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DIAGNOSTICS FOR HYPERSONIC ENGINE CONTROL

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Hypersonic Sciences Branch
High Speed Systems Division

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Interim Report

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14. ABSTRACT
The overall goal of the research is to find diagnostic measurements that reliably indicate changes in the dynamics of hypersonic flow paths – scramjet engines in particular. Of primary interest are measurements that serve to indicate that gross changes in flow behavior are about to happen. A priori, it is not known if such measurements exist. Local values of state variables (temperature, pressure, velocity, etc.) will necessarily follow changes. The question is whether or not some particular combination of state variables or an additional measureable quantity or quantities can serve as a precursor of impending dynamic changes. Most interesting for hypersonic engine control are changes in isolator margin, inlet mass capture, and performance (thrust, combustion efficiency, etc.).

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diagnostics, boundary layer, scramjets, isolator

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Research Objectives:

The overall goal of the research is to find diagnostic measurements that reliably indicate changes in the dynamics of hypersonic flow paths – scramjet engines in particular. Of primary interest are measurements that serve to indicate that gross changes in flow behavior are about to happen. A priori it is not known if such measurements exist. Local values of state variables (temperature, pressure, velocity, etc.) will necessarily follow changes. The question is whether or not some particular combination of state variables or an additional measureable quantity(ies) can serve as a precursor of impending dynamic changes. Most interesting for hypersonic engine control are changes in isolator margin, inlet mass capture, and performance (thrust, combustion efficiency, etc.) To meet this goal we have pursued the following research objectives:

- Determine if an upstream propagating "signal" can be found in the subsonic portion of the boundary layer that precedes gross changes in isolator margin.
- Identify measureable quantities other than thermodynamic state variables that indicate changes in flow dynamics prior to state variable changes.
- Assess the ability of in-stream optical measurements along a few lines of sight at both the isolator entrance and combustor exit to follow changes in flow and heat release and accurately identify the engine state.

Technical Summary:

During the reporting period, work continued on evaluating the utility of low-power light sources to make in-stream measurements of the flow in model scramjet combustors. The overall intent is to identify optical measurements that provide useful information for benchmarking modeling efforts and/or lead to the development of sensors that can be used as part of scramjet engine control strategies. Activities included work on strategies for measurements both upstream and downstream of the combustor.

An example of work downstream of the combustor is shown in Figure 1. In general, line-of-sight optical transmission measurements can be used to reconstruct a 2-D image of a flow variable such at static temperature or concentration of an absorbing species. Mathematical algorithms are widely used in other technology and medical fields to execute tomography from transmission measurements for cases in which thousands of lines-of-sight have been employed. The hardware limitations associated with scramjet engine research limits the number of lines-of-sight over which transmission data can be collected to roughly a dozen. The sparse nature of the data sets prevents use of existing tomographic reconstruction algorithms. We therefore are working with researchers at Purdue University to develop new algorithms to fit our tomography needs. A great deal of progress has been made to date. In Figure 1, the phantom water concentration and static temperature fields in the top row were numerically reconstructed to yield the results shown in the bottom row. The algorithm makes use of an eigen image expansion of the reconstructed fields.

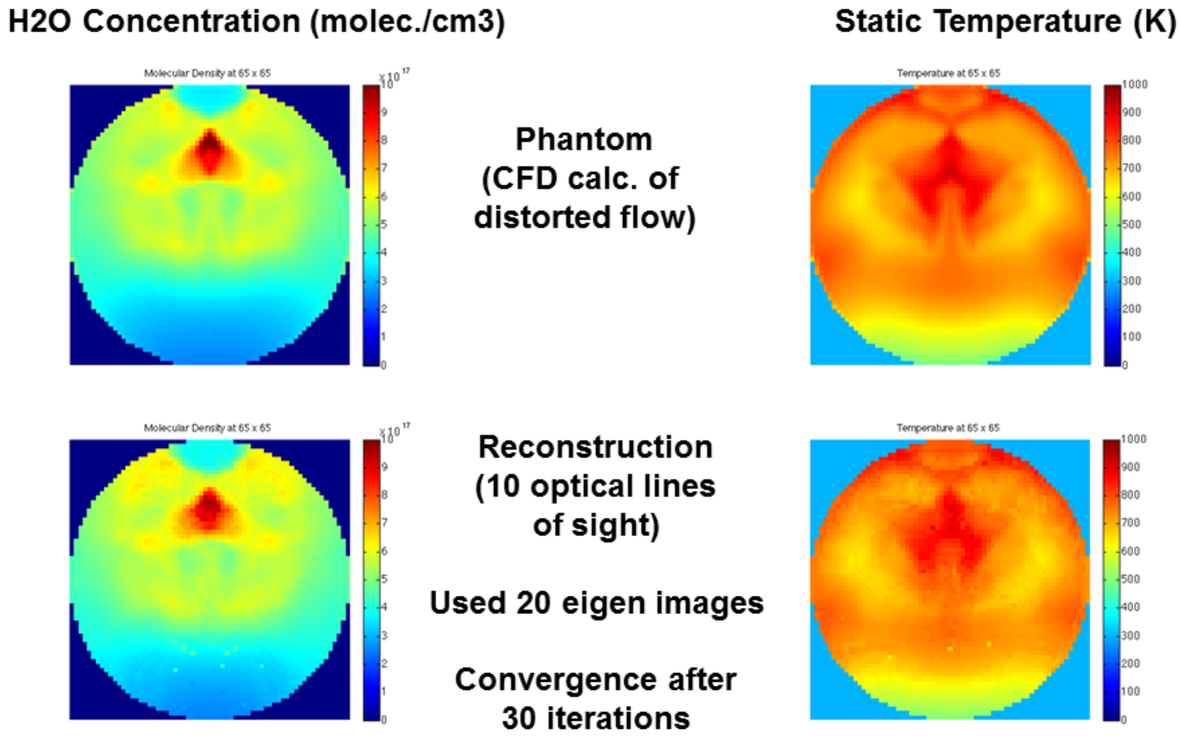

Figure 1. Example of tomography algorithm development.

Laser beams that propagate across a supersonic flow acquire useful information in two ways. First, if the beams are resonant with a molecular absorption feature of one of the constituent species, information about the concentration of the absorbing species is recorded along with the local static temperature and pressure. Second, density fluctuations along the beam path transiently steer the beam slightly off its original path and this leads to fluctuations in the amplitude of the recorded transmission signal. The power spectrum of such fluctuations is an indication of the turbulence levels within the flow. We are currently making such measurements to assist in the testing of high fidelity CFD efforts. An example of such a power spectrum is shown in Figure 2. The optical transmission data was recorded with a laser beam propagating across a Mach 2 flow in an isolator at the mid-plane of the core flow. The dashed line indicates the slope for textbook turbulent flow.

Absorption-based measurements upstream of the flameholding region of a model scramjet engine cannot rely on the presence of water. Instead, light sources operating at wavelengths resonant with molecular oxygen are employed. Unfortunately, the O_2 resonances easily accessible are relatively weak typically leading to low signal-to-noise ratios. Such signals can be enhanced using modulation schemes. We have begun investigating broadband modulation methods to enable math tricks to be employed to affectively drive the noise down. An example of an O_2 absorption feature captured using both a direct scan and a modulated scan is shown in Figure 3. Demodulation during signal processing removes some of the noise.

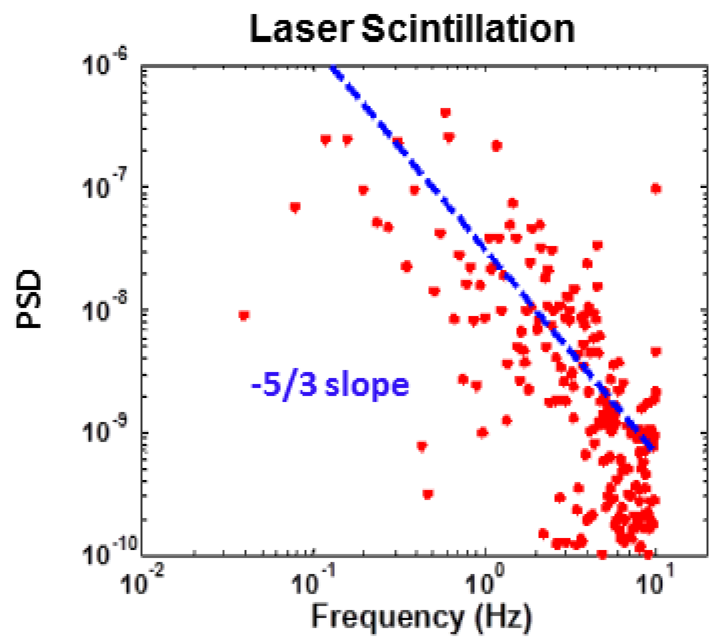

Figure 2. Power spectrum of transmitted beam amplitude fluctuations (scintillation). Frequency axis is normalized.

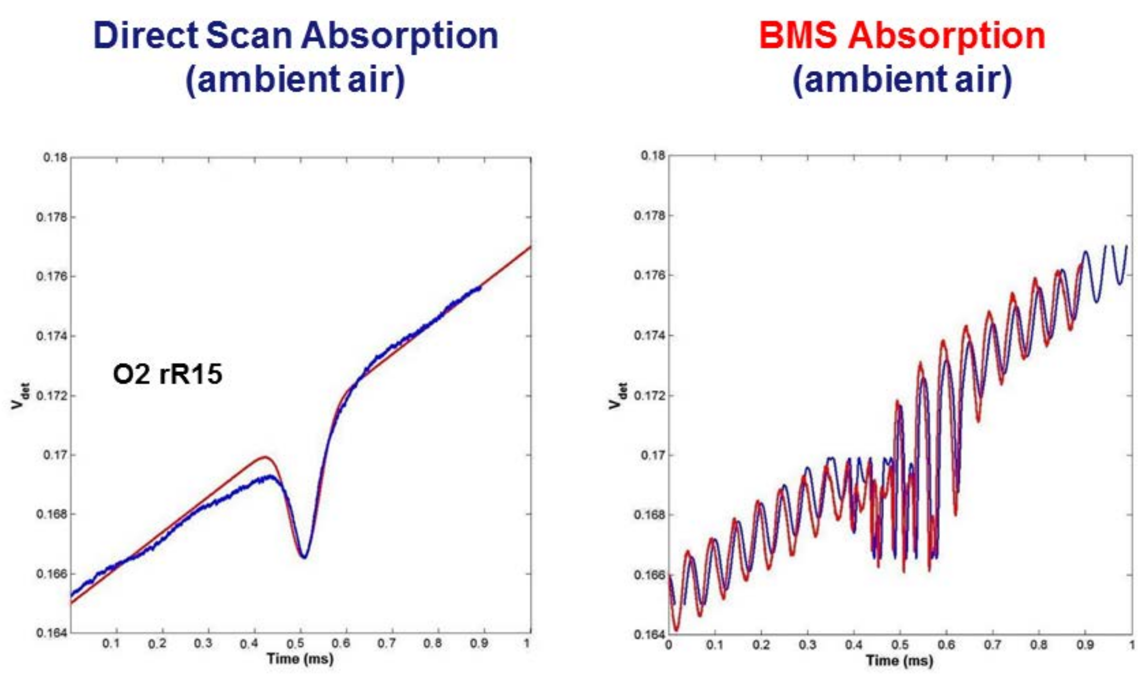

Figure 3. Oxygen absorption feature recorded using direct scanning of the laser light source (left) and modulated scanning (right). Numerical demodulation of the signal (right) removes out-of-band noise.

If the transmitted laser beams are recorded with a camera rather than with a point detector, certain types of image information can be recorded. We have examined two such approaches for use in engine isolators particularly with regards to behavior of the boundary layer. Figure 4 shows a setup in which two beams traverse an isolator just upstream of a cavity flameholding region. One beam passes through the core flow and the other through the boundary layer. The intensity pattern of both transmitted beams is dominated by window blemishes pre-ignition. Post ignition, the beam transmitted through the core flow (free stream) appears unchanged. However, the intensity pattern of the beam lying in the boundary layer is changed. The change is due to thermal lensing owing to a local change in the boundary layer temperature where some combustion is now present.

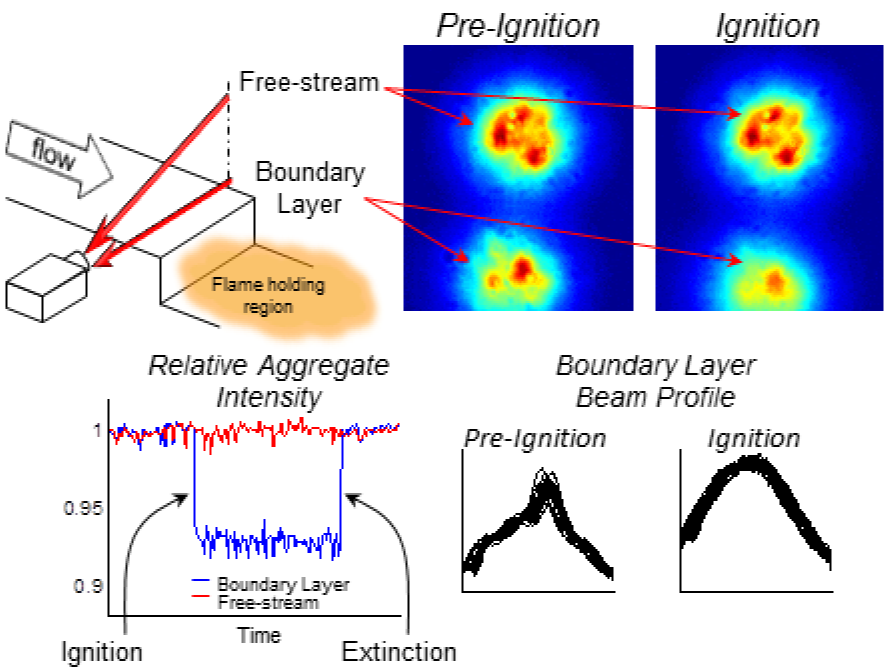

Figure 4. Example of 2-beam shadowgraphy. Intensity profile of beam propagating in the boundary layer changes in the presence of combustion.

If the two transmitted laser beams cross at some point they will both carry information about the flow in the cross-over region. To date we have investigated ways to isolate (mathematically) the common information from information carried by the individual beams. Figure 5 provides an example of this work using a static test article (sonic nozzle). The image in the lower right of the figure shows the shock pattern above the nozzle. This pattern is present in both beams.

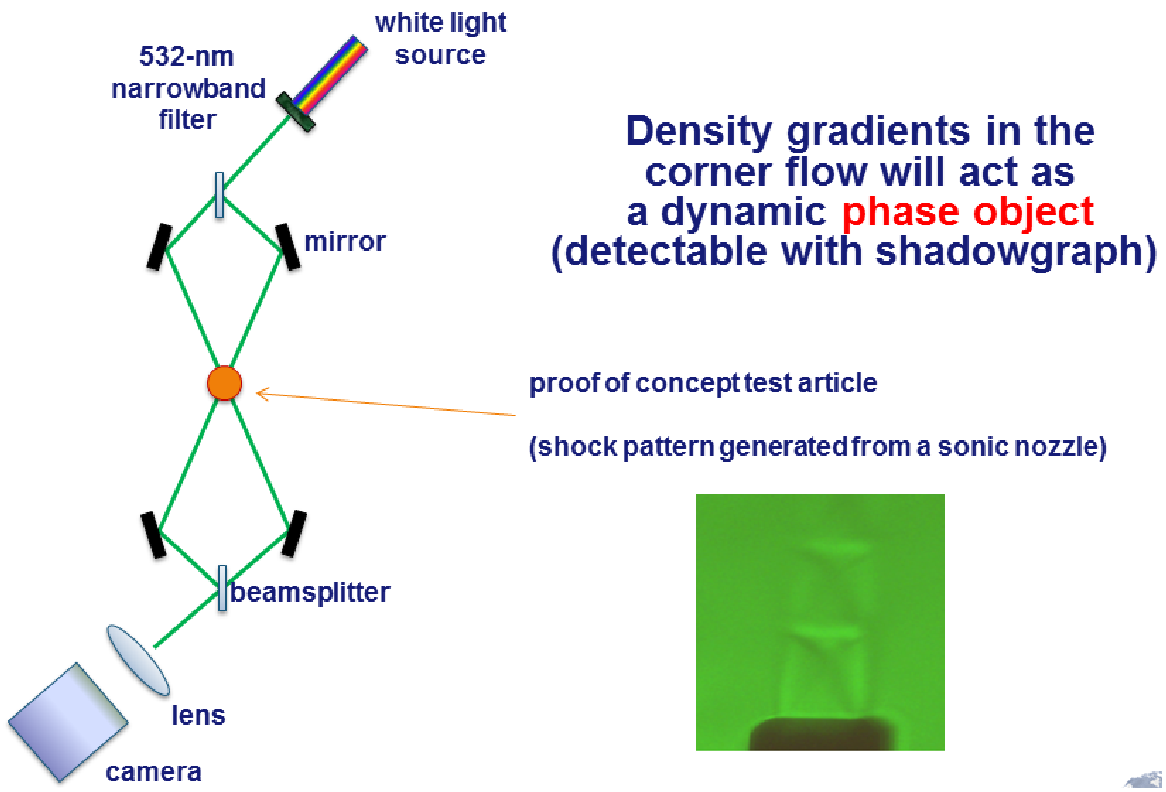

Figure 5. Example of dual beam shadowgraphy. Aim is to extract only the image information common to both paths.

Publications and Presentations:

A. J. Crow, I. D. Boyd, J. Liu, M. S. Brown, "Thermal Radiative Simulations and Measurements of the HIFiRE Direct Connect Rig," Journal of Propulsion and Power, 30 (6), 1543-1550 (2014), http://arc.aiaa.org/doi/abs/10.2514/1.B35207.

M. S. Brown, C. A. Bouman, M. L. Comer, "Advanced Signal Processing Routine for TDLAS Tomography," 34th JANNAF Air Breathing Propulsion Conference, Albuquerque, NM, December 8-12, 2014.

M. S. Brown, J. M. Donbar, and E. Belmont, "ICOS Measurements in Model Scramjet Engines," 34th JANNAF Air Breathing Propulsion Conference, Albuquerque, NM, December 8-12, 2014.

M. S. Brown, T. Barhorst, M. Hagenmaier, and A. Castrogiovanni, "Planned TDLAS Measurements in MSCC Testing," 34th JANNAF Air Breathing Propulsion Conference, Albuquerque, NM, December 8-12, 2014.

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M. S. Brown and J. M. Donbar, "Optical Diagnostics for Hypersonic Engine Control," AFOSR Program Review, Arlington, VA, July 16, (2014)

(INVITED) M. S. Brown, "TDLAS Deployed on HIFiRE Flights 1 and 2," AFOSR Program Review, Arlington, VA, June 5, (2014).

K. M. Busa, J. C. McDaniel, M. S. Brown, G. S. Diskin, "Implementation of Maximum-Likelihood Expectation-Maximization Algorithm for Tomographic Reconstruction of TDLAT Measurements," AIAA Paper No. 2014-0985, 52nd AIAA Aerospace Sciences Meeting, National Harbor, MD, (January 2014).

M. S. Brown, "Optical Diagnostics for Hypersonic Engines," Aerospace Engineering Seminar Series, the Ohio State University, Columbus OH, September 27, 2013.

M. S. Brown and M. Gruber, "Analyzing Optical Data from HIFiRE Flight 2 Ground Tests," 38th Annual Dayton-Cincinnati Aerospace Sciences Symposium, Dayton, OH (6 March 2013).