Validation of the Aeolus L2B wind product: A new, very fast algorithm for the Fizeau fringe analysis based on pixel intensity ratios

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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.

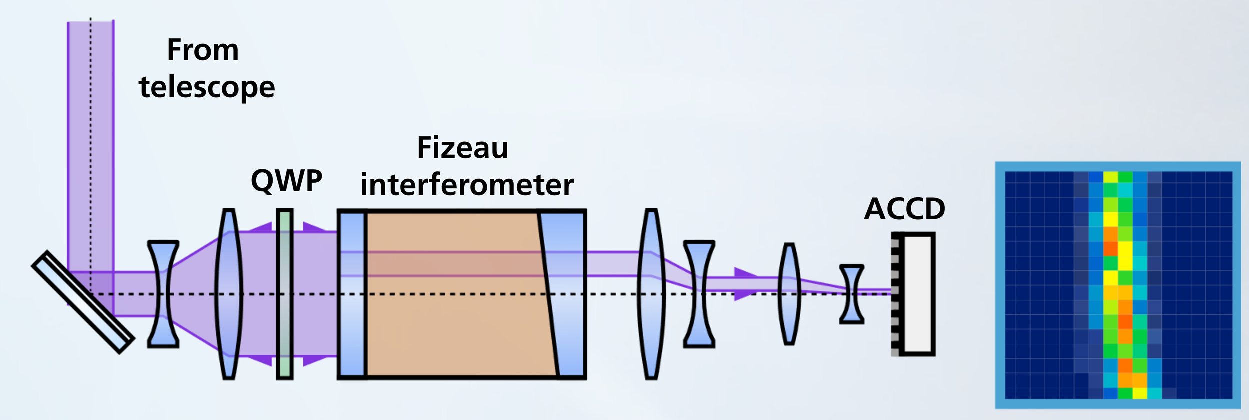

Fig. 1: Simplified sketch of the A2D Mie channel setup. QWP: quarter wave plate, ACCD: accumulation charge-coupled device.

"Mie wind" retrieval algorithms used for Aeolus

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.

Recent investigations based on **atmospheric ground return signals and laser pulse internal reference signals** demonstrated that the Mie fringe profile is better described by a **pseudo-Voigt function** $\mathcal{V}(x)$ which improves the accuracy of the retrieved scattering ratio, and thus, is supposed to also improve the accuracy of the fringe position determination. The Voigt fit was implemented in the L1B processor in 2022 as the **Mie core 3 algorithm** for an improved retrieval of the **scattering ratio.**

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

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

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

$\mathcal{V}(x)$ 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 alternative Fizeau-fringe analysis algorithm – The 4-channel ratio R_4

Simulated Fizeau fringe profiles

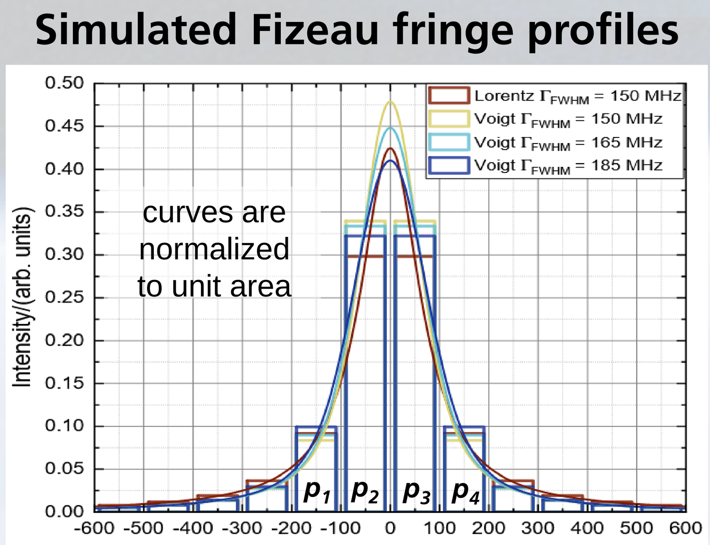

Fig. 2: Fizeau fringe profiles simulated by different model functions (Lorentzian and pseudo-Voigt) and different widths (see label) for a spectral pixel width of 100 MHz (bars).

- 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:

$$R_4 = \frac{(p_1+p_2)-(p_3+p_4)}{(p_2+p_3)-(p_1+p_4)}$$

R_4 response along one pixel

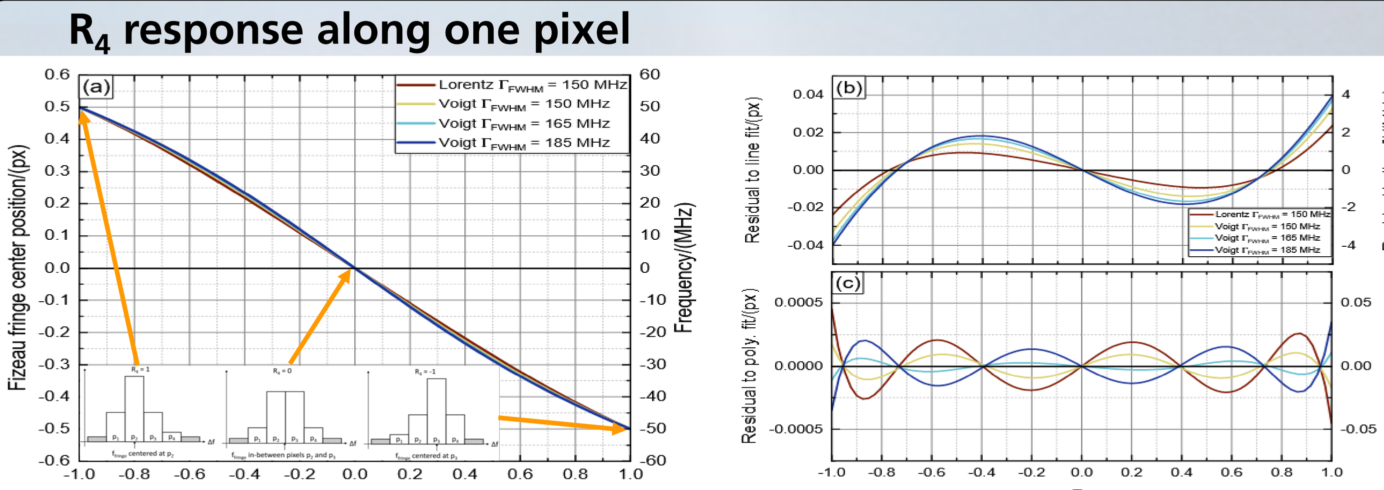

Fig. 3: R_4 values depending on the fringe position for different Fizeau fringe profiles along 1 pixel (px) (left) and the residuals to line fits (right, top) and 5th order polynomial fits (right, bottom).

- 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 Fizeau-fringe analysis algorithms – MRC and wind retrieval using A2D data

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

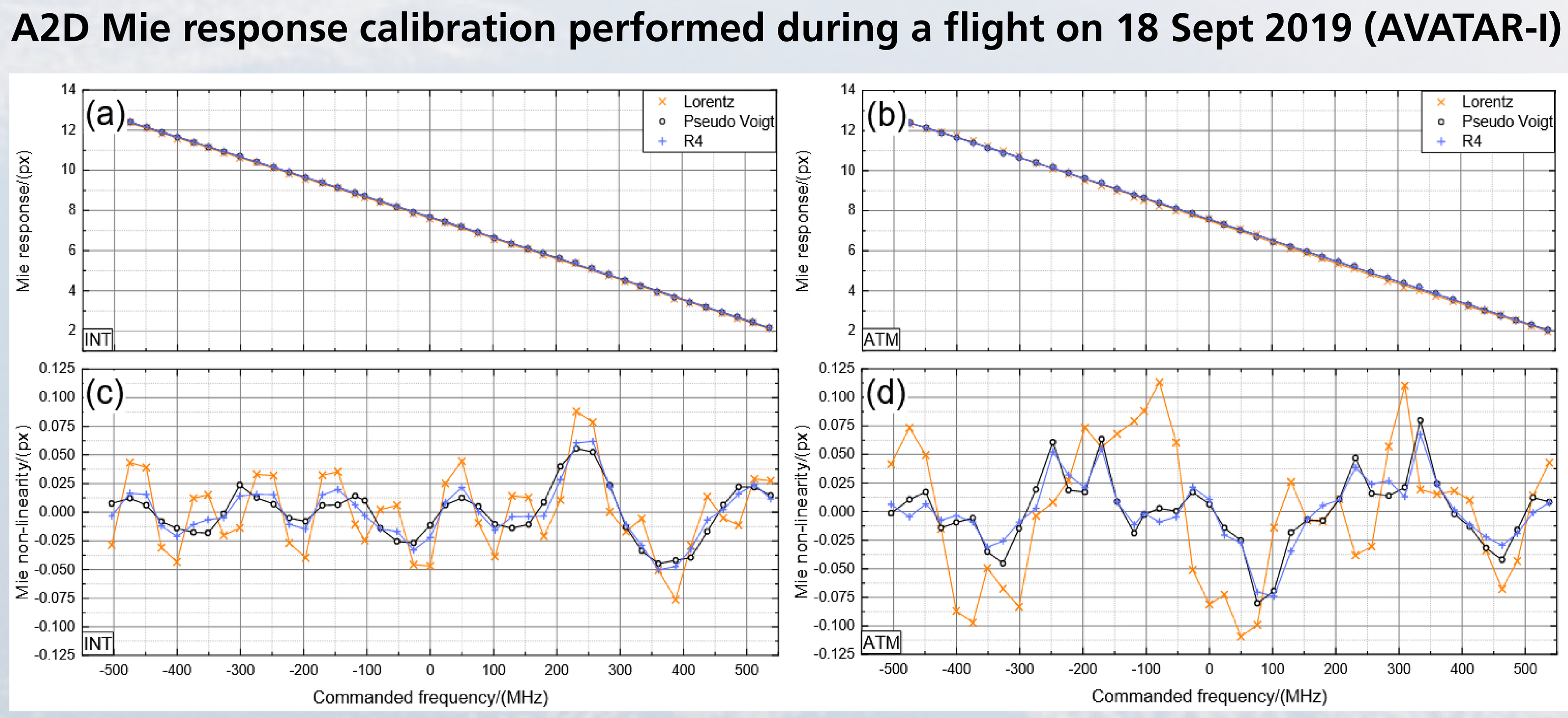

Fig. 4: Mie response of the internal reference signal (a) and ground return signal (b) retrieved by the Lorentzian fit (orange), the pseudo-Voigt fit (black), and the R_4 algorithm (blue), from data acquired with the A2D on 18 September 2019 (AVATAR-I). The residual to a third-order polynomial fit is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

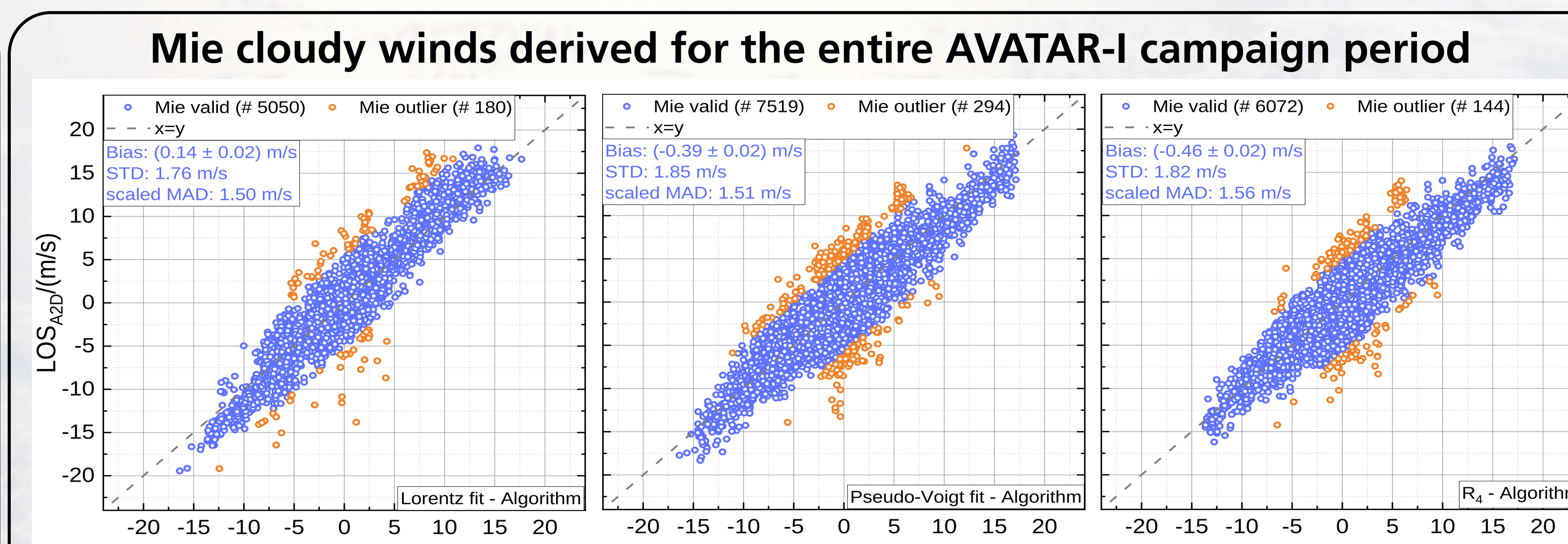

Fig. 5: A2D Mie cloudy LOS winds plotted against the 2-μm DWL wind speed projected onto the A2D LOS direction for the 10 research flights performed during AVATAR-I, analyzed with the Lorentzian fit algorithm (left), the pseudo-Voigt fit algorithm (middle) and the R_4 algorithm (right). Valid wind measurements are indicated in blue, and outliers that exceeded a modified Z-score threshold of 3.5 are indicated in orange, respectively.

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 ~100 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 data acquired during the 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. Furthermore, **an alternative Fizeau fringe analysis algorithm** based on an intensity ratio approach **was developed**. This algorithm is about **100 computationally times faster** than the fit-based ones, and also shows a better performance than the Lorentzian-based algorithm. **20% more valid Mie winds** with similar accuracy and precision are retrieved.

In the near future, the **Mie core 3 algorithm is foreseen to be implemented in the operational Aeolus processor** to verify if similar improvements can be obtained. Furthermore, **for large datasets,** (e.g., single pulse analysis over the entire mission time frame of 4.5 years) **the much faster R_4 algorithm can be used**.