

Comparative assessment of LIF and Mie scattering for mixing measurements in turbulent jets

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ABSTRACT

Laser-Induced Fluorescence (LIF) and Mie scattering are widely used optical techniques for concentration field measurements in turbulent flows, yet systematic quantitative comparisons between the two methods across a range of flow regimes remain limited in the literature. In this work, simultaneous LIF and Mie scattering measurements are performed in a turbulent round air jet seeded with anisole vapor and DEHS oil droplets over a range of Reynolds numbers spanning the transitional to fully turbulent regime ($Re = 2500, 6000, 10000, 15000$). A statistical analysis quantitatively compares the two methods based on the mean intensity, standard deviation, and coefficient of variation of the signal intensity.

The standard deviation reveals a fundamental structural difference between the two methods: the LIF images exhibit elevated fluctuations in the jet shear layers, while Mie scattering shows an inverted pattern with highest values in the jet core. This inversion is attributed to the inability of inertial particles to follow diffusive scalar transport, which is an effect also visible in the instantaneous images, where vortex cores at $Re = 2500$ show diffusively homogenized LIF intensity but granular Mie scattering signal.

The coefficient of variation (CV), defined as the ratio of standard deviation to mean intensity, substantially improves the spatial agreement between the two methods by normalizing out absolute signal level differences. The global spatial correlation coefficient between the CV fields shows a non-monotonic dependence on Reynolds number, rising from $R = -0.12$ in the transitional regime to a maximum of $R = 0.94$ at $Re = 6000$, before decreasing gradually to $R = 0.69$ at $Re = 15000$. This behavior is interpreted as reflecting the competing influences of molecular diffusion at low Reynolds numbers — where Mie scattering fails to capture diffusive mixing — and preferential particle concentration at high Reynolds numbers, where inertial effects cause the particle field to deviate from the scalar field.

These results demonstrate that Mie scattering provides a reliable proxy for scalar concentration fluctuations in the fully turbulent regime at intermediate Reynolds numbers but should be interpreted with caution at very high Reynolds numbers.

1. Introduction

Optical measurement techniques play a central role in the experimental characterization of turbulent mass transfer and gas-phase scalar mixing fields in jet flows. Laser-Induced Fluorescence (LIF) and Mie scattering are two widely used approaches, each with distinct physical principles and inherent limitations. LIF provides a continuous, molecularly resolved concentration field through the fluorescence emission of a gas-phase tracer and it has been extensively applied in turbulent jet flows (Dimotakis, 1983; Dahm et al., 1996, 1998). Mie scattering, by contrast, relies on the detection of discrete tracer particles (Long et al., 1979; Clemens & Mungal, 1991). While Mie scattering is most widely used for velocity measurements in particle image velocimetry (PIV), its application as a measurement technique for mixing requires careful consideration of the particle-scalar relationship, which is the focus of the present study. The signal is inherently discrete and near-binary at the pixel level, with its statistical properties governed by the local particle number density. The particle number density must furthermore be kept sufficiently low to avoid multiple scattering effects, which introduce systematic errors in the intensity-concentration relationship (Mishchenko et al., 2006). Finally, due to their high Schmidt number, the tracers do not follow molecular diffusion and their mass transport may deviate from the gas phase transport at sufficiently small scales or under conditions where diffusion plays a significant role (Hanson, 1986).

While both techniques have been extensively applied individually, systematic quantitative comparisons across a range of flow regimes remain limited in the literature. In particular, the behavior of Mie scattering in transitional and low-Reynolds-number flows, where molecular diffusion dominates over turbulent dispersion has received little attention. Furthermore, the role of particle inertia and the high Schmidt number of aerosol tracers in limiting the fidelity of Mie scattering as a proxy for scalar mixing remains an open question, particularly in the context of particle clustering at high Reynolds numbers.

In this work, simultaneous Anisole LIF (Faust et al., 2014; Voivenel et al., 2017) and DEHS oil droplet Mie scattering measurements are performed in a turbulent jet over a range of Reynolds numbers spanning the transitional to fully turbulent regime. In statistical analysis, the two methods are quantitatively compared. While LIF provides a signal directly proportional to the local tracer concentration, the Mie scattering signal is inherently discrete at the single-shot level, representing the presence or absence of individual particles at a given pixel location. Nevertheless, qualitative concentration differences are discernible in instantaneous images through the local spatial density of detected particles, which contains information on mixing states when the particle

number density is sufficiently high and the structures of interest are large compared to the inter-particle spacing. Quantitatively, the time-averaged Mie scattering field is interpreted as a local particle detection probability — the fraction of frames in which a particle is detected at a given location.

The standard deviation of the signal intensity field is used as a measure of absolute flow fluctuations, providing a physically direct but method-dependent quantity that reflects turbulent mixing. To enable robust comparison across different Reynolds numbers and between the two methods, whose absolute signal levels differ due to the distinct physical origins of fluorescence and scattering, the coefficient of variation is additionally computed as a normalized measure of relative fluctuation intensity. The results reveal systematic discrepancies between the two methods that are dependent on Reynolds number, providing quantitative evidence for the limitations of Mie scattering in diffusion-dominated and low-particle-density regimes.

2. Methods

The jet is generated by a simple tube with a contracting nozzle that reduces the diameter by a factor of ten, resulting in a nozzle exit diameter of 12 mm. The flow velocity and thus Reynolds number are determined from the pressure difference between the atmosphere and a manometer located beneath the nozzle, using Bernoulli's equation. The jet is fed by two separate supply lines: one carrying Di-Ethyl-Hexyl-Sebacate (DEHS) oil droplets in air for Mie scattering, and one carrying anisole vapor in air for LIF. Oil droplets are generated using a LaVision aerosol generator,

producing sub-micron DEHS droplets. The anisole tracer is introduced using a simple bubbler through which pressurized air is passed.

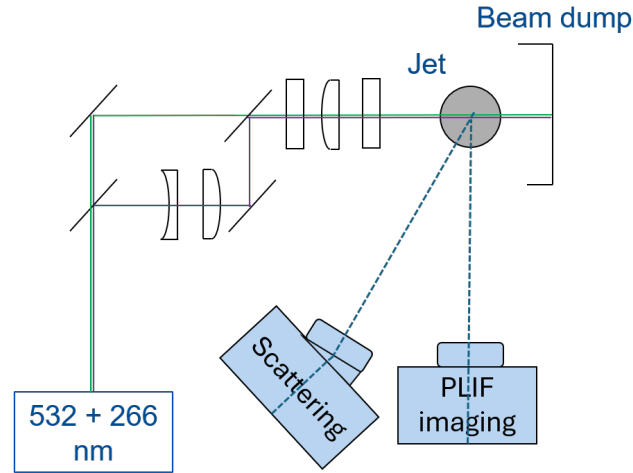


Figure 1: Schematic of optical Setup

Figure 1 shows a schematic of the optical setup. Illumination is provided by a Brilliant B Twin Nd:YAG laser with a 4 ω unit, operated with a single cavity. The crystal is detuned to achieve simultaneous dual-wavelength emission at 266 nm and 532 nm with an output power of 0.9 W. The two beams are independently conditioned to achieve spatial overlap of their focal points and to compensate for their lateral offset at the laser exit. The resulting light sheet is 40 mm tall and 750 μm thick.

Mie scattering from oil droplets is imaged using a LaVision sCMOS camera equipped with a tilt-and-shift Scheimpflug adapter and a Nikon 105 mm lens at $f/2.8$. LIF is detected using an EHD CMOS UV camera with a Cerco 100 mm UV transparent lens at $f/2.8$.

Prior to statistical analysis, images are corrected for background illumination by subtracting a time-averaged background image acquired under identical laser conditions but without flow. For LIF, an additional flat-field correction is applied to account for spatial non-uniformities in the laser sheet and camera response. A detection threshold is determined for each dataset from a quiescent region of the flow field which is physically never traversed by the jet, as the mean intensity plus three standard deviations of the background, providing a physically motivated criterion for separating jet fluid from ambient. Pixels below this threshold are excluded from all subsequent analysis.

The spatial resolution of the measurements is determined by the projected pixel size of 15 μm and the applied 2 $\times$ 2 pixel binning, resulting in an effective resolution of 30 μm per pixel. To assess whether this resolution is sufficient to capture the relevant scalar structures, a comparison with

the Kolmogorov length scale η , the smallest scale at which turbulent kinetic energy is dissipated, is desirable. However, an accurate estimate in the near field of the jet is non-trivial, as self-similar scaling relations for the dissipation rate are not yet established at the downstream distances considered here. The effective spatial resolution of 30 μm after 2×2 pixel binning is expected to resolve the dominant turbulent structures, while the finest scalar scales may not be fully captured. This limitation is inherent to the present experimental configuration, is common to both measurement techniques, and does not affect the statistical quantities reported here, which are primarily determined by the large-scale concentration field.

For each pixel location (x,y) , the time-averaged mean intensity μ and standard deviation σ are computed from $N = 500$ image frames. The standard deviation σ reflects the combined effect of turbulent concentration fluctuations and measurement uncertainties, including photon shot noise and camera read noise common to both methods.

To enable robust comparison between the two methods and across Reynolds numbers, the coefficient of variation

$$CV = \frac{\sigma(x,y)}{\mu(x,y)}$$

is computed as a normalized measure of relative fluctuation intensity. This normalization reduces the sensitivity to absolute signal level differences and provides a quantity that is directly comparable between LIF and Mie scattering.

3. Results

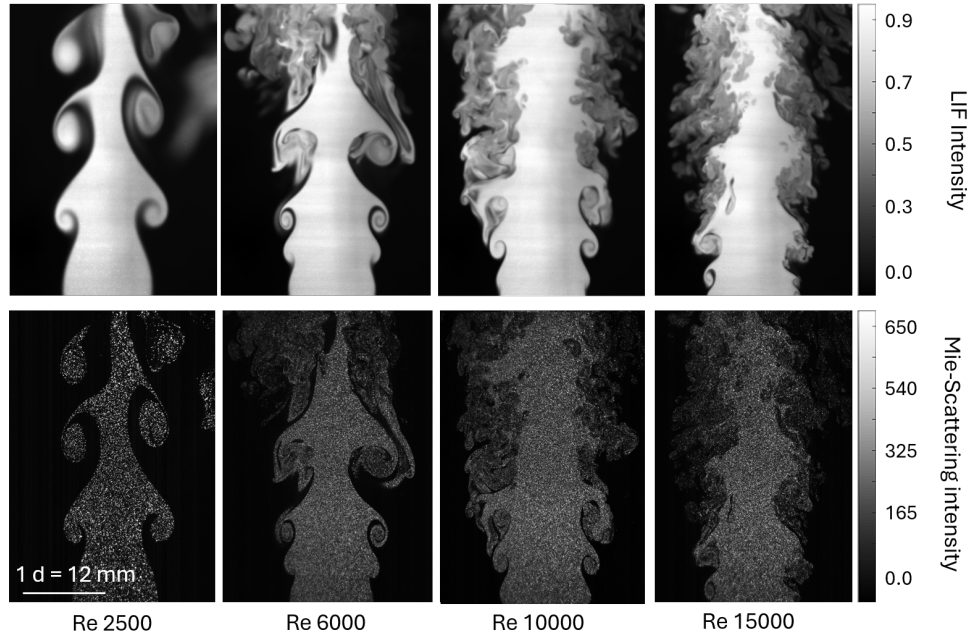


Figure 2: Single-shot images of the jet at different Reynolds numbers, captured simultaneously with LIF and Mie-scattering. The lower image border is located 4 mm above the nozzle.

Simultaneous single-shot images of the jet at different Reynolds numbers are shown in Fig. 2. The instantaneous LIF images reveal coherent large-scale structures across all Reynolds numbers, with clearly defined jet boundaries and smooth intensity gradients reflecting the continuous nature of the fluorescence signal. The Mie scattering images show qualitatively similar large-scale structures; however, the discrete particle signal produces a granular texture that becomes increasingly pronounced at lower particle number densities in the far field of the jet. This distinction is particularly evident in the vortex cores visible at $Re = 2500$, where the LIF signal appears smooth and homogeneous while the Mie scattering signal displays sharp edges.

The standard deviation fields (Fig. 3a) reveal a striking structural difference between the two methods. The LIF field exhibits a characteristic V-shaped pattern mirroring the jet geometry, with two distinct lobes of elevated fluctuation intensity co-located with the jet shear layers. These lobes extend and widen downstream as the shear layers grow, while the jet core shows comparatively low values, particularly in the near-nozzle region. With increasing Reynolds number, the overall magnitude increases and the spatial structure becomes more diffuse, reflecting the broadening of the shear layers and increasing turbulence intensity.

The Mie-scattering standard deviation field presents an essentially inverted distribution: rather than elevated values in the shear layers, the highest standard deviation is found in the jet core, decreasing towards the jet boundaries. This central maximum is most pronounced at $Re = 6000$ and $Re = 10000$, forming a broad, elongated region aligned with the jet axis, and broadens considerably at $Re = 15000$. The correlation fields confirm this structural mismatch, showing

predominantly negative values in the jet core and near-zero or weakly positive values in the shear layer regions, with global correlation coefficients close to zero or negative across all Reynolds numbers ($R = -0.29$ to 0.01). The fluctuations in high concentration areas are innate to the discrete nature of scattering images and hence overpower fluctuations due to mixing processes.

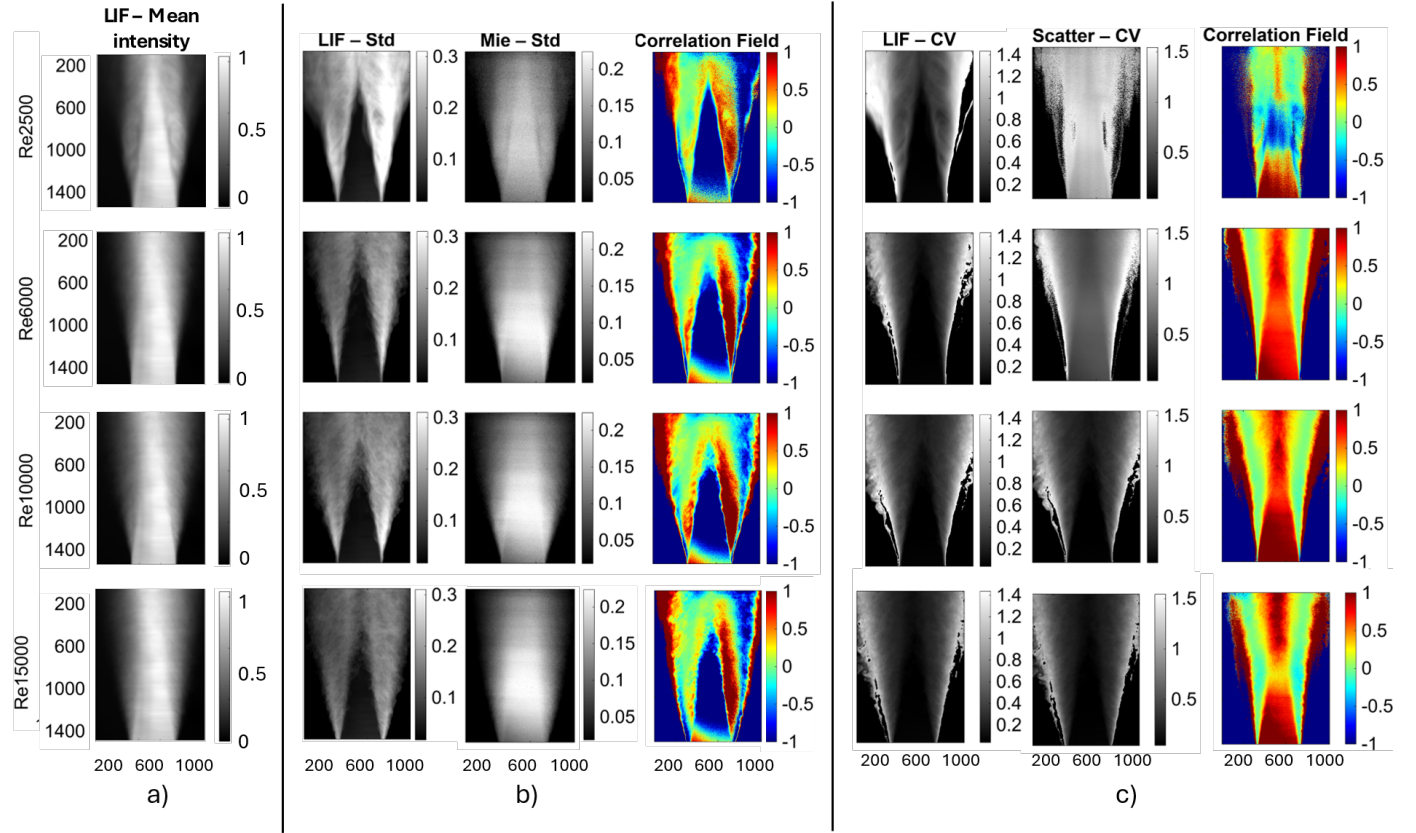


Figure 3: a) LIF mean intensity for $Re = 2500, 6000, 10000$, and 15000 (top to bottom). B) Standard deviations for LIF (left) and Mie scattering (center), and pixel-wise spatial correlation field (right) for $Re = 2500, 6000, 10000$, and 15000 (top to bottom). c) Coefficient of variation for LIF (left) and Mie scattering (center), and pixel-wise spatial correlation field (right) for $Re = 2500, 6000, 10000$, and 15000 (top to bottom).

Normalizing the standard deviation by the local mean intensity, that is the coefficient of variation, $CV = \sigma/\mu$, substantially improves the spatial agreement between the two methods (Fig. 3b). At $Re = 2500$, the LIF CV field shows pronounced spatial structure with elevated values at the jet boundaries, while the Mie scattering CV field does not display any discernible spatial organization, reflected in a global correlation coefficient of $R = -0.12$, as shown in figure 4. At $Re = 6000$, both methods show qualitatively similar CV fields with elevated values in the jet shear layers, yielding the highest correlation of $R = 0.94$. At $Re = 10000$ and $Re = 15000$, the spatial agreement remains qualitatively consistent but the correlation coefficient decreases progressively to $R = 0.88$ and $R = 0.69$, respectively, with increasing structural differences visible particularly in

the shear layer regions at intermediate downstream distances. It is to be noted, however, that the CV is highly sensible to seeding densities on the scattering side. The low seeding density particularly for the Re 2500 case may impact these results.

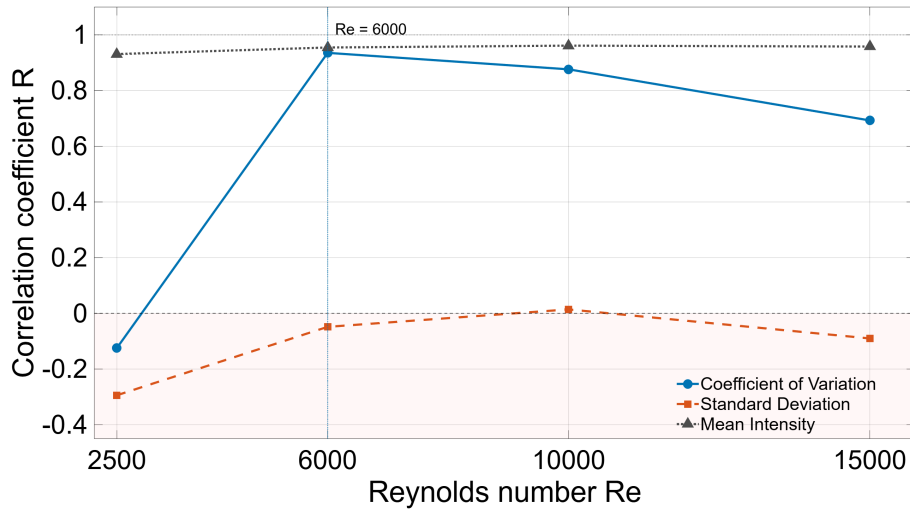


Figure 4: Global spatial correlation coefficient R between LIF and Mie scattering fields as a function of Reynolds number for the coefficient of variation (blue), standard deviation (orange), and mean intensity (black). The vertical line marks $Re = 6000$.

The non-monotonic dependence of the method agreement on Reynolds number is summarized in Fig. 5. The mean intensity fields show consistently high correlation across all Reynolds numbers ($R = 0.93$ – 0.96), confirming that both methods capture the time-averaged concentration field with comparable fidelity independent of Reynolds number. The standard deviation fields show near-zero or negative correlation throughout, while the CV yields substantially improved agreement in the fully turbulent regime, peaking at $Re = 6000$.

Discussion

The spatial structure of the standard deviation fields reveals a fundamental difference between the two measurement techniques. The LIF standard deviation field exhibits elevated values in the jet shear layers, reflecting the intense turbulent mixing activity at the interface between jet fluid and ambient, where the local concentration fluctuates strongly as parcels of jet fluid and ambient are alternately advected through a given location. The Mie scattering standard deviation field, by contrast, shows an inverted spatial pattern with elevated values in the jet core.

This inversion points to a fundamental difference in the physical quantities captured by the two methods. LIF measures the concentration of a molecularly dissolved tracer that tracks the full scalar field, including its diffusive contributions. Mie scattering measures the local number density of inertial particles, whose transport is governed by advection rather than molecular diffusion. Moreover, the discrete nature of Mie scattering imaging leads to unavoidable fluctuations even in high seeding density areas. Standard deviations therefore capture methodical fluctuations more

so than physical flow quantities. Consequently, the two methods are sensitive to different processes, and the resulting standard deviation fields are not directly comparable in an absolute sense, irrespective of the Reynolds number.

The coefficient of variation partially compensates for this structural difference by normalizing the fluctuation field by the local mean, reducing the sensitivity to absolute signal level differences and to the spatial distribution of the mean concentration field. As shown in Fig. 4, this normalization yields substantially improved spatial agreement between the two methods, with a global correlation coefficient of $R = 0.94$ at $Re = 6000$. The non-monotonic dependence of R on Reynolds number suggests that the degree of equivalence between the two methods is strongly flow-regime dependent.

At $Re = 2500$, in the transitional regime, molecular diffusion plays a significant role in the mixing process at the scales resolved here. Since Mie scattering particles do not follow diffusive transport, the two methods capture fundamentally different aspects of the concentration field, resulting in near-zero or negative correlation. The low CV values there are, however, partially influenced by the lower seeding density.

At $Re = 6000$, in the fully turbulent regime, advective transport dominates over molecular diffusion at all resolved scales, and the particle field more closely approximates the gas phase scalar field, yielding the best agreement between the methods. The gradual decrease in correlation at $Re = 10000$ and $Re = 15000$ may reflect the increasing importance of the Stokes number of the particles, leading to preferential concentration effects that cause the particle field to deviate from the scalar field. This hypothesis is consistent with the spatial structure of the correlation fields at high Reynolds numbers (Fig. 4), which show increasing decorrelation in the shear layer regions where turbulent velocity gradients are largest and fluctuation scales are smallest.

Taken together, these results suggest that Mie scattering provides a reliable proxy for mixing and flow fluctuations in the fully turbulent regime at intermediate Reynolds numbers, where advective transport dominates. Outside this regime, in transitional flows where diffusion is significant, or at very high Reynolds numbers where preferential concentration becomes relevant, the two methods diverge, and Mie scattering should be interpreted with caution. The present results provide a basis for assessing the range of validity of Mie scattering as a concentration measurement technique in turbulent jet flows.

Conclusions

Simultaneous LIF and Mie scattering measurements have been performed in a turbulent jet over a range of Reynolds numbers spanning the transitional to fully turbulent regime. In statistical analysis, their capability in capturing flow fluctuations is compared, based on the mean intensity, standard deviation, and coefficient of variation of the intensity fields.

The standard deviation fields reveal a fundamental structural difference between the two methods: while LIF exhibits elevated fluctuations in the jet shear layers, the Mie scattering standard deviation is highest in the jet core. This is attributed to the inability of inertial particles to follow diffusive scalar transport.

The coefficient of variation substantially improves the spatial agreement between the two methods by normalizing out absolute signal level differences. The global correlation coefficient between the CV fields shows a non-monotonic dependence on Reynolds number. This behavior is interpreted as reflecting the competing influences of molecular diffusion at low Reynolds numbers, where Mie scattering fails to capture diffusive mixing, and preferential particle concentration at high Reynolds numbers. Particle seeding density impacts this as well, displaying the need for dense stable seeding conditions in Mie scattering imaging applications while avoiding multiple scattering.

These results demonstrate that Mie scattering provides a reliable proxy for scalar concentration fluctuations in the fully turbulent regime at intermediate Reynolds numbers, but should be interpreted with caution outside this range. It should be noted, however, that the limitations identified here are inherently scale-dependent. At the pixel-level resolution of the present study, diffusive transport and preferential concentration effects may manifest as measurable discrepancies between the two methods. When quantities are spatially averaged over larger regions, for example in bulk mixing characterization or integral-scale analysis, many of these pixel-level discrepancies are likely to cancel, and the two methods may converge to comparable results regardless of Reynolds number. The present study therefore provides a quantitative basis for assessing the validity of Mie scattering as a concentration measurement technique at the scale of resolved turbulent structures, and highlights the coefficient of variation as a robust and directly comparable statistical quantity for cross-method validation.

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