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Prospects for Nonlinear Laser Diagnostics in the Jet Noise Laboratory

Gregory C. Herring, Roger C. Hart, Mark T. Fletcher, R. Jeffrey Balla, and
Brenda S. Henderson
Langley Research Center, Hampton, Virginia

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National Aeronautics and
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Langley Research Center
Hampton, VA 23681-2199

Abstract

Two experiments were conducted to test whether optical methods, which rely on laser beam coherence, would be viable for off-body flow measurement in high-density, compressible-flow wind tunnels. These tests measured the effects of large, unsteady density gradients on laser diagnostics like laser-induced thermal acoustics (LITA). The first test was performed in the Low Speed Aeroacoustics Wind Tunnel (LSAWT) of NASA Langley Research Center's Jet Noise Laboratory (JNL). This flow facility consists of a dual-stream jet engine simulator (with electric heat and propane burners) exhausting into a simulated flight stream, reaching Mach numbers up to 0.32. A laser beam transited the LSAWT flow field and was imaged with a high-speed gated camera to measure beam steering and transverse mode distortion. A second, independent test was performed on a smaller laboratory jet (Mach number ≤ 1.2 and mass flow rate ≤ 0.1 kg/sec). In this test, time-averaged LITA velocimetry and thermometry were performed at the jet exit plane, where the effect of unsteady density gradients is observed on the LITA signal. Both experiments show that LITA (and other diagnostics relying on beam overlap or coherence) faces significant hurdles in the high-density, compressible, and turbulent flow environments similar to those of the JNL.

Key Words: Laser-induced thermal acoustics (LITA), Laser beam steering, Aero-optics, Jet Noise Laboratory (JNL)

I. Introduction

To help with the aircraft noise reduction program at NASA Langley Research Center (LaRC), we recently considered laser-induced thermal acoustics (LITA) as a candidate for unseeded off-body velocity measurements in the Jet Noise Laboratory (JNL). The JNL includes a Low Speed Aeroacoustics Wind Tunnel (LSAWT) that provides a simulated flight stream reaching a maximum Mach number of 0.32. A dual-stream Jet Engine Simulator (JES), equipped with electric heaters and propane burners, is often tested in this low-speed flight stream. Any concerns about the application of LITA to the LSAWT will have a more general applicability to other similar facilities and diagnostics. LITA is one example of a nonlinear optical technique where the coherence properties of the laser beam are necessary for a successful measurement. Descriptions of

LITA and demonstrations of velocimetry and thermometry in low-speed, incompressible flows can be found in Refs. 1-3. Laser Doppler velocimetry (LDV) is another well-known diagnostic that requires laser beam coherence. For comparison, other optical diagnostics such as spontaneous Rayleigh scattering and particle image velocimetry (PIV) are techniques that do not require coherence between different laser beams.

Beam steering is well recognized [Refs. 4 and 5] as a potential problem for optical diagnostics in some wind tunnels with compressible or turbulent flows. Unsteady flow fields that have both large total densities ($\geq$ 1 amagat) and large fractional density gradients, will also have large index-of-refraction gradients (1 amagat is the density at 273 K and 101 kPa). These index-of-refraction gradients can either directionally steer the entire light beam away from its intended destination or spread the beam into a variety of directions. The severity of the beam steering is also a function of the beam-path lengths. Two examples of this type of hindrance are discussed in Refs. 6 and 7, where Rayleigh scattering and interferometry were both adversely affected when imaging the gas density in the ~ 5 amagat compressible flow in the LaRC 0.3-meter Transonic Cryogenic Tunnel.

In comparison, other facilities, e.g., Unitary Plan Wind Tunnel at LaRC, operate at relatively smaller total densities ($\leq$ 0.1 amagat), but still may have large fractional density gradients. However at low total gas densities, the magnitude of the index-of-refraction gradients remains small even with significant density gradients, and beam steering is typically not important. Thus low-density supersonic tunnels, with or without significant density gradients, are often successfully probed with optical diagnostics, including LITA.

In this report, we study the flow-induced beam perturbations in the high-density compressible 1-amagat flow at the JNL in order to access whether nonlinear laser diagnostics are viable. In considering LITA for the JNL, we initially suspected beam-steering problems because of the large and compressible flow densities that occur at the JNL. Attempting to demonstrate velocimetry with a simple trial-and-error approach with a full LITA setup could prove wasteful. To optimize the use of the JNL facility time, we decided to perform a quick, preliminary test to check for beam steering problems. This test consisted of directing a Helium-Neon (HeNe) laser beam across the concentric jets of the JES (normal to the jet axes) and imaging the beam with a time-gated camera. Observation of the beam position and beam profile illustrates the presence or absence of beam perturbations caused by the flow. This first test was complemented with a second test that did not involve the JNL, but did use a full LITA instrument in a roughly similar flow. The second test consisted of performing LITA velocimetry measurements on a small modestly-heated laboratory jet, which served to approximate the transonic, turbulent flow in one stream of the JES. Results of these two tests are presented in this report; the effect of the unsteady density gradients on optical beams traversing compressible flow fields is illustrated. This information will be useful for assessing the potential for LITA and other optical diagnostics at the JNL and other facilities that have similar unsteady gradients in high-density ($\geq$ 1 amagat) flows.

II. Beam Steering Test at the LSAWT in the JNL

A. Experimental Setup

Details of the first test were dictated by the motivation to produce the smallest perturbation to the facility test schedule. This test required about one day of setup time and one-half day of run time. A side-view schematic of this test is shown in Fig. 1a, while an end-view is shown in Fig. 1b. The LSAWT of the JNL, including the JES, is intended to mimic the flow from a typical turbojet engine and consists of two concentric jets, a central core jet (radius = 5 cm) with an external plug, surrounded by an annular fan jet flow (outer radius = 10 cm). To achieve realistic engine exhaust temperatures, the central core jet is propane vitiated, which greatly increases the total temperature of the flow before it exits the jet. These concentric jets exhaust into a rectangular 1.4 x 1.4-meter simulated flight stream at mach 0.1. Additional details of the facility can be found in Ref. 8. The six flow conditions studied in the present work are summarized in Table I, which includes total temperature T, total pressure P, Mach number M, and nozzle pressure ratio (NPR). The bypass ratio was 5.

Table I: Flow Conditions in the LSAWT

Flow	Fig. 1 Location	M	NPR	T (K)	P (atm)	Mass Flow (kg/s)
1. Core Jet (Hot)	A	0.8	1.6	830	1.6	2
2. Fan Jet (Hot)	B	0.9	1.8	360	1.8	7
3. Core Jet (Cold)	A	1	1.9	300	1.9	2
4. Fan Jet (Cold)	B	0.9	1.4	300	1.4	7
5. Flight Stream	C	0.1	1.007	300	1.007	80
6. No Flow	-	0	0	300	1	0

To observe unsteady density gradients, a 5-mW HeNe laser (633 nm) was mounted on a linear translator on one side of the JES, and a high-speed detector (CCD camera) was mounted on a second translation stage on the other side of the JES. These translators were located downstream of the nozzle trailing edges and to the side of the jet plume. The approximately collimated (1-mm diameter) HeNe beam traversed the concentric jet flow and impinged on the camera. In Fig. 1a, the laser beam propagates in a direction perpendicular to the plane of the figure. The translators, the laser and the camera are omitted from Fig. 1a for clarity. In Fig. 1b, the distance from the laser to the centerline is about 2 m, and the distance from the centerline to the camera is also about 2 m. At each vertical position (e.g., A, B, and C), the beam steering that is observed is integrated over the entire horizontal beam path, from laser to camera. Different vertical positions were readily observed by common translation of the two translators. Temporal resolution was obtained by gating the camera intensifier for 20-100 nsec once each video frame; thus the flow is frozen for each image. Instantaneous images of the transmitted laser beam were recorded as a function of position and flow condition.

B. Beam Steering Results at the LSAWT

The main result obtained in this test is illustrated in Fig. 2, where 12 different beam profiles of the HeNe laser are shown. In Fig. 2a, for reference, four single images of single laser pulses (i.e., instantaneous) are shown for a no-flow condition where the flight-stream flow and both jets are off (condition 6 in Table I). The full-width-half-maximum diameter of the beam is about 4 mm on the camera cathode and is reduced to about 1 mm on the CCD array, as in beam images of Fig. 2a. In Fig. 2b, four single images are shown for flow condition 3. Careful inspection of these images shows slight perturbations to the laser beam. In Fig. 2c, four single images are shown for location A with hot flow (using propane fuel in condition 1 of Table I). Fig. 2c shows large and random alterations to the beam intensity profile, in comparison to the smooth and reproducible profiles of Fig. 2a. Note that interference fringes, from the camera window, are clearly visible in the beam profiles for all flow conditions.

Time-averaged beam profiles look significantly better than the single shots. For the extreme flow of condition 1, real-time observation of 30-Hz video data of the transmitted beam shows a clear time varying perturbation of the beam (i.e., averaging over ≈ 5 successive frames). However, the degree of perturbation is not nearly as much as can be seen in the single-shot images of Fig 2c. Averaging over 15 single frames with post processing produces a smoother beam profile than for 5 frames. The time-averaged image continues to improve as the averaging increases to 50 frames.

Results of the observed beam profiles for other run conditions can be summarized as follows. Location A with hot flow (condition 1), by far, shows the largest perturbations to the laser beam transverse mode structure as shown in Fig. 2c. This result makes sense from the point of view that vitiating the center jet creates a flow with the strongest and most dynamic density gradients, due to the significant heat release. The center jet location A with cold flow (condition 3), the non-reacting fan jet location B (conditions 2 and 4) and flight-stream location C (condition 5), respectively, generated progressively weaker disruptions to the beam than those of the vitiated central jet (condition 1). In fact, in the flight stream, there were no observable perturbations to the beam, i.e., the images looked similar to those of Fig. 2a with no flow (condition 6).

III. LITA Measurements in a Transonic Laboratory Jet

A. Experimental Setup

A second test was used as a complement to the first test of Section II in this study. This second test consisted of making LITA velocity and temperature measurements at a single point just beyond the exit plane in a laboratory jet of considerably smaller scale than the JNL flow. But, the transonic and turbulent gas densities of this smaller jet should crudely approximate the dynamic nature of the JNL jet in the cold-flow mode. With this laboratory jet, we were able to further study the effect of compressible flow, with unsteady densities gradients, on LITA without using valuable JNL runtime.

The laboratory jet consists of a small-volume single-cavity stagnation chamber (no inserts, baffles or effort made to minimize flow turbulence) followed by a simple converging nozzle. This approach exaggerates the unsteadiness and turbulence in the emerging jet. The free jet expands into room air, where the Mach number is varied from 0.2 to 1.2 by varying the stagnation pressure. The exit-plane jet diameter is 1.5 cm, and the maximum mass flow rate is about 0.1 kg/sec at Mach 1. The jet includes modest electric heating capability before the stagnation chamber, so the static temperature of the jet at the exit plane can be kept as high as 280 K, if desired, when operating near Mach 1.

LITA is a noninvasive method for off-body velocimetry and thermometry, without seeding [1-3]. The LITA setup is shown schematically in the top view of Fig. 3. Measurements are obtained in the ellipsoidal-shaped sample volume where the three input laser beams cross. The size of the sample volume is about 1 cm along the laser beams (transverse to the jet flow) and 0.2 mm transverse to the beams (along the jet axis). In LITA, temperature and velocity information from the flow are obtained from the modulation frequencies of the scattered LITA signal light. Additional details of the LITA method and setup are given in Refs. 1 and 9.

B. LITA Velocimetry and Thermometry Results in the Laboratory Jet

Three examples of single-shot temporal profiles from the axial component of the LITA signal are shown in Fig. 4 for Mach numbers of 0, 0.285, and 0.65. With no flow, the LITA signal shows maximum quality, indicated by the slowly-decaying sinusoidal oscillation of the diffracted probe intensity in Fig. 4a. As the gas speed increases from Mach 0.285 in Fig. 4b to Mach 0.65 in Fig. 4c, the size of the low-frequency baseline noise increases significantly. The signal-to-noise ratio (SNR) observed in these highly compressible flows, is much worse than we previously [1, 9] observed in incompressible flows. This low-frequency noise continues to increase dramatically (compared to Fig. 4c) as the Mach number is raised to ≈ 1, and is clearly caused by dynamic density gradients. A second observation in Fig. 4 is that the lifetime of the acoustic wave packets is reduced as Mach number is increased. We speculate that the accelerated acoustic decay is related to turbulence on the scale of the grating size that washes out the acoustic grating.

Our previous work [1, 9] has demonstrated single-shot measurements of velocity and temperature with LITA in incompressible flows. The low-frequency noise shown in Fig. 4 prohibits single shot determination of the flow parameters in the turbulent jet of the present work. However, averaging over 500 laser shots (17 sec) yields good results. Mach number and temperature are shown in Fig. 5, where the measured LITA results are compared with the jet conditions calculated from pressure and temperature measurements in the stagnation chamber, assuming a subsonic 1-d isentropic expansion. Since the LITA measurements are confined to the 1-cm central core region just downstream of the exit plane, irreversible frictional effects with the jet wall are small. We observe excellent agreement of these averaged LITA measurements and the expected jet conditions up to Mach 1. If the jet is operated near the Mach-1 region, shocks and expansion fans form near the nozzle exit plane and non-isentropic effects render the 1-d isentropic-expansion calculation inaccurate. Thus we attribute the disagreement at ≥ Mach 1 in Fig. 5a (≤ 220 K in Fig. 5b) to breakdown of the isentropic flow and our rough calculation, rather than an error in the LITA measurement.

We estimate the uncertainties in these averaged LITA measurements from the differences with respect to the expected flow conditions. Considering only the five data points below Mach 1, the average difference between the LITA and expected values are 0.011 and 1.9 K for Mach number and temperature, respectively. These estimated uncertainties for 500-shot averages are comparable to previous [1, 9] single-shot uncertainties in flows wit less turbulence and unsteadiness.

For Mach $\geq$ 1, the jet operates in a near pressure-matched condition; but the gas density at the exit plane is not matched to room-air density if there is no heating of the gas entering the stagnation chamber. We adjusted the jet to obtain matched-densities by heating the input gas to the stagnation chamber. This increases the stagnation temperature (at constant stagnation pressure and Mach number) and lowers the total density at the exit plane. We observed that the size of the low-frequency noise in Fig. 4 was diminished and the LITA SNR improved as the jet exit-plane density approached room-air density. This supports the hypothesis that density gradients are an important factor in the observed degradation of the LITA SNR.

IV. Discussion

A. Laser Beam Perturbations

The beam perturbations illustrated in Fig. 2c and 4c have consequences for the typical nonlinear optical diagnostic. Perturbations in the propagation of the various beams may reduce or destroy the ability to generate optical signal. In the LSAWT, this problem will be most severe for the centerline location (hot flow with maximum heating), where it is desirable to make measurements for many aeroacoustic applications. For the tests of Sections II and III, there is a variety of ways in which the unsteady nature of the beam-steering density gradients can reduce the quality of the diagnostic. Three mechanisms are: prevention of straight-line propagation of the laser beams, reduction of the overlap of two or more beams at the crossing point, and addition of random phase perturbations over the spatial profiles of the various laser beams involved in the diagnostic.

The results in Fig. 5 show that the current version of LITA may be useful for providing time-averaged velocity and temperature information in spite of some moderate beam steering due to fluctuating density gradients. Single-shot measurements are generally more useful in many aerodynamic applications, but are difficult (if not impossible) for LITA under the transonic conditions of the jet of Fig. 3. However, the spectral characteristics of the LITA signals in Fig. 6 suggest a potential optical diagnostic for the measurement of density fluctuations in turbulent flow fields.

B. Proposed Optical Diagnostic for Turbulence Measurement

Consider typical temporal profiles, such as those of Fig. 4, and their Fourier transforms. Frequency domain data for no-flow and Mach-1.1 conditions are shown in Figs. 6a and 6b, respectively. For both cases, the transform of each individual laser shot is first computed and then summed over 500 shots. The no-flow condition of Fig. 6a shows the isolated LITA signals (-8 and +8 MHz) for stationary fluid, while the spectrum of Fig. 6b shows only a single LITA signal (+15 MHz) for the moving fluid. Fig. 6b also shows a very low-frequency (≈ 0 MHz) noise continuum that decays rapidly with increasing frequency. This low-frequency noise masks the left-hand LITA signal which has shifted to the zero-MHz region for this flow condition. A second peak at F = 6 MHz also occurs for this run. This is a low-frequency noise (compared to the LITA signal at 15 MHz) that is modestly banded and peaked at 6 MHz. We suggest that it arises due to beam steering by unsteady density gradients in the flow. The observed value of F increases as the jet Mach number increases.

We anticipate that this prominent noise frequency F may be related to the flow speed V_{flow} according to $F = V_{flow} / D$, where D is a characteristic length of the apparatus. Using V_{flow} = 300 m/sec and an exit-plane diameter of 1.5 cm for D, we expect a frequency of F ~ 200 kHz, clearly not that of Fig. 6b. Using the laser beam diameters of ~ 200 μm for D gives a better match, but still not great. However, the acoustic wavelength (λ ~ 40 μm) of the wave packets that the LITA pump laser induces in the gas gives F ~ 7 MHz, a promising match. Using $D = \lambda$ = 43 um, and the velocity data of Fig. 5a, the expected frequencies (V_{flow} / λ) are plotted against measured flow-induced noise frequencies in Fig. 6c. The linear trend of the data suggests a real correlation. Considering the rough nature of this comparison, the small difference (less than a factor of 2) between exact agreement and the observed linear fit also supports such a correlation. Thus we tentatively propose that the 6-MHz noise peak shown in Fig. 6b is due to naturally-occurring unsteady density structures in the flow field that scatter light into the LITA detector. This process is simply gas-phase spontaneous Brillouin scattering, detected in a nonstandard manner.

If our speculative interpretation is correct, this suggests a diagnostic, one that is spatially resolved and does not require seeding. We have in mind (Fig. 7) a bright light source (probably a laser) that illuminates a flow field containing time-dependent density gradients. The transmitted light is detected with a high-speed detector with a Ronchi ruling just in front of the detector surface. Thus naturally-occurring turbulent structures will Bragg-diffract incident light off of one particular turbulent spatial frequency into a detector at fixed scattering angle. Independent of the scattering angle, the spacing of the Ronchi ruling determines which spatial acoustic frequencies will modulate the scattered light intensity on the detector, creating an easily distinguishable signal.

Different versions of this basic concept are possible, including (1) narrow and broadband light sources, (2) detection at a single fixed point or multiple points with a camera or diode array, and (3) automated variation of the Ronchi ruling wavelength. Versions 2 and 3 allow fast acquisition of a frequency-resolved turbulence spectrum. Extension to simultaneous measurement of three orthogonal components of flow fluctuations is straightforward with three detectors oriented along different directions. Fig. 7 illustrates only a 1-d version. This proposed turbulence diagnostic is relatively simple compared to other common laser techniques. If proven technically achievable, it has potential for wide adaptation in the wind tunnel community because of the simple nature of diagnostic and the necessity for the day-to-day presence of optical experts would be reduced.

An alternative to this hypothesized interpretation is that the 6-MHz signature is simply a beam pointing modulation that the flow induces on the LITA signal beam. In this case, the measured frequency content would still be useful for flow analysis.

V. Summary

(A) We performed two tests to check the possibility of using LITA velocimetry in air flows similar to those of the JNL, i.e., flows that simultaneously contain both high densities ($\geq$ 1 amagat) and severe density gradients.

(B) The first test was performed in the LSAWT of the JNL. A HeNe laser beam transited the concentric-jet flow field ($\approx$ 10 kg/sec) and was imaged with a high-speed gated camera to measure beam steering and distortion in the transverse mode (spatial intensity profile). We believe that our results suggest that the spatial profile of beam intensity was perturbed to such a degree that single-shot LITA measurements will be difficult in the core flow of this facility.

(C) In the second test, LITA velocimetry was performed at the exit plane of a smaller laboratory jet ($\leq$ 0.1 kg/sec) exhausting into room air. At Mach ~ 1 conditions, this flow approximated the flow density and turbulence of the JNL. Single-shot LITA velocimetry was not practical, because of a low-frequency noise interfering with the signal. However, averaging 500 laser shots over 17 sec, we accurately measured exit-plane Mach number and temperature.

(D) Although not always impossible, as indicated in the results of Fig. 2b and 5, these two tests suggest that optical diagnostics, relying on phase coherence or multiple-beam overlap, face formidable hurdles in the JES flow field with its dynamic large total density and large fractional density gradients.

(E) Although the outlook for the use of nonlinear optical diagnostics in the JNL is unclear, the two tests suggest other possibilities. One example, suggested here, is a single-laser approach with a Ronchi ruling and detector illuminated with Bragg-diffracted light off of the naturally occurring density fluctuations in the turbulent flow.

VI. Acknowledgement

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VIII. Figure Captions

1. Schematic of (a) side-view and (b) end-view of the JES in the LSAWT, showing three measurement locations A, B, and C, and typical flow conditions.
2. Four different single (i.e., instantaneous) images of the transmitted HeNe laser beam intensity profile at location A in Fig. 1, for (a) condition 6, (b) condition 3, and (c) condition 1 of Table I.
3. Top-view schematic of LITA setup and laboratory jet for velocity and temperature measurements near the nozzle exit plane.
4. Single-shot temporal profiles of the LITA signal for flow conditions of (a) no flow, (b) Mach 0.285, and (c) Mach 0.65.
5. 500-shot, time-averaged (17 sec) LITA measurements of the (a) axial Mach number and the (b) translational gas temperature compared to the expected flow conditions based on measured stagnation pressures and isentropic flow expansion.
6. 500-shot, time-averaged LITA frequency spectra for the (a) no flow and (b) Mach 1.1 conditions. Expected noise frequency ($F = V_{flow} / \lambda_{sound}$) versus measured LITA noise frequency for the same data of Fig. 5 is shown in (c).
7. Schematic of proposed optical diagnostic based on beam steering induced by naturally occurring density gradients in a compressible, turbulent flow field.

Figure 1a

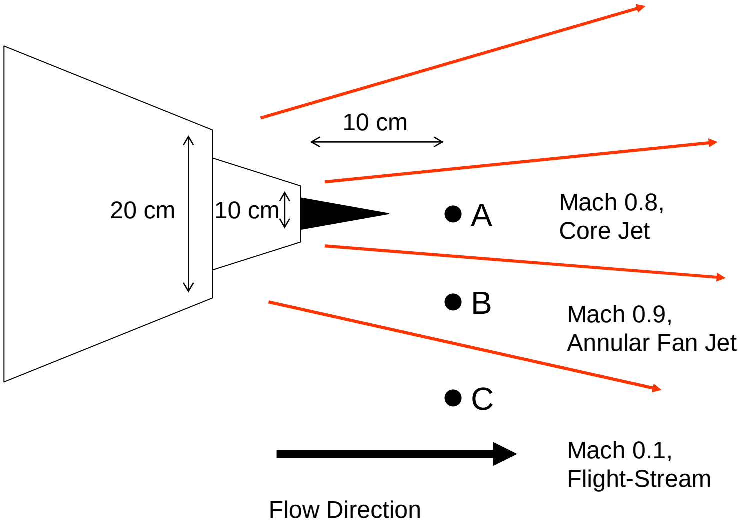


Figure 1b

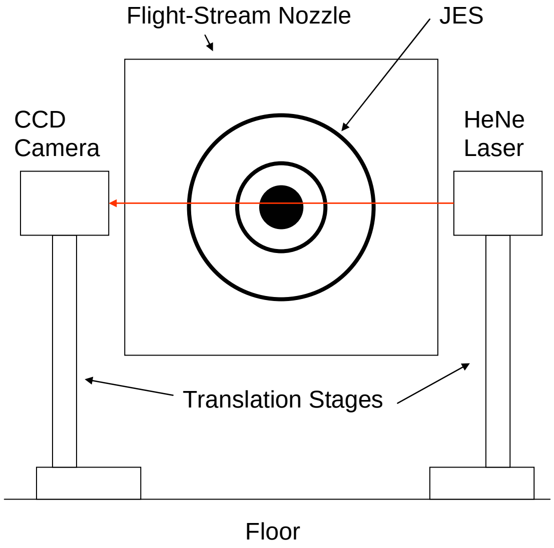


Figure 2a

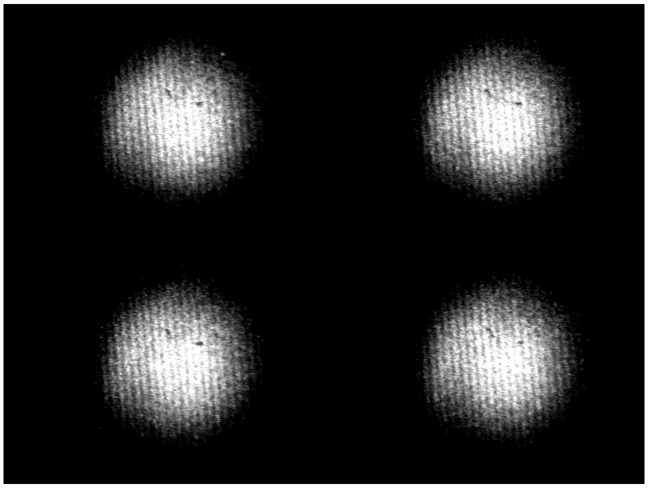


Figure 2b

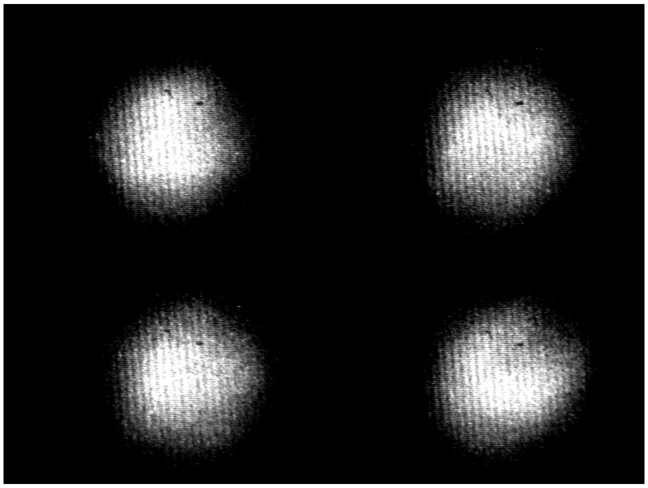


Figure 2c

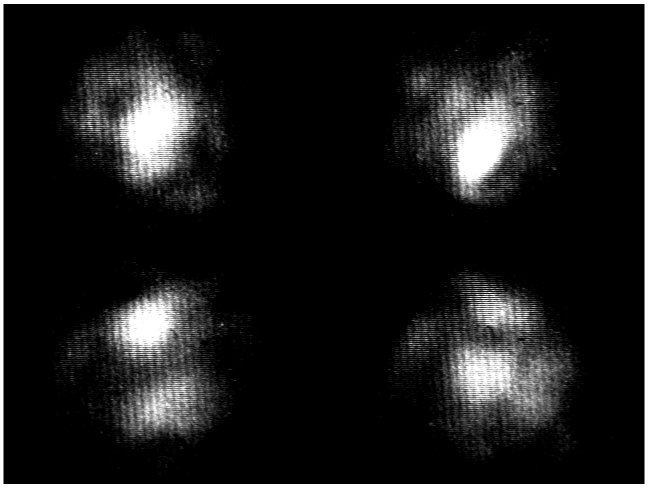


Figure 3

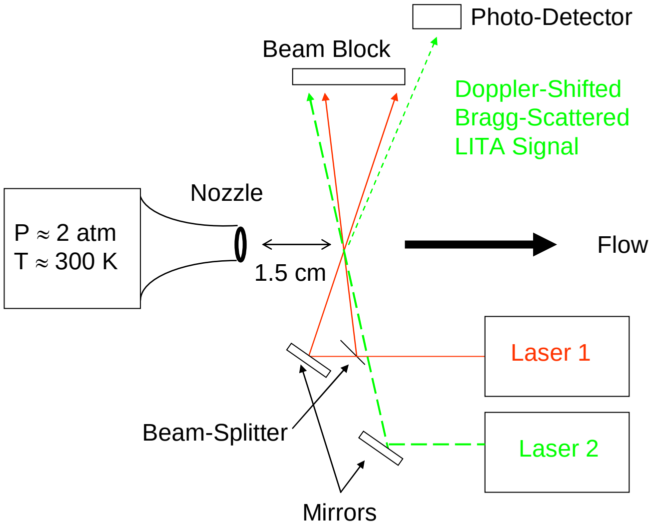


Figure 4

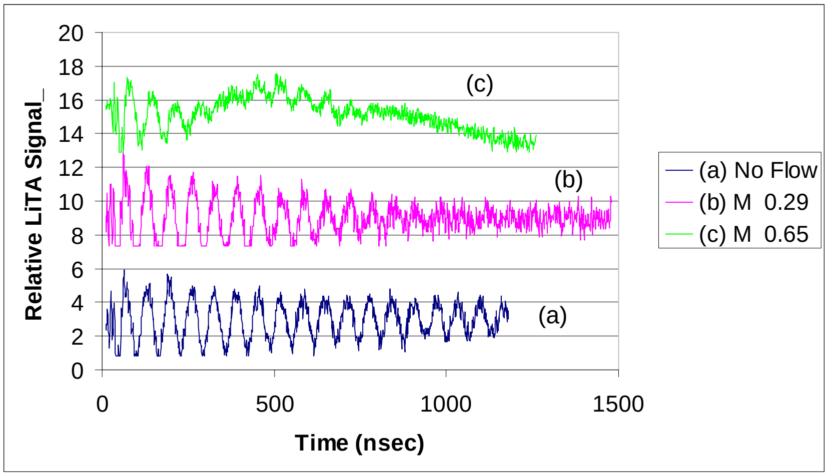


Figure 5a

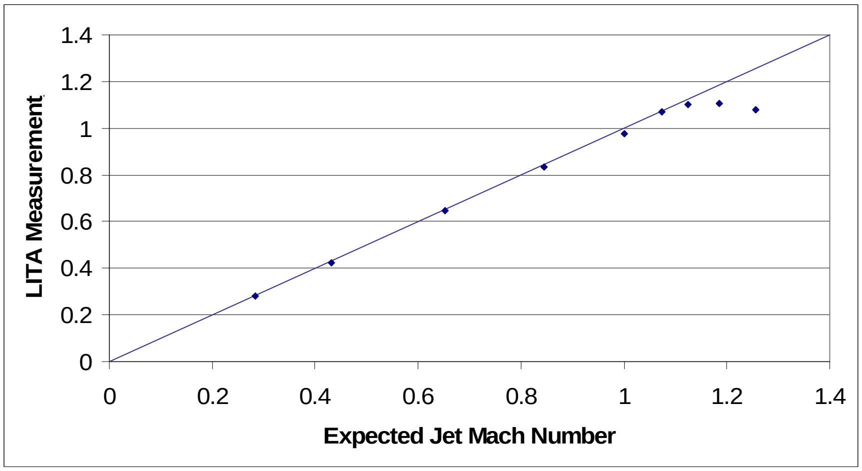


Figure 5b

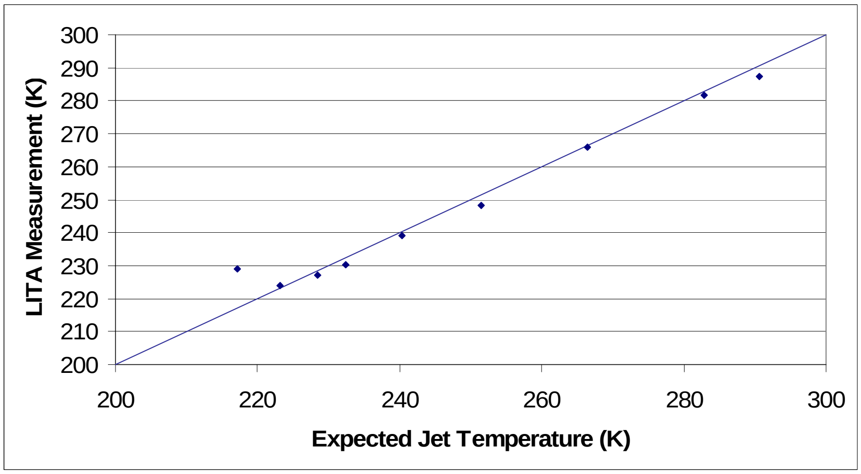
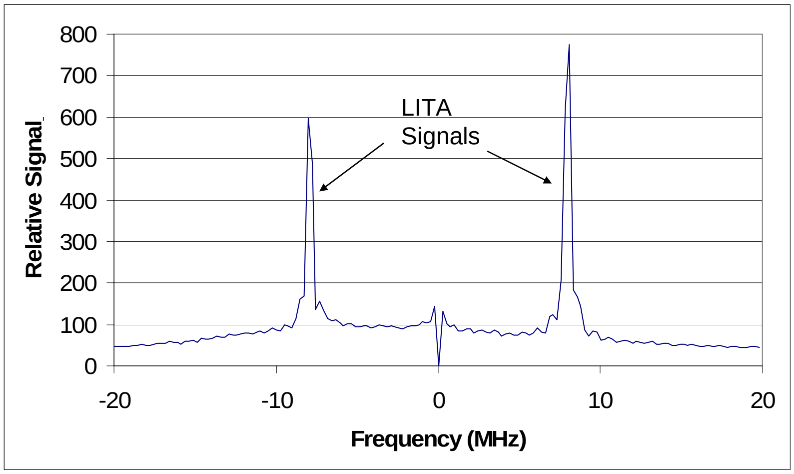


Figure 6a



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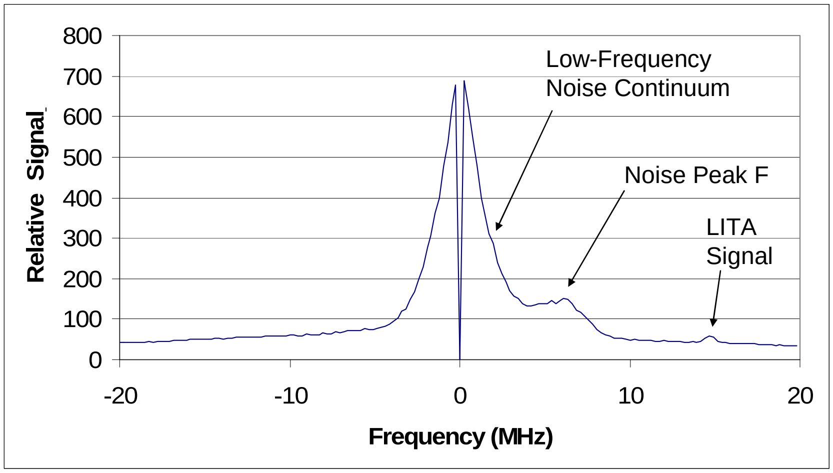


Figure 6c

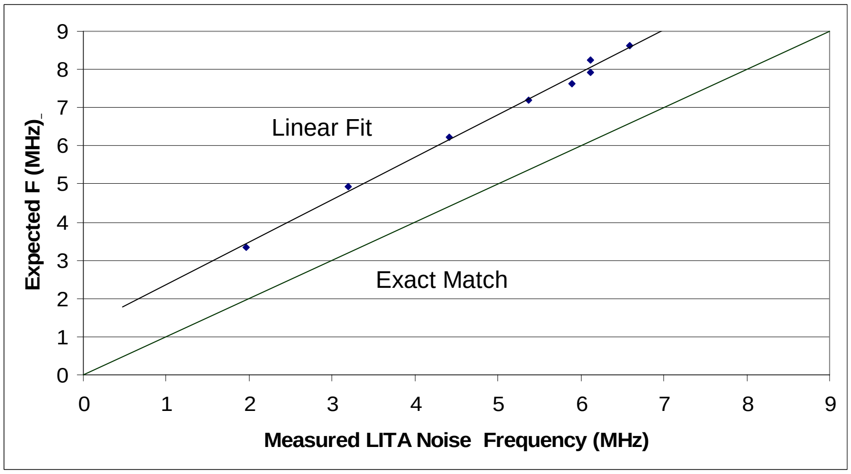
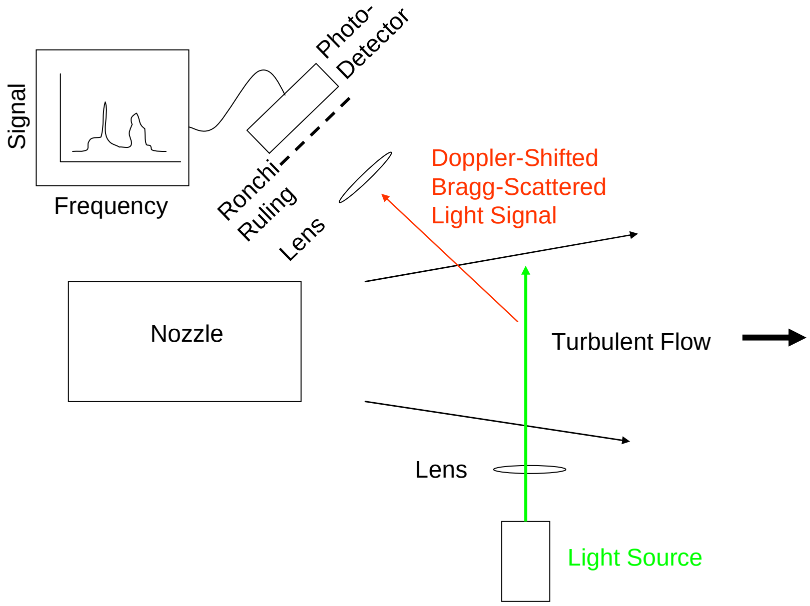


Figure 7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Signal
Frequency
Ronchi
Ruling
Lens
Doppler-Shifted
Bragg-Scattered
Light Signal
Nozzle
Turbulent Flow
Lens
Light Source

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14. ABSTRACT

Two experiments were conducted to test whether optical methods, which rely on laser beam coherence, would be viable for off-body flow measurement in high-density, compressible-flow wind tunnels. These tests measured the effects of large, unsteady density gradients on laser diagnostics like laser-induced thermal acoustics (LITA). The first test was performed in the Low Speed Aeroacoustics Wind Tunnel (LSAWT) of NASA Langley Research Center’s Jet Noise Laboratory (JNL). This flow facility consists of a dual-stream jet engine simulator (with electric heat and propane burners) exhausting into a simulated flight stream, reaching Mach numbers up to 0.32. A laser beam transited the LSAWT flow field and was imaged with a high-speed gated camera to measure beam steering and transverse mode distortion. A second, independent test was performed on a smaller laboratory jet (Mach number < 1.2 and mass flow rate < 0.1 kg/sec). In this test, time-averaged LITA velocimetry and thermometry were performed at the jet exit plane, where the effect of unsteady density gradients is observed on the LITA signal. Both experiments show that LITA (and other diagnostics relying on beam overlap or coherence) faces significant hurdles in the high-density, compressible, and turbulent flow environments similar to those of the JNL.

15. SUBJECT TERMS
Aero-optics; Jet Noise Laboratory (JNL); Laser beam steering; Laser-induced thermal acoustics (LITA)

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