High-repetition-rate interferometric Rayleigh scattering for flow-velocity measurements

JORDI ESTEVADEORDAL,[1,*] NAIBO JIANG,[2] ANDREW CUTLER,[3] JOSEF J. FELVER,[2] MIKHAIL N. SLIPCHENKO,[2] PAUL M. DANEHY,[4] JAMES R. GORD,[5] AND SUKESH ROY[2]

[1]*Mechanical Engineering Department, North Dakota State University, 111 Dolve Hall, Fargo, ND 58108, USA*
[2]*Spectral Energies, LLC, 5100 Springfield St., Suite 301, Dayton, OH 45431, USA*
[3]*School of Engineering and Applied Science, George Washington University, 800 22nd St. NW, Washington, DC 20052, USA*
[4]*Advanced Measurements and Data Systems Branch, NASA Langley Research Center, Hampton, VA 23681, USA*
[5]*Aerospace Systems Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433, USA*

High-repetition-rate interferometric-Rayleigh-scattering (IRS) velocimetry is implemented and demonstrated for non-intrusive, high-speed flow-velocity measurements. High temporal resolution is obtained with a quasi-continuous burst-mode laser that is capable of providing bursts of 10-msec duration with pulse widths of 10–100 nsec, pulse energy > 100 mJ at 532 nm, and repetition rates of 10–100 kHz. Coupled with a high-speed camera system, the IRS method is based on imaging the flow field though an etalon with 8-GHz free spectral range and capturing the Doppler shift of the Rayleigh-scattered light from the flow at multiple points having constructive interference. The seed-laser linewidth permits delivery of a laser linewidth of < 150 MHz at 532 nm. The technique is demonstrated in a high-speed jet, and high-repetition-rate image sequences are shown.

Optical diagnostic techniques based on high-repetition rates are currently capable of providing both temporally and spatially resolved measurements of flow and combustion properties [1–4]. These measurements are proving to be unique and crucial in the tracking of fast occurring phenomena such as those encountered in combustion, high-speed, and turbulent flows and have the capability to provide accurate and reliable experimental validation of models used in numerical simulations.

The key features of the instrument system used in these high-repetition-rate investigations are the high-power laser burst and the narrow linewidth. These features allow the capture of spatially and temporally varying flow parameters, including velocity, density, pressure, and temperature. Turbulent and high-fluctuation flows such as those occurring in the inner structure of supersonic jet cores can be tracked. The added instrument feature of narrow-bandwidth "seed" laser line makes accurate high-repetition-rate measurements feasible using techniques such as interferometric Rayleigh scattering (IRS) and filtered Rayleigh scattering (FRS) [5–8] that require a fine spectral laser line.

Traditional measurement techniques have been based on intrusive-probe-type devices that disturb the flow field; such devices include hotwires and the use of particle/molecular-seeding techniques that are not feasible in certain testing facilities or are inadequate in specific flow regions such as shocks, boundary layers, and stagnation regions. In addition, seeding can contaminate the test section in tunnels and facilities, can become expensive, and can reduce the effective run time--particularly in large-scale wind tunnels. Thus, alternative techniques that are non-intrusive and unseeded are required in many applications.

Among the numerous optical-based velocimetry techniques that have been developed over the past several decades for fluid flow and combustion measurements, most utilize lasers for either simple illumination or resonant/non-resonant molecular-excitation-based tracking. A comprehensive list of such techniques may include seeded techniques such as planar, stereoscopic, and tomographic Particle-Imaging Velocimetry (PIV) [9], Laser Doppler Velocimetry (LDV) [10], Planar Doppler Velocimetry (PDV) [11], Molecular-Tagging Velocimetry (MTV) [12], and Laser-Induced Fluorescence (LIF) [13] and unseeded techniques such as Raman Excitation plus Laser-Induced Electronic Fluorescence (RELIEF) [14], Air Photolysis and Recombination Tracking (APART) [15], Femtosecond-Laser Electronic-Excitation Tagging (FLEET) [16], and FRS and IRS methods [5-8]. Most of these techniques have shortcomings related to signal levels, requirement of flow containing certain molecules, lack of sensitivity at high flow velocities, and complexity for harsh environments, for example.

As compared to all of the velocimetry techniques outlined above, the Rayleigh-scattering-based IRS technique has significant advantages, including the ability to measure several flow parameters simultaneously with a single laser beam and applicability over a wide range of flow temperatures and working gases (e.g., air, N_2, vitiated air, and argon).

The IRS technique has been performed at low repetition rates (e.g. 10 Hz) for flow instantaneous measurements [7, 8] and at high repetition rates (e.g. 32 kHz) using continuous wave lasers for time-averaged flow measurements [6]. However, to the authors' knowledge, no instantaneous (e.g. with time exposures <10 ns) IRS measurements have been performed at the high repetition rates (>10 kHz) necessary for resolving high-speed, high-frequency, turbulent flow phenomena having very short time scales. In the present study, a step toward time-resolved measurements was demonstrated with 10-kHz IRS using the high-speed system for multi-point, time-resolved flow-velocity determination.

The basic principle of the IRS technique is that Rayleigh-scattered light from the flow of interest is imaged through a Fabry-Perot interferometer (etalon) [5–8]. Since the transmission properties of the etalon depend both on the wavelength of light and on the angle of incidence of light on the etalon, the image contains both spatial and frequency information, allowing the Doppler shift due to flow velocity to be determined at multiple locations in the flow. The velocity can be obtained based on the Doppler-frequency shift $\Delta \boldsymbol{f_d}$ through the following expression [5–6]:

$$\Delta \boldsymbol{f_d} = \frac{(\vec{s}-\vec{o})}{\lambda}.\vec{\boldsymbol{V}} \quad \textbf{(1)}$$

Here $\vec{\boldsymbol{o}}$ is the unit vector in the direction of the incident/object laser light, $\vec{\boldsymbol{s}}$ the unit vector in the scattering/observation direction, λ the wavelength of the light, and $\vec{\boldsymbol{V}}$ the flow velocity vector.

A schematic of the setup used in this investigation is shown in Fig. 1 with an acquired IRS sample image with quiescent flow. In this setup the narrow-linewidth, ns-pulsed second-harmonic beam of 532 nm from the burst-mode laser is focused to form the laser-beam waist in the measurement region of interest via focusing lenses. Rayleigh-scattered light from this thin line in the measurement region is collected and collimated by lenses in the normal direction to the vertical polarization plane for maximizing Rayleigh-scattering- light collection. This collimated light then passes through a solid etalon with an 8.3-GHz free spectral range (FSR) and the measurement region is imaged via a focusing lens onto a high-speed, intensified, complementary-metal–oxide–semiconductor (CMOS) camera. Diffuse light from the laser source (not Rayleigh scattered) is introduced into the optical path via a polarizer as a reference. The polarizer was used to combine the Rayleigh signal with the unscattered laser light. The pulse-burst laser was run at a rate of 10 kHz, and the pulse energy was about 20mJ/pulse. A 10-ms burst was created, and each burst contained about 100 pulses of 10 nsec duration. A high-speed Photron SA-Z CMOS camera and a LaVision IRO intensifier were used to record the IRS images. The intensifier gain was ~ 60%. In this experiment the field of view was about 4 × 4 mm^2; the IRS velocity measurements were made in a 4-mm-inner-diameter lab-scale jet; and the measurement area was about four diameters downstream of the nozzle exit. Pulse linewidth and power were monitored using a power meter and wavemeter via optical fibers (O.F.). The image consists of a set of concentric bright rings resulting from the diffuse-reference-source constructive interference angles and a set of aligned bright spots due to imaging of the focused laser beam. The etalon acts as a filter that transmits light at a set of radial distances from the image center that repeats following a constructive interference pattern where each ring corresponds to a different angle of view [5]. Thus, a radial cut through the laser beam image provides the spectra of the scattered and reference light sources at a few spatial locations.

Radial displacement of the scattered light relative to the reference rings is due to the velocity Doppler shift, while radial broadening of the width of the spots relative to the reference rings is due to various molecular-broadening scattering components of the scattered light relative to a narrow-line laser source [5]. The linewidth radial broadening is dependent on the molecular weight and temperature, and images such as this can be analyzed, in addition to velocity components, for temperature (if the gas composition and pressure are known). Also, since the integrated Rayleigh-scattered light intensity is proportional to the gas number density (for a given gas composition), the system can be calibrated to measure density also [5, 6, 18].

The detected Doppler shifts of scattered light from the incident object beam $\vec{\boldsymbol{o}}$ in the direction of the collected scattered laser light $\vec{\boldsymbol{s}}$ are due to the component of velocity lying in the bi-sector of the plane formed by the two vectors $\vec{\boldsymbol{o}}$ and $\vec{\boldsymbol{s}}$ [5, 6]. Then, with the jet nozzle set to an angle α of 45° between the laser beam and the scattering direction (Fig. 1), the main flow velocity is obtained by

$$\boldsymbol{V} = \Delta \boldsymbol{f} \cdot \boldsymbol{\lambda}/\sqrt{\boldsymbol{2}} \quad \textbf{(2)}$$

Arrangements for measuring other velocity components have been shown in the literature [7, 8] by multi-pass beams in different directions. This investigation focused on the demonstration of burst-mode IRS for a single component of velocity.

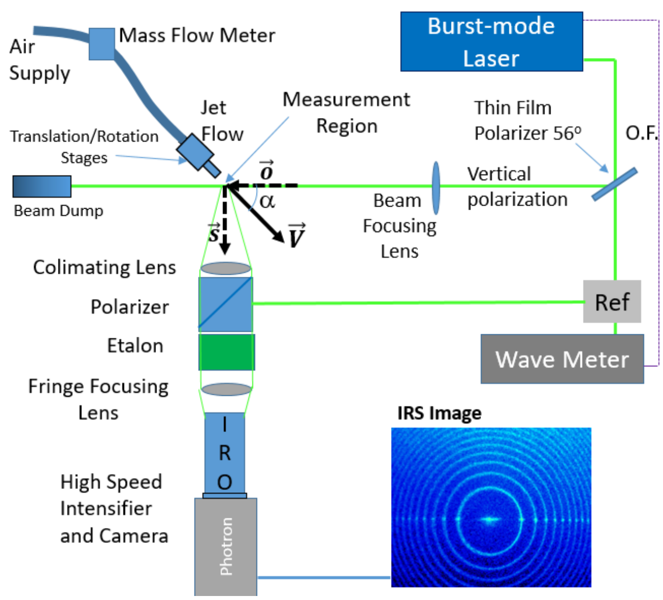


Fig. 1. Schematic of IRS system for focused laser beam interrogation.

The IRS technique depends upon Rayleigh scattering, which is an elastic process that does not change with the flow. However, Rayleigh scattering is weak and diffuse, and the transmission efficiency of the etalon is low. Thus, high-energy laser sources and scattered-light collection over large solid angles are required for precise measurements. Maximum pulse energy is limited by laser-induced gas breakdown near the focus of the laser beam. The burst-mode laser offers two major advantages: very high pulse energy with adjustable pulse length (up to 100 ns at 532 nm) so that substantially more energy can be delivered to the measurement volume, and high repetition rate (up to 100 kHz) over the duration of the burst that allows temporal resolution of high-speed flow events. High pulse energy, in turn, may allow relaxation of the requirement for light collection over a large solid angle (i.e., "fast" optics), which is often difficult to achieve in wind-tunnel facilities. Since Rayleigh scattering is at the same wavelength as the incident laser (except for small Doppler shift and line broadening), there can be interference from particles and surfaces. The signal can be improved by introducing a molecular filter (such as iodine for 532 nm) to remove unwanted Mie and other light-scattering noise [5, 8]. The IRS technique can also minimize such localized interferences in image analysis. Such interference is further reduced (and signal increased) at shorter laser wavelengths because Rayleigh-scattering intensity scales with wavelength to the negative fourth power, while scattering from large particles and surfaces is approximately independent of wavelength.

The pulse energy is also limited by the onset of ionization and plasma generation, which causes bright flashes that overpower the Rayleigh signal. Plasma breakdown occurs when the peak power exceeds a certain threshold, which imposes an upper limit on the total energy that can be used for a given spot size and pulse width. Rayleigh scattering is a linear process, with a signal level that increases with the number of photons, or total energy, and is not dependent on the laser pulse width. It can, therefore, be advantageous to deliver the energy over a longer period of time for avoiding unwanted effects such as ionization or damage to optical components and wind-tunnel windows. However, it is also desirable to make Rayleigh measurements with pulsed lasers and gated detectors so that the detector can be turned off between pulses to filter out contributions from background signals. For these reasons, the burst-mode laser with tunable pulse width offers a significant advantage.

The laser linewidth is another critical parameter for IRS measurements. It is directly related to the measurement uncertainties of the velocity. Since IRS velocimetry is a Doppler-shift technique, with a narrow linewidth laser the Doppler-shifted signal peak can be separated from the reference interference rings, which can result in very accurate velocity determinations. Provided that a high enough resolution etalon is used, the laser linewidth limits the size (how small) of the Doppler shift that can be measured accurately. As mentioned in the discussion on data fitting, the peaks of the Rayleigh signal and the reference rings are normally fitted with theoretical distributions to solve for Doppler shift and other parameters. The fitting uncertainties could be about 1 – 2% of the measured velocity.

When narrow seed-laser source having a linewidth of < 50 MHz was used, the burst-mode laser system linewidth at 532 nm was < 150 MHz at 10-kHz rate measured by a WS7 wavemeter. It is noteworthy that the linewidth measurement based on etalon rings depends on the quality of the etalon such as the etalon surface flatness. Therefore, the ring thickness shown in the IRS images could be only broader than the actual laser linewidth. The etalon quality also depends on the degree to which the two solid etalon surfaces are parallel. A high-quality surface flatness better than $\lambda/100$ is required for the etalon. For a typical Mach-1 flow of ~340 m/s, the Doppler shift will be close to 600 MHz if the flow direction is parallel to the velocity the system is sensitive to. With theoretical fitting, the Rayleigh-scattering peaks should be well recognized with the 600-MHz separation from the 150-MHz (even 400 MHz if the etalon quality was taken into account) reference rings.

First, a typical IRS image sequence obtained with room air at a 10-kHz rate (which means that the inter-image spacing is 100 μs), is shown in Fig. 2 with a six-image sequence sample. As explained above, the un-scattered reference light imaged through the etalon generates the circular rings, and the Rayleigh scattering signal from the focused laser beam generates the discrete points in the image-sequence centerlines, which should appear as a uniform horizontal line when imaging without the etalon. Here, the different points reflect the Rayleigh-scattering signals at different positions in the test area, which could yield the multi-point velocities of the flow. Since the flow speed is zero, no Doppler shift was observed. The Rayleigh-scattering points overlap well with the reference scattering rings. Focus on the most inner position ring reveals that its size does not change during the burst. This is a good indication that the laser wavelength is very stable during the 10-ms burst. Nonetheless, the laser frequency is monitored in each image so that even if the laser frequency drifted during a pulse or between pulses, it would be corrected during analysis.

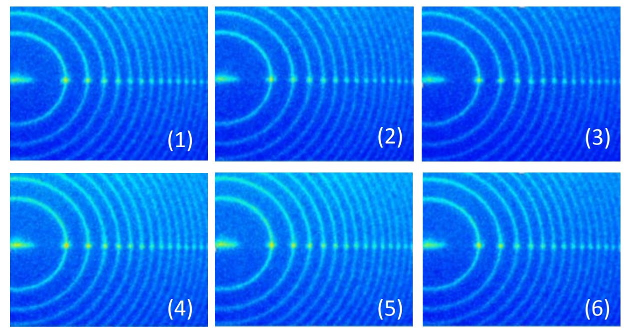


Fig. 2. Typical 10-kHz image sequence of IRS with zero flow speed.

Figure 3 shows a detailed raw image of a 100 × 60 pixel sub-region and the corresponding fitting image of the inner ring obtained using a data-fitting program. The theoretical model assumes the collimated focus of a laser beam and a uniform light field behind it. The light scattered from the laser beam is distributed spatially as a Gaussian of constant height perpendicular to the direction of the beam and has a constant intensity along the direction of the beam. The scattered, focused laser light (broadened by the Rayleigh-scattering process) and the uniform background (having the same spectrum as the laser source) are both Gaussian in wavelength with fitted FWHM linewidths and Doppler shift. The IRS image is generated by filtering the image of the focused laser beam plus background by the etalon/lens transmission characteristics. The fitted linewidth is ~ 500 MHz due to the etalon quality that was discussed earlier. The fitted Rayleigh-scattered linewidth is ~ 2.2 GHz, in agreement with the Tenti linewidth at room-air conditions of 2.2 GHz [5].

Doppler-shifted frequencies within a burst using Eq. (1) showed that the mean is 22.2 MHz and the standard deviation is ± 53.7 MHz, which represents bias and precision error in the Doppler shift; it corresponds to 8.36 m/s and ± 20.2 m/s. Note that the 8.3-GHz FSR of the etalon represents the full scale of the instrument; therefore, as a fraction of instrument range, this is 0.27% and 0.65% (% of full scale), respectively. For a 300-m/s flow velocity measurement, 20 m/s corresponds to 6.7% measurement uncertainty. The use of a higher resolution etalon in future work could improve these errors.

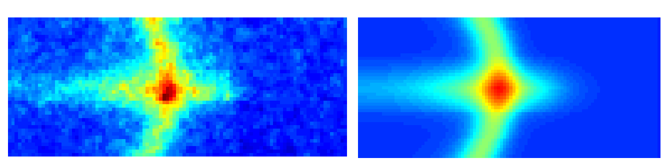


Fig. 3. Typical local fitting of IRS image with zero flow speed.

Figure 4 shows an IRS image detail for a jet flow of ~ 300 m/s. The corresponding sub-region fitting image is shown on the right. It is obvious that the Rayleigh-scattering signal is Doppler shifted relative to the reference scattering rings because of the high-speed flow. The images were taken at 10-kHz, and Figure 5 shows a six-image sequence as a high-speed IRS example. The Doppler-shifted frequencies have significant fluctuations due to the high-speed jet fluctuations and turbulence. The fitted Doppler shift for the particular image shown in Figure 4 is 706 MHz, which corresponds to a flow speed of 266 m/s. The Rayleigh-scattering linewidth is 1.86 GHz because of a slightly lower flow temperature.

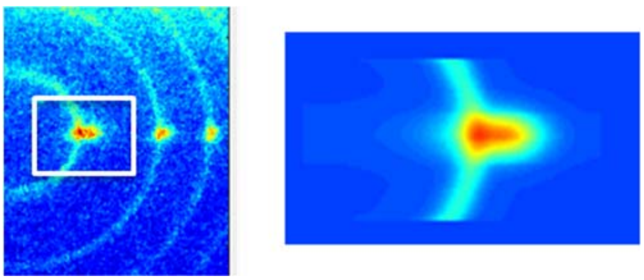


Fig. 4. IRS image fitting with a free jet. The flow speed is ~ 300 m/s.

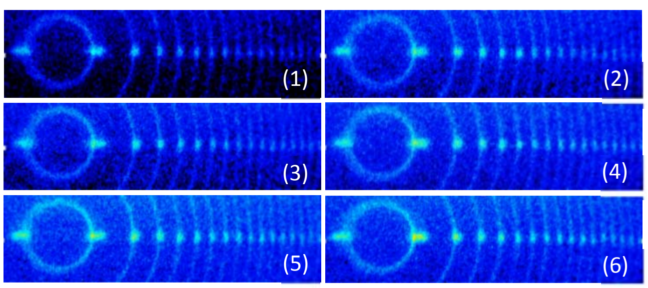
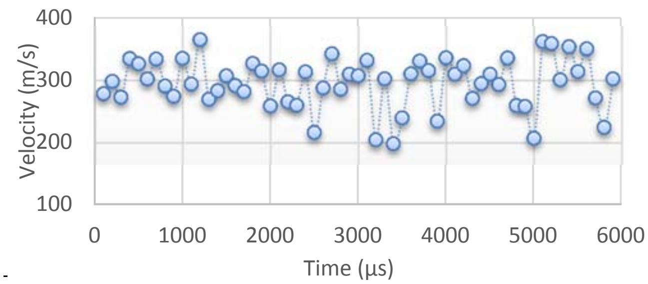


Fig. 5. 10-kHz IRS image sequence with flow speed of ~ 300 m/s.

Figure 6 shows the jet-flow, center-velocity time-evolution profile measured with 10-kHz IRS. Sixty measured data points are shown. The flow velocities fluctuate from 200 m/s to 370 m/s. The velocity measurement uncertainty is about 20 m/s, based on the analysis of no-flow conditions. For this flow-speed range, a 10-kHz repetition rate does not seem sufficiently fast to capture the flow dynamics. Thus the plan is to apply a 100-kHz rate IRS velocity measurement in the future. In addition, since multiple points in the jet centerline are available from each ring location, a time-resolved, centerline jet-velocity profile is also feasible. With multiple laser beam passes at different locations, a time-resolved evolution of the spatial profile can also be obtained as well as a second, perpendicular component of velocity.

In conclusion, the high-repetition-rate burst-mode-laser-based IRS velocimetry experiment has been demonstrated at a 10-kHz rate with time-freezing capabilities of <100 nsec. The laser was successfully extended for operation in a special "Giant-Pulse" mode, which allows the pulse width to be stretched from 5 ns up to 1 µs. The linewidth of the burst-mode-laser output at 532 nm that was measured with an 8.3-GHz etalon and wavemeter yielded a laser linewidth of < 150 MHz. The flow-velocity evolution within a 10-ms burst has been recorded in a high-speed turbulent jet with mean velocity of ~ 300 m/s. The IRS measurement uncertainties were analyzed, and a data fitting program was developed for IRS image processing.



Funding. NASA SBIR Contract No. NNX16CA27P and Air Force Research Laboratory Contract No. FA8650-15-D-2518**.**

Acknowledgment. The authors thank Drs. Jayanta Panda and Amy Fagan of NASA for many helpful discussions. Dr. Jordi Estevadeordal acknowledges AFRL Summer Faculty Fellowship Program and North Dakota State University support.

References

1. M. N. Slipchenko, J. D. Miller, S. Roy, J. R. Gord, S .S. Danczyk, and T. Meyer, Opt. Lett. **37** (8) 1346 (2012).
2. N. Jiang, M. Nishihara, and W. R. Lempert, Appl. Phys. Lett. **97** (22), 221103 30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference (2010).
3. R. A. Patton, K. N. Gabet, N. Jiang, W. R. Lempert, and J A. Sutton, Appl. Phys. B **108**, 377 (2012).
4. K. N. Gabet, R. A. Patton, N. Jiang, W. R. Lempert, and J. A. Sutton, Appl. Phys. B **106.** 569 (2012).
5. R. B. Miles, W. R. Lempert, and J. N. Forkey, Meas. Sci. Technol. **12**, R33-R51 (2001).
6. A. F. Mielke, K. A. Elam, and C.J. Sung, AIAA Journal, 47(4), 850-862 (2009).
7. D. Bivolaru, P.M. Danehy, and J. W. Lee, Opt. Lett. **31** (11) 1645-1647, (2006)
8. R. G. Seasholtz, A. E. Buggele, and M. F. Reeder, Opt. Lasers Eng. **27**, 543-570 (1997).
9. G. E. Elsinga, F. Scarano, B. Wieneke, and B. W. van Oudheusden, Exp. Fluids **41**, 933 (2006).
10. T. Ecker, D. R. Brooks, K. T. Lowe, and W. F. Ng, Exp. Fluids **55**, 1819 (2014).
11. B. Thurow, N. Jiang, W. Lempert, and M. Samimy, AIAA J. **43**, 500-511 (2005).
12. W. R. Lempert, N. Jiang, S. Sethuram and M. Samimy, AIAA J. **40**, 1065-1070 (2002).
13. S. V. Naik, W. D. Kulatilaka, K. K. Venkatesan, and R. P. Lucht, AIAA J. **47**, 839-849 (2009).
14. R. B. Miles, J. Grinstead, R. H. Kohl, and G. Diskin, Meas. Sci. Technol. **11,** 1272–1281 (2000).
15. N. M. Sijtsema, N. J. Dam, R. J. H. Klein-Douwel, and J. J. Meulen, AIAA J. **40**, 1061-1064 (2002).
16. N .J. DeLuca, R. B. Miles, W. D. Kulatilaka, N. Jiang, and J. R. Gord, 30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, AIAA-2014-2227 (2014).
17. J. Panda and R. G. Seasholtz, Phys. Fluids **11**, 3761 (1999).

REFERENCES WITH FULL TITLES

1. M.N. Slipchenko, J.D. Miller, S. Roy, J.R. Gord, S.S. Danczyk, and T. Meyer, Opt. Lett. **37** (8) 1346, (2012)
"Quasi-continuous burst-mode laser for high-speed planar imaging."
2. N. Jiang, M. Nishihara, and W.R. Lempert, Appl. Phys. Lett. 97 (22), 221103, (2010)
"Quantitative NO_2 molecular tagging velocimetry at 500 kHz frame rate"
3. R.A. Patton, K.N. Gabet, N. Jiang, W.R. Lempert, and J.A. Sutton, Appl. Phys. B 108 : 377 (2012)
"Multi-kHz temperature imaging in turbulent non-premixed flames using planar Rayleigh scattering"
4. K.N. Gabet, R.A. Patton, N. Jiang, W.R. Lempert, and J.A. Sutton, Appl. Phys. B 106 : 569 (2012)
"High-speed CH_2O PLIF imaging in turbulent flames using a pulse-burst laser system"
5. R.B. Miles, W.R. Lempert, J.N. Forkey. Meas. Sci. Technol. (12) (2001) R33-R51
"Laser Rayleigh scattering"
6. A. F. Mielke, K. A. Elam, and C. J. Sung, AIAA Journal, 47(4), 850-862 (2009)
"Multi-Property Measurements at High Sampling Rates Using Rayleigh Scattering"
7. D. Bivolaru , P.M. Danehy, and J. W. Lee, Opt. Lett. 31 (11) 1645-1647, (2006)
"Intracavity Rayleigh-Mie Scattering for Multipoint Two-component Velocity Measurement"
8. R.G. Seasholtz, A.E. Buggele, and M.F. Reeder, Opt. and Lasers in Eng., 27, 543-570, (1997)
"Flow Measurements Based on Rayleigh Scattering and Fabry-Perot Interferometer"
9. G.E. Elsinga, F. Scarano, B. Wieneke, B.W. van Oudheusden, Exp Fluids 41:933 (2006)
"Tomographic particle image velocimetry"
10. T. Ecker, D.R. Brooks, K.T. Lowe, and W.F. Ng, Exp Fluids 55:1819 (2014)
"Development and application of a point Doppler velocimeter featuring two-beam multiplexing for time-resolved measurements of high-speed flow."
11. B. Thurow, N. Jiang, W. Lempert, and M. Samimy, AIAA J. 43, 500-511 (2005)
"Development of megahertz-rate planar Doppler velocimetry for high speed flows"
12. W.R. Lempert, N. Jiang, S. Sethuram and M. Samimy, AIAA Journal, 40, 1065-1070 (2002)
"Molecular tagging velocimetry measurements in supersonic microjets"
13. S.V. Naik, W.D. Kulatilaka, K.K. Venkatesan, and R.P. Lucht, AIAA Journal, 47, 839-849 (2009)
"Pressure, temperature, and velocity measurements in underexpanded jets using laser-induced fluorescence imaging"
14. R.B. Miles, J. Grinstead, R.H. Kohl, and G. Diskin, Meas. Sci. Technol. 11 1272–1281 (2000)
"The RELIEF flow tagging technique and its application in engine testing facilities and for helium-air mixing studies"
15. N.M. Sijtsema, N.J. Dam, R.J.H. Klein-Douwel, and J.J. Meulen, AIAA Journal, 40, 1061-1064 (2002)
"Air photolysis and recombination tracking: A new molecular tagging velocimetry scheme"
16. N.J. DeLuca, R.B. Miles, W.D. Kulatilaka, N. Jiang, and J.R. Gord, AIAA-2014-2227 (2014)
"Femtosecond Laser Electronic Excitation Tagging (FLEET) Fundamental Pulse Energy and Spectral Response"
17. J. Panda and R.G. Seasholtz, Phys. Fluids (11) 3761, (1999).
"Measurement of shock structure and shock-vortex interaction in underexpanded jets using Rayleigh scattering"