

Experimental Methods to Improve Multi-Parameter Estimation of filtered Rayleigh scattering for High Temperature Flows

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ABSTRACT

This work experimentally evaluates two strategies for improving the estimation uncertainty in multi-parameter FRS measurements in high temperature, Doppler broadened flows: frequency scanning over multiple Iodine absorption features and joint estimation using multiple camera perspectives. These strategies were tested on a Honeywell TFE-731 turbofan exhaust, where the measurement spans both low and high Doppler broadening conditions. It is found that the use of multiple Iodine absorption features reduced the median absolute errors in total temperature and total pressure by a factor of up to 4.2. Furthermore, multi-camera joint estimation, relative to single-camera estimation, reduced the median absolute errors by a factor of up to 17.4. The reduction in uncertainty using these strategies also follow similar trends. These results demonstrate that the addition of highly informative observations can significantly reduce measurement uncertainty and error.

1. Introduction

Non-intrusive, planar measurements of flow-field quantities are highly desirable for many diagnostic applications, such as for high temperature reacting flows, but is seldom achieved. Filtered Rayleigh scattering (FRS) offers this capability by extracting spectral information on static density, static temperature, and velocity from light scattered by molecular gases. It achieves this by using a coherent laser source, formed into a point, line, or plane of laser light and directed to the measurement plane of interest. Laser Rayleigh scattering (LRS, Fig. 1a) has static temperature encoded into the Full-Width Half-Maximum (FWHM) of the spectral distribution, arising from thermal, random motion of the gas molecules. Static density depends on the number of scatters within the fluid volume. Lastly, bulk motion of the gas stemming from aerodynamic velocity results in a Doppler frequency shift of the LRS spectrum with respect to the incident laser frequency (Miles et al., 2001; Cutler & Lowe, 2023; S. W. Powers et al., 2023; S. Powers et al., 2022).

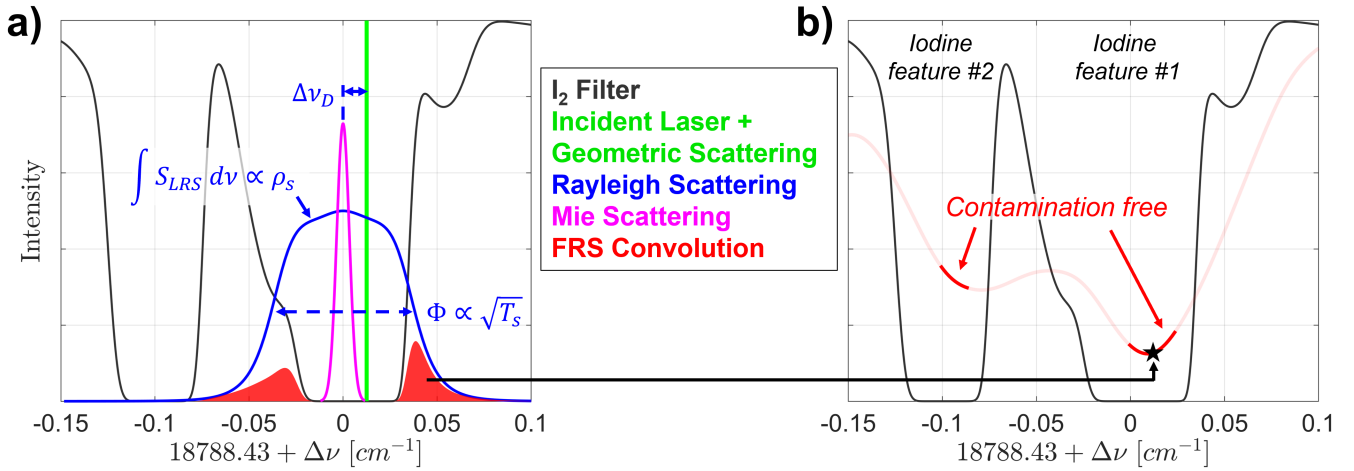


Figure 1. a) Illustration of the Rayleigh scattering signal (and additional Mie and geometric scattering) and the transmission of the iodine filter. The functional dependencies of static temperature, static density, and the Doppler shift due to bulk velocity on Rayleigh scattering are shown. b) The resulting convolution a.k.a. the FRS signal. The darker red regions indicate where the FRS signal is free from Mie and geometric contamination.

Sources of contamination, such as light scattering from large (Mie) particles, or surface reflections (geometric scattering), are often several orders of magnitude stronger than LRS (Fig. 1a) (Boyda et al., 2020). To suppress these contributions, a vapor filter (e.g. Iodine for 532nm laser light) is used, where its absorption bands act as an optical notch filter (Devlin et al., 1971). However, once the scattered light passes through the filter, the integrated intensity is collected onto a camera sensor, and the underlying spectral information of LRS is lost. A frequency-scanning method (FSM-FRS) attempts to recover the spectral information encoded into the LRS signal by tuning the incident laser frequency across the absorption bands of the vapor filter, effectively probing the convolution of the LRS spectrum and the transmission profile of the filter (Fig. 1b) (Miles et al., 1996; Forkey, 1996). By doing this, multi-parameter estimation of static density, static temperature, and vector velocity is possible.

Multi-parameter FSM-FRS has seen many successes in different flowfield applications, such as in ducted flows (U. Doll et al., 2014), laboratory jets (U. Doll et al., 2017), and turbofan engines (S. Powers et al., 2025). However, there is a lack of high temperature applications beyond the joint work of U. Doll et al. (2016) and Schroll et al. (2016) at approximately 1100 K. An underlying reason for this is due to the inherent challenge of collecting sufficient information in the measurements for multi-parameter estimation, as recently detailed by Hanley et al. (2026) in measurements on a combustion jet rig up to $T_t = 1300$ K. As the flowfield temperature increases, the LRS signal broadens, causing the resulting FRS signal to become flat over the frequency scan points. In essence, spectral information degrades as this so-called Doppler broadening of the LRS signal becomes extreme. Hanley et al. (2026) was able to empirically show the degradation of the FRS model sensitivity, as well as the degradation and cross-sensitivity within the Fisher information matrix and error co-

variance matrix. Ultimately, this led to poor precision of the estimator, reaching up to 40% of the measured value. However, the study did not investigate solutions to the problem.

Therefore, the objective of this paper is to test whether the degrading sensitivity and increasing uncertainty in Doppler broadened FSM-FRS signals can be mitigated by adding informative observations into FRS processing. Two strategies are considered: scanning across multiple Iodine absorption features (depicted in Fig. 1b), and joint estimation from multiple camera perspectives. These studies are conducted on a Honeywell TFE-731 turbofan exhaust with probe validation data to assess both the uncertainty and error of these different strategies across a wide range of Doppler broadening parameters.

The remainder of this paper is organized as follows. Sections 2 and 3 covers the theory of FRS and Fisher Information, respectively. Section 4 explains the methodology used in this study. Section 5 contains the results, and 6 provides a discussion of the findings. Finally, Section 7 provides conclusions and future directions.

2. FRS theory

The base measurement model for FRS is:

$$S_{FRS}(\nu_0) = C\rho_s \frac{d\sigma}{d\Omega} \left[\int_{-\infty}^{\infty} S_{LRS}(X, Y) \tau_{I_2}(\nu - \nu_0 + \Delta\nu_D) d\nu + B(\nu_0) \right] \quad (1)$$

where $S_{FRS}(\nu_0)$ is the FRS signal collected at the incident laser wavenumber. The integral represents the convolution of the LRS signal S_{LRS} and the transmission profile of the Iodine filter τ_{I_2} (visually depicted in Fig. 1). S_{LRS} is a function of Y parameter and dimensionless frequency X :

$$Y = \frac{p_s}{\sqrt{2}K u_0 \eta} = \frac{\rho_s R T_s}{\Phi \eta} \quad (2)$$

$$X = \frac{2\pi(\nu - \nu_0)}{\sqrt{2}K u_0} = \frac{2\pi(\nu - \nu_0)}{\Phi} \quad (3)$$

where $K = \frac{4\pi}{\lambda} \sin\left(\frac{\theta}{2}\right)$ is the magnitude of the interference wave vector between the incident and scattered light, $u_0 = \sqrt{k_B T_s / m}$ is the thermal velocity of a molecule, m is the mass of the gas molecule, η_B is the bulk viscosity, and k_B is the Boltzmann constant. Φ is the Doppler broadening parameter, which controls the FWHM of the LRS signal (Fig. 1a). As empirically demonstrated by Hanley et al. (2026), increasing amounts of Doppler broadening lead to a flattening of the FRS signal, which leads to a decrease in the information available in the signal, which ultimately increases measurement uncertainty. In summary, the convolution mainly controls the shape of the FRS signal across ν_0 and has the functional dependencies of static temperature T_s , static pressure

p_s or static density ρ_s , and scattering angle of the camera perspective θ (see Fig. 2b). Outside of the brackets contain intensity scaling terms, namely the intensity scaling parameter, C , the differential scattering cross-section, $\frac{d\sigma}{d\Omega}$ (gas species dependent), and static density. Lastly, $B(\nu_0)$ describes any other signal contributions, such as Mie and geometric scattering.

Doppler shift can be converted to aerodynamic velocity via:

$$\Delta\nu_D = \frac{\vec{V} \cdot (\hat{o} - \hat{i})}{c\lambda} = \frac{V_s}{c\lambda} \approx \frac{W(\hat{o} - \hat{i})_z}{c\lambda} \quad (4)$$

where c is the speed of light, $\vec{V}$ is the velocity vector, $\hat{o}$ and $\hat{i}$ are the observation and laser directions, respectively. One can obtain the velocity vector entirely by expanding the dot product into a system of three or more equations, provided that three or more camera perspectives/Doppler shifts are obtained. However, for reasons that will be expounded upon in Sections 5 and 6, a one-component velocity assumption is employed in this paper, where the velocity is assumed to be predominantly in the axial direction (W , see Fig. 2b).

3. Fisher Information Theory

To obtain the multi-parameter flow field quantities, the model (Eq. 1) is fit to the measured FRS data via a nonlinear least squares minimization problem (S. Powers et al., 2022):

$$\min_{\mathbf{x}} \|\mathbf{S}_{\text{FRS}}(\mathbf{x}) - \mathbf{y}\|_2^2 \quad (5)$$

where $\mathbf{S}_{\text{FRS}}$ is the modeled signal from Eq. (1) and $\mathbf{y}$ is the measured data, and the 2-norm is taken across the frequency scan points ν_0 . Solving this minimization problem is typically done iteratively using Levenberg-Marquardt algorithms (S. Powers et al., 2022). Typically, $\mathbf{x} = [C]$ is estimated using data collected at reference (i.e. ambient) conditions, and, depending on the processing technique, $\mathbf{x} = [\rho_s, T_s, V_s]$ is estimated using data collected during the flow field experiment (S. Powers et al., 2022). Details about the processing techniques used in this paper will be presented in Section 4.

After achieving a least-squares solution to Eq. (5), an important question a practitioner must ask is: what is the uncertainty of the estimated parameters from the FRS model fit? One option is to perform Monte Carlo simulations of the model fitting procedure with a given noise model to generate a statistical uncertainty estimate for each parameter (S. Powers et al., 2022). The noise model can be theoretical or estimated from measured data. Another approach, commonly employed for experiment design (Fischer et al., 2008; Fischer & Czarske, 2010; Fischer et al., 2010; Cadel & Lowe, 2016; Pitt, 2023), is to use the Cramér-Rao lower bound (CRLB) Theorem. The CRLB Theorem states that the variance of any unbiased estimator must satisfy the following:

$$\text{var}(\hat{\mathbf{x}}) \succeq \Gamma(\mathbf{x})^{-1} \quad (6)$$

The CRLB provides a lower theoretical bound for the achievable variance of an estimator (Kay, 1993).

$\Gamma(\mathbf{x})$ is the Fisher Information Matrix (FIM), which is defined as:

$$\Gamma(\mathbf{x})_{ij} = -E \left[\frac{\partial^2 \ln p(S_{FRS}, \mathbf{x})}{\partial x_i \partial x_j} \right] \quad i, j \in (1, 2, \dots, M) \quad (7)$$

Mathematically, it describes the expected curvature of the log-likelihood function. The FIM describes the likelihood of observing an FRS signal, given $\mathbf{x}$. This can be interpreted in two ways:

- Signal perspective: A signal is said to have a high amount of Fisher information when only a narrow set of signals could possibly be realized at a given $\mathbf{x}$.
- Parameter perspective: A signal is said to have a high amount of Fisher information when only a narrow set of parameter values could possibly explain the realized signal.

Referring back to Eq. (6), in order to minimize the variance of the estimator, one must maximize the Fisher information, or minimize the range of parameter values that could explain the realized signal.

As shown by Fischer & Czarske (2010), the FIM can be computed for Eq. (1) in a straightforward manner, following a manipulation of Eq. (7) into:

$$\Gamma(\mathbf{x})_{ij} = \sum_{k=1}^K \frac{1}{V_k} \frac{\partial^2 S_{FRS_k}}{\partial x_i \partial x_j} \quad i, j \in (1, 2, \dots, M) \quad (8)$$

A critical element in this approach is the selection of an appropriate noise variance model V_k . For experiment design, it is typical to assume the minimum achievable noise of the instrument. For photon-counting process (Poisson distributed), which is the case for FRS, the variance is equal to its expectation, or $V_k = S_{FRS}(\nu_{0_k})$ (Hasinoff, 2014). With this assumption, the variance of Eq. (6) corresponds directly the CRLB (Kay, 1993). In contrast, this work estimates the noise variance based on the residual between the the model fit to the measured data, or $V_k = \text{Var} [\mathbf{S}_{FRS}(\mathbf{x}) - \mathbf{y}]$. This provides a more realistic estimate of measurement uncertainty for a given dataset, under the assumption that the residual is dominated by random noise.

Eq. (8) is a summation of the "per-observation" contribution $\frac{1}{V_k} \frac{\partial^2 S_{FRS_k}}{\partial x_i \partial x_j}$ of all observations within the set $k = 1, 2, \dots, K$. As found by Hanley et al. (2026), Fisher information decreases as a function of Φ , ultimately producing poor uncertainty estimates. This was largely due to a diminution of

the FRS model sensitivity $\frac{\partial^2 S_{FRS_k}}{\partial x_i \partial x_j}$, which led to poor estimation (Kay, 1993). One of the logical solutions to this problem is to increase the Fisher information available for Doppler broadened FRS signals by increasing the number of informative observations. The two strategies tested in this paper to add these informative observations are frequency scanning over multiple Iodine absorption features, and joint inversion from multiple camera perspectives. In the next section, these two strategies are described in detail.

4. Methodology

4.1. Frequency Scanning

The first approach is to scan over Fisher-informative frequency scan points. As mentioned in Section 2, FSM-FRS is limited to scanning over frequencies where Iodine absorption features are present in order to suppress contamination. Fig. 1b shows an example Iodine transmission, where FRS measurements are usually taken where the Iodine transmission is below 10^{-5} , where the filtering of narrowband contamination is effective (Warner et al., 2025; U. Doll et al., 2014). To that point, many applications in literature choose the Iodine feature #1 (Fig. 1b), centered around 18788.43 cm^{-1} for its strong suppression performance. It is common to collect several dozen frequency scan points across its available scanning range. However, the resulting FRS sensitivities $\frac{\partial^2 S_{FRS_k}}{\partial x_i \partial x_j}$ over this narrow scanning range are similar, which results in diminishing returns to the reduction in uncertainty when increasing the number of frequency scan points. Instead, multiple Iodine absorption features can be scanned, visually depicted in Fig. 1b. Employed previous in works by U. Doll et al. (2023) and G. C. Doll U.;Stockhausen (2018), each scanning range probes a different portion of the FRS convolution, producing a unique sensitivity, ultimately providing a unique benefit to the overall FIM. In this paper, this strategy shall be tested using the aforementioned Iodine feature and a neighboring feature centered around 18788.32 cm^{-1} (Iodine feature #2, Fig. 1b).

4.2. Multi-Camera inversion

The second approach is to use joint estimation from multiple camera perspectives. As initially mentioned in Section 2, FSM-FRS is commonly done using three camera perspectives, since it enables estimation of the three Cartesian velocity components. This is because each unique camera perspective provides a different Doppler shift, which in turn allows one to solve a system of equations to transform the Doppler shifts into the three components of velocity. From the perspective of Fisher information, multiple camera perspectives looking at the same region of the flow benefit the estimation of the scalar flowfield quantities, static density and static temperature. From Eq. (8),

each camera perspective adds an additional K observations, with unique FRS sensitivities, adding significant amounts of Fisher information to the inverse problem. In this paper, both frequency scanning and multi-camera inversion approaches shall be tested to quantify the improvement in error and estimation uncertainty.

4.3. TFE-731 Exhaust Measurement

To test these uncertainty reduction strategies, FRS measurements were taken on the exhaust on the Honeywell TFE-731 at Virginia Tech's TurboLab (Fig. 2a, yellow). The TFE-731-2 is a 2:1 geared turbofan engine with a bypass ratio of approximately 2.6 and a maximum thrust at sea level of 15,500 N (TFE731 Turbofan Engine, n.d.; Garrett TFE731, n.d.). A bellmouth (Fig. 2a, blue) is used to guide air into the inlet of the engine and an ejector (Fig. 2a, red) is used to guide the turbofan exhaust out of the test cell, minimizing recirculating air. The engine is mounted on a gantry frame (Fig. 2a, pink) on top of rails (Fig. 2a, cyan), which allows the engine to be pushed towards the front of the test cell such that the bellmouth ingests unperturbed freestream air. The engine was run at approximately 80% corrected fan speed, the same engine operating condition as S. Powers et al. (2025).

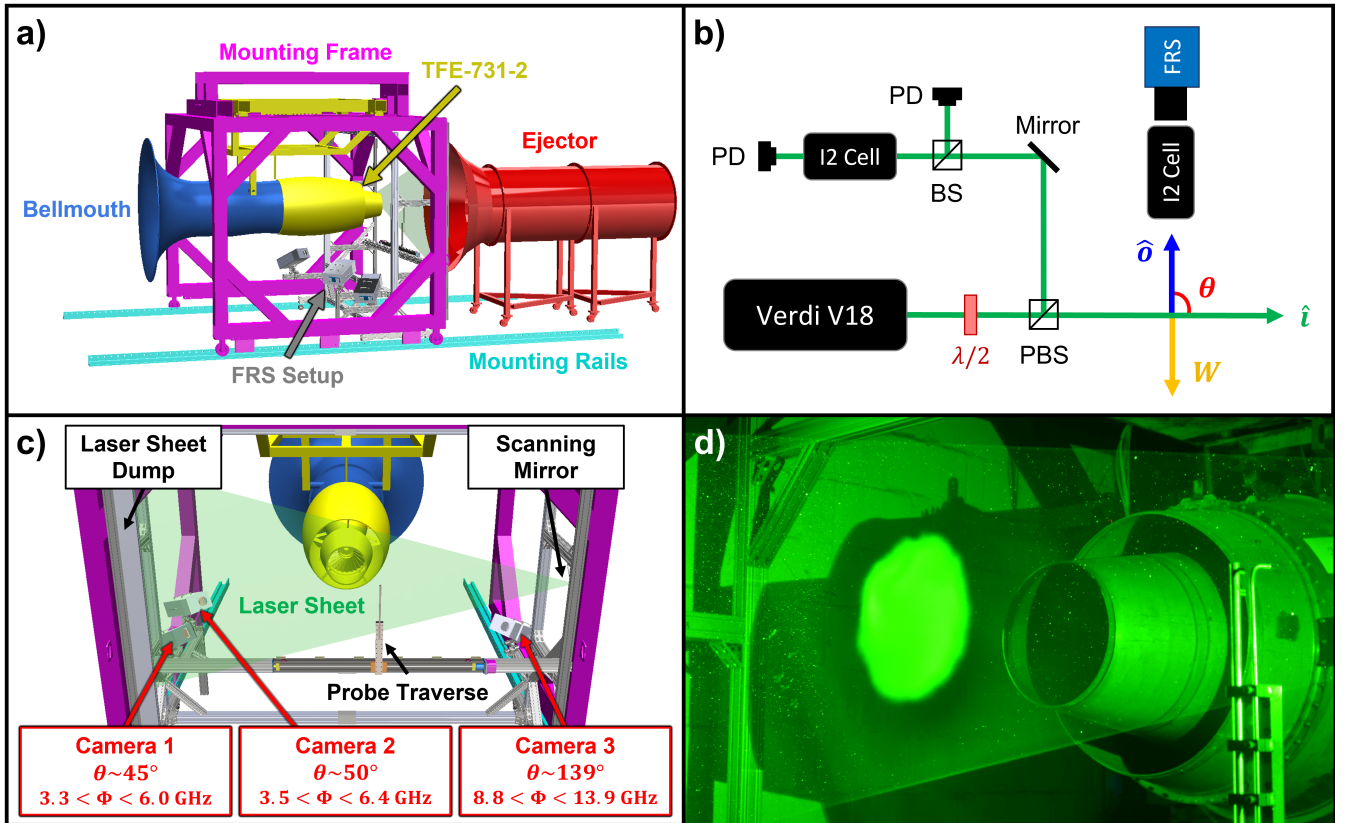


Figure 2. a) CAD of TFE-731-2 facility with FRS installation. b) Optical diagram of FRS system. c) Close-up of FRS Setup. d) Facility image of FRS measurements during TFE-731 operation.

Fig. 2b shows the optical system for FRS, which involves a Coherent Verdi V18 532nm CW laser (C. Corp., 2025), in which the majority of the power is directed to the test cell using a series of mirrors. However, a small fraction of the laser power is split off using a $\lambda/2$ plate and a polarized beamsplitter (PBS). In this path, the laser frequency is monitored with a 0.06 torr Iodine cell (ISSI I2S-5 (Innovative Scientific Solutions, 2025)) and two photodiodes (PD, Thorlabs PDA100A (Thorlabs, 2026)). By fitting the PD measurements to a calibrated Iodine transmission, an indirect measurement of laser frequency can be obtained (S. Powers et al., 2022).

Fig. 2c shows the measurement setup used in this experiment. A planar sheet of laser light is generated via a scanning mirror (Thorlabs GVS311 (Thorlabs, 2025)) to measure a cross-section of the turbofan exhaust, perpendicular to the axial velocity direction W . The measurement plane is roughly 375 mm downstream of the TFE-731 core nozzle, which corresponds to $x/D = 1.35$, where $D = 279$ mm is the diameter of the core nozzle. The laser light is terminated on a sheet dump to minimize stray laser reflections. Three FRS cameras were used, each positioned around the TFE-731 with a variety of scattering angles θ (see Fig. 2b for visual definition), which then produces a wide range of Doppler broadening parameters Φ . Fig. 2c displays nominal scattering angle and Φ range of each camera. Fig. 2b shows a simplified version of the FRS cameras, which are Excelitas pco.edge 4.2 bi UV (E. T. Corp., 2019) cameras, each equipped with a 50 mm lens, ± 5 nm bandpass filters, and 2 torr Iodine cells. Fig. 2d shows a facility (non-FRS) image during the experiment, where the bright circle in the middle of the image is the turbofan core flow and the faint, darker ring surrounding it is the turbofan bypass flow.

In addition to the FRS measurement, validation data was collected using a total temperature, total pressure probe that was traversed horizontally across the turbofan exhaust centerline, located approximately 15 mm downstream of the FRS measurement plane. This was done due to concerns that vibrations would lead to the probe blocking the laser path during engine operation. The total temperature probe was a shielded type K thermocouple, which based on the turbofan exhaust temperature and Mach number, necessitated radiation and Mach number correction factors, resulting in a maximum total correction of 15 K. Pressure was measured using a calibrated Scanivalve ZOC17 pressure scanner (Scanivalve, 2026). 106 locations along the turbofan exhaust centerline with a step size of 6.35 mm (0.25 in) were collected. At each traverse step, 16 seconds of settling time was exercised to allow the measurement to stabilize before data collection. Then, 100 temperature and pressure samples were collected over 4 seconds, then averaged to obtain the centerline profiles. The maximum uncertainties of the total temperature and total pressure probe measurements are 7 K and 500 Pa, respectively. Additionally, an uncertainty of ± 6.35 mm (0.25 in) is prescribed for the horizontal alignment between the probe and FRS data, which shall appear in Section 5.1.

4.4. Post-processing

As introduced in Section 3, two FRS datasets are collected: one collected at a reference condition, that being ambient air, and the other collected during engine operation. The reference dataset is used to estimate the calibration constant $x = [C]$ by least squares fitting of the FRS model to the measured data. The calibration result is then used as an input to processing the "engine-on" dataset.

The central objective of this paper is to assess 2 strategies of uncertainty reduction for Doppler broadened FRS signals. To achieve this, 3 different processing methods on the "engine-on" FRS data were conducted. An overview of each processing method is provided in Table 1.

Table 1. Table of different processing methods tested in this study.

Processing Method	Camera inversion	Frequency Scan Range	Estimators
Method #1	Single-camera	Iodine feature #1	ρ_s, T_s, V_s
Method #2	Single-camera	Iodine feature #1 and #2	ρ_s, T_s, V_s
Method #3	Multi-camera	Iodine feature #1 and #2	$\rho_s, T_s, V_{s1}, V_{s2}, V_{s3}$

Method #1 involves processing the FRS data using a single-camera processing approach, using frequency scan points exclusively from Iodine feature #1 (see Fig. 1b). Single-camera processing involves estimating $x = [\rho_s, T_s, V_s]$ using the FRS data from a single camera perspective. Then V_s is mapped to the axial velocity W using a 1-component velocity assumption (see Section 2). This procedure is repeated for each of the three camera perspectives used in this experiment. Method #2 is also a single-camera processing approach and follows a similar processing procedure, but now leverages frequency scan points from both Iodine feature #1 and #2 (Fig. 1b). Method #3 is a multi-camera joint inversion, where FRS data from all three cameras and both Iodine features are used to estimate $x = [\rho_s, T_s, V_{s1}, V_{s2}, V_{s3}]$, where the subscripts in V_s represent the three sensed velocities from each camera perspective. Typically, one would use the system of equations from Eq. (4) to convert these sensed velocities to the aerodynamic velocity vector within the world coordinate frame. However, for reasons that will be made clear in Sections 5 and 6, processing method #3 shall use a 1-component velocity assumption for cameras 1 and 2. The axial velocity results from these cameras are then averaged together and utilized to derive other quantities. By structuring the processing methods in this manner, the two uncertainty reduction strategies can be evaluated separately.

Table 2. Table of the gas species mole fractions present in the core region of the turbofan exhaust.

N_2	O_2	CO_2	H_2O
0.733	0.192	0.053	0.022

The effects of gas species were accounted for in all processing methods by using a mole-fraction weighted summation of Eq. (1) for the major gas species in the exhaust. As will be discussed later in Section 5, the turbofan exhaust is comprised of a core region, where hot combustion products from the engine are present, and the bypass and ambient regions of the exhaust, which is simply quiescent air. Mole fractions of the core region were determined using a chemical equilibrium balance using Cantera (Goodwin et al., 2023) and are tabulated in Table 2. The gas composition of the shear layer between these two regions was estimated by interpolating between the composition of quiescent air and the values in Table 2. It was found that by incorporating gas species effects, the change in estimated static temperature and camera sensed velocities (relative to an air only assumption) to be less than 0.6%, except for the sensed velocity of camera 3 at 4%. This will be discussed further in Section 6. The largest change was in static density at roughly 5%, which is due to the change in differential scattering cross section between air and the combustion species (Eq. 1).

5. Results

In this section, results shall be presented on the TFE-731 measurement. The results are organized in the following manner. First, planar results are shown using Method #3 in Section 4. Then, both uncertainty reduction strategies are quantified in terms of error with respect to the probe data and uncertainty.

5.1. Planar Results

Planar results of the exhaust are shown in Fig. 3, where contours a)-e) are the primary quantities estimated with Method #3 (Table 1) and contours f)-j) are quantities derived from the primary quantities via Eq. 4 and isentropic relations. The contours in Fig. 3 show several distinct regions of the flowfield. Starting from the outer edges of the contour working inwards, the ambient, stagnant air surrounding the exhaust is present, most prominently in contours a), b), and g). Next, the bypass portion of the turbofan exhaust is present, as noted by the ring of roughly 200 m/s axial velocity flow in contour g). Lastly, the hot core section of the turbofan exhaust is present in the center of the contours, reaching around 700 K in static temperature (contour d). In between the core and bypass flow lies a thin shear layer, where sharp gradients in static density, static temperature, and velocity lie. The effects of this shear layer are apparent in the derived Mach number (contour h), where there is a ring of lower Mach Number due to the changing static temperature. Contour c) shows that the sensed velocity from camera 3 (backward scatter, high Φ) exhibits a non-physical structure and large magnitudes relative to the other cameras. As it will be further analyzed and discussed in the rest of Section 5 and Section 6, the sensed velocity from camera 3 was poorly estimated. This is the main reason why processing method #3 is restricted to a 1-component velocity

assumption as opposed to estimating all components of the aerodynamic velocity vector.

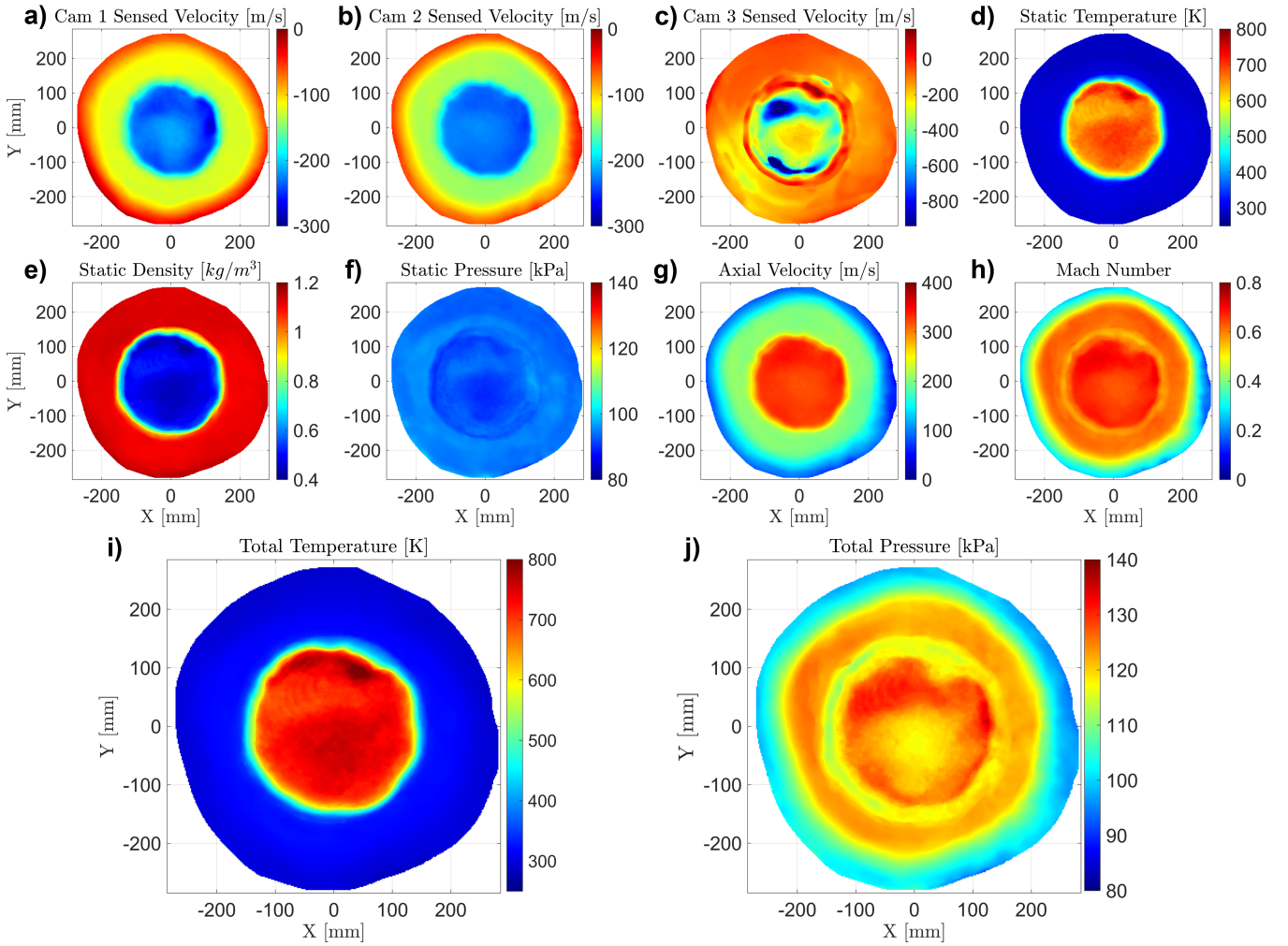


Figure 3. Planar Results of the TFE-731 Exhaust. Contours a)-e) are the primary quantities measured with FRS. Contours f)-j) are quantities derived from the measured quantities. All contours are shown with a 5x5 median filter applied.

Measured and modeled FRS signals are shown for the ambient, bypass, shear layer, and core regions of the turbofan exhaust for each camera in Fig. 4. Two groupings of data are present on the plots, each corresponding the Iodine features #1 and #2. There is an apparent shift in signals to the right as a result of the Doppler shift from the flow, increasing as one progresses from ambient to the core. Changes in bulk signal intensity is mainly attributed to variations in static density as well as the calibration constant. As mentioned in Sections 1 and 2, variations in signal curvature is mainly attributed to Doppler broadening of the LRS signal (Hanley et al., 2026). For example, cameras 1 and 2 with a range of low Doppler broadening parameters (Fig. 2c) retain a visible curvature across each Iodine feature. Changes in static temperature, static density, and Doppler shift (velocity) produce distinguishable changes in the FRS signal across frequency, which leads

to precise estimation of these quantities. In contrast, camera 3 has a much larger scattering angle and thus a larger Doppler broadening parameter. the FRS signal is substantially flatter across frequency with roughly 2-3 times less signal variation across a single scan range than in cameras 1 and 2. In this Doppler broadening regime, different parameter combinations can produce equally high quality fits, particularly for velocity. So despite all model fits achieving $R^2 > 0.98$, indicating that the model can reproduce the measured signal, this does not necessarily indicate that the fitted parameters are precisely estimated.

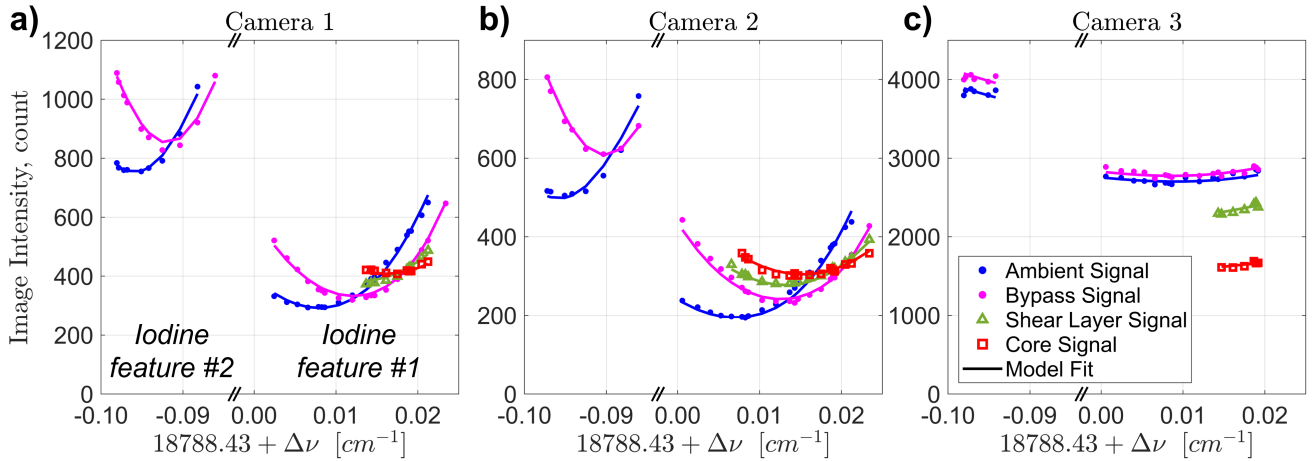
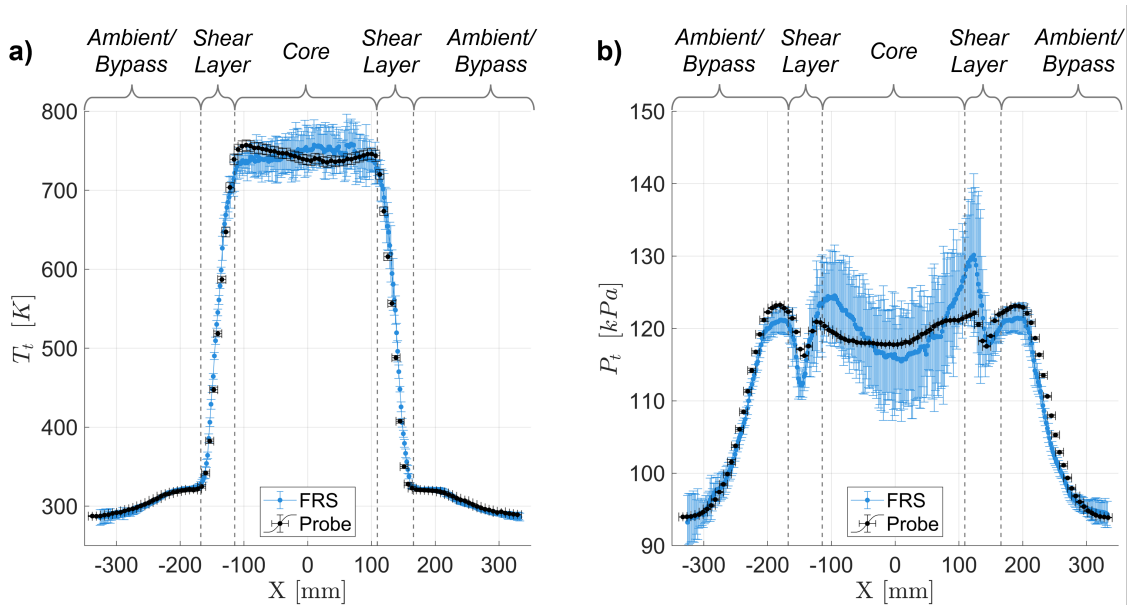


Figure 4. Measured FRS signals across different regions of the turbofan exhaust and their corresponding model fit. Markers indicate measured data and solid line indicate the modeled signal. a) Camera 1 signals. b) Camera 2 signals. c) Camera 3 signals.

Fig. 4 also reveals the amount of points each region in the turbofan exhaust that were used in the fitting process. Exact amounts for each camera and each region are listed in Table 3. Most notably, data from Iodine feature #2 was used for fitting signals in the ambient and bypass region, but not for the core and shear layer. Furthermore, very few points were leveraged in the core region. As will be further discussed in Section 6, the reason for limited fitting points is due to contamination at high Doppler shifts, as also experienced by U. Doll et al. (2014) in ducted flow measurements. Geometric scattering exists at the same frequency as the incident laser light, whereas Mie scattering is, in many cases, Doppler shifted (Boyda et al., 2020). As a result, these two sources of contamination spectrally lie in different places along the x-axis in Fig. 1a, separated by the Doppler shift of the flowfield. In the presence of large Doppler shifts, such as in this case of this measurement where sensed velocities reach -300 m/s, it becomes increasingly challenging to suppress both sources of contamination simultaneously with a single Iodine absorption feature. This leads to a reduced contamination-free scanning range and in the case of Iodine feature #2, the entire scanning range was contaminated. Consequently, the inverse problem in these regions is constrained by both reduced sensitivity and reduced observation count, compounding the degradation of measurement uncertainty.

Table 3. Table of the number of frequency scan points used for FRS model fitting across the different Iodine features and camera perspectives.

	Ambient	Bypass	Shear Layer	Core
Camera 1				
Iodine feature #1	19	20	10	10
Iodine feature #2	9	10	--	--
Camera 2				
Iodine feature #1	20	21	17	16
Iodine feature #2	8	8	--	--
Camera 3				
Iodine feature #1	18	18	7	6
Iodine feature #2	6	6	--	--

**Figure 5.** Comparison of FRS results (computed with processing method #3) with total temperature/total pressure probe data across the turbofan exhaust centerline. Regions of the turbofan exhaust are labeled. a) Total temperature profile. b) Total pressure profile.

The two primary quantities of interest in this paper are total temperature (Fig. 3i) and total pressure (Fig. 3j), which can be compared to the probe validation data. Figs. 5a) and b) show the FRS total temperature and total pressure profiles from processing method #3 (Section 4), compared to the probe validation data, respectively. 95% confidence interval uncertainty bars for FRS are computed based on methods described in Section 3. The profiles qualitatively match in shape, with FRS exhibiting a more pronounced total pressure profile. In the ambient/bypass regions, the total temperature and total pressure error is within 1.5% and 5%, respectively. In the core, these values

are both around 4% and largely within uncertainty. The shear layer shows the most discrepancy between probe and FRS results, which is most noticeable in total pressure. This is due to sharp gradients in both static temperature and static density field, which are difficult to resolve accurately in terms of spatial location, which then impact the FRS-derived static pressure field. For this reason, data from the shear layer shall be omitted in the error analyses in the following section to more definitively assess the two uncertainty reduction strategies.

5.2. Error Reduction

The purpose of these next two subsections is to assess whether scanning over multiple Iodine absorption features as well as multi-camera joint inversion can reduce uncertainty and error for Doppler broadened FRS signals. To do this, three different processing methods described in Section 4.4 are compared, which test the two strategies and progressively add more Fisher information into the inverse problem. Starting with error, the probe result is taken as ground truth, and FRS error is calculated as $\Delta x = x_{FRS} - x_{probe}$ for both total temperature and total pressure. Fig. 6 summarizes the total temperature and total pressure error in histograms. Histograms are separated into ambient/bypass and core regions, because Iodine feature #2 could not be used due to contamination at large Doppler shifts (see Section 5.1). Processing method #2 is therefore absent from Figs. 6b and d. The median absolute error ($MAE_x = Median(|\Delta x|)$) is used as a robust scalar measure of improvement because the error distributions are not strictly Gaussian. The median absolute error is computed for each histogram and is tabulated in Table 4.

Table 4. Table of the median absolute error in total temperature and total pressure across different processing methods and regions of the turbofan exhaust.

	Method #1		Method #2		Method #3
Ambient/Bypass					
MAE_{T_t}	48.2 K	$\overrightarrow{4.2x}$	11.4 K	$\overrightarrow{6.3x}$	1.8 K
MAE_{P_t}	7.4 kPa	$\overrightarrow{1.7x}$	4.3 kPa	$\overrightarrow{3.6x}$	1.2 kPa
Core					
MAE_{T_t}	125.8 K		$\overrightarrow{10.2x}$		12.3 K
MAE_{P_t}	31.4 kPa		$\overrightarrow{17.4x}$		1.8 kPa

From these results, there is a systematic reduction in error from processing method #1 $\rightarrow$ #2 $\rightarrow$ #3. In the ambient/bypass histograms (Figs. 6a and c), the second Iodine feature reduced the median absolute error by a factor of 4.2 for total temperature and 1.7 for total pressure. This improvement is notable because only 6-10 additional frequency scan points from Iodine feature #2 were available, depending on camera perspective (Table 3). This indicates that these limited number of frequency scan points sampled a portion of the FRS convolution with unique sensitivity, thereby significantly increasing Fisher information.

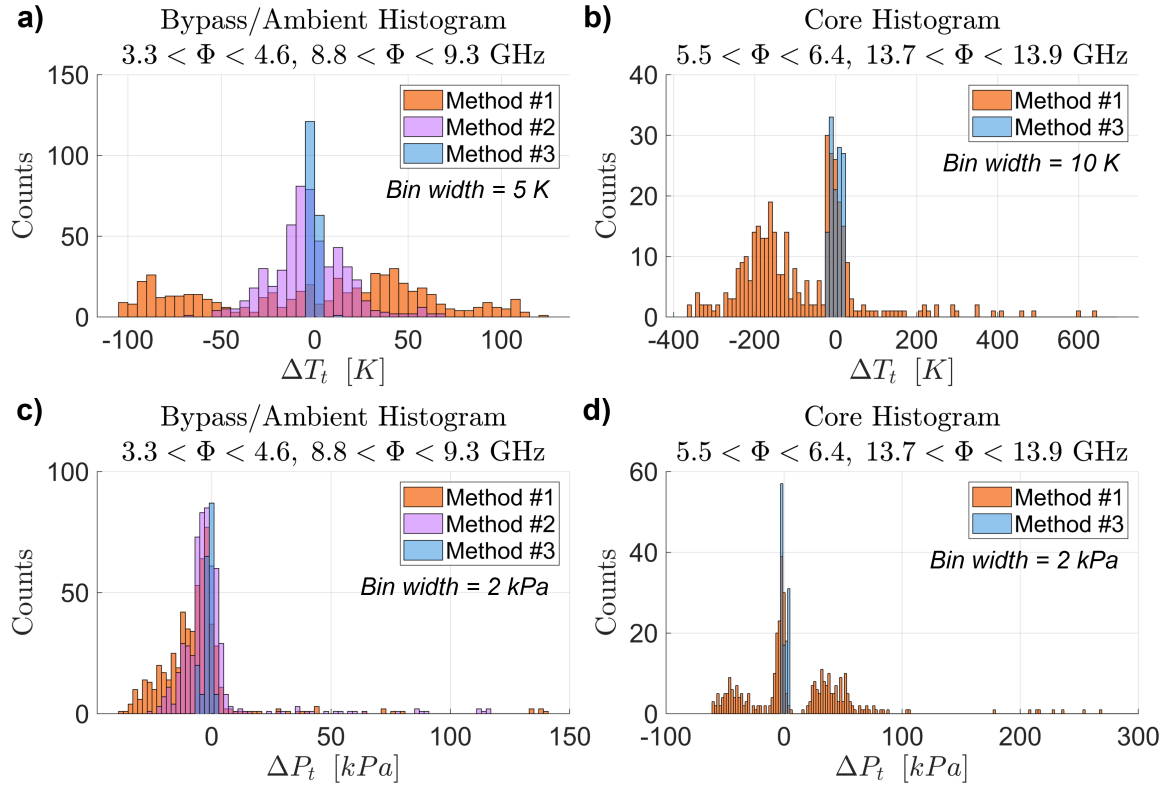


Figure 6. Histograms of error across the different processing methods. Doppler broadening ranges that each histogram covers is also listed. a) Total temperature error in the bypass and ambient regions of the turbofan exhaust. b) Total temperature error in the core region of the turbofan exhaust. c) Total pressure error in the bypass and ambient regions of the turbofan exhaust. d) Total pressure error in the core region of the turbofan exhaust.

Even larger improvements occurred when the data from all camera perspectives were fit simultaneously. Going from processing method #2 $\rightarrow$ #3, there is a reduction in total temperature and total pressure median absolute error in the ambient/bypass histograms by a factor of 6.3 and 3.6, respectively. In the core histograms, where Iodine feature #2 could not be used due to contamination, multi-camera inversion reduced the median absolute errors by a factor of 10.2 for total temperature and 17.4 for total pressure. These reductions show that by utilizing camera perspectives that have different scattering angles and Doppler broadening parameter ranges, each camera can produce FRS signals and their respective sensitivities that are significantly different from one another, which is visibly apparent in Fig. 4. This leads to an aggregation of many Fisher-informative observations in the multi-camera joint inversion and ultimately significant reductions in uncertainty.

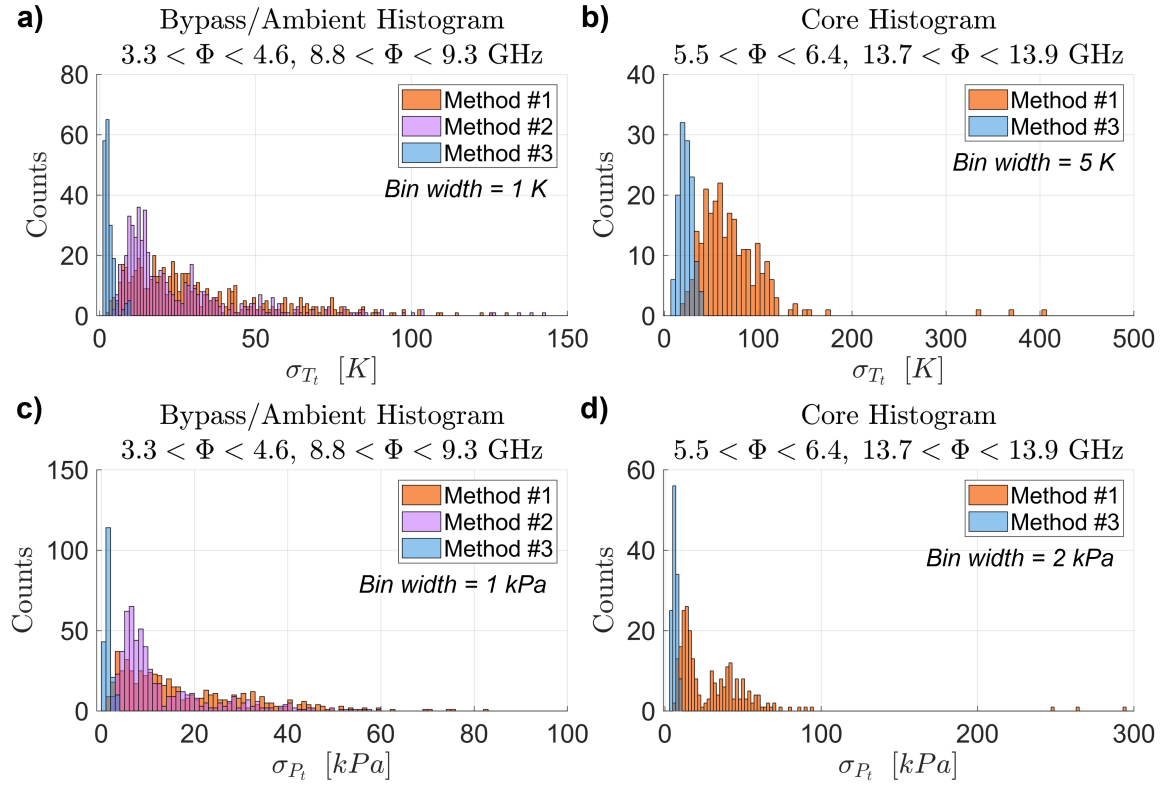


Figure 7. Histograms of uncertainty across the different processing methods. Doppler broadening ranges that each histogram covers is also listed. a) Total temperature uncertainty in the bypass and ambient regions of the turbofan exhaust. b) Total temperature uncertainty in the core region of the turbofan exhaust. c) Total pressure uncertainty in the bypass and ambient regions of the turbofan exhaust. d) Total pressure uncertainty in the core region of the turbofan exhaust.

5.3. Uncertainty Reduction

The total temperature and total pressure uncertainties are calculated following the approach described in Section 3, and are summarized in histograms in Fig. 7, with a similar organization as Fig. 6. Additionally, median uncertainties are tabulated in Table 5. Similar trends are found for uncertainty as those in error (Fig. 6 and Table 4). By leveraging Iodine feature #2 (processing method #1 → #2), the uncertainty estimate reduces by a factor 1.5 in total temperature and in total pressure in the ambient/bypass region. Additionally, using multi-camera inversion (processing method #2 → #3) reduces the uncertainty estimate by a factor 6.8 in total temperature and 5.9 in total pressure for the ambient/bypass region. In the core, these reductions are 3.9 for total temperature and 6.6 for total pressure. The histogram distributions of processing method #2 (relative to method #1) shows a shift of histogram counts towards lower uncertainty estimates around 10 K and 6 kPa. Hence, Table 5 possibly understates the reduction in uncertainty when leveraging Iodine feature #2. Additionally, multi-camera inversion further shifts the histogram towards lower uncertainty estimates.

Table 5. Table of the median total temperature and total pressure uncertainties across different processing methods and regions of the turbofan exhaust.

	Method #1		Method #2		Method #3
Ambient/Bypass					
Median σ_{T_t}	25.5 K	$\overrightarrow{1.5x}$	17.1 K	$\overrightarrow{6.8x}$	2.5 K
Median σ_{P_t}	13.2 kPa	$\overrightarrow{1.5x}$	8.8 kPa	$\overrightarrow{5.9x}$	1.5 kPa
Core					
Median σ_{T_t}	87.5 K		$\overrightarrow{3.9x}$		22.4 K
Median σ_{P_t}	42.0 kPa		$\overrightarrow{6.6x}$		6.4 kPa

6. Discussion

There are several important details that influence the interpretation of the results in Section 5. First, these results demonstrate that additional, Fisher-informative observations can substantially reduce uncertainty and error in Doppler-broadened FRS measurements, but the benefit depends on what type of information those observations add. For example, frequency scanning over multiple Iodine absorption features adds Fisher information to the same camera signal and can directly improve estimation of both the scalar quantities (ρ_s, T_s) as well as the sensed velocity of the given camera. In contrast, multi-camera inversion pools Fisher information from all camera perspectives, which most significantly benefits the estimation of scalar quantities. The sensed velocities of each camera is indirectly benefited, as sensed velocity is weakly coupled with scalar quantities (Hanley et al., 2026). Despite this, the sensed velocity for camera 3 was still poorly estimated using processing method #3, with a computed measurement uncertainty of 140 m/s in the core region of the turbofan exhaust. For comparison, the uncertainties from cameras 1 and 2 were <7 m/s across all regions of the turbofan exhaust. The poor estimation was noted earlier in Fig. 3, with large magnitudes and a planar distribution that was different and unusual when compared to the sensed velocity contours from the other cameras. Furthermore, Section 4.4 mentioned the influence of gas species effects changed the sensed velocity of camera 3 by 4%, a change several times larger than the sensed velocity from cameras 1 and 2. Camera 3 does provide Fisher information for density estimation, as evidenced by the changes in bulk intensity in figure 4c. But, due to the flat FRS signal as well as insufficient number of frequency scan points fit over, this leads to poor velocity estimation for this particular camera.

Frequency scanning over multiple Iodine absorption features is only useful when the added scan range remains contamination-free. Initially mentioned in Section 5.1, large Doppler shifts observed in the core and shear layer regions of the turbofan exhaust led to a reduced contamination-free frequency scan range for Iodine feature #1 (Fig. 4). For Iodine feature #2, the weaker suppression performance and narrower available frequency scan range for led to complete contamination. As

a result, only processing method #2 was evaluated in the ambient and bypass regions. This highlights an important design constraint for this uncertainty reduction strategy for future high temperature FSM-FRS measurements; the Doppler shift a given camera perspective observes should also be considered when designing an FRS measurement to effectively utilize the contamination-free scanning range of Iodine absorption features, especially ones that have a narrow suppression range.

Fig. 5 and the subsequent error analysis in Section 5.2 is most sensitive to horizontal alignment between the probe and FRS data. As mentioned in Section 4.3, the the uncertainty in the horizontal alignment is ± 6.35 mm (0.25 in). Furthermore, probe measurements were taken approximately 15 mm downstream of the FRS measurement plane. Because the shear layer of the turbofan exhaust contains sharp gradients in static density, static temperature, and velocity, small horizontal offsets between the probe and FRS data can produce large calculated errors $\Delta x = x_{FRS} - x_{probe}$ despite the two measurements being qualitatively similar. To avoid skewing the results of Fig. 6 and Table 4 due to this alignment uncertainty, data from the shear layer was omitted. However, it should be noted that in the case of total pressure (Fig. 5b), spatial alignment uncertainty does not fully explain the differences in the shear layer, and instead the multi-parameter estimation of static density and static temperature producing a non-constant static pressure is more likely to be the potential reason for this difference.

7. Conclusion

This paper experimentally evaluated two strategies for improving multi-parameter FSM-FRS estimation in high temperature, Doppler broadened flows: frequency scanning over multiple Iodine absorption features and jointly fitting multiple camera perspectives. These strategies were tested on a Honeywell TFE-731 turbofan exhaust, where through the hot core region and the cold bypass/ambient regions of the exhaust produced a wide range of Doppler broadening parameters. The results show that Doppler broadening remains a primary limitation for high temperature, multi-parameter FRS because it flattens the FRS signal across the frequency scan range, degrading Fisher information and ultimately increasing the uncertainty of the estimators. However, the results also show that this limitation can be mitigated by adding Fisher-informative observations that provide unique FRS parameter sensitivity.

Scanning over multiple Iodine absorption features reduced the median absolute error (with respect to probe validation data) by factors as much as 4.2 in the ambient/bypass region, despite the limited number of usable frequency scan points in the second Iodine feature. Multi-camera joint inversion provided the largest improvement across the ambient, bypass and core regions of the turbofan exhaust, reducing median absolute errors by factors as much as 17.4. A similar reduction in the respective uncertainties was found, highlighting that a few Fisher-informative observations

can significantly reduce both uncertainty and error.

These results also highlighted important constraints and limitations for future high temperature FRS applications. Additional Iodine absorption features are useful in reducing uncertainty only when their frequency scan ranges remain contamination-free, especially in flows with large aerodynamic Doppler shifts and Iodine features with weaker and narrow suppression ranges. In multi-camera joint inversion, cameras with a high Doppler broadening parameter may improve estimation for scalar thermodynamic quantities, but not provide sufficient FRS sensitivity for precise Doppler shift estimation. Overall, this paper demonstrates that Fisher information-guided measurement design provides a practical path for extending FRS to higher temperature flow environments.

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