Development of Laser Velocimetry for Turbofan Engine Inlet Distortion Applications

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ABSTRACT

While always a concern, the topic of inlet distortion has grown in importance as contemporary airframe designers seek extremely compact and highly integrated inlets. Research has been conducted for a number of years at Virginia Tech on both classical total pressure distortion and, recently with much interest, in swirl distortions. To adequately characterize the flow fields of such complex distortions, we have incorporated laser velocimetry techniques, namely stereoscopic particle image velocimetry (PIV) and Doppler velocimetry based upon filtered Rayleigh scattering (FRS), into inlet distortion studies. These methods were highly developed in the laboratory before efforts were conducted to scale them to the turbofan research engine inlet at Virginia Tech. A guiding philosophy for these developments has been to seek the simplest, most robust arrangement of hardware and post-processing, given contemporary instrumentation component technologies. The resulting methods have proven scalable, with many lessons learned along the way for optimal means of implementation. The basic methods and some results are presented, showing the value of the techniques for ground test. In addition, the fundamental operating principles and the core component-scale technologies are assessed for their potential to scale to flight applications. Overall, our results and experience indicate that the pathway for robust integration of FRS technologies into flight systems is clearer and more robust than for PIV.

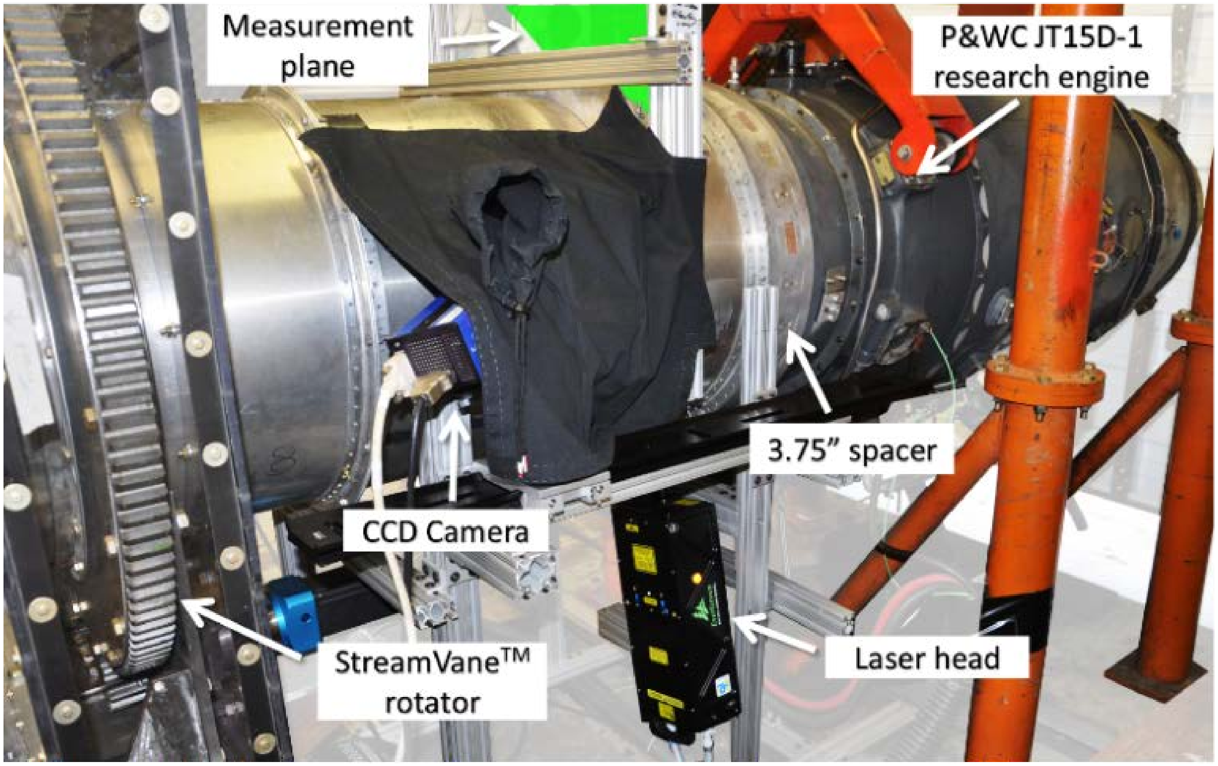
1.0 INTRODUCTION

Technological advances in laboratory techniques for optically-based flow measurements have been staggering in recent years. These developments have led to unprecedented temporal response in flow velocimetry [1-3], the ability to measure flow velocity, temperature, and pressure without probes or the addition of seeding particles [4], and a number of fundamental aerodynamics discoveries (e.g., confirmed existence of coherent wavepackets in supersonic jets [5], presence of reverse flow in flat plate turbulent boundary layers [6]). Several of these laboratory advances may be transitioned for applications to complex rigs, or even full-scale flight systems, given clever instrumentation engineering. Some notable examples of optical instrumentation transitioning to large-scale, harsh applications include the in-flight application of background-oriented schlieren [7,8] and time-resolved particle-image velocimetry in the wake of a utility-scale wind turbine [9,10]. In this contribution, we review past and on-going work at Virginia Tech in which the advances made possible at the component- and algorithm-level enable transition of laser-based velocimetry technologies to the ground test of aircraft engine inlet distortion. The discussion is concluded by identifying the progress needed to further develop technologies to flight applications.

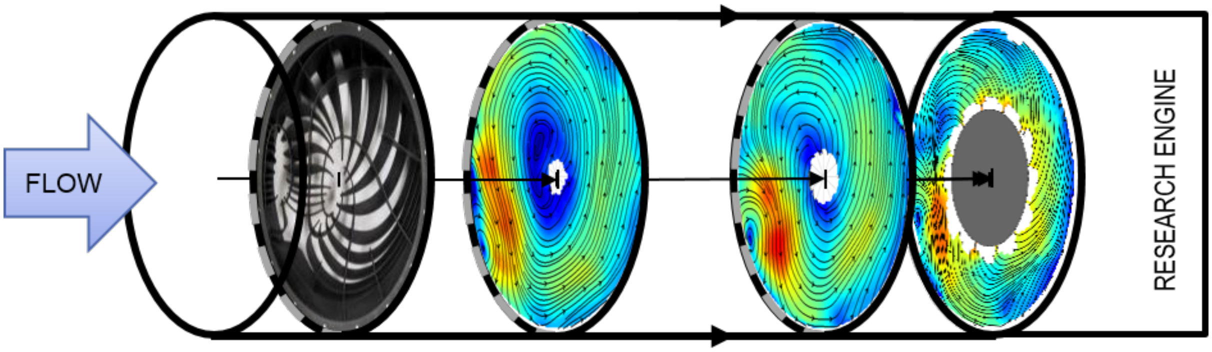
2.0 ENGINE INLET STEREOSCOPIC PARTICLE IMAGE VELOCIMETRY

Particle image velocimetry is a highly developed velocimetry technique which relies upon cross-correlation analysis of successive images taken of particles present in flow fields. Similar to laser-Doppler velocimetry, the basic assumption of PIV is that the measurement of particle velocities is representative of the local, unsteady continuum flow velocity in the region of interest. The basic hardware needed for PIV is a double-pulsed laser that illuminates the flow for the successive images and line interlaced cameras to view three-spatial-component displacements of particles at time-scales short enough to freeze the flow. PIV measurements provide instantaneous images of 2- or 3-component flow-field velocities.

The Virginia Tech team has successfully implemented stereoscopic PIV into engine applications a number of times (e.g., [11-14]). An example setup is depicted in Figure 2-1(a) for inlet distortion measurements upstream of a JT15D-1 fan. Two windows are used to view the laser sheet that enters at stations chosen to provide flow axial development insight. Full annulus reconstructions, like those in Figure 2-1(b), were obtained in these measurements by rotation of the distortion while leaving the instrumentation stationary. Extensive analysis of the PIV data has yielded information on the mechanisms for mean flow axial development, interaction details between the distortion and the spinner, fan acceleration effects on the mean swirl distortion, and detailed turbulence characteristics of distortion patterns. The tool has proven extremely valuable in understanding inlet flow characteristics.



(a)



(b)

Figure 2-1: Stereoscopic PIV for inlet distortion measurements. (a): Arrangement in the JT15D-1 test rig; (b): Example visualization of mean flow development with colors representing secondary flow magnitudes (red large, blue small) and streamlines depicting the direction of local secondary flow.

3.0 SEEDLESS VELOCIMETRY: FILTERED RAYLEIGH SCATTERING

While stereoscopic PIV provides three-velocity component measurement of both mean and turbulence quantities, it has some practical limitations such as the need for a near-optimal distribution of seeding particles and difficulties for measuring scalar flow properties. Recently, the Virginia Tech team has begun to develop a robust application of the filtered Rayleigh scattering technique for mean measurements of vector velocity, temperature and pressure [15,16]. The overall objective of the effort is to replace S-16 standard inlet distortion rakes with this high resolution optical method.

Rayleigh scattering is a wave optics phenomenon resulting from the interaction of light and matter on the scale of, or smaller than, the wavelength of the laser light. Summarizing the key attributes of the Rayleigh scattering signal,

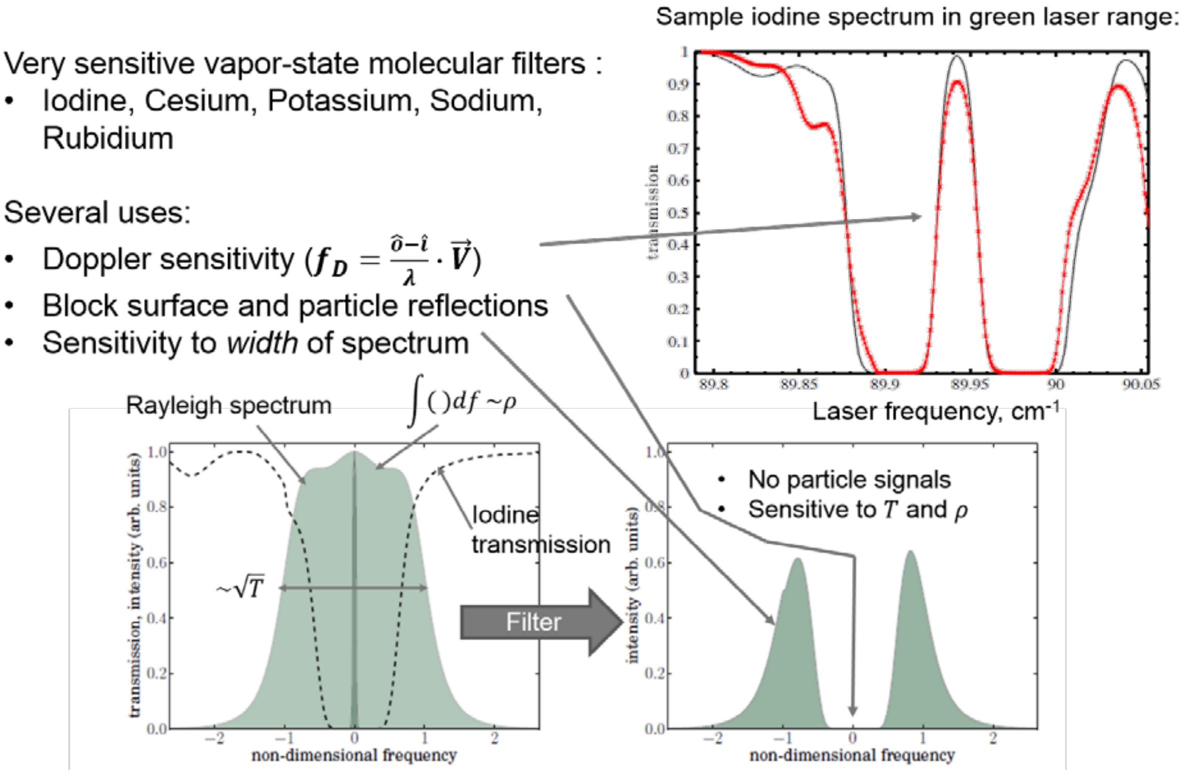
1. It is elastic: no net energy transfer between photon and matter.
2. It occurs down to molecular levels.
3. The probability of scattering increases with number of molecules per volume.
4. Even stagnant gas molecules are constantly moving—kinetic theory of gases—and impart a Doppler shift related to temperature.
5. Molecules have bulk motion in a flow and impart a flow Doppler shift, as well.

Items 3-5 yield the measurement principles, namely that one may directly measure density (3) and temperature (4) to get static pressure from the state equation, while the mean Doppler-shifted signal yields flow velocity. These effects are all observed by making use of a molecular filter, in our case iodine vapor in an optical cell. A basic schematic depicting several aspects of the use of an iodine filter is provided in Figure 3-1.

To date we have applied the filtering techniques for velocity measurements in flows with particles at a number of scales, from 1.8 m wide wind tunnels to over-expanded supersonic jets. We have also applied the molecular Rayleigh scattering technique for planar measurements in uniform and distorted free jets. Results are provided in Figure 3-2 for velocity validation, as well as planar velocity and total pressure measurements. The velocity comparisons are made between the axial velocity and Pitot pressure probe-derived axial velocity (Figure 3-2(a)).

Furthermore, total pressure ratio was computed using the local kinetic energy computed from the velocity measurements and local static temperature, showing total pressure loss and redistribution caused by the vortex generator placed upstream (Figure 3-2(c)).

The technique is currently being extended for measurements in the JT15D-1 engine rig inlet for back-to-back comparisons with PIV and standard rakes, with measurements expected by fall 2018. As this technology progresses, flight applications become attractive in that no particle seeding is needed, while much-needed scalar measurements are obtained simultaneously.



Very sensitive vapor-state molecular filters :

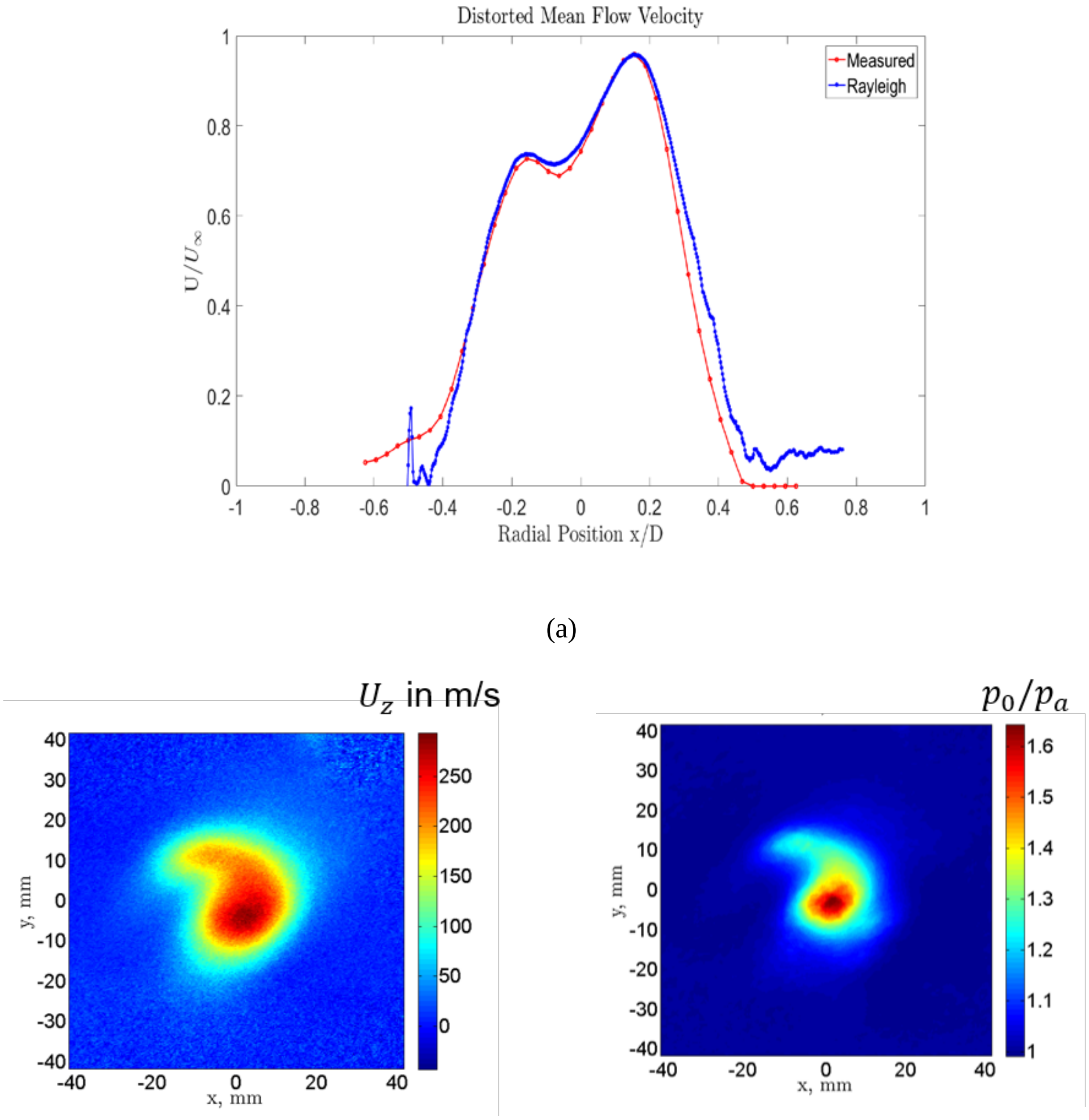
- Iodine, Cesium, Potassium, Sodium, Rubidium

Several uses:

- Doppler sensitivity ($f_D = \frac{\hat{o}-\hat{\imath}}{\lambda} \cdot \vec{V}$)
- Block surface and particle reflections
- Sensitivity to *width* of spectrum

- No particle signals
- Sensitive to T and ρ

Figure 3-1: Some attributes of filtered Rayleigh scattering principles.



(a)

(b)

(c)

Figure 3-2: Results from filtered Rayleigh scattering measurements in a free jet containing a stream-wise vortex. (a) Axial velocity validation with total pressure probe measurements; (b) Axial velocity planar distribution; (c) Total pressure distribution obtained from combination of velocity and scalar measurements.

4.0 TOWARD IN-FLIGHT APPLICATIONS

Both techniques for inlet velocimetry discussed above have shown promising results for ground test applications. Methods and procedures for adequate risk reduction are in place to ensure efficient transition from laboratory to ground test facilities, and the reader is referred to our references to understand the transition (e.g., [11,12]) . Not surprisingly, going beyond ground test and extending to flight applications offers a number of new challenges, most of them related to integration. Prior to discussing integration challenges, however, first consider the measurement challenges associated flight atmospheres.

4.1 Atmosphere scaling

The methods discussed, PIV and FRS, rely upon laser light scattering for the return signal. PIV requires particles to be present for a measurement, severely limiting the applicable flight conditions that will result in quality measurements. Even uniformity of particle spatial distribution is a key attribute for low uncertainty PIV. In flight conditions, the appropriate particle loading for quality PIV can only be expected while flying through clouds. Furthermore, particle sizes and concentrations in clouds vary greatly with local conditions and altitude [17], with particular concern for the efficacy of high altitude cirrus clouds for inlet PIV given low ice crystal concentrations of relatively large crystals, O(100’s of micrometers) [18], resulting in large Stokes numbers.

In contrast, FRS does not suffer from susceptibility to particle loading variations, but it is sensitive to altitude variations. The FRS signal strength is directly proportional to the local air density [19], meaning that signal returns will reduce with altitude. For instance, an altitude increase from sea level to 10 kilometers reduces the density by a factor of three; the FRS signal can be expected to reduce by the same factor. Fortunately, this effect can be compensated by increasing the integration time of measurements by the same factor; but it must be assumed that measurement durations may require up to three-times that at sea level assuming the same laser power.

4.2 Integration

The final integration of laser velocimetry into flight systems requires solving a number of engineering challenges to meet the demanding requirements. As with many advanced instrumentation systems, the issues of size and weight are major concerns. The core basic hardware present in both approaches are lasers, cameras and processing computers. Further, optical access into the flight inlet must be considered.

4.2.1 Laser

The requirements for the lasers for PIV and FRS are somewhat different; notably, PIV requires a pulsed laser (usually a flash-lamp-pumped laser), while FRS demands a single-frequency, continuous wave laser (usually diode-pumped solid state lasers) with frequency scanning capability. Custom pulsed lasers for PIV can be made relatively small, but cooling demands for generating sufficient pulse energy remain a concern. The continuous wave lasers used for past applications of FRS are bulky and require environmental controls for temperature and vibrations. In contrast to PIV lasers, however, FRS laser delivery may be achieved via single-mode fiber optics. Fiber lasers, the heads of which are considerably more compact than flash lamp pumped or diode-pumped solid state lasers, offer a possible improvement to packaging. Considering the current state of the art and trajectory of laser packaging and technologies, it is feasible for either system to be integrated for flight test using existing technologies, while production integration will require state-of-the-art improvements.

4.2.2 Cameras and optics

The cameras are different across the techniques, as well. PIV makes use of an interline camera (capable of taking two frames at very short and precise delay times), or a high speed camera (such as those produced currently by Photron and Phantom). While most prior FRS work has utilized high performance, and bulky, scientific cameras, in recent work the Virginia Tech team has shown that low cost, small volume machine vision cameras perform adequately for low uncertainly FRS. The dimensions of these cameras are approximately 3 cm x 3 cm x 3 cm, with a mass of 36 grams, without lenses. It is believed that ongoing engineering can lead to proper integration of these machine vision cameras to a flight-ready package. Given timing features present on these devices, it may be feasible to extend them for the short, precise delay times needed for PIV by using two cameras for a single frame.

In addition to cameras, both systems require lenses to capture images of the scattered laser light. Using stock lenses approximately doubles the volume of the machine vision cameras, though specially designed compact, short focal length lenses are promising for reducing this size.

The FRS technique must contain a glass optical vapor cell, which acts as a filter in front of the camera lens. The in-flight LIDAR community also makes use of these cells [20], and progress has been made toward developing commercially available compact cells. A challenge in the current application is that relatively high optical density of the absorbing vapor is necessary, such that a short cell must have a large vapor pressure. The pressure/temperature phase transition limits of iodine and the non-linear characteristics of high vapor pressure absorption both must be considered as fundamental limits to packaging. It is reasonable to assume that existing technologies may be integrated for FRS cameras that are significantly more compact than past laboratory and ground test implementations.

4.2.3 Data acquisition, processing, and interface with flight data systems

Both systems require similar processing algorithms. Given the current state of the art, it is thought that relatively simple on-board computers may fill the demands. Interfacing with the machine vision cameras is possible using USB 3 protocols, providing relatively compact connectivity. Wiring size, weight and egress paths all must be considered at a later stage, but these concerns are likely outweighed by development needs of the hardware components mentioned above. A wide array of information may be obtained from the data acquired by these systems, and integration into the flight data systems may be desirable. Online information such as inlet mass flow and inlet distortion indices [21-23] are examples of reduced information that would be feasible to compute on the fly.

4.2.4 Optical access

Both of these techniques require optical penetration into the inlet for collecting scattered laser light. It is possible that optical fiber bundles will be necessary to minimize the penetration size and enable packaging of the cameras near the windows. The close coupling between the PIV operating principles and the resolution of the imaging system creates challenges associated with using fiber optic bundles with such a system. In contrast, the FRS principles are independent of imaging resolution. It is well known that imaging fiber bundles reduce light collection efficiency [24]; thus, FRS applications with fiber bundles will require longer exposure times than a similar imaging application using free-space optics. Finally, given the small size of the machine vision cameras, an optimization is possible using variables of field of view, circumferential arrangement of windows, and number of cameras.

4.3 Overall assessment of flight scaling potential

The assessments above suggest that current technologies may be integrated in a clever manner for flight test applications, while production systems will require advances in the state of the art for individual component technologies.

Each of the two techniques, PIV and FRS, offer their own advantages and challenges, but overall, the transition of FRS for mean flow field measurements has a considerably clearer path for in-flight applications. For instance, it has already been shown in the author’s laboratory that the compact machine vision cameras work well for FRS (in fact, owing to improved quantum efficiencies, at a shorter exposure time than that required for scientific CMOS cameras). The applicability of fiber optics for laser light delivery and fiber bundles for collection opens the design space for FRS considerably. Since FRS does not rely upon particles, yet can work even when particles are present [25], this technique is robust to a wide array of flight conditions. The signal for FRS may be improved by integrating scattered light measurements over a longer period of time, a feature not available in PIV. Further, the same FRS processing algorithm works over a range of flight Mach numbers from 0.3 to 4, while PIV would require some algorithm scheduling with Mach number to be adapted. Finally, FRS offers the potential to go beyond velocimetry, with sensitivity to static temperature and density.

5.0 CONCLUSIONS

Two techniques with the potential for in-flight aircraft inlet laser velocimetry are discussed. Particle image velocimetry is a commonly used laboratory tool that has been transitioned to a number of impressive applications such as very large scale atmospheric measurements and inlet ground test applications. Filtered Rayleigh scattering has been developed for a number of applications for which particle seeding is not feasible, and offers measurements of local static temperature and density in addition to velocity. FRS is also being extended to inlet ground test applications.

In assessing the feasibility of in-flight applications of each of these technologies, several component technologies and flight environment aspects have been considered. It is asserted that flight test applications are feasible for either technique by integrating existing component technologies, though PIV will require careful consideration of flight conditions to ensure the presence of adequate natural seeding provided by droplets for ice crystals in clouds. In contrast, FRS can work with or without the presence of particles, and is robust in a number of other fundamental ways as well. FRS also provides the potential to estimate flow static temperature and pressure, quantities that are beyond the state-of-the-art for measurement by PIV in naturally seeded flows. For these reasons, it is thought that PIV is best suited for ground test, while FRS offers immediate high potential for ground and flight test, with feasibility for integration in production systems with advances in component technologies.

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