

Toward a Fully Fiber-Integrated Filtered Rayleigh Scattering System

Connor Belt^{1,*}, Gwibo Byun¹, Evan Warner², K. Todd Lowe¹

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

2: Advanced Measurements Research & Development, Pratt & Whitney, Middletown, Connecticut, United States

*Corresponding author: cbelt5@vt.edu

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ABSTRACT

This paper presents an experimental investigation of the feasibility of a fully fiber-integrated filtered Rayleigh scattering (FRS) system that utilizes both fiber optic laser delivery and imaging bundle collection. A fully fiber-based delivery architecture offers a promising path towards moving away from bulky, constrained optical systems that will allow for measurements in increasingly difficult and confined spaces. A series of controlled measurements were performed using multi-mode fibers, combined with simultaneous direct and fiber-bundle imaging across multiple scattering geometries, to better understand the impact of fibers on the measured FRS signal. The experiments were designed to assess preservation of the filtered Rayleigh line shape, wavelength-dependent transmission behavior, and the introduction and potential removal of fiber-generated background signal. Across all the tested light delivery fibers, no observable distortion or broadening relative to the free-space laser was measured, and the iodine transmission curve was preserved in both the direct and fiber-based imaging. The system was then evaluated through staged flow-on measurements, progressing from a controlled benchtop jet to an in situ Virginia Tech High-Speed Wind Tunnel configuration. These measurements demonstrated recovery of the primary velocity and Mach number trends, with final wind-tunnel results showing qualitative agreement between FRS-derived and five-hole-probe flow-field measurements. These results establish a foundation for applying fully fiber-integrated FRS to confined internal flows and future inlet distortion measurements.

1. Introduction

Filtered Rayleigh scattering (FRS) over the past couple of decades has emerged as a powerful laser-imaging diagnostic tool for planar measurements of aerodynamic flow fields. This is due to this technique's ability to simultaneously measure density, temperature, and three-component velocity wherever the laser light interacts with the flow field. This is done in FRS by using a narrow-band laser and imaging the scattered light through a molecular absorption filter so that the elastically scattered light from large-particle (Mie) and geometric scattering becomes strongly attenuated,

while the weaker Rayleigh signal from the gas molecules is transmitted. By precisely scanning the laser across the molecular absorption features, the flow parameters can be inferred from the filtered spectra that are obtained for each pixel.

This frequency scanning method filtered Rayleigh scattering (FSM-FRS) approach has extended well beyond laboratory jet flows and now supports multi-parameter measurements in a range of scientifically relevant environments. Recent work has shown the FSM-FRS technique implemented in free shear layers, supersonic and heated jets, and overexpanded exhaust flows for planar flow field measurements (Doll et al. (2017); Saltzman et al. (n.d.)). Further development has focused on measurement capability in the presence of strong Mie and geometric scattering using structured illumination and cross-correlation techniques to obtain the weaker Rayleigh signal from the background signal (Boyda et al. (2019, 2020)). Finally, work has demonstrated the capability of using this technique to measure internal near-wall structures of confined ducts and turbomachinery passages where optical access is constrained (Doll et al. (2014); Byun et al. (2025); Powers et al. (2022)). These advances highlight the growing maturity of this diagnostic technique and the desire to further implement FRS into increasingly complex environments. Particularly, recent work in literature focused on aero-engine inlet distortion has highlighted the need for non-intrusive, multi-parameter diagnostics capable of resolving highly distorted and potentially unsteady flow fields at the aerodynamic interface plane (AIP), where conventional measurement techniques are insufficient (Doll et al. (2023); Migliorini et al. (2025)).

Despite this vast acceleration of advanced demonstrations in the field, implementing FRS into turbomachinery and engine environments still presents numerous challenges. While efforts have been made to overcome factors such as restricted optical access or strong laser-induced reflections from walls and hardware (Doll et al. (2014)), much improvement is still required. The use of molecular filtering makes FRS better suited for these environments than some of its counterpart techniques due to its suppression of Mie and geometric signals, but most state-of-the-art techniques still rely on free-space optics for laser light delivery and imaging of the flow field (Doll et al. (2014)). Due to this, FRS optical arrangements tend to stay in optically-accessible configurations, rather than truly *in situ* measurements. This limitation becomes exacerbated when considering internal flow field measurements in inlet ducts and confined turbomachinery passage ways, where highly relevant flow physics is occurring but conventional free-space optics are impractical or impossible to implement.

As a result, enabling FRS measurements within these environments requires a transition from the traditional free-space optical architectures that are typically utilized, towards an increasingly compact and versatile optical delivery and imaging system. Fiber optics provide a pathway to potentially achieve this goal, offering the ability to route laser light to the measurement region of interest and receive the scattered signal through increasingly strained geometries. The adoption of such a technique must first be validated to ensure that the full fiber architecture does not have a

lasting impact on the underlying spectroscopic measurement.

Motivated by these constraints, the broader laser diagnostic community have attempted to address this problem through the implementation of fiber-based imaging and endoscopic optics into their measurement systems. Previous studies have demonstrated the use of fiber-optic imaging for FSM-FRS in ducted flow environments (Doll et al. (2014, 2017)). This configuration utilized a laser sheet generated using free-space optics, but the test section was monitored using an endoscope connected to an image fiber bundle which relayed the scattered light from the flow field back to a camera. This endoscopic imaging enabled measurements in a confined inlet where conventional free-space imaging techniques would have struggled, while preserving the spatial fidelity required (Doll et al. (2017)). Additional implementations have been seen through the use of multi-branch imaging fiber bundles to obtain multiple viewing angles in order to achieve multi-parameter FRS measurements in inlet-type configurations (Doll et al. (2023)). This further demonstrates the potential capability of fully-fiber integrated architectures in confined geometries, but still rely on conventional free-space optics for laser delivery.

Extending this concept to a fully fiber-integrated architecture, where both laser delivery and signal collection are fiber-based, introduces additional challenges. The use of such an architecture has the potential to introduce fiber-induced optical effects and artifacts that can impact the FRS signal in relevant ways. Experimental studies of commercially available image bundles have shown that their core materials can generate autofluorescence and Raman scattering particularly in the visible and near-UV, which produces an additive background that varies with wavelength and excitation conditions (Udovich et al. (2008)). In earlier-mentioned endoscopic work, laser-induced background from the fiber bundle was observed and attributed to autofluorescence, Rayleigh, and Raman scattering (Doll et al. (2014)). This background impacted the FRS signal and had to be treated as a calibration offset in order to process the results. Detailed characterization of imaging bundles for coherence-domain applications revealed that commercial image bundles are often multi-mode in nature and exhibit optical path length variability and coherent cross-talk between cores (Steelman et al. (2018)). These observations highlight that while a fully fiber-integrated architecture enables access to increasingly confined and inaccessible measurement locations, a careful evaluation of such components is required to ensure that they do not introduce bias into the measured spectral signal or the derived flow quantities.

Despite these identified challenges, prior works have demonstrated that reliable FRS measurements can be taken using fiber-based imaging alone, indicating that full fiber integration is plausible. Related fiber-coupled laser diagnostic architectures have also been demonstrated for Doppler Global Velocimetry (DGV), including configurations using optical fibers for laser delivery and fiber-optic imaging bundles for scattered-light collection (Meyers et al. (2006), Meyers et al. (2010)). To the authors' knowledge, however, no prior work has been identified that systematically investigates the impacts of a full fiber optic system for both light delivery and image collection in

molecular FRS applications. The presented work addresses this gap in knowledge by attempting to perform a series of laboratory measurements to investigate the feasibility of a full fiber optic FRS system. Building upon the established work presented on the characterization of imaging bundles and nonlinear effects experienced in waveguides, the experiments examine the use of a full fiber system and its impact on FRS spectral behavior to better understand the reliability of the system to further advance FRS for implementation in turbomachinery environments. Specifically, this work seeks to validate that a fully fiber-integrated FRS system preserves the measured iodine transmission and resulting velocity, temperature, and density measurements across progressively complex test environments, thereby establishing the foundation required for future internal flow measurements.

2. Methodology

2.1. Filtered Rayleigh Scattering Theory

Rayleigh scattering results from the interaction of laser light with gas molecules whose thermal and collisional motion results in a molecular spectrum. In the absence of flow, molecules still undergo random thermal motions that create a series of Doppler shifts, creating a spectrum that directly relates to temperature (Byun et al. (2025)). When a bulk motion in the molecules occurs, the molecular spectrum is shifted in the frequency domain along the scattering vector that now correlates to the velocity. The scattering intensity scales with molecular number density, which enables a density estimation that can then be related to static pressure with an equation of state.

Directly measuring these weak molecular scattering signals can be difficult, as the presence of elastic scattering sources, such as Mie and geometric scattering, is much stronger. In order to filter this elastic scattering, FRS introduces a molecular absorption cell whose transmission exhibits deep and narrow troughs (Doll et al. (2014)). The Rayleigh spectrum is significantly broader than the absorption feature, allowing the narrow unshifted laser-line component to be attenuated while the Doppler-broadened molecular scattering spectrum is transmitted.

As the laser frequency is scanned across the absorption feature, each camera pixel records a local filtered spectrum intensity that corresponds to a spatial region of the flow field. This intensity is then scaled by the optical efficiency of the system and governed by the local density, temperature, and Doppler shift (velocity) (Forkey et al. (1996)). The flow properties are then obtained by matching the measured spectra to modeled lineshapes, typically generated using kinetic-theory frameworks like the Tenti S6 model (Tenti et al. (1974)), through nonlinear regression methods. Accurate interpretation of these signals relies on preserving the beam's spectral properties when delivering the light to the region of interest, while also ensuring that the detection system is not introducing wavelength-dependent distortion before reaching the camera sensor.

In order to resolve all three components of the velocity vector, more than one scattering angle is required. This is because one viewing angle provides sensitivity only to the velocity component projected along its Doppler sensitivity vector. The Doppler shift that is measured is dependent on the difference between the observation direction and laser propagation direction, $(\hat{o} - \hat{i})$, which represents how each perspective weights the velocity component (Warner & Lowe (2025)). Thus, for a single viewing angle, only one linear combination of the velocity component can be resolved, requiring more observations to solve the underdetermined problem (Warner & Lowe (2025)).

2.2. Test Configuration and Measurement Approach

The experimental configurations used in this study consist of a progression of flow-off (ambient) optical measurements to flow-on measurements conducted in both a benchtop and *in situ* wind tunnel configuration. This series of staged measurements were designed to build toward a wind tunnel based measurement series, where each step of the process is meant to isolate specific aspects of the systems performance. The flow-off experiments are used to establish first a baseline optical behavior and characterize any potential fiber-induced effects. The benchtop flow-on configuration is then meant to introduce controlled flow conditions to assess the architectures ability to accurately capture known flow conditions on a well characterized lab free-jet rig. Lastly, the *in situ* configuration integrates the full Virginia Tech High Speed Wind Tunnel (VT-HSWT) test section into the benchtop rig to evaluate performance in a near-realistic environment prior to full VT-HSWT operation, which introduces higher-speed flows and increased mechanical disturbances. All measurements were performed using a tunable Azurlight-Systems fiber laser seeded by an NKT Adjustik Y10 seed laser, providing single-frequency continuous-wave output at 532 nm with up to 10 W of power and an estimated linewidth below 40 kHz based on the specified seed-laser linewidth of less than 20 kHz.

2.2.1. Flow-Off (Ambient) Optical Configuration

A series of flow-off (ambient) experiments was performed in order to evaluate the feasibility of a fiber-based laser delivery and imaging system for an FRS measurement. These experiments were performed using two iodine absorption cells, one cell used as a reference while the other is used to monitor the scattered light within the test section. The laser light was delivered to the test section via free-space propagation (directly from the laser head), a 10 μm multi-mode high-power fiber of length 10 m, a 50 μm OZ Optics high-power multi-mode fiber of length 4 m (denoted as 50 μm short) and 35 m (denoted as 50 μm long), and a 50 μm OZ Optics high-power graded-index (GRIN) fiber of length 35 m (OZ Optics Ltd. (2005)). The scattered signal was monitored through a single fiber imaging leg, and each mode of light delivery was terminated on and monitored using amplified photodetectors (Thorlabs, PDA100A) (Thorlabs, Inc. (2025)).

This configuration, as shown in Figure 1a, utilized a single iodine absorption cell that was positioned directly in front of a 50:50 beam splitter. This enabled simultaneous acquisition of direct free-space imaging and fiber-based imaging during the same frequency scan. The scattered light was collected at a scattering angle of 45° , 90° , and 135° relative to the incident beams of light. At each scattering angle, the laser was scanned across a single iodine absorption features ($18788.4 - 18788.47 \text{ cm}^{-1}$). This provided direct comparisons of the FRS signals for the free-space versus fiber-delivered light, and direct imaging versus fiber-imaging.

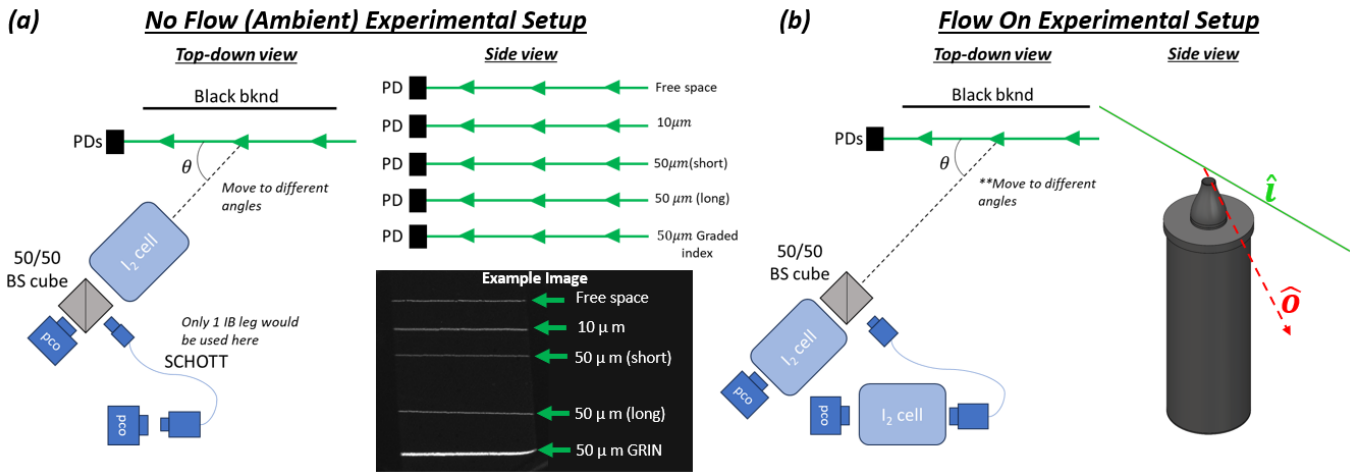


Figure 1. Optical measurement configurations used for flow-off and flow-on benchtop testing. (a) Flow-off (ambient) experimental setup illustrating laser delivery paths, iodine absorption filtering, and multi-mode fiber configurations for direct and fiber-based imaging. (b) Flow-on benchtop configuration showing the integration of scattering geometry, beam-splitting optics, and imaging paths for evaluating optical system performance under controlled flow conditions.

2.2.2. Flow-On Benchtop Optical Configuration

The flow-on benchtop configuration, shown in Figure 1b, is designed to introduce a controlled flow condition while still maintaining a simplified optical measurement. In this configuration, flow is introduced without the complexity of the full wind tunnel test section, allowing for evaluation of optical system performance under low-speed conditions. This optical setup only utilizes free-space light propagation and a 50 μm GRIN fiber. The placement of the iodine absorption filters has been modified to better replicate the configuration typically used in camera-based measurements and to assess background generation, signal attenuation, and spectral distortion introduced by light propagation through the imaging fiber bundles. Each mode of light delivery continues to be terminated on and monitored using an amplified photodetector.

This configuration serves two primary purposes. First, it acts as an intermediate step between ambient testing and full *in situ* measurements, enabling isolation of flow-induced effects on the optical system. Second, it provides a direct comparison between direct imaging and imaging bundle configurations with respect to the measured flow quantities.

2.2.3. Flow-On In Situ Optical Configuration

The flow-on *in situ* configuration, as seen in Figure 2a, is meant to integrate the optical measurement system to the VT-HSWT test section while still operating under low-speed uniform flow conditions. This system now collects the scattered light through all four imaging bundle legs, mounted to the VT-HSWT test section. Based upon the findings for the configuration in Section 3.2, it was decided to measure both 50 μm and 10 μm high-power multi-mode fibers. This configuration serves as the final validation step prior to VT-HSWT measurements, providing a controlled environment to assess system robustness, signal quality, and alignment sensitivity under realistic in-duct flow conditions.

2.2.4. High-Speed Wind Tunnel Facility

All facility inlet measurements were conducted in the VT-HSWT located in the "Advanced Power and Propulsion Laboratory" (APPL). The facility operates in a suction-driven configuration where the flow is drawn through a 6-inch diameter circular flow duct to the test section using a downstream exhaust system. Two exhaust systems are coupled in parallel to achieve test-section flow rates up to approximately Mach 0.6 under unobstructed-flow conditions, prior to the installation of distortion-generating hardware or other flow-obstructing test articles. These systems consist of a Hoffman 75103A multistage centrifugal blower and a Panther WA3125D rotary-lobe positive-displacement blower, with maximum flow capacities of approximately 5000 CFM at low pressure rise and 1000 CFM, respectively.

As seen in Figure 2b, the flow is drawn through a flow conditioning section to reduce large scale non-uniformities before passing through a bell-mouth contraction that transitions the flow into the 6-inch diameter duct. Once in the duct, distortion devices can be introduced upstream of the test section to impose a controlled non-uniformity. The distortion device is mounted on a rotational traverse system, allowing controlled circumferential positioning relative to the measurement plane. For the purposes of this report, only uniform flow cases have been studied within the tunnel. Following the test section, a diffuser is used to guide the flow toward the exhaust system.

The test section consists of a straight 6-inch diameter duct segment designed to provide both optical access and flow measurement capability at a defined measurement plane. The section is instrumented with eight circumferentially spaced wall static pressure taps located in a ring around the measurement plane, allowing characterization of the static pressure distribution. The measurement plane utilizes a crossed laser-line configuration, enabling localized, non-intrusive interrogation of the flow field at the intersection region. The laser light was delivered to the test section with the use of 10 μm high-power multi-mode fibers.

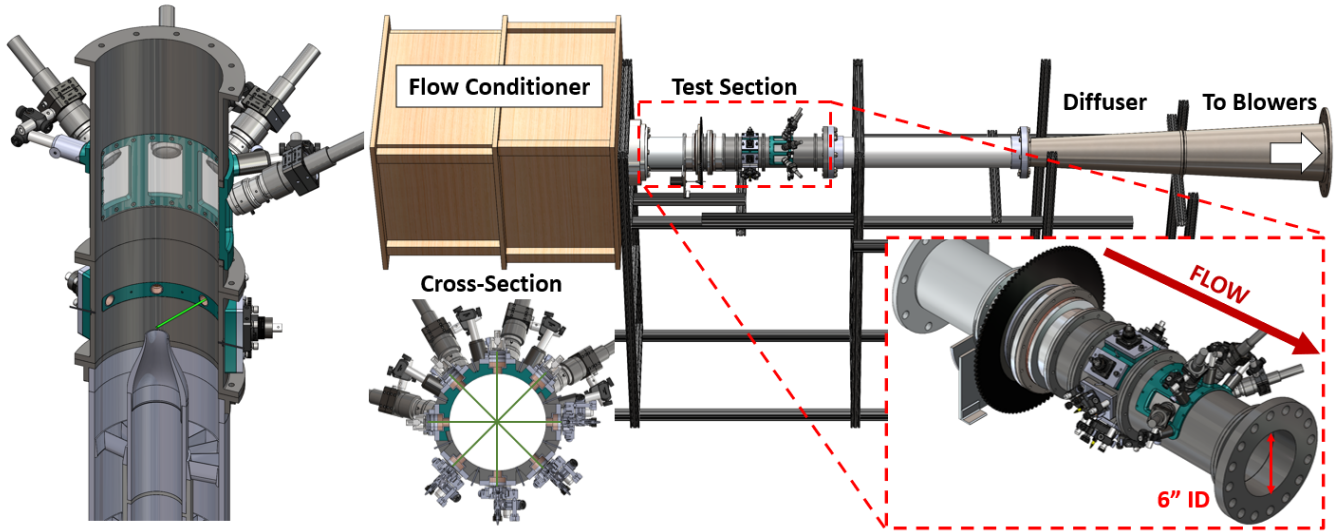
(a) Flow On In Situ Experimental Setup**(b) High Speed Wind Tunnel (HSWT) Experimental Setup**

Figure 2. Experimental configurations used for flow-on testing. (a) Flow-on in situ optical measurement setup integrated within the test section, showing laser and optical access locations. (b) Schematic of the Virginia Tech High-Speed Wind Tunnel (VT-HSWT) highlighting a detailed view of the test section instrumentation.

3. Results & Discussion

3.1. Flow-Off (Ambient) Results

The no flow benchtop results, plotted in Figure 3, shows the normalized scattered intensity as the laser frequency is scanned across the iodine absorption feature. For each region of interest, the resulting signal was normalized by its corresponding mean intensity across the full wavelength scan. The x-axis on all figures represents the shift from the center wavenumber of the absorption feature located at $18,788.435 \text{ cm}^{-1}$. During processing, five regions of interest were selected, each centered on the high-intensity core of one laser-delivery path shown in the example image in Figure 1a. These regions correspond to free-space delivery, the $10 \mu\text{m}$ fiber, the short $50 \mu\text{m}$ fiber, the long $50 \mu\text{m}$ fiber, and the $50 \mu\text{m}$ graded-index fiber. Importantly, these regions represent separate light-delivery signals within the image, not separate physical locations in the flow field. For each laser frequency, a mean pixel count was extracted from each region of interest and then background subtracted and normalized by the total mean signal for each light delivery case. The bottom row of plots in Figure 3 show the mean normalized response for the image bundle and camera paths, with 95% confidence limits computed from the variation between the five delivery cases.

When analyzing the measurements for both the image bundle and free-space imaging, the different fiber types all collapse onto the free-space spectral signal. The near-single-mode $10 \mu\text{m}$ fiber and increasingly multi-mode $50 \mu\text{m}$ fibers all overlay closely with little to no detectable shift or

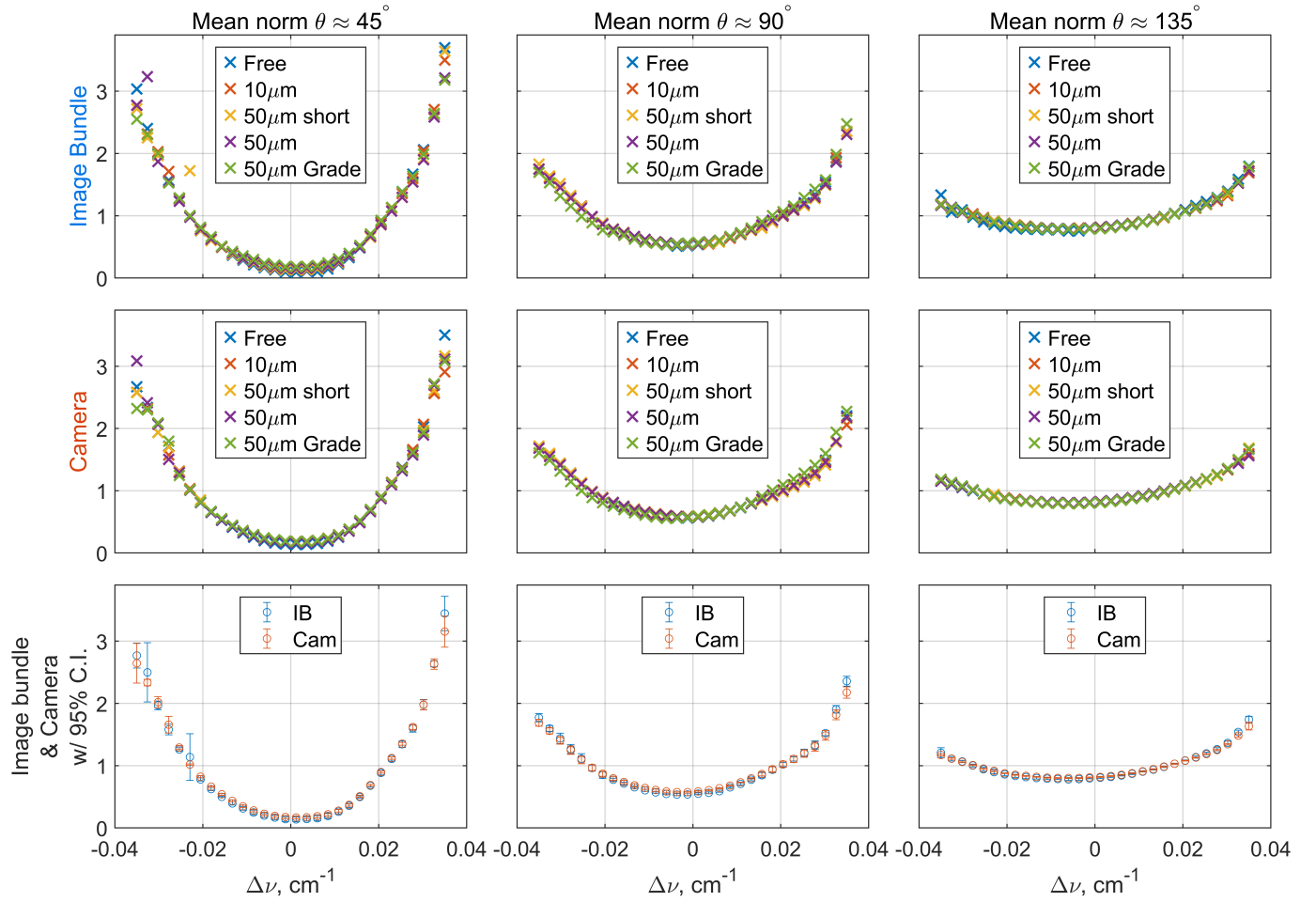


Figure 3. Normalized iodine-filtered spectral response measured under flow-off (ambient) conditions for varying laser delivery configurations and scattering angles. The top row shows image bundle measurements, the middle row shows direct camera measurements, and the bottom row compares the image bundle and camera responses with 95% confidence limits. Results are shown for free-space delivery, 10 μm , 50 μm short, 50 μm , and 50 μm GRIN fibers at scattering angles of $\theta \approx 45^\circ$, 90° , and 135° .

broadening. This indicates first that the fiber light delivery does not introduce a detectable relative shift from that of the free-space light deliver. Second, it suggests that fiber length, core diameter, and modal content do not appear to have an initial affect on the measured spectral response under ambient conditions.

Additionally, the bottom row of plots show reasonable agreement between the image bundle and direct imaging paths. When looking at the combined light delivery spectral trends with 95% confidence limits, the image bundle and direct imaging curves closely overlap for all three scattering angles. This indicates that the propagation of the filtered Rayleigh signal through the imaging fibers does not introduce a detectable distortion in the measured signal.

This behavior is consistent across all three of the scattering angles, $\theta \approx 45^\circ$, 90° , and 135° . The absolute shape of the normalized measured signal changes with scattering angle due to the mea-

surement geometry's impact on the observed signal intensity. The same conclusions presented above still hold true for each scattering angle, showing that the fiber-delivered cases overlay with free-space, and the image bundle overlays with the direct camera response. Thus, in the absence of flow, laser light delivery fibers and the use of imaging bundles appear to have no detectable impact on the measured filtered signal.

3.2. Flow-On Benchtop Results

The flow-on benchtop measurement was evaluated against a controlled jet condition where the expected Mach number is approximately 0.4 for the jet centerline. In Figure 4, the top row of plots shows the free-space laser delivery while the bottom row shows the results for the 50 μm GRIN fiber. For each row, the imaging bundle has been plotted against the direct imaging measurements for axial velocity, static density, static temperature, and Mach number.

When looking at the free-space results, strong agreement can be seen between the direct imaging and the image bundles. Both measurement approaches capture the expected jet structure. The velocity field shows a clear peak near the jet centerline with a peak Mach number within the

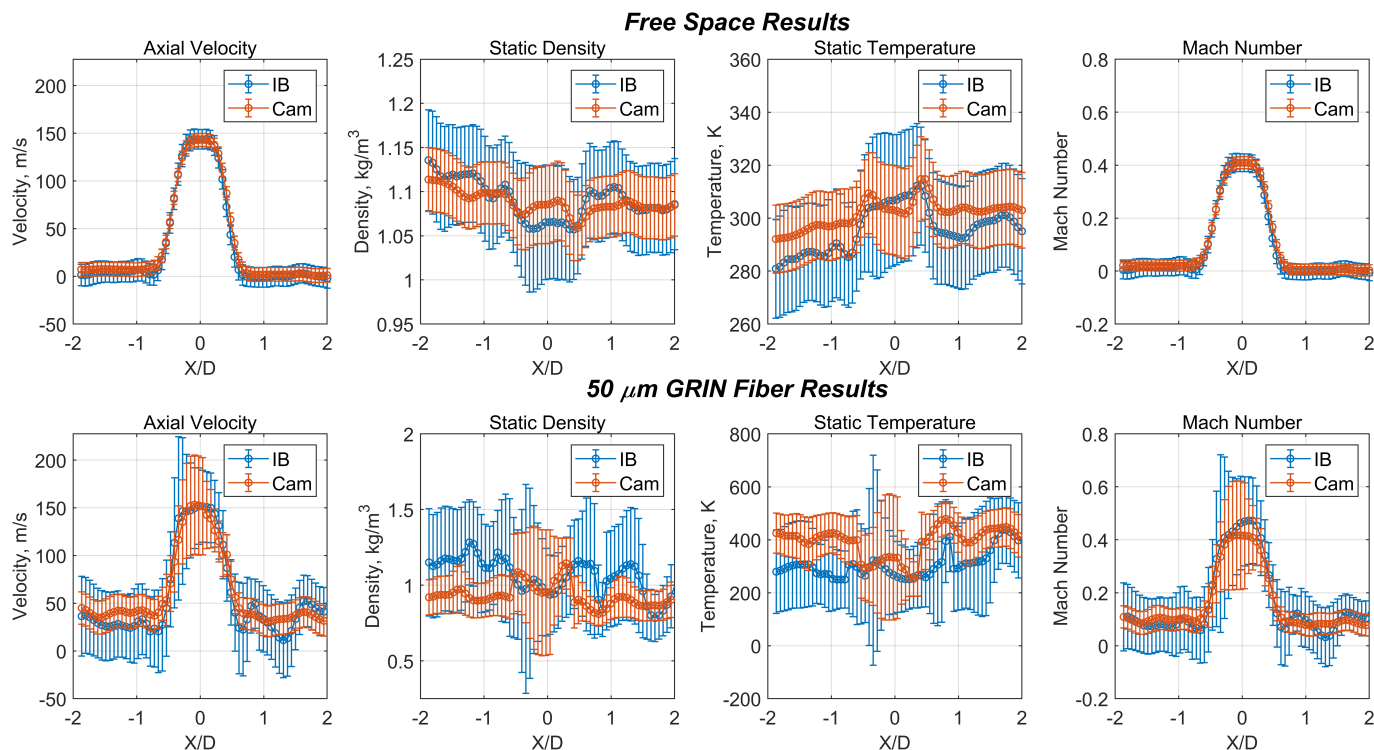


Figure 4. Comparison of FRS-derived flow quantities obtained during controlled benchtop jet measurements for free-space and 50 μm GRIN fiber laser delivery configurations. The top row shows the free-space delivery results, while the bottom row shows the 50 μm GRIN fiber results. Comparisons between the image bundle (IB) and direct camera (Cam) measurements are shown for axial velocity, static density, static temperature, and Mach number distributions across the jet centerline.

expected range. The static temperature additionally shows the expected profile for this jet configuration. The ambient temperature during the measurement was measured to be 295 K, with an expected core temperature of approximately 315 K. This indicates that for free-space light delivery, both imaging paths are able to recover the expected flow quantities along with the expected profile of the jet.

The 50 μm GRIN captures the main velocity and Mach number behavior of the jet for both the direct imaging and image bundle cases. However, when looking at the thermodynamic quantities, a degraded measurement performance is shown compared to that of the free-space case. The temperature profile captured by both the direct and fiber-based imaging does not capture the jet core temperature profile, and instead shows a constant ambient temperature across the core. These results suggest that the 50 μm GRIN is sufficient for capturing the Doppler shift for velocity, but introduces enough spectral or intensity instability to degrade the recovery of more sensitive thermodynamic quantities.

These benchtop flow on results motivated the additional *in situ* testing with the 10 μm fiber. Since the 50 μm GRIN fiber did not reliably capture the known temperature increase, the 10 μm fiber was tested to reduce modal effects and improve spectral stability. For the purpose of testing, the 50 μm GRIN fiber is preferred for its availability to couple higher laser power into the test section. As shown later though in the *in situ* measurements, this change to a smaller fiber core enabled the density dynamics to be recovered more reliably.

3.3. Flow-On In Situ Results

Finally, Figure 5 highlights the flow on *in situ* results using the VT-HSWT test-section configuration with 4 image bundles. For this test, no direct imaging analysis has been performed, and instead, the results show the combined response from all four imaging bundle legs, labeled as all cams. The top row of plots shows the results for the 50 μm multimode (long) fiber while the bottom row shows the results for the 10 μm multimode fiber. Within these figures the dashed horizontal line in the static density and static temperature plots represents the known ambient reference condition. This decision to transition from the 50 μm GRIN fiber to the 50 μm multimode fiber was made because the GRIN fiber is not designed for high-power optical coupling, as specified by the manufacturer. This change enabled increased power delivery through the fiber and, consequently, a higher signal intensity within the measurement plane.

When first examining the 50 μm multimode fiber, the axial velocity profile results continue to capture the primary flow structure within the jet core. However, the corresponding static density and temperature profiles show increased variability from the known ambient conditions. The temperature response appears to show broader fluctuations than that of the flow-on benchtop results, and the mean density no longer agrees with that of the known ambient conditions. This may indicate

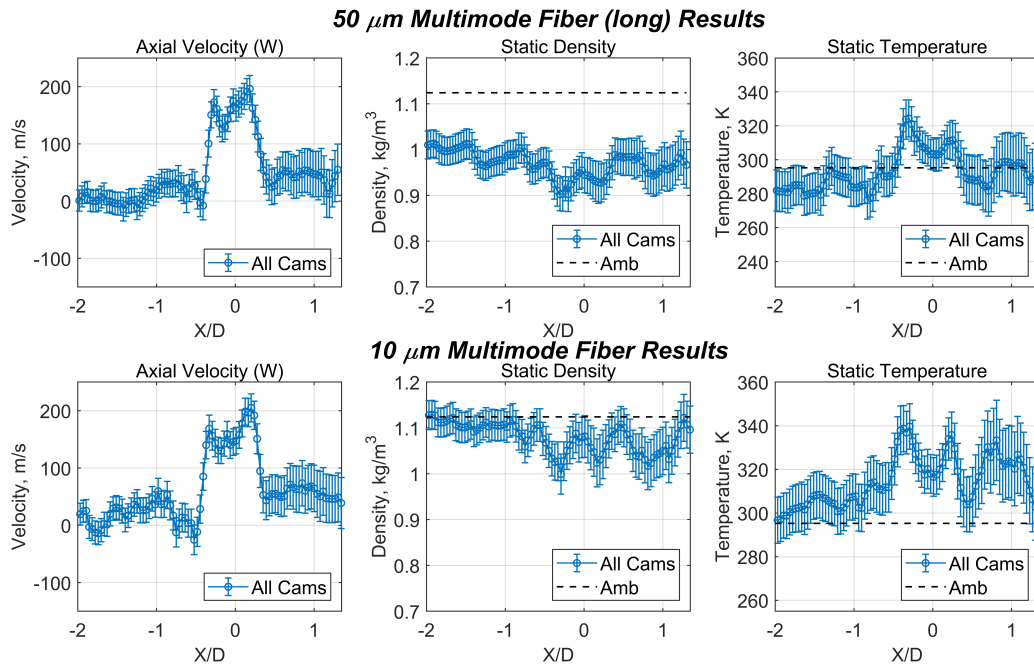


Figure 5. FRS-derived flow quantities measured within the VT-HSWT test section using the imaging-bundle-based architecture under nominally uniform flow conditions. Results are shown for the 50 μm multimode fiber (top row) and 10 μm multimode fiber (bottom row) delivery configurations. Data is shown for the combined imaging bundle response (All Cams) are presented for axial velocity, static density, and static temperature. Dashed lines indicate the known ambient reference conditions for density and temperature.

that the larger core structure of the light delivery fiber leads to spectral or intensity variability that degrades recovery of the flow properties. This, coupled with warping and additional losses from the test section acrylic window, has led to the loss of accurately obtainable flow quantities.

Switching to the 10 μm multimode fiber, an overall improved agreement between known flow parameters can be seen to that of the measured FRS results. The jet velocity profile still reports that of the expected but the recovered density remains closer to the known ambient reference across the measurement domain. This suggests that the smaller-core fiber has an impact on the spectral response for the *in situ* configuration. This behavior is consistent with the motivation for testing the 10 μm fiber as discussed at the end of Section 3.2.

Comparing the static temperature results for both fiber configurations show that the thermal response is only partially captured in the jet core. The 10 μm multimode case appears to produce a broader temperature variation with larger fluctuations, while the 50 μm case yields a more bounded response that remains closer to the expected temperature range. Both cases still exhibit an oscillatory behavior and deviations from the ambient reference, indicating that temperature remains the most sensitive recovered quantity in the *in situ* environment.

Overall, these findings demonstrated that the fully fiber-integrated architecture can successfully recover the primary flow quantities and structures of the benchtop jet. Based upon the presented

results the 10 μm fiber show improved results beyond that of the other fibers due to a reduction in modal effects within the delivered light leading to an improved measured spectral signal under realistic flow conditions. Due to this, the following inlet distortion measurements were performed with the use of the 10 μm fibers.

3.4. High-Speed Wind Tunnel Facility Results

Following this analysis, the VT-HSWT measurements were conducted under a uniform flow condition in an effort to understand the full fiber architecture's ability to recover primary flow structures in a facility environment. Figure 6 compares the FRS-derived measurement using four 10 μm fibers monitored by the image bundle relay against the reference 5-hole probe measurement. This analysis compares Mach number and axial flow distribution across the measurement plane. The upper row shows the results collected by the 5-hole probe, while the lower row shows the corresponding FRS derived results.

The 5-hole probe under these uniform flow conditions captures the radially symmetric profile

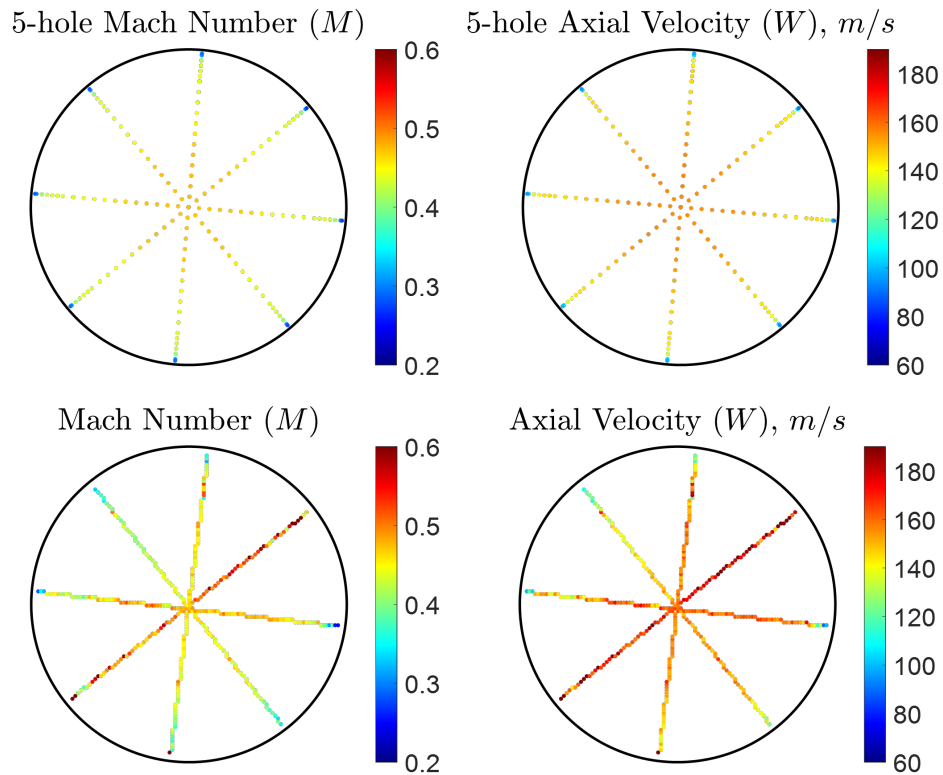


Figure 6. Comparison of five-hole probe and FRS-derived measurements within the VT-HSWT under nominally uniform flow conditions. The top row shows the reference five-hole probe measurements, while the bottom row shows the corresponding FRS-derived results. Mach number distributions are shown in the left column and axial velocity distributions are shown in the right column.

expected for the development of a 6-inch ducted tunnel. The measured Mach number distributions show a peak value near the center, with a gradual reduction towards the radial wall. The axial velocity shows a similar trend, with the peak velocity at the centerline with a reduction near the wall at the boundary layer.

Analyzing the FRS-derived measurement, there is a strong qualitative agreement to that of the 5-hole probe results. The spatial trend that is observed for both the Mach number and axial velocity match that of the 5-hole probe indicating that the architecture accurately captures the primary flow structure. The FRS-derived profiles show a reduction trending towards the wall capturing the expected flow gradient. While the overall structure exists, point to point variability can be seen, especially towards the outer edge near the boundary layer region. These fluctuations are likely associated with low signal to noise ratio due to factors such as increased reflections of the laser lines off components such as entry and exit windows along with photodetectors. Overall, despite some of this variability, the results indicate that this architecture is capable of recovering realistic flow quantities when integrated with the VT-HSWT environment. The ability of the FRS system to reproduce the global flow structure using fiber delivery and imaging represents an important validation step toward future measurements in more complex flow environments, including high-speed distorted inlet flows.

4. Conclusions

The work presented here has shown a staged experimental evaluation of a full fiber integrated FRS measurement architecture intended for implementation at the Virginia Tech High-Speed Wind Tunnel (VT-HSWT). The experimental campaign progressed from a flow off ambient measurement, to a benchtop flow on measurement, leading to an informed *in situ* wind tunnel measurement, and finally to a fully integrated wind tunnel measurement. This progression was meant to isolate specific aspects of the optical systems performance prior to operation in a full-scale wind tunnel.

Initial flow-off benchtop measurements showed that neither the laser delivery fibers or the imaging bundle introduced a detectable spectral shift relative to the free-space light delivery or direct imaging. By varying the scattering angle it can be seen that for free-space, 10 μm , and varying 50 μm light delivery methods, all collapse closely onto the same curve for both imaging cases. This close agreement between imaging type, fiber type, and scattering angle sets an important baseline demonstrating that integration of fibers does not initially alter the spectral signal.

From here, an evaluation of the system ability to recover known flow quantities was performed by performing measurements on a controlled Mach 0.4 jet flow. The free space light delivery configuration showed that for both the direct imaging and fiber imaging, the expected jet velocity profile, Mach number distribution, and associated temperature increase was accurately captured. On the other hand, the 50 μm multimode fiber continued to recover the primary velocity and Mach

number behavior, the thermodynamic quantities showed degraded performance and increased variability. This is believed to be due to the larger core causing increased spectral or intensity variability that impacts the recovery of more sensitive flow quantities such as temperature.

The desire for increased power, and thus an increased Rayleigh signal within the flow environment, motivated the continued testing of the 50 μm multimode fiber, but also the 10 μm multimode fiber in an attempt to better understand the modal impact on derived flow quantities. Due to this, the measurement architecture was extended to an *in situ* realistic in duct flow measurement using these two fiber types. This is meant to help better understand what would actually be recovered in a facility measurement. From this work, the 10 μm fiber showed improved agreement over that of the 50 μm fiber. Both fiber types showed similar velocity profile recovery, but the 10 μm fiber showed increased sensitivity to capturing more sensitive flow properties such as density. Although, the recovered temperature fields for both light delivery cases showed increased variability for the derived temperature field. From this, it was concluded that the reduced modal effects associated with fiber core diameter does impact the spectral stability under realistic operating conditions.

Finally, the VT-HSWT facility measurement provides a direct comparison of an FRS-derived and 5-hole probe measurement that demonstrates that the optical architecture can successfully recover the primary flow structures within the tunnel environment. The FRS measurement was capable of reproducing a global Mach number and axial velocity distribution that was captured by the 5-hole probe. Although the FRS measurements exhibited increased point-to-point variability, the overall agreement validated the ability of the fiber-integrated architecture to operate within a realistic in-duct flow environment. Overall, the presented work establishes a foundational framework for implementing a fiber-integrated FRS architecture in confined and inaccessible measurement environments.

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Nomenclature

FRS Filtered Rayleigh Scattering

VT – HSWT Virginia Tech High Speed Wind Tunnel

GRIN Graded Index Fiber *M* Mach number

PD photodetector

R/D radial position normalized by duct diameter

T static temperature

u axial velocity

WN optical wavenumber

X/D axial position normalized by duct diameter

$\Delta\nu$ wavenumber shift relative to the iodine absorption feature center

θ scattering angle relative to the incident laser beam

ρ static density

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