

Planar Concentration Measurements in a Co-Axial Jet with Structured Illumination Assisted Polarization Separation Filtered Rayleigh Scattering (PS-FRS) Technique

Utkun E. Malkocoglu¹, Samuel C. Woolsey², Gwibo Byun¹, K. Todd Lowe^{1,*}

1: Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, Virginia 24061, United States of America

2: George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, United States of America

*Corresponding author: malkocoglu@vt.edu

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ABSTRACT

The current work introduces an enhanced background mitigation strategy for Filtering Rayleigh Scattering (FRS) measurements, with the integration of polarization separation and structured illumination methodologies. Polarization separation efficiently isolated the target polarized FRS signal from the other irrelevant scattering sources with a limited additional effort and setup complexity, and minimized the effect of the polarization-insensitive background in FRS images. In addition to that, single-phase structured illumination spatially modulated the FRS signal further distinguishing it from the rest with the help of lock-in analysis, which specifically targets the spatial modulation frequency to extract the scattering signal. The inclusion of the structured illumination enhanced the FRS signal in a round co-axial He/N₂ mixing jet stream by up to ~15%, despite the low overall FRS signal levels associated with a small Rayleigh scattering cross section of the He flow.

1. Introduction

Laser diagnostic techniques have a key role in fluid mechanics research enabling non-intrusive measurements with high accuracy, however, conventional measurements using a physical probe might be infeasible for experimental setups with limited access, or it can alter the flow field by introducing disturbances (Xing et al., 2016). In addition, a probe or surface pressure port can only obtain local information at a point (Doll et al., 2012), where laser diagnostics can achieve line, planar, or even volumetric measurements. Furthermore, laser techniques based on molecular-level scattering such as Rayleigh scattering, laser induced fluorescence (LIF), Raman scattering, etc. allow for the multiple flow properties to be measured simultaneously (Warner et al., 2024), which can significantly reduce the complexity of the instrumentation.

Filtered Rayleigh Scattering (FRS) has been increasingly adopted by the flow diagnostics community since the 1990s (Ground et al., 2023). This technique was introduced as an improvement

to conventional laser Rayleigh scattering (LRS), where an additional vapor cell is placed in front of the detector functioning as a spectral filter to remove undesired scattering contributions from Mie (particles/droplets) and geometric (background) scattering in the collected Rayleigh signal. Although not as many as its counterparts in common fields such as thermometry and velocimetry, it is possible to find a few works in the literature which used FRS to obtain mixture composition (McGaha and Reeder, 2007; Patton and Sutton, 2013; Allison et al., 2016; Krishna et al., 2019; Malkocoglu et al., 2025; Bundy et al., 2026), including the ones carried out for supersonic flows (Reeder, 1996; Ground et al., 2018; Gopal and Maddalena, 2020). This study aims to introduce a framework to improve signal quality of the FRS concentration measurements combined with “*polarization separation (PS)*” and “*structured illumination (SI)*” methodologies, with an application of round co-axial He/N₂ jet at ambient conditions.

The next part of the review is dedicated to the polarization separation (PS) methodology, which is based on a practical principle of acquiring images for the different polarization states of the incident laser illumination. PS has a promising potential for increasing signal-to-noise ratio (SNR) of the measurements with different molecular scattering techniques such as Rayleigh, Raman, Thomson, etc., since their relatively weak polarization-dependent signals can be distinguished from the polarization-independent signal contaminants (e.g. stray light and geometric scattering from background) just by adjusting the incident laser light polarization. Regarding Rayleigh scattering specific applications with PS, Barat et al. (1991) performed instantaneous flame temperature measurements in a toroidal jet stirred combustor with polarization-based Rayleigh signal extraction and successfully eliminated interferences from severe background glare and blackbody radiation. Fielding et al. (2002) separated polarized and depolarized Rayleigh scattering to measure mixture fraction and temperature in a laminar methane diffusion flame diluted with argon and air, which yielded ~ 10 times stronger signal levels and more than 3 times higher SNR when compared to Raman scattering. Similarly, Chakravarthy et al. (2023) used Polarized–Depolarized Rayleigh Scattering (PDRS) technique for simultaneous measurements of temperature and mixture fraction in non-reacting jet mixing under non-isothermal conditions to mimic practical mixing scenarios relevant to combustion and cooling applications. When it comes to the particular applications of PS for FRS technique, the only work to the authors’ knowledge is a recent study by Malkocoglu et al. (2026). This work incorporated the PS methodology into FRS and effectively isolated the Rayleigh scattering signals of the high pressure high temperature premixed Jet A/air flame in a lab-scale combustor from the background, but more importantly, from the broadband flame luminosity. Given that these artifacts can still have signal levels significantly higher than the target FRS signal of interest, their successful suppression demonstrates the ability of PS to achieve FRS measurements with high enough quality despite challenging conditions.

The last category for the review will cover the literature relevant to structured illumination (SI) along with lock-in analysis, which is commonly used to demodulate the SI images to obtain the target signal of interest. Similar to PS, the SI approach was also motivated by the need for suppressing stray light in laser based measurements which can severely interfere with the weak signals of interest, especially in challenging environments like flames, particle laden flows and sprays with droplets, turbid media, etc. By applying a periodic pattern through the laser illumination (generally a sheet) with a carefully selected spatial modulation frequency and using the lock-in analysis to demodulate the scattering signal imprinted in the acquired image, this technique is capable of providing accurate quantitative results despite the presence of strong stray light, thereby improving the measurement reliability and precision in situations with limited optical access or intense background (geometric) scattering. The early structured illumination microscopy (SIM) studies by Neil et al. (1997) and Gustafsson (2000) can be evaluated to lay the foundations of the actual SI methodology, which were focused on out-of-focus light rejection and surpass the classical diffraction limit of lateral resolution, respectively. Concerning SI applications particular to Rayleigh scattering, Structured Light Illumination Planar Imaging (SLIPI) is widely used in combustion research (Kristensson and Berrocal, 2016; Kempema and Long, 2014; Kristensson et al., 2015). The basic principle of the SLIPI technique implies that a DC offset coming from the background in the images does not follow any spatial phase-shift in the intensity modulation pattern. As a result, the contribution of the constant background is removed when images of different spatial phases are subtracted from each other, only leaving the signal of interest (Berrocal et al., 2008). This becomes important when it is difficult to distinguish the original signal from the stray light due to the elastic nature of Rayleigh scattering. In that context, SLIPI emerges as a powerful tool for aerodynamic and combustion measurements with its robustness to background contamination. When it is considered there is no existing study to the authors' knowledge that specifically combines FRS and PS+SI, this study intends to be the first demonstrator for both PS and SI approaches simultaneously introduced into the FRS technique. This new strategy for enhanced suppression of the signal contamination sources is applied through an example of the He/N₂ co-axial mixing jet, which has a relatively weak scattering signal due to the presence of helium with a low Rayleigh scattering cross-section.

The remainder of this manuscript will continue as follows: the FRS methodology employed in this study will be introduced in Section 2, the experimental rig consisting of FRS imaging and custom-built He/N₂ round co-axial jet setups will be described in Section 3, which is then followed by the results for the post-processed He mole fraction field presented in Section 4. Lastly, the abstract is going to be concluded by a summary of key findings and future remarks in Section 5.

2. Comprehensive FRS Methodology for Binary Mixture Measurements

The fundamentals of the FRS concentration measurements root back to mixture measurements with LRS (Ground et al., 2023), which is the precursor of the FRS technique as previously mentioned. It was demonstrated in these works that the time averaged mole fraction of a binary gas phase mixture can be expressed ratiometrically via FRS signals of the mixture and its pure constituents (Seasholtz and Buggele, 1997). For the mixture case of He/N₂ in this paper, the definition of the helium mole fraction (χ_{He}) becomes as follows:

$$\chi_{He} = \frac{S_{FRS,mix} - S_{FRS,N_2}}{S_{FRS,He} - S_{FRS,N_2}} = \frac{S_{FRS,mix} - S_{TOT,N_2} \circledast \mathcal{F}_T}{S_{TOT,He} \circledast \mathcal{F}_T - S_{TOT,N_2} \circledast \mathcal{F}_T} \quad (1)$$

where $S_{FRS,mix}$, S_{FRS,N_2} and $S_{FRS,He}$ are the FRS signals of the helium/nitrogen mixture, pure nitrogen and pure helium, respectively. On the other hand, S_{TOT} corresponds to the total unfiltered collected signal including RBS lineshape $\mathcal{R}$ along with Mie and geometric scattering contributions, S_{Mie} and S_{Geo} , where the $\circledast$ represents the convolution operation with the vapor filter transmission spectrum, $\mathcal{F}_T$. In Eq. 1, $S_{FRS,mix}$ was not extended as was done for the pure species since it requires a more detailed elaboration, which will be explained following the discussion for the pure species. Given the basic definitions, the FRS signal S_{FRS} can be written as follows:

$$S_{FRS} = S_{TOT} \circledast \mathcal{F}_T = CI_0N\sigma \left(\int_{-\infty}^{\infty} \mathcal{R}(\nu' - \nu_L) \mathcal{F}_T(\nu - \nu' - \nu_L) d\nu' + B \right) \quad (2)$$

with C , I_0 , N , σ and ν denoting the calibration constant for optical collection efficiency, incident laser intensity, number density of the gas, Rayleigh scattering absolute cross-section, and wavenumber, respectively. The final parameter newly introduced in Eq. 2 is B , described as the FRS signal bias parameter that embodies the influence of S_{Mie} and S_{Geo} in S_{FRS} (Warner et al., 2024). Note that, any functional dependencies of $\mathcal{R}$ and B on flow parameters such as pressure, temperatures, velocity, etc. were not stated explicitly for the sake of brevity. Regarding the analysis of the variables in Eq. 2, C and I_0 are the setup-specific parameters and can be assumed as constant/invariant for the measurements. N can be derived from the ideal gas law, or via a proper equation of state with compressibility correction when pressure and/or temperature approach their critical conditions, implying deviations from the ideal gas behavior. On the other side, the bias parameter B is negligible for the case of an efficient spectral filtering within the low transmission region, e.g., $\mathcal{F}_T < 10^{-5}$. As a result, the remaining parameters of interest become σ and $\mathcal{R}$, which have the most immediate impact on S_{FRS} . To begin with σ , it is found by integration of the polarization-dependent differential Rayleigh scattering cross-section $\frac{d\sigma}{d\Omega}(\phi)$ with respect to the collection solid angle Ω :

$$\frac{d\sigma}{d\Omega}(\phi) = \left(\frac{2\pi}{\lambda^2} \right)^2 \left(\frac{n-1}{N} \right)^2 \sin^2 \phi \quad (3)$$

where ϕ is the angle between the polarization direction of the incident electric field and polarization direction. By following the intermediate relations provided by Cutler and Lowe (2023) and Manin et al. (2021), one can derive the final form of σ as follows:

$$\sigma = \frac{24\pi^2}{\lambda^4 N^2} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2 F_K \quad (4)$$

where λ is the incident laser wavelength, n is the refractive index of the scattering gas, and $F_K = (6 + 3\rho_0)/(6 - 7\rho_0)$ is the King correction factor to account for the anisotropy of molecular polarizability, with ρ_0 denoting the polarization ratio. Note that, $F_K = 1$ for spherically symmetric species such as He and $F_K \approx 1$ for nitrogen used in this study (Miles et al., 2001), so the effect of F_K in σ can be neglected for both. It is a common practice that σ is calculated at standard pressure and temperature (STP) conditions, as such $N = N_0$. Equation 4 is important to show the λ^{-4} dependency of σ , and thus, that of S_{FRS} . Using the dispersion relations for n like the ones provided by Thalman et al. (2014) and Snee and Ubachs (2005), σ can be found at known gas pressure and temperature along with λ . All these relations described so far yielded a Rayleigh scattering cross section ratio of $\sigma_{N_2}/\sigma_{He} \approx 65 \pm 1$ as a crucial outcome, since that much difference between these two species makes the detection of the lighter helium easier in the He/N₂ mixture due to its much lower signal compared to heavier nitrogen according to Eq. 2.

Another factor that has a major effect on S_{FRS} different from σ is the convolution of the RBS lineshape with vapor filter transmission (refer to Eq. 2). A carefully tuned laser wavenumber aligning with sharp absorption features of the vapor filter transmission $\mathcal{F}_T$ allows the broader Rayleigh-Brillouin scattering (RBS) spectral lineshape $\mathcal{R}$ to be partially transmitted to the detector, while rejecting the narrowband geometric (background) and Mie (particle) scattering components (Fig. 1). Where there are studies accurately predicting and measuring the $\mathcal{F}_T$ of vapor filters such as Forkey et al. (1997) for iodine vapor (532.2 nm green laser used in this study), both measurement or modeling of $\mathcal{R}$ is relatively burdensome. In terms of measurements, spectroscopic studies could be performed with interferometers to obtain $\mathcal{R}$ directly at relevant conditions, though they generally require rigorous and precise experimentation takes long times, which is far from being practical (Witschas et al., 2010; Gu and Ubachs, 2014; Teav and Steinberg, 2023). As for the modeling side, there have been various gas kinetic models proposed in the literature to characterize the spectral behavior of the $\mathcal{R}$ based on the double Fourier transform of the density-density correlation function (Boguszko and Elliott, 2005) with complexities varying from single monatomic species to molecules and even binary gaseous mixtures (Hanson and Morse, 1967; Yip, 1971; Cohen et al., 1971; Letamendia et al., 1985). It is also possible to encounter some analytic and empirical models (Binietoglou et al., 2016; Doll et al., 2016; Hunt et al., 2020) for their practicality and simpler implementation, as well as the more recent advanced models with improved treatments in gas kinetic equations, depolarized contributions from Raman scattering, mixing dynamics in binary mixtures, etc. (Zheng, 2007; Wang et al., 2021; Warner and Lowe, 2025). Among all, Tenti S6 model by Tenti

et al. (1974) is the most commonly accepted model in Rayleigh scattering studies, and became a *de facto* standard for spontaneous RBS lineshape modeling (Teav and Steinberg, 2024). Even though it was originally developed for monatomic and diatomic species, its usage has been extended with air effectively treated as “single species” (Gu et al., 2015) and gaseous mixtures (McManus et al., 2019).

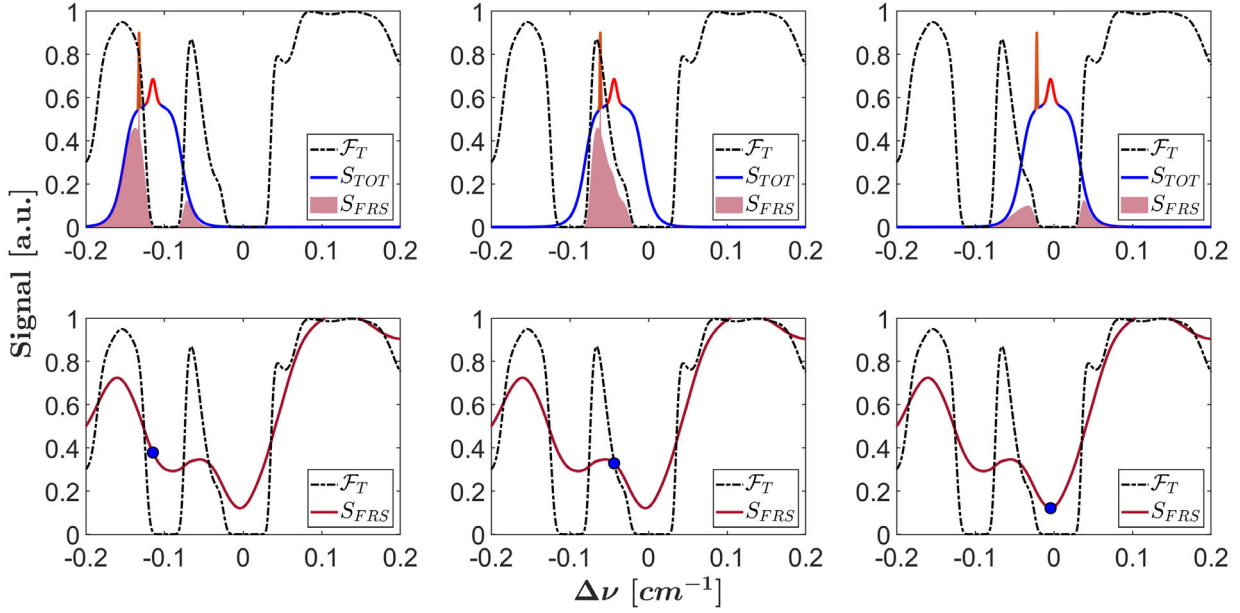


Figure 1. Variation of the FRS signal (S_{FRS} , shaded maroon area in the top row and solid maroon curve in the bottom row) with the detuned laser wavenumber as a result of the convolution process between the total detected signal (S_{TOT}) and the vapor filter transmission ($\mathcal{F}_T$, dash dotted black). S_{FRS} at three different detuning wavenumbers are indicated with round blue markers in the bottom row, which correspond to the center wavenumber of the spectral profiles at their counterparts in the top row. S_{TOT} consists of the target Rayleigh-Brillouin Scattering (RBS) signal ($\mathcal{R}$, solid blue) along with Mie (S_{Mie} , solid red) and geometric (S_{Geo} , solid orange) scattering contributions.

As for mixture FRS signal interpretation, a widely adopted approach is the “dilute limit assumption” (McManus et al., 2019; Allison et al., 2016), in which the interaction between the diluted and the diluent gases is regarded to be weak, and thus, the overall mixture FRS signal ($S_{FRS,mix}$) of a simple species can be expressed as the mole-fraction weighted summation of the FRS signals coming from each mixture component by using Eq. 2:

$$S_{FRS,mix} = CI_0 N_{mix} \sum_i \chi_i \sigma_i \int_{-\infty}^{\infty} \mathcal{R}_i(P_{mix}, T_{mix}, \nu' - \nu_L, \dots) \mathcal{F}_T(\nu - \nu' - \nu_L) d\nu' \quad (5)$$

where N_{mix} and χ_i are the total number density of the mixture at (P_{mix}, T_{mix}) conditions, and the mole fraction of the mixture component i , respectively. Note that, $\mathcal{R}$ and σ are now given for the same mixture component i . Furthermore, the signal bias parameter B due to signal contaminants was omitted in the convolution term in the presence of efficient spectral filtering coming from the

vapor filter. The dilute limit mainly holds for the mixtures with low mole fractions of diluents and relatively low pressure/temperature cases, and is expected to be valid in this study based on the experimental conditions provided in the Section 3.

The next part of the experimental framework will go through the implementation of the polarization separation methodology. It would be noticed in Eq. 3 and its illustration in Fig. 2a that the Rayleigh scattering signal has a dependence on the angle ϕ , while the mostly suppressed signal contaminants such as background/stray light and also depolarized rotational Raman scattering do not have such a specific polarization orientation. Although the latter has a weak signal (commonly $< 2\%$ of the overall detected signal (Boguszko and Elliott, 2005; Cutler and Lowe, 2023)), its influence on the total FRS signal might become important depending on the molecular structure of the species used (molecular anisotropy) and their scattering regime, i.e., Y parameter (Warner and Lowe, 2025). To obtain the actual desired FRS signal by eliminating these undesired contributions from the FRS total signal a can be extracted by carefully choosing two different polarization states with one of them maximizing the collected FRS signal and other minimizing it by adjusting their ϕ , which can be practically performed through rotation a half wave plate. From now onward, this procedure will be called as “*polarization separation filtered Rayleigh scattering (PS-FRS)*”, which requires FRS signals of two different polarization states to be measured:

$$S_{FRS,\parallel} = S_{FRS} + S_{FRS,res} \quad , \quad S_{FRS,\perp} = S_{FRS,res} \quad \rightarrow \quad S_{FRS,raw} = S_{FRS,\parallel} - S_{FRS,\perp} \quad (6)$$

In Eq. 6 above, $S_{FRS,\parallel}$ and $S_{FRS,\perp}$ denote the collected FRS signals for the polarization states parallel (*p-polarized*, $\phi = 0^\circ$) and perpendicular (*s-polarized*, $\phi = 90^\circ$) to the scattering plane, where $S_{FRS,res}$ and $S_{FRS,raw}$ are the residual FRS signal arising from the aforementioned contamination sources, and the raw FRS signal after the subtraction of the polarization states (ideally identical to the desired FRS signal S_{FRS}), respectively. Note that, the scattering plane is defined by the incident laser propagation ($\hat{i}$) and observation direction vectors ($\hat{o}$), as depicted in Fig 2b.

The remainder of this section will describe the SI implementation coupled with lock-in analysis to demodulate the spatially modulated FRS signal obtained with SI. As it was mentioned in Section 1, the main motivation of the SI in laser diagnostics is to isolate the signal of interest from the intense background and fluorescence, where the former only applies to this work. In SI methodology for the planar measurements, the conventional laser sheet is replaced with a spatially modulated illumination pattern (generally sinusoidal), while the background does not follow this modulation and acts as a DC component in the incident laser sheet intensity profile I . Setting the laser propagation direction in x and assuming that the incident laser illumination is only modulated in the direction y ($x \perp y$), I as a function of y can be written as follows:

$$I(y) = I_{MS}(y) + I_{SS} \cdot \sin(2\pi y \nu_{sm} + \varphi), \quad (7)$$

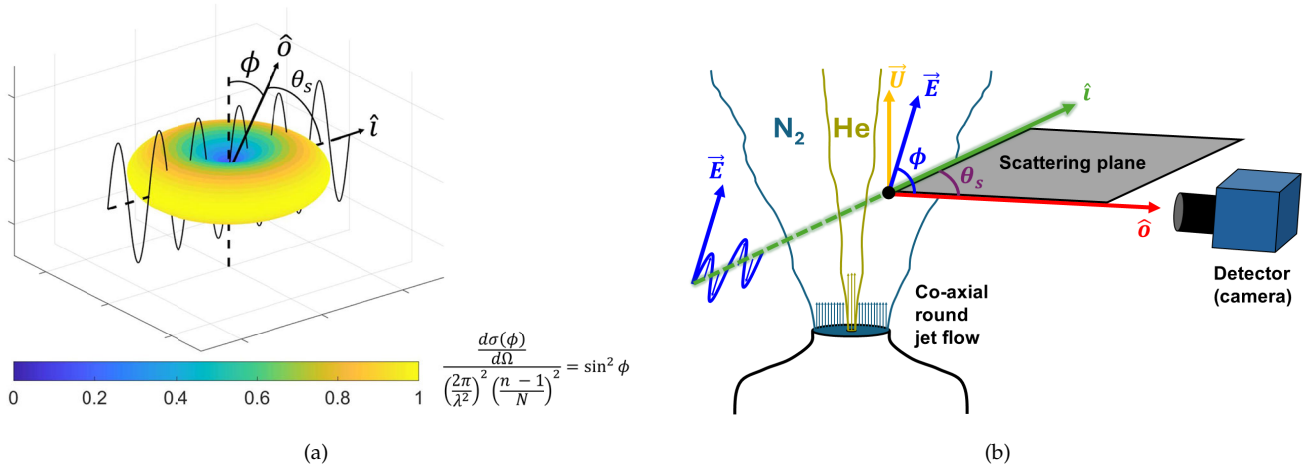


Figure 2. Geometric illustration of the FRS process (a) $\sin^2(\phi)$ directivity of Rayleigh scattering differential cross section induced by a linearly polarized incident electric field $\vec{E}$ (adapted from Warner et al. (2024)) (b) scattering vector and angle definitions.

where I_{MS} , I_{SS} , ν_{sm} , and φ denote multiply (background) and singly scattered (Rayleigh) incident laser intensities, frequency of the spatial modulation, and arbitrary phase shift (offset) of the spatial modulation. Using the definition of the FRS signal in Eq. 2, a transition can be made from I to S_{FRS} :

$$S_{FRS,raw}(y) = S_{Bknd}(y) + S_{FRS} \cdot \sin(2\pi\nu_{sm}y + \varphi), \quad (8)$$

with $S_{FRS,raw}$, S_{Bknd} and S_{FRS} denoting the raw FRS signal acquired via detector, background signal to be removed, and the polarization subtracted FRS signal as the target quantity to be used in Eq. 1 for χ post-processing. S_{FRS} is frequently extracted from the raw images via the three phase SLIPI (3p-SLIPI) method, requiring three images with different spatial phase shifts φ to be used. However, this study makes use of single phase SLIPI approach (1p-SLIPI) with only one image proposed by Berrocal et al. (2012), and follows the studies by Kristensson et al. (2014) and Mishra et al. (2017), which integrated 1p-SLIPI with spatial lock-in analysis to systematically demodulate the target signal from the raw FRS image as visually described in Fig. 3. While interested readers are referred to these publications for more detail in depth, this concept will be explained here as necessary. The lock-in algorithm uses two reference signals phase shifted by $\varphi = \pi/2$, $S_{ref,1}$ and $S_{ref,2}$, which carry the information from the S_{FRS} through the same known ν_{sm} :

$$S_{ref,1}(y) = \sin(2\pi\nu_{sm}y) \quad (9a)$$

$$S_{ref,2}(y) = \cos(2\pi\nu_{sm}y) \quad (9b)$$

Their multiplication with $S_{FRS,raw}(y)$ yields the following:

$$S_{FRS,1}(y) = S_{FRS,raw}(y) \times S_{ref,1}(y) = \frac{1}{2}S_{FRS}[\cos(\varphi) - \cos(4\pi\nu_{sm}y + \varphi)] + S_{Bknd} \sin(2\pi\nu_{sm}y) \quad (10a)$$

$$S_{FRS,2}(y) = S_{FRS,raw}(y) \times S_{ref,2}(y) = \frac{1}{2} S_{FRS} [\sin(\varphi) - \sin(4\pi\nu_{sm}y + \varphi)] + S_{Bknd} \cos(2\pi\nu_{sm}y) \quad (10b)$$

with the intermediate steps for re-organizing the trigonometric terms next to S_{FRS} excluded for the sake of brevity. When $S_{FRS,1}(y)$ and $S_{FRS,2}(y)$ are analyzed in the frequency domain via 1-D Fourier transform, a non-modulated DC component is seen accompanied by a modulated component associated with ν_{sm} (1st order), where there might be leakage into the higher n^{th} orders of ν_{sm} ($n\nu_{sm}$) in practice due to the imperfections in the modulation pattern ((A) in 3). The multiplication of $S_{FRS,raw}(y)$ with $S_{ref,1}(y)$ and $S_{FRS,raw}(y)$ with $S_{ref,2}(y)$ essentially switches the spatial frequencies of the non-modulated and modulated components in $S_{FRS,raw}$, placing the non-modulated component in the place of the modulated component with ν_{sm} , and vice versa ((B-1) and (B-2) in 3). In the next step, a Gaussian bandpass spatial filter of choice with cut-off frequency limit $\nu_c \approx (2/3)\nu_{sm}$ around the origin is applied separately to $S_{FRS,1}(y)$ and $S_{FRS,2}(y)$ to remove S_{Bknd} from them, yielding $\tilde{S}_{FRS,1}$ and $\tilde{S}_{FRS,2}$ ((C-1) and (B-2) in 3). As a result, the target low-pass filtered lock-in FRS signal $\tilde{S}_{FRS}$ is obtained through the inverse Fast Fourier Transform (FFT) of twice the square root of their squared amplitudes summed ((D) and (E) in 3):

$$\tilde{S}_{FRS,1} = \frac{1}{2} \tilde{S}_{FRS} \cos(\varphi) ; \quad \tilde{S}_{FRS,2} = \frac{1}{2} \tilde{S}_{FRS} \sin(\varphi) \quad \Rightarrow \quad \tilde{S}_{FRS} = 2\sqrt{(\tilde{S}_{FRS,1})^2 + (\tilde{S}_{FRS,2})^2} \quad (11)$$

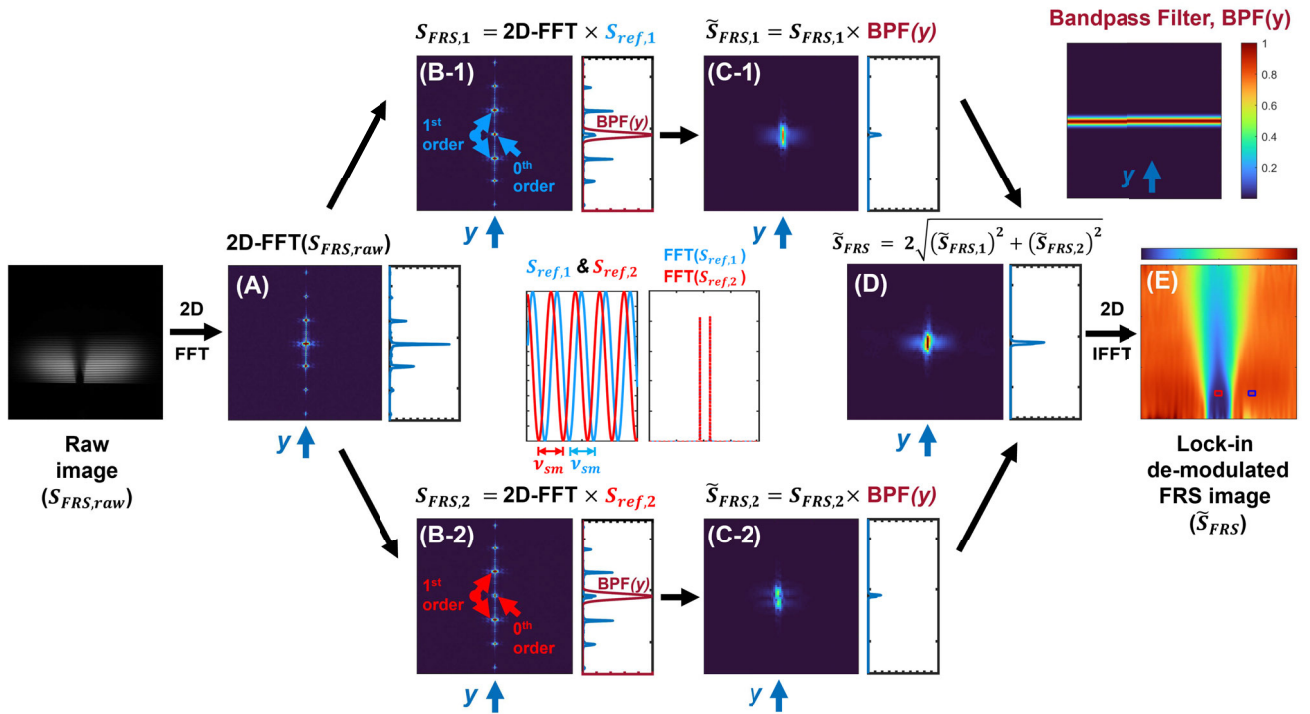


Figure 3. Illustrative description of the lock-in algorithm in the frequency domain: (A) 2D FFT of the raw image (B-1/B-2) column-wise multiplication of the raw FFT with the reference 1-D signals $S_{ref,1}$ (sine) and $S_{ref,2}$ (cosine) (C-1/C-2) band-pass filtering applied to both reference-multiplied FFTs (D) combining the band-pass filtered FFTs (E) inverse 2D FFT of the combined FFT, resulting in the demodulated FRS image signal $\tilde{S}_{FRS}$.

With the background of the FRS framework of this study introduced, the next section will go through the implementation of the FRS concentration measurements in a round co-axial He/N₂ jet coupled with PS and SI methods, along with the concentration probe measurements for validation purposes. In that regard, the experimental setup and test conditions will be addressed.

3. Experimental Setup

The overall experimental setup shown in Fig. 4 is configured in a closed laboratory room at Virginia Tech to create stagnant ambient jet outlet conditions. The setup is mainly comprised of a custom 3D printed co-axial jet nozzle along with its gas supply equipment, and FRS system with imaging camera and free-space optics for laser delivery besides the PS and SI implementation. This section will introduce the aforementioned components in detail.

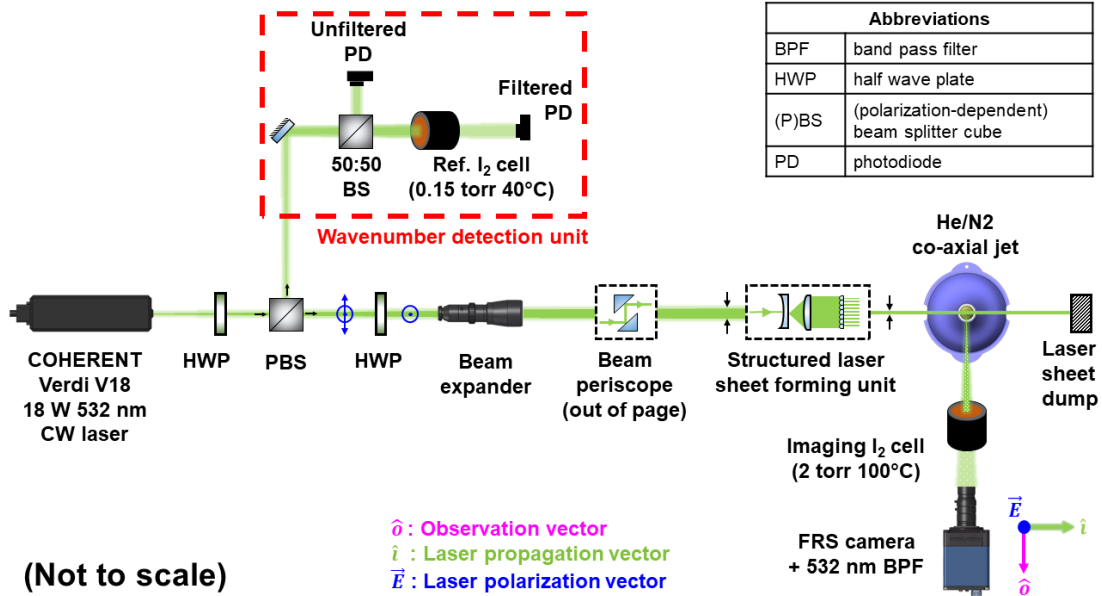


Figure 4. Schematic illustration of the experimental setup.

The co-axial jet nozzle with its details given in Fig. 5 was built with multiple 3D printed parts for practical manufacturing purposes, and also for an easy replacement, if required. Its main components are concentric inner (He) and outer (N₂) nozzles to create a co-axial round jet streams. The purpose for the selection of this co-axial jet configuration is to form a sensible concentration gradient; hence, a mixing layer between those streams to be imaged by FRS technique. The other elements of the jet setup are the honeycomb structures for each stream as flow conditioner, a base plate section and an 8020 frame structure, on which the nozzle is mounted. The flow inlets are located at the bottom of the nozzle; helium core flow is supplied from the center barbed fitting (outer $\varnothing 3.18$ mm - 1/8") and nitrogen co-flow is supplied through two side barbed fittings with

the same size to ensure flow symmetry around the core helium flow. He and N₂ gas flows are provided from industrial grade compressed gas cylinders with >99% purity (Airgas HE 300 and NI 200, respectively), where their flow rates are regulated through a thermal mass flow controller for each line (Alicat Scientific BASIS 100 SLPM). After nitrogen flow is introduced into the outer nozzle through the side inlets, it first passes through the porous base plate, which is then followed by an aluminum honeycomb grid before reaching the outlet. As for helium flow, it directly encounters its own 3D printed honeycomb structure before the outlet section. The nozzle narrows down through the outlet, where the upper portion follows a 5th degree polynomial curve for a smooth contraction. The round jet outlet cross-section has the nominal dimensions $\varnothing 44.45$ mm ($\varnothing 7/4''$) outer diameter for the N₂ flow, and $\varnothing 6.35$ mm ($\varnothing 1/4''$), with an inner jet lip thickness of $t = 0.25$ mm (0.01"). Since both nitrogen and helium pose a risk of asphyxiation, the jet flow is routed outside with a collection hood hooked up sufficiently high above the outlet in order not to disturb the flow field, where it is connected to a vacuum cleaner to exhaust the mixture content.

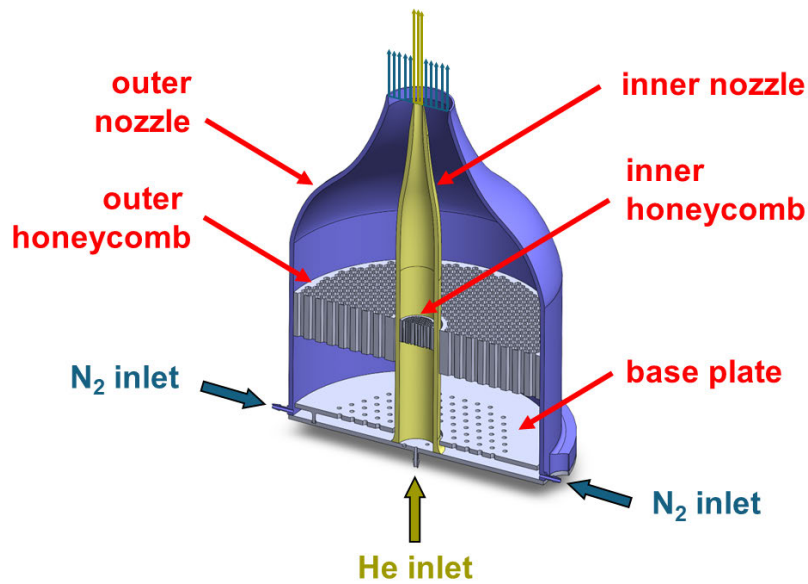
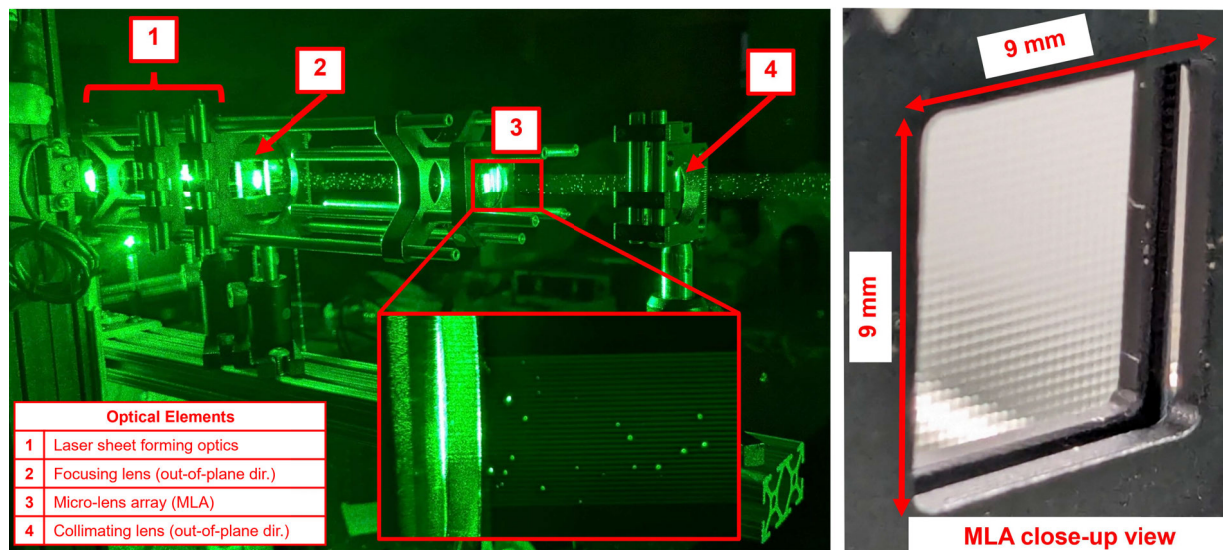


Figure 5. He/N₂ co-axial jet system with 3D printed nozzle and flow conditioners.

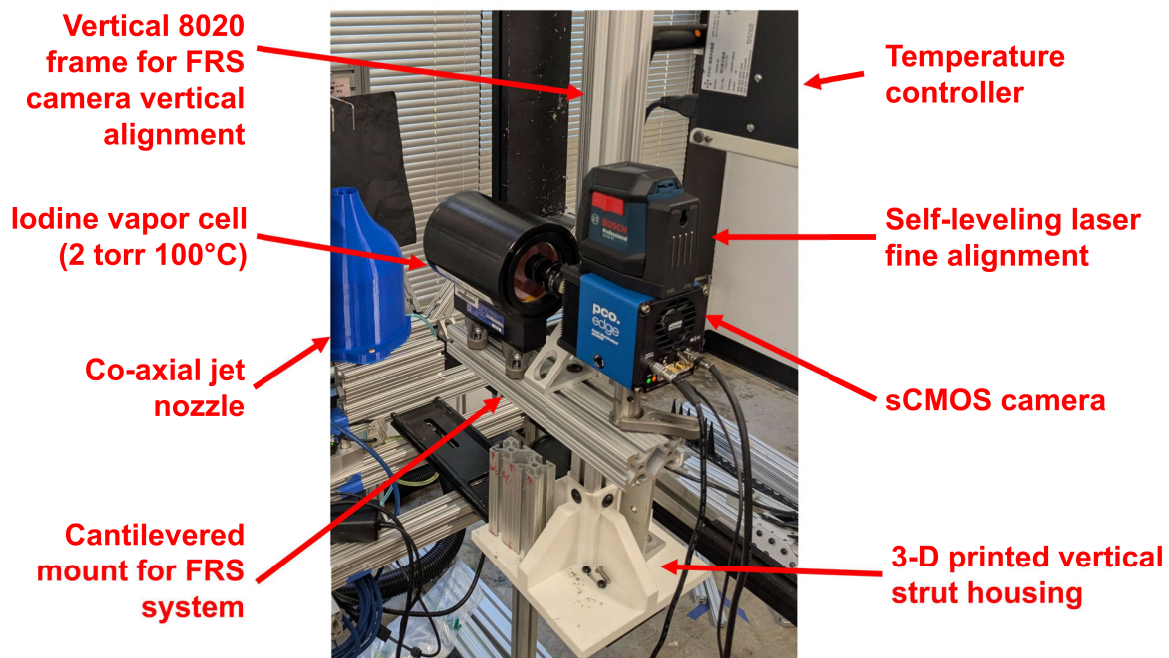
The final part of the experimental rig is the FRS setup shown in Fig. 6, including both free-space optics and imaging setups. For the flow field illumination, a 532 nm continuous wave tunable diode-pumped solid state Nd:YVO₄ laser with 18 W power output (COHERENT Verdi V18) was used. The laser beam with $\varnothing 2.25$ mm output diameter was first passed through a polarization-dependent beam splitter cube with a built-in zero-order half-wave plate installed (THORLABS VA5-532) to divert a small portion of the laser power to the reference beam optics for laser wavenumber detection (interested readers are referred to Malkocoglu et al. (2026) for more details). The main laser beam portion was passed through another zero-order half wave plate (THORLABS WPH05M-514) on a graduated rotation mount to be used for PS method by

adjusting the polarization angle ϕ . After the half wave plate, the beam was steered to the beam expander (THORLABS BE02-05-A) equipped with a ring actuated iris (THORLABS SM1D12D) to minimize the reflections on the input side. This beam expander was used to adjust the size of the collimated beam steered to the SI sheet forming sub-setup given in Fig. 6a, which is located on another motorized linear translation stage for height adjustment (VELMEX BiSlide MN100). This sub-setup first takes the input beam and expands it into a 2-D sheet via a concave-convex pair of cylindrical lenses before transmitted to a “micro-lens array (MLA)” (THORLABS MLA300-14AR-M). MLA is the key optical element of the SI methodology in this work, which has a 30×30 array of micro lenses with $f = 14.2$ mm and $\varnothing 300 \mu\text{m}$ lens pitch, i.e., $9 \text{ mm} \times 9 \text{ mm}$ aperture. Regarding the basic working principle of the MLA, each micro lens in this array focuses its incident portion and converts it into a focused beam. Since the thickness of the incoming laser sheet on the MLA was reduced by focusing it in the out-of-plane direction with another convex cylindrical lens, only 2×30 portion of the MLA was used to form the 2-D structured illumination pattern by slicing the laser sheet into multiple individual streaks. MLA was essentially preferred for this study to form the structured illumination pattern unlike its similar counterparts typically using a subtractive Ronchi grating or a scanning mirror, where the former blocks $\sim 50\%$ of the incident laser power and the latter might require long mirror scan times (hence, exposure time) to accumulate enough amount of signal to avoid insufficient irradiance. The laser sheet coming out of the MLA naturally has a divergence as a result of a focusing process, while it was minimized by a careful alignment of the aforementioned sheet forming optics. As a result, the resultant single phase structured pattern with streaks formed illumination plane. After crossing the jet flow, it was terminated with a sheet dump mounted on the same 8020 frame structure that holds the jet nozzle. To further isolate the jet flow region from interferences caused by external reflections and background, the beam inlet and outlet sides of the nozzle along with jet nozzle background were shielded with matte black sheets. As regards to the FRS imaging setup provided in Fig. 6b, it consists of a sCMOS camera (pco.edge 4.2 bi UV USB) equipped with 50 mm, $f/2.8$ imaging lens (NAVITAR MVL50M23) and a second iodine vapor cell (ISSI I2S-5) at 2 torr 100°C with its temperature controlled by a temperature controller (DigiSense TC5000). To further reject the stray light, a 532 nm center wavelength (CWL) 1 nm full width at half maximum (FWHM) bandpass filter was mounted on the camera lens (THORLABS FLH532-1). Both the FRS camera and iodine cell was cantilevered on a vertical strut mounted on a rail carrier to adjust the camera working distance with respect to jet flow.

To briefly summarize the image acquisition procedure with this setup, the FRS images were recorded by scanning a set of discrete wavenumber points within the second trough of the double trough region in the iodine vapor transmission (laser center wavenumber $\nu_L = 18788.4321 \text{ cm}^{-1}$). This region corresponds to a theoretical Forkey transmission level of $\approx 10^{-10}$ for the particular iodine vapor cell used, where the measured transmission level is higher and typically between $10^{-5} - 10^{-6}$. The wavenumber scan was separately performed for each incident laser polarization state (ϕ angle) that minimizes and maximizes the FRS signal imaged by the camera, which were determined



(a)



(b)

Figure 6. The key components of the FRS setup: (a) SI laser sheet forming unit with micro-lens array (MLA) (b) FRS imaging system including the camera filtered by the iodine vapor cell.

before the image acquisition by adjusting the angle indicator of the graduated rotation mount that houses the aforementioned half-wave plate. The scan points were then set by detuning the laser wavenumber with a programmable DC power supply (B&K Precision 1787B), which supplies the necessary voltage to the piezoelectric transducer (PZT) for the internal laser etalon. The PZT voltage range was set by a National Instruments (NI) LabVIEW VI program, which is coupled with the image acquisition process. FRS camera was simultaneously triggered in synchronization

with laser wavenumber detuning, and images were recorded with 10 seconds exposure time. A single scan typically took between 120 and 150 seconds with 9 scan points in an overall detuning frequency range of $-2 \times 10^{-3} \text{ cm}^{-1} < \Delta\nu = \nu - \nu_L < 27 \times 10^{-3} \text{ cm}^{-1}$.

4. Results

In this section, the results obtained with the FRS methodology and experimental setup described. Before going through the results, the core parameters and test conditions of this study are listed in Table 1. The values of the average ambient static pressure and temperature conditions, P_{amb} and T_{amb} , were obtained from the Virginia Tech Airport (KBCB) daily weather observation reports for the time at which the measurements were carried out. The diameter-based He jet Reynolds number $Re_d = 800$ for core helium flow was adopted from a similar LRS study performed by Su et al. (2010).

Table 1. Test conditions and FRS model parameters used in the study.

Parameter	Nominal Value	
	He	N ₂
P_{amb} [atm]	1.013	
T_{amb} [K]	298.15	
d [mm]	6.35	44.45
Re_d [-]	800	≈ 150
Q [SLPM]	35.4	54.4
$\sigma \times 10^{-27}$ [cm ²]	0.08 ± 0.003 ^{[11], [49]}	5.28 ± 0.050 ^{[24], [49]}
M [g/mol]	4.003	28.014
μ [$\mu\text{Pa}\cdot\text{s}$]	19.85 ^[30]	17.81 ^[31]
κ [W/m·K]	0.155 ^[30]	0.026 ^[31]
c_{int} [-]	0.00	1.00
(μ_B/μ) [-]	≈ 0	0.73 ^[10]
θ_s [°]	90	
ν_L [cm ⁻¹] (nm)	18788.43 (532.24)	

The workflow for obtaining the time averaged helium mole fraction field $\langle \chi_{He} \rangle$ from the raw FRS images is visually described in Fig. 7. The FRS images of the orthogonal polarization states are first subtracted from each other to eliminate the background, which is obvious in the subtracted image $S_{FRS,raw}$. Then, the resulting subtracted FRS image is demodulated using the lock-in algorithm described in Section 2, followed by a laser-sheet intensity normalization to account for inhomogeneities in the incident laser illumination. The reference intensity distribution for this

normalization was obtained from a separate measurement with no-flow conditions at pure ambient air. In addition to this normalization, a (10×5) spatial median filtering was applied to the FRS image for smoothing out the signal noise. As the next step, the intensity averaging zones (20×10 pixels / 1.30×0.06 mm) for pure nitrogen and pure helium streams near the jet outlet in the intensity-normalized FRS image were chosen to determine S_{FRS,N_2} and $S_{FRS,He}$. The final phase of the post-processing is obtaining χ_{He} of the He/ N_2 jet through pixel-wise calculation, in which the actual pixel intensity value $S_{FRS,mix}$ is plugged in Eq. 2 as well as the S_{FRS,N_2} and $S_{FRS,He}$ intensities found in the previous step.

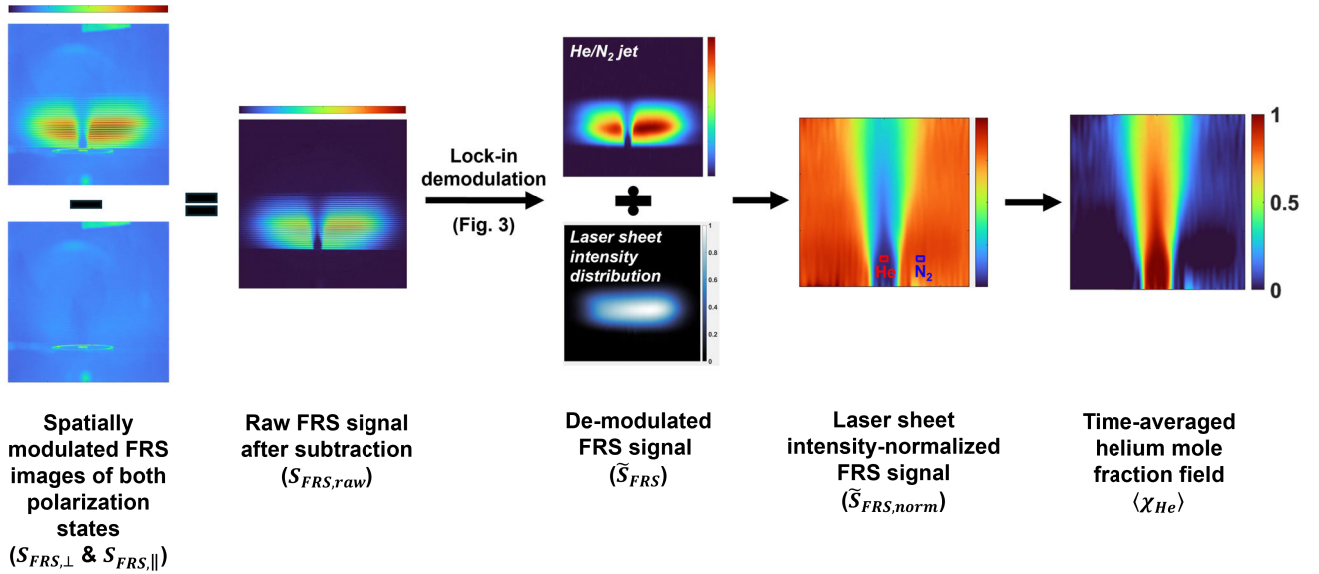


Figure 7. Post-processing procedure to obtain time-averaged helium mole fraction $\langle \chi_{He} \rangle$ from raw PS-FRS images.

Figure 8 presents the results of FRS image post-processing, demonstrating the cases with and without frequency-domain lock-in demodulation. The top row in the left half shows the laser sheet intensity normalized FRS image (Fig. 8a) and its corresponding helium mole fraction field (Fig. 8b) obtained without lock-in demodulation, where (Fig. 8c) and (Fig. 8d) are their lock-in demodulated counterparts following the same order. Starting with the FRS image intensities, the helium jet structure is evident in both demodulated and non-demodulated images with considerably lower intensities compared to the surrounding co-flowing nitrogen stream around it. The difference between their maximum intensities can be immediately noticed. Where the reduction in the image intensities can be anticipated due to the lock-in procedure with bandpass filtering, it removes up to %60 of the FRS signal (Fig. 8a versus c). However, the lock-in demodulated FRS image is spatially much smoother than its non-demodulated counterpart (excluding near jet outlet at the lower right side), despite the same steps applied except for the lock-in demodulation. The non-demodulated FRS image (Fig. 8a) still has visible traces of the structured illumination pattern. In addition, the presence of the localized pockets with near-maximum intensities in this

image is another prominent feature observed in the non-demodulated FRS image, which points to the necessity of a more rigorous treatment of these regions in the intensity normalization process. The lock-in modulated FRS image (Fig. 8c) has similar regions as well, although these are smaller and also closer to the jet outlet. On the other hand, both lock-in modulated and non-demodulated FRS images suffer from spatially non-homogeneous intensities outside the helium jet, where this region is ideally expected to be uniform within the co-flowing pure nitrogen stream. This artifact is considered to arise from the combination of laser sheet intensity normalization and frequency domain filtering, where the latter is sensitive to the filter shape and width.

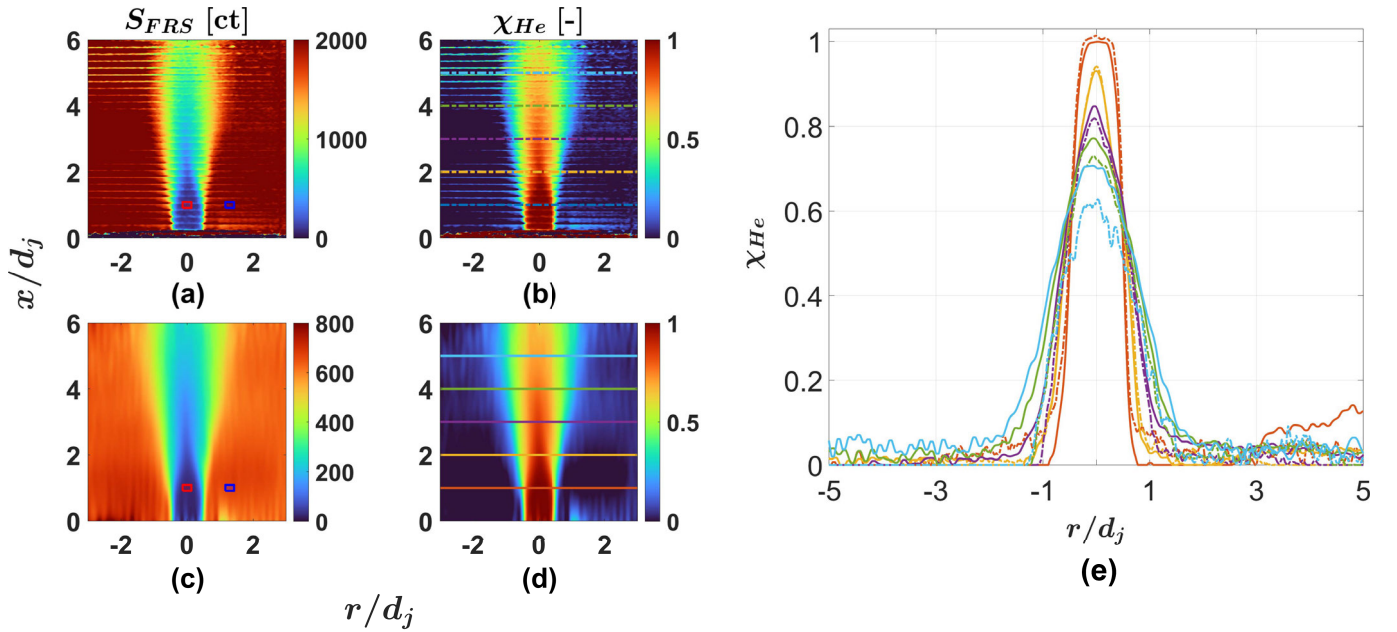


Figure 8. Post-processed SI assisted PS-FRS image intensities for $Re_d = 800$: (a) without lock-in demodulation (b) with lock-in demodulation, and time-averaged helium mole fraction fields $\langle \chi_{He} \rangle$: (c) without lock-in demodulation (d) with lock-in demodulation. Cross-sectional $\langle \chi_{He} \rangle$ profiles extracted from the PS-FRS images with (solid, —) and without lock-in demodulation (dash-dotted, ---) are presented in (e) at different jet streamwise stations indicated in (b) and (d): $x_d/r_j = 1$ (—), 2 (—), 3 (—), 4 (—), 5 (—).

Regarding the time-average helium mole fraction fields in Fig. 8b and d, they share the same aspects with Fig. 8a and c, respectively, owing to the linear relationship through Eq. 1. To provide a more detailed evaluation between them, $\langle \chi_{He} \rangle$ profiles sampled at different jet streamwise stations varying between $x/d_j = 1$ to 5 are plotted in Fig. 8e, with their color-coding identical to the marking lines in (Fig. 8b) and (Fig. 8d). Solid and dash-dotted curves in this subfigure indicate the cases with and without lock-in demodulation, respectively. The profiles clearly depict the concentration shear layer near the jet outlet, and its smearing trend further in the jet streamwise direction due to the enhanced mixing. As previously mentioned for the FRS images, the lock-in demodulated profiles are overall smoother than the non-demodulated ones, including the regions outside the helium jet. These two profiles at the same streamwise station follow each other quite closely up to

$x/d_j = 2$ (within $\sim 3\%$ for $|r/d_j| = 1$). Beyond that streamwise location, the discrepancies become more apparent and also non-demodulated profiles start to become lower than their demodulated counterpart in the helium jet. At $x/d_j = 3$, the difference between these two profiles has a peak $\approx 5\%$ near the jet centerline, where $x/d_j = 4$ has a similar difference across the jet diameter. At $x/d_j = 5$ where the laser sheet intensity is lower compared to the rest, the deviations between the profiles reach up to 15% near $r/d_j = -0.4$ and drop down to $\sim 10\%$ near the jet centerline. These outcomes are important for demonstrating the capability of the lock-in demodulation to improve the FRS signal even in the flows with low signal levels, while still retaining the flow structures.

5. Conclusions

This work developed a comprehensive Filtered Rayleigh Scattering (FRS) framework by combining polarization separation (PS) and structured illumination (SI) methodologies, along with single-phase lock-in demodulation for planar concentration measurements. This new FRS implementation was demonstrated on a round co-axial He/N₂ mixing jet, with low signal levels associated with helium-rich regions. Polarization-based image subtraction strategy helped isolate the desired Rayleigh scattering signal from any polarization-insensitive contaminants, such as background. Unlike the conventional variants like subtractive gratings, the structured illumination pattern was formed via a micro-lens array (MLA) to transmit the incident laser through the flow field with minimal losses. Spatially modulated images were then demodulated through lock-in process in frequency domain, and helium mole fraction fields were extracted from these images with ratiometric FRS signal processing.

The results revealed that the processed helium mole fraction fields and 1-D concentration profiles obtained from SI-assisted PS-FRS imaging have smoother mole fraction fields with a clear concentration shear layer, when compared to their PS-only counterparts. Despite the challenges posed by the relatively low Rayleigh scattering cross-section of the core helium stream compared to co-flowing nitrogen, the lock-in process successfully restored the helium concentration field. On the other hand, artifacts related to laser sheet intensity normalization are evident away from the helium jet, which necessitate improvements in the image processing phase to remove local inhomogeneities. Nevertheless, the lock-in demodulation procedure is seen to boost the FRS signal up to 15% in the helium jet with lower Rayleigh scattering signals, showing the robustness of the technique.

Overall, this work establishes the SI-assisted PS-FRS approach as a promising non-intrusive diagnostic strategy for optically harsh environments and low signal-to-background ratios. From this point forward, future efforts will pursue more complex cases to validate the robustness of the SI-assisted PS-FRS approach through physical concentration probe measurements and also extend it to realistic mixtures, such as fuel mixing in combustors with intense background and

particle contamination.

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Nomenclature

B	FRS signal bias parameter [a.u.]
C	calibration constant for optical collection efficiency [-]
d	jet diameter [in]
$\vec{E}$	electric field of the incident laser [V/m]
F_K	King correction factor [-]
$\mathcal{F}_T$	vapor cell transmission spectrum [-]
f	lens focal length [mm]
I_0	incident laser power intensity [W]
I_{MS}	multiply scattered incident laser intensity [a.u.]
I_{SS}	singly scattered incident laser intensity [a.u.]
$\hat{i}$	laser propagation vector [m^{-1}]
$\vec{K}$	scattering wave vector [cm^{-1}]
N	number density [m^{-3}]
n	refractive index of the scattering medium [-]
N_0	Loschmidt constant [m^{-3}]
$\hat{o}$	scattering observation vector [m^{-1}]
P	pressure [psia]
R_{gas}	ideal gas constant [$\text{J}/(\text{kg}\cdot\text{K})$]
R_{int}	internal relaxation number [-]
$\mathcal{R}$	Rayleigh-Brillouin spectral lineshape [a.u.]
Re_d	diameter based jet Reynolds number [-]
S_{Geo}	geometric (background) scattering signal intensity [a.u.]

S_{Mie}	Mie (particle) scattering signal intensity [a.u.]
S_{FRS}	Filtered Rayleigh Scattering (FRS) signal intensity [a.u.]
S_{LRS}	Laser Rayleigh Scattering (LRS) signal intensity [a.u.]
S_{TOT}	total collected unfiltered signal including all scattering contributions [a.u.]
t	thickness of the jet nozzle [mm]
T	temperature [K]
$\vec{U}$	flow velocity vector [m/s]
x	lateral image coordinate [pix]
y	vertical image coordinate [pix]
χ	mole fraction [-]
$\Delta\nu_D$	Doppler frequency shift [cm ⁻¹]
κ	thermal conductivity [W/(m·K)]
λ	incident laser wavelength [nm]
μ	shear (dynamic) viscosity [Pa·s]
μ_B	bulk viscosity [Pa·s]
ν	wavenumber [cm ⁻¹]
ν_L	laser center wavenumber [cm ⁻¹]
ν_{sm}	spatial modulation frequency [pix ⁻¹]
$\varnothing$	diameter [mm]
ϕ	angle between polarization direction and observation vector [°]
φ	spatial phase shift of modulation [°]
ρ	mass density [kg/m ³]
ρ_0	polarization ratio [-]
$\frac{d\sigma}{d\Omega}$	Rayleigh scattering differential cross-section [cm ² /sr]
σ	Rayleigh scattering absolute cross-section [cm ²]
θ	scattering angle [°]
ξ	mixture fraction [-]

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