useful signal is **contained in the inner 4 pixels**
- The **outer 12 pixels mainly contain noise**
- The **imaged fringe** shape significantly **depends on the applied spectral corrections**

→ **A ratio of the intensities contained in the inner 4 pixels of the Mie fringe – R_4 – is defined and used to determine the fringe position:**

$$R_4 = \frac{(Ip_1 + Ip_2) - (Ip_3 + Ip_4)}{(Ip_2 + Ip_3) - (Ip_1 + Ip_4)}$$

R_4 response along one pixel

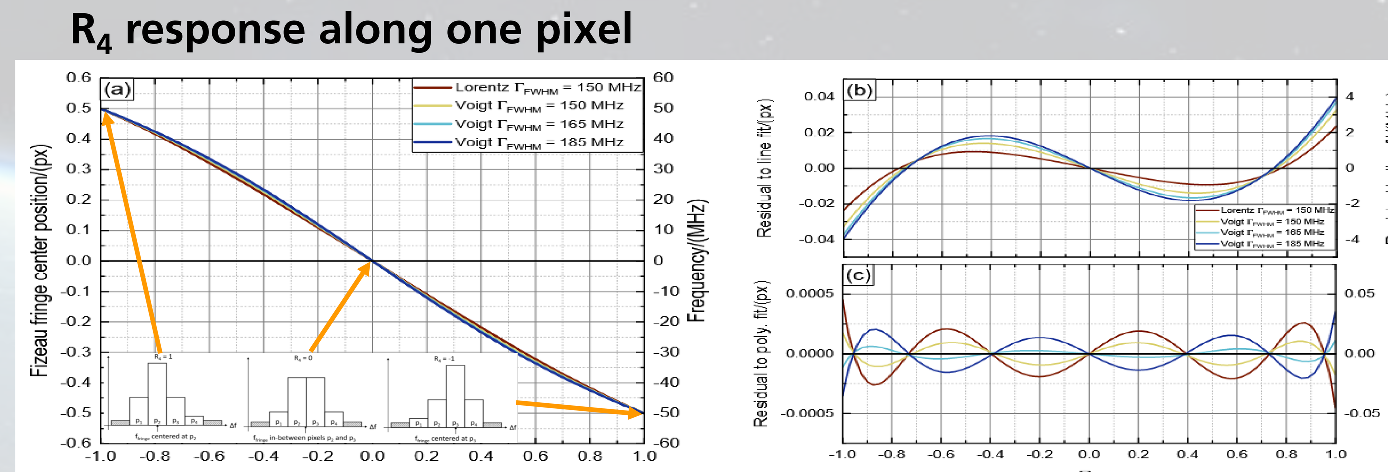

Fig. 3: R_4 values depending on the fringe position for different Fizeau fringe profiles along 1 pixel (px) (left) and the residuals to line fits (right, top) and 5th order polynomial fits (right, bottom).

- Rather **uniform change of R_4** within on pixel (left); "non-linearity" **< ±4 MHz** (right)
- The residual to a 5th-order polynomial fit is **< ±0.03 MHz** (independent of the profile)
- R_4 is **not affected by uniform background** (e.g. Rayleigh or solar background)

Performance analysis of different peak centroid algorithms for Aeolus Mie-wind retrieval – A2D data

A2D Mie response calibration performed on 18 Sept 2019 (AVATAR-I)

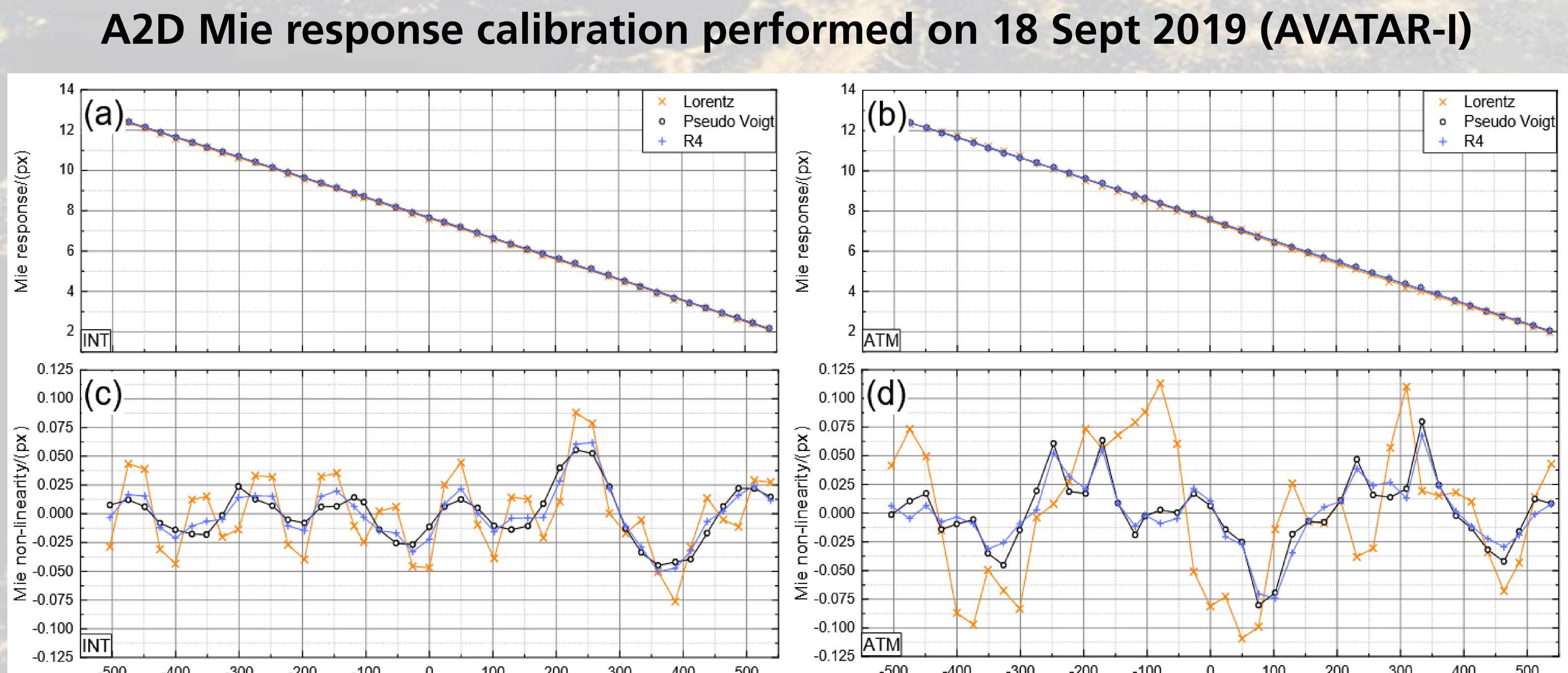

Fig. 4: Mie response of the internal reference signal (a) and ground return signal (b) retrieved by the Lorentzian fit (orange), the pseudo-Voigt fit (black), and the R_4 algorithm (blue), from data acquired with the A2D on 18 September 2019 (AVATAR-I). The residual to a third-order polynomial fit is shown below in panels (c) and (d).

- For the internal reference signal (left), the **Lorentzian-based algorithm (orange) shows the largest deviations** caused by the so-called pixelation effect. This effect is **less pronounced for the pseudo-Voigt and the R_4 analysis.**
- For **atmospheric ground returns (right), the residuals are generally larger** compared to the internal reference signal, and also **worse for the Lorentzian-based algorithm**.

Mie cloudy winds derived for the entire AVATAR-I campaign period

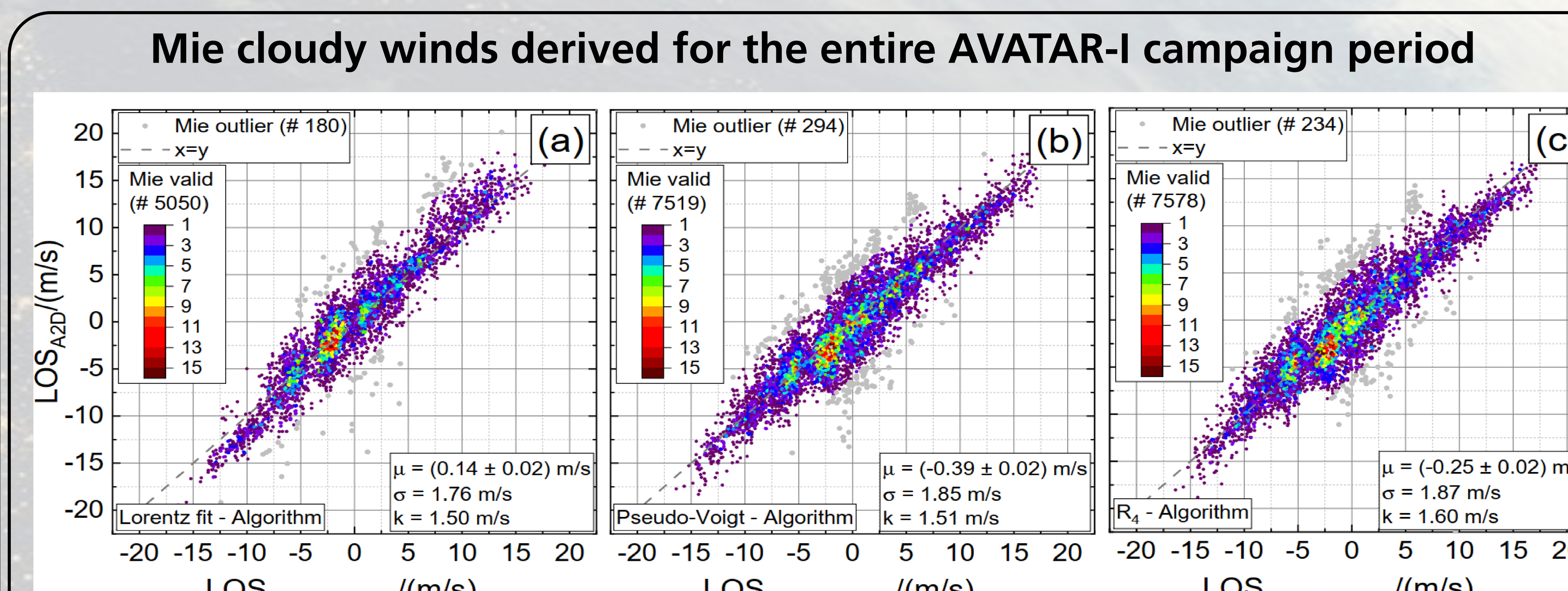

Fig. 5: A2D Mie cloudy LOS winds plotted against the 2-μm DWL wind speed projected onto the A2D LOS direction for all 10 research flights performed during AVATAR-I, analyzed with the Lorentzian fit algorithm (a), the pseudo-Voigt fit algorithm (b) and the R_4 algorithm (c). The color of the points indicates the number of data counts at certain wind speeds. Outliers that exceeded a modified Z-score threshold of 3.5 are indicated in gray.

Algorithm	Valid data points	Outliers[a]	Random error[b]/(m/s)
Lorentz	5050	180 (3.6%)	1.50
Pseudo Voigt	7518 (49% more)	294 (3.9%)	1.51
R_4	6072 (20% more)	144 (2.4%)	1.56

- The **pseudo-Voigt-based algorithm shows very good performance.** Almost **50% more valid Mie winds** compared to the Mie core 2 (Lorentzian) analysis, but a similar random error.
- The **R_4 algorithm represents a good alternative,** being **~700 times faster** than the fit-based algorithms, and yielding ~20% more valid Mie winds compared to the Mie core 2 analysis.

Summary

Based on airborne A2D (AVATAR-I campaign, Iceland, 2019), it is demonstrated that the pseudo-Voigt-based fit algorithm (Mie core 3) performs appreciably better than the Lorentzian-based fit algorithm (Mie core 2). Nearly **50% more valid Mie winds** could be retrieved with similar quality. **The novel R_4 algorithm shows a similar performance as the Mie core 3, but with a factor 700 faster computation time** → The R_4 algorithm can be regarded as a suitable alternative for applications where a fast computation time is needed.

The R_4 algorithm might also be useful for the fast and accurate analysis of spectrograms from heterodyne-detection wind lidars.