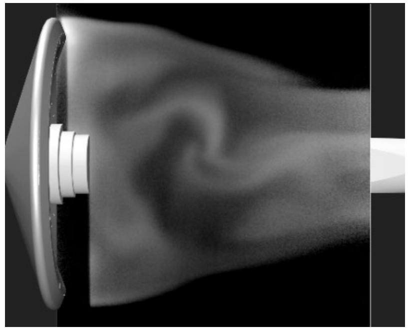
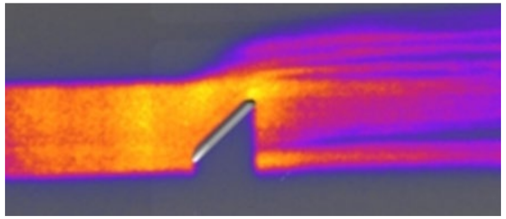
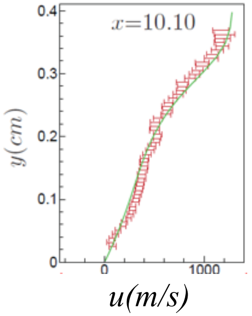
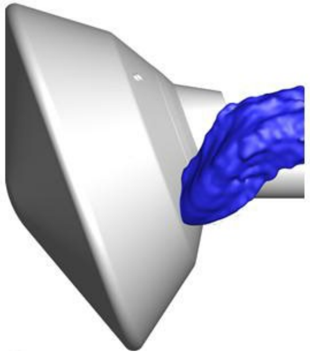
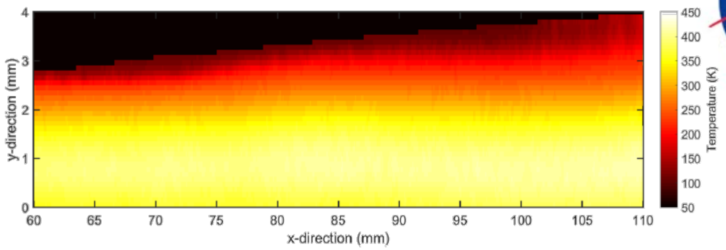










Review of planar laser-induced fluorescence measurements in the NASA Langley 31-Inch Mach 10 Air Tunnel

Paul M. Danehy, Brett F. Bathel, Neil S. Rodrigues and Jennifer Inman

NASA Langley Research Center, Hampton, VA, 23681, United States

Craig T. Johansen

Dept. of Mechanical and Manufacturing Engineering, University of Calgary, Canada

AIAA SciTech 2024
Orlando, Florida, Jan 9-12, 2024

Overview

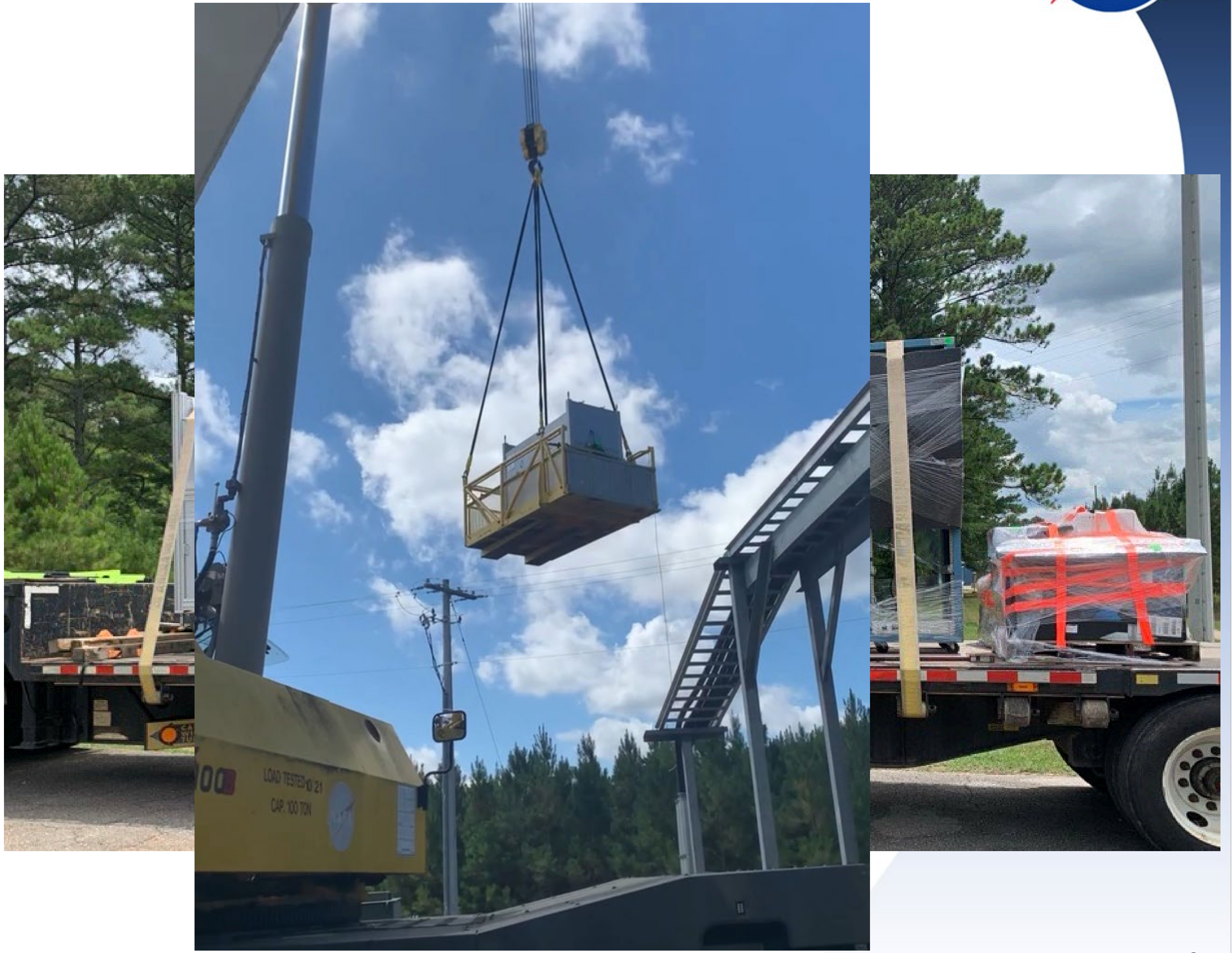
- Planar Laser Induced Fluorescence (PLIF) effort at NASA Langley started in earnest in 2003
  - Mobile PLIF System design, characterization reported at JANNAF, Dec 2003 – 20 years ago.
  - PLIF Space Shuttle Return to Flight after Columbia Accident (Langley 15-Inch Mach 6 wind tunnel chamber)
    - Nitric oxide PLIF study of impinging jet flow inside Orbiter wing → J. Inman PhD dissertation (College of W&M, 2007)
  - OH PLIF for combustion studies for flow control and supersonic combustion experiments.
- In 2005 began a series wind tunnel tests at ***NASA Langley's 31-Inch Mach 10 Air Wind Tunnel***
  - Topic of the current paper: Review of 14 NO PLIF Measurement Campaigns (23 pages, 118 references)

- Describe NASA's mobile system (as well as Ohio State's high-speed system)
  - Strategy, features, typical Installation at the facility
- Overview of measurement campaigns
- Seeding methods (minimally intrusive vs flow control)
- Post-processing methods (Virtual Diagnostics Interface [ViDI])
- Examples
  - 10 Hz planar, 3D scanned, stereoscopic imaging, molecular tagging velocimetry (MTV), thermometry
  - kHz-MHz planar and stereo imaging
- Outlook for the future

- Vehicles:
  - X-33, X-43
  - IRVE, LOFTID
  - Shuttle Orbiter
  - Orion/Apollo
  - Mars Science Lab

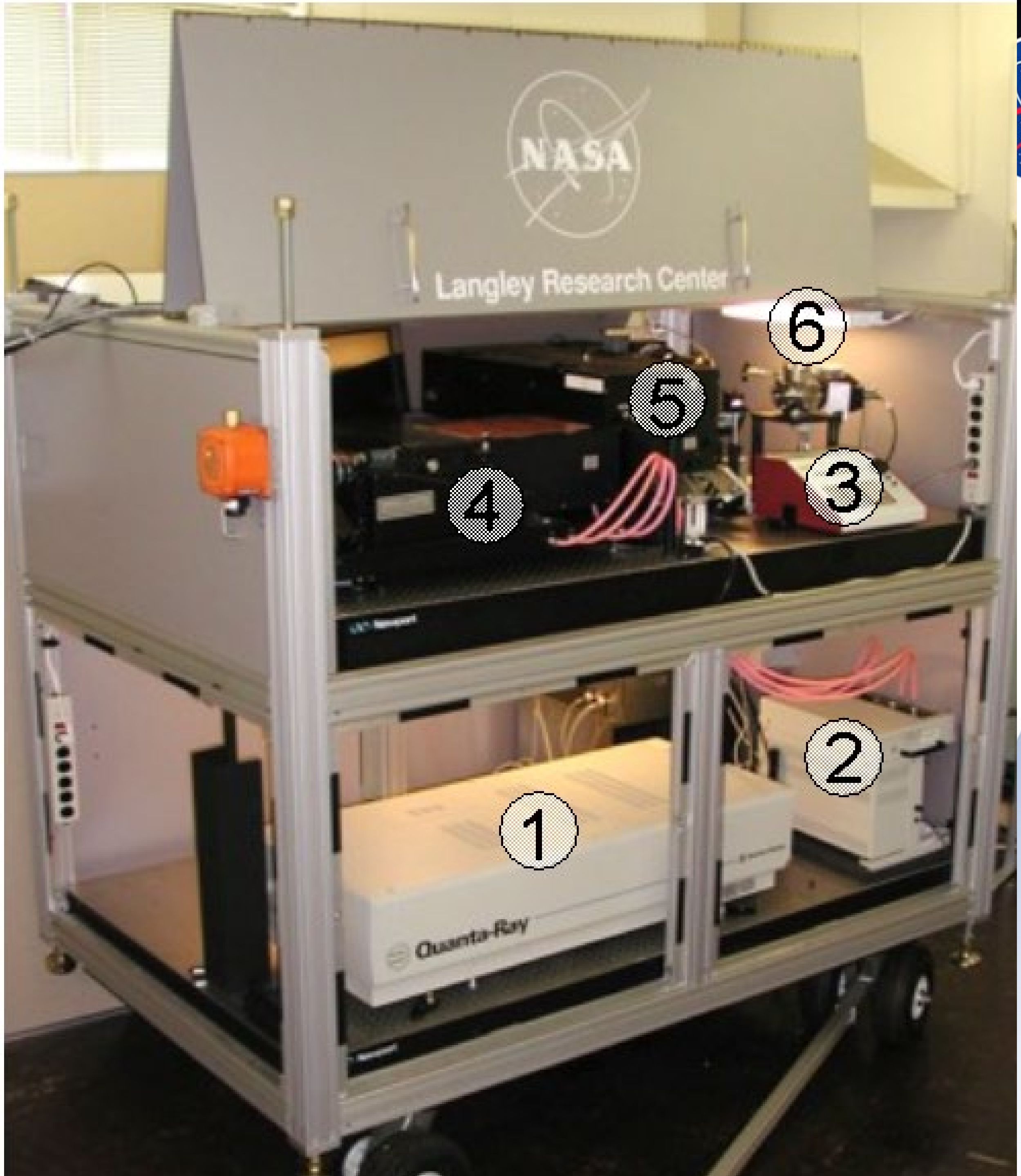
Mobile PLIF System and Measurement Strategy

- Mobile measurement systems
  - Develop methods in lab
  - Move in, get set up quick & get out
  - A few weeks to test
- Automated operation
  - Acquire thousands of measurements if possible
  - Remote operation
- Hardened hardware
  - Cooled / Heated, SSD, Robust construction
- Prefer simple methods
  - Fewer lasers the better
  - Fewer laser beams the better
- $PLIF_1$, $PLIF_2$, CARS, FLEET
- Used at: CUBRC, NASA Marshall, NIA, UVa, NASA Langley's Mach 10, HYMETS, AHSTF, various labs.

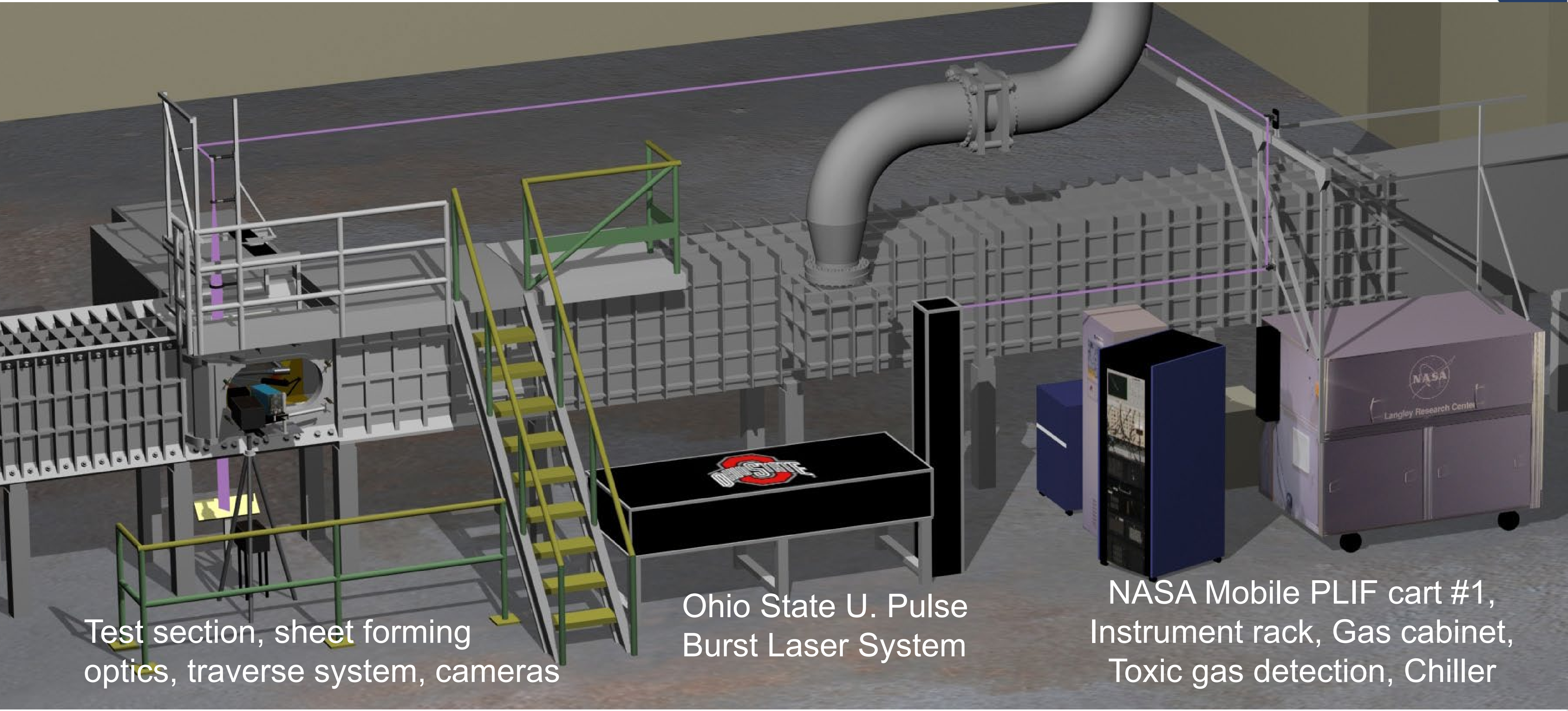


Mobile PLIF System

- 2003 Cart Contents:
  - (1) Nd:YAG laser,
  - (2) dye circulators,
  - (3) wavelength controller for the
  - (4) pulsed dye laser, and
  - (5) wavelength extender,
  - (6) low-pressure monitoring gas cell with PMT and absorption photodiodes
- Typically: ~1-3 mJ/pulse
- Commonly tuned to Q-branch band head of NO, at a wavelength of 226.256 nm
  - Strongest line of NO at lower temperatures
- 2007 upgraded dye laser and built 2nd cart (5-10 mJ/pulse):
  - Sirah Cobra Stretch dye laser
  - Sirah frequency conversion unit (FCU).



Typical Setup at NASA Langley 31-Inch Mach 10



Core team: 2003-

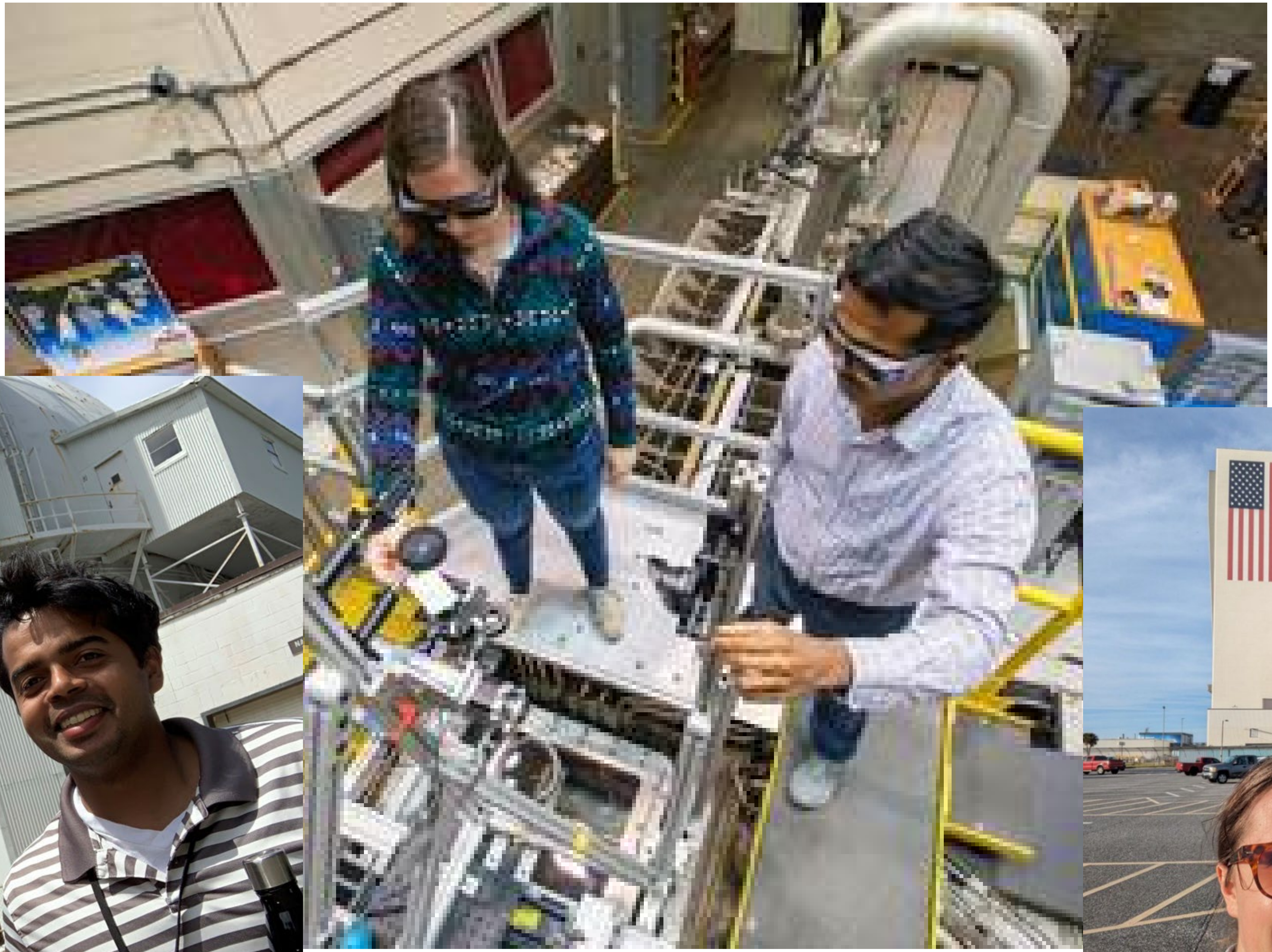
- Jen (Wilkes) Inman, Steve Jones, David Alderfer, Tony Robbins, Paul Danehy
- Many students contributed…

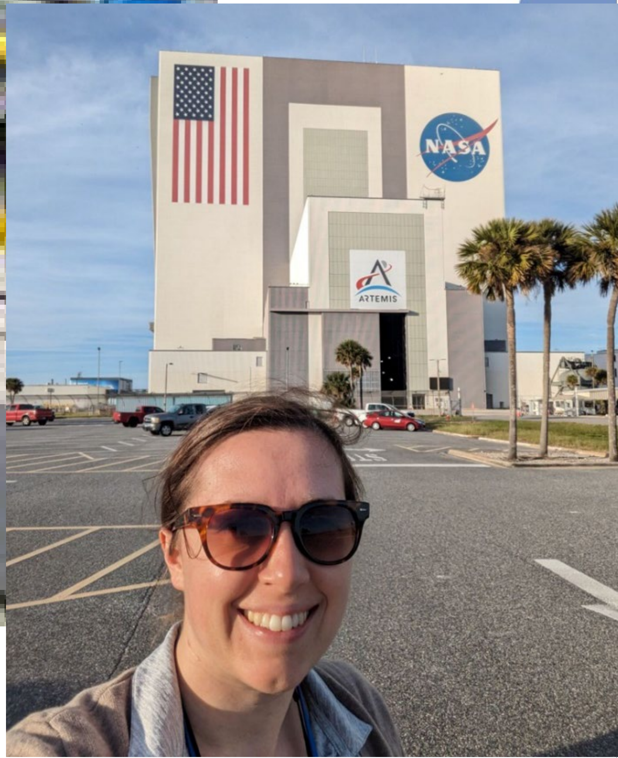
Core team additions, 2007, 2010

- Brett Bathel (2007), Iowa, UVa, NASA
- Craig Johansen (2010), U of Calgary

Current PLIF team members:

- Neil Rodrigues (2020)
  - PhD, Purdue
- Olivia Tyrrell (2020)
  - BS, Iowa State
- Paul Danehy



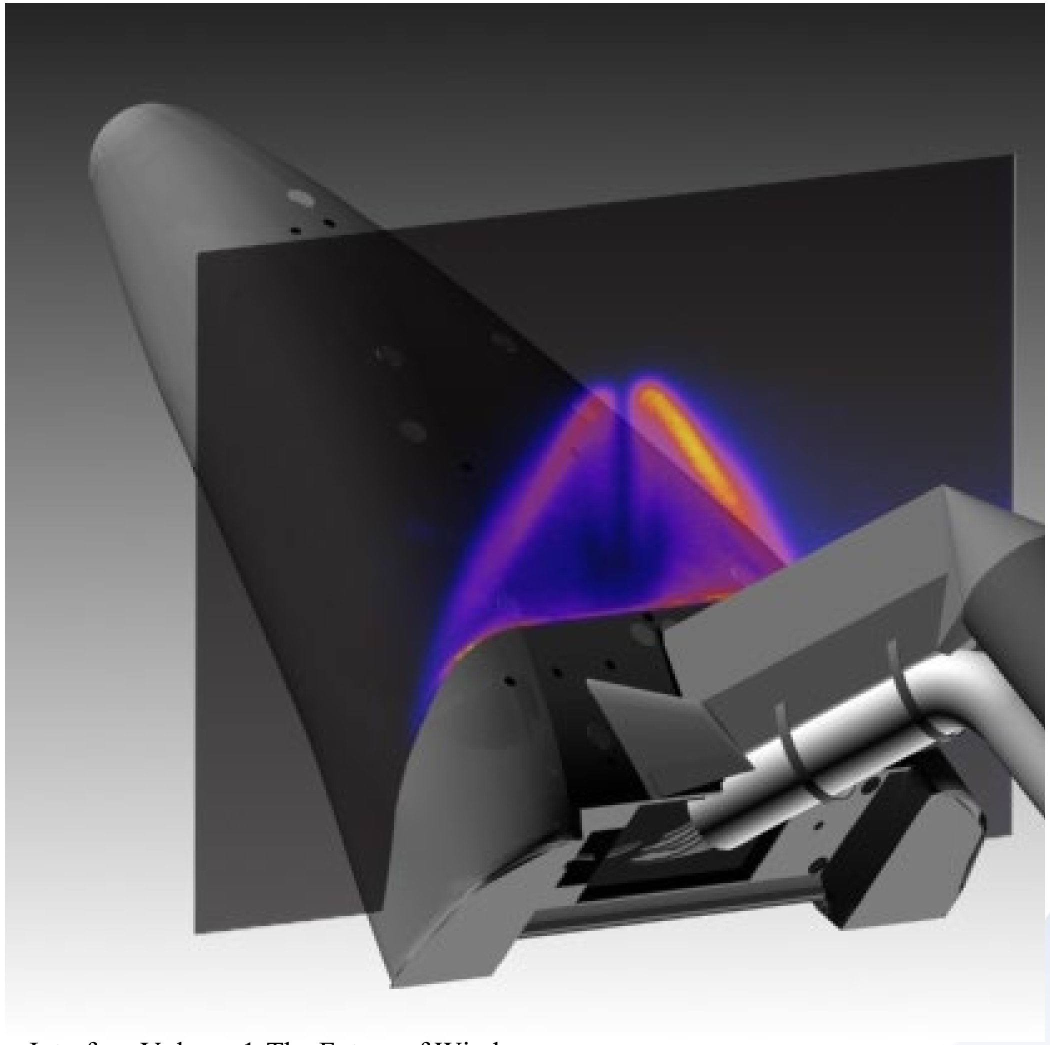


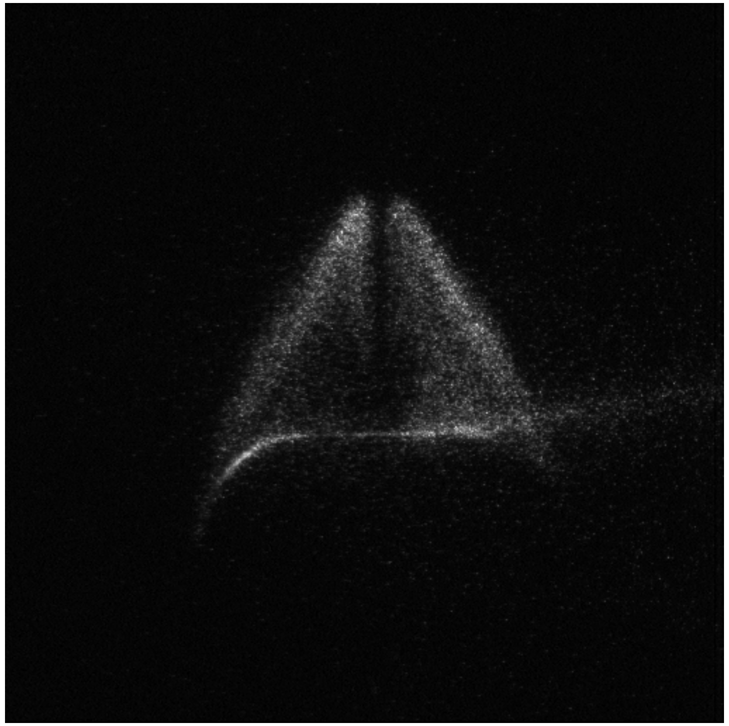
14 Measurement Campaigns over 20 years

Test #	Start Date	Model(s)	Purpose	References
400	Apr. 22, 2005	Wedge, Apollo, X-33, blunt cone	Planar visualizations of wedge model flow with a cavity; Apollo RCS jet, shear layer and wake seeding; X-33 wake seeding; AGARD 70-degree blunt cone wake seeding.	8, 36, 37
419	Apr. 13, 2006	Wedge, Apollo, Orion CEV, IRVE, MSL	Planar visualizations of triangular- and rectangular-shaped Space Shuttle Orbiter 'gap filler' trip on wedge model; Apollo RCS and wake seeding; investigation of different methods of rapid prototyping wind tunnel models (Orion, IRVE, MSL) and seeding methods for such models.	8, 9, 34, 35, 36
438	Apr. 26, 2007	Apollo, Orion CEV	Planar visualizations of RCS jets, wake shear layer, and forebody seeding simulating ablation. PSP, TSP also acquired.	7, 31, 32, 33, 39
441	Jul. 19 2007	X-43	Planar and stereo visualizations of the Hyper-X (X-43) forebody flow using blowing as active flow control.	29, 30
443	Oct. 4, 2007	Wedge	Planar visualizations of boundary layer flow over hemispherical, triangular, cylindrical discrete roughness, Oil flow surface streamline visualizations. Stereo PLIF on cylindrical roughness.	1, 2, 24, 28, 30
454, 455	July 10, 2008	Orion CEV	Planar visualizations of Orion CEV with different RCS jets and PSP.	21, 40
462	Feb. 19, 2009	Wedge	Planar visualizations of Space Shuttle Orbiter BLT-DTO trip, rectangular trip at 45 degrees and TSP. First NO MTV and thermometry, Wind-off runs for MTV accuracy, precision measurement.	1, 2, 5, 11, 12, 13, 15, 23, 18, 25, 27
463	Mar. 17, 2009	Wedge	Planar MHz visualization of cylindrical trips, Space Shuttle Orbiter DTO trip, triangular trip, rectangular fence. Compression Corner.	6, 24, 25, 26
467	Sep. 9, 2009	Wedge, Apollo	10 Hz and planar MHz and stereo MHz PLIF for boundary layer flow over cylindrical roughness and Space Shuttle BLT-DTO trips, Apollo model RCS: 10 Hz and 500 kHz MTV.	18, 22, 25
473	Sep. 2, 2010	MSL	Planar visualizations and NO PLIF MTV for Mars Science Laboratory capsule wake and RCS jets.	3, 4, 17, 20
477	Sept 24, 2010	Wedge	Planar NO and NO_2 MTV over hemispherical and cylindrical discrete roughness; Wind off runs for accuracy, precision measurement	13, 15, 19
481	July 2011	Wedge	Planar NO_2 MTV over BLT-DTO, cylindrical, hemispherical discrete roughness, Wind off runs for accuracy, precision measurement.	14, 15, 16
548	October 2022	LOFTID	Planar NO visualizations, MTV, thermometry, for wake of 70-degree sphere-cone model with seeding	10

Virtual Diagnostics Interface (ViDI)

With ViDI:





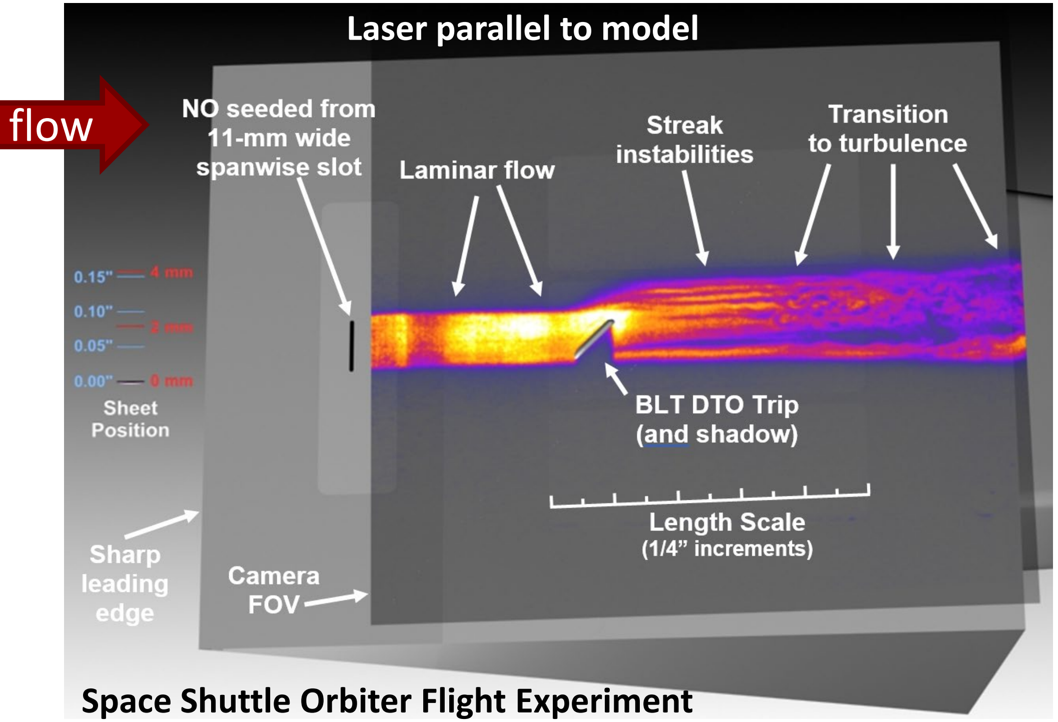
Without ViDI:

"What am I looking at?"

R. J. Schwartz, "ViDI: Virtual Diagnostics Interface Volume 1-The Future of Wind Tunnel Testing" Contractor Report NASA/CR-2003-212667, December 2003

Seeding Methods

- Need to seed nitric oxide (NO) into this blowdown Mach 10 air facility
  - NO is toxic, corrosive, can react with O_2 or H_2O and release heat, must be seeded, detected for safety
  - NO absorbs and fluoresces at convenient wavelengths, strong fluorescence, well understood spectroscopy
- Want to be minimally perturbative for many types of experiments
  - Low flowrate (0.1-5 slpm) pure NO seeded plumbed to model
  - Boundary layers
    - Flow over trips, cavities



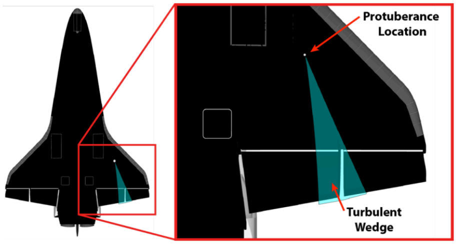


Figure 3. Selected protuberance location and predicted turbulent wedge.

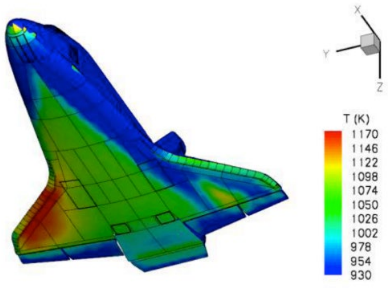
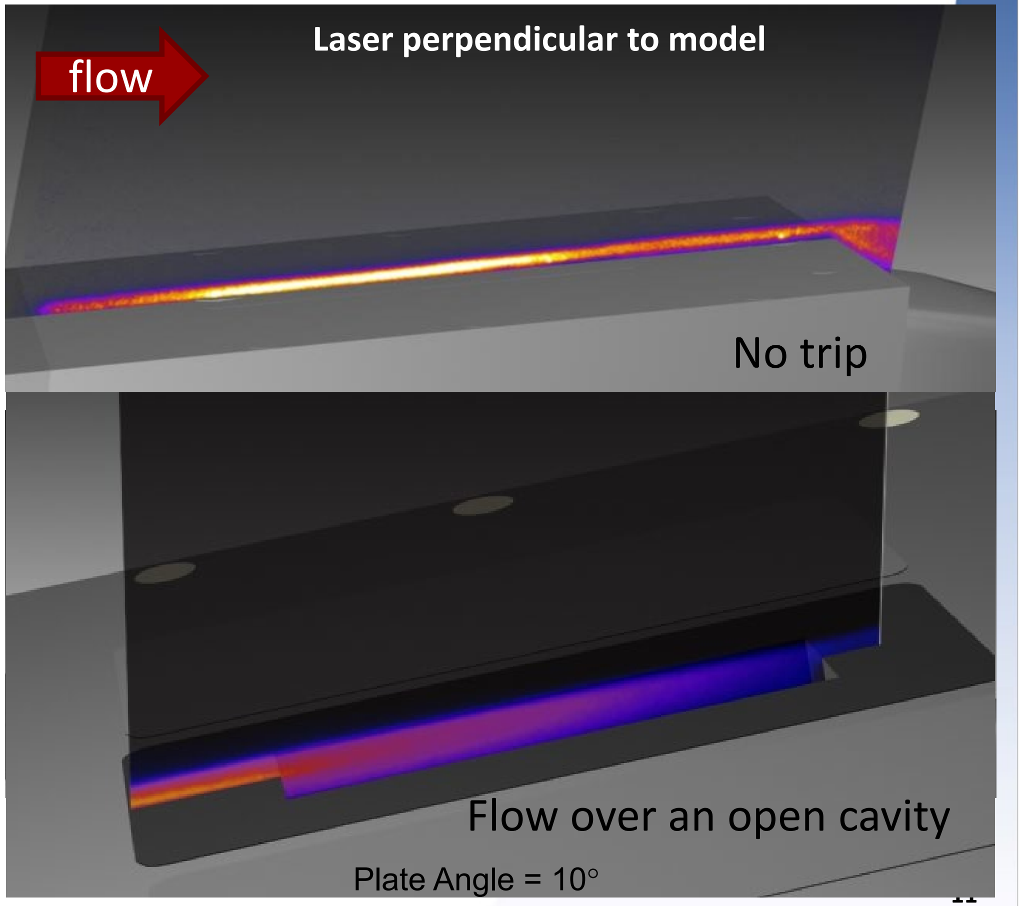


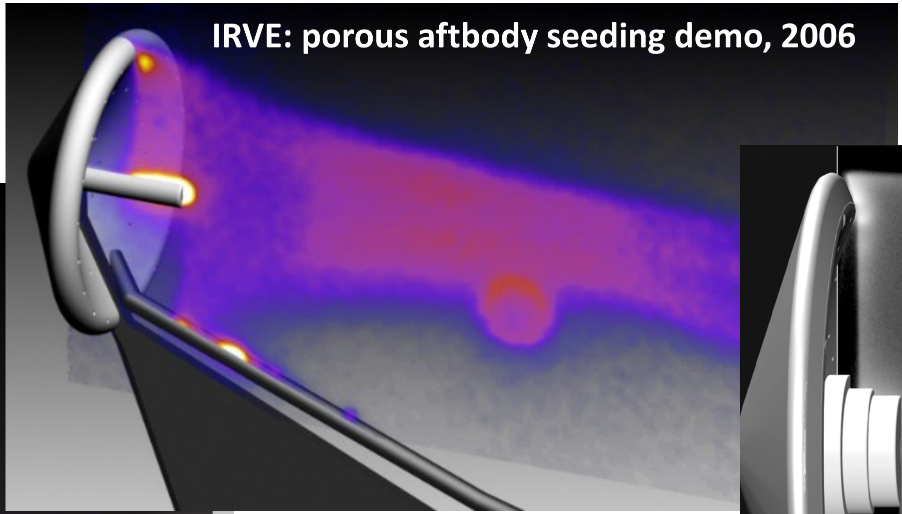
Figure 6. HYTHIRM 3D Mapped Image for STS-119, captured at Mach 8.4.

Berry et al, NASA, AIAA 2016-3533, "Flight experiment verification of shuttle boundary layer transition prediction tool"

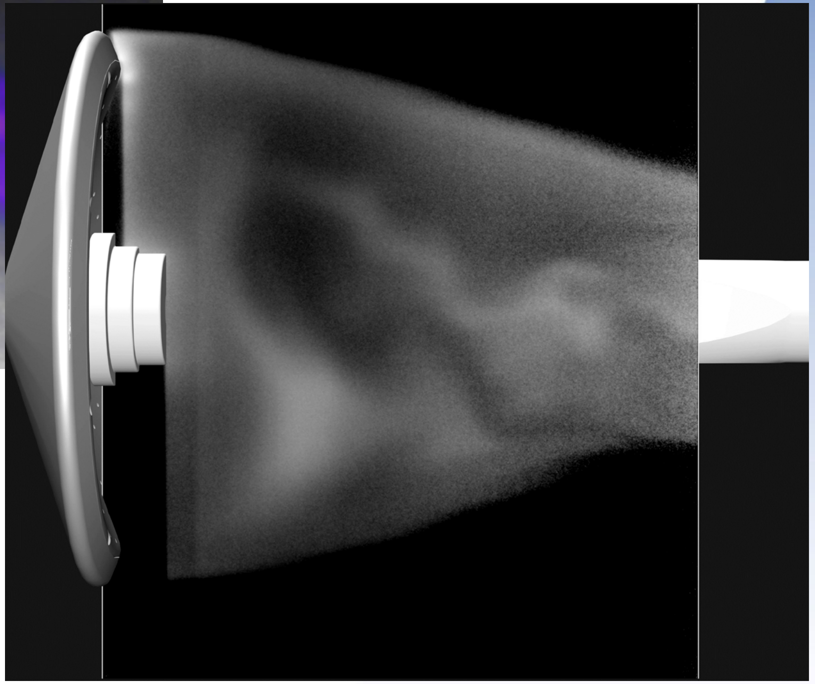


Seeding Methods

- Need to seed nitric oxide (NO) into this blowdown Mach 10 air facility
  - NO is toxic, corrosive, can react with O_2 or H_2O and release heat, must be seeded, detected for safety
  - NO absorbs and fluoresces at convenient wavelengths, strong fluorescence, well understood spectroscopy
- Want to be minimally perturbative for many types of experiments
  - Low flowrate (0.1-5 slpm) pure NO seeded plumbed to model
  - Boundary layers
    - Flow over trips, cavities
  - Hypersonic vehicle wake flows

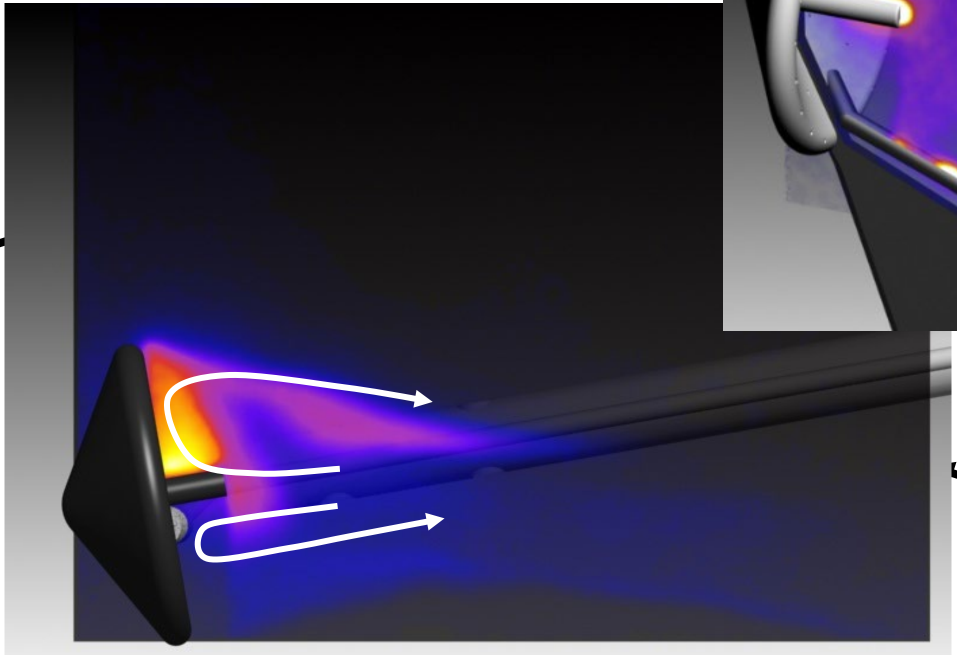

IRVE: porous aftbody seeding demo, 2006

Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID), 2022
LOFTID Model: Beth Rieken, Mark Cagle



Flow Direction

Inflatable Reentry Vehicle Experiment (IRVE) Model Additively manufactured

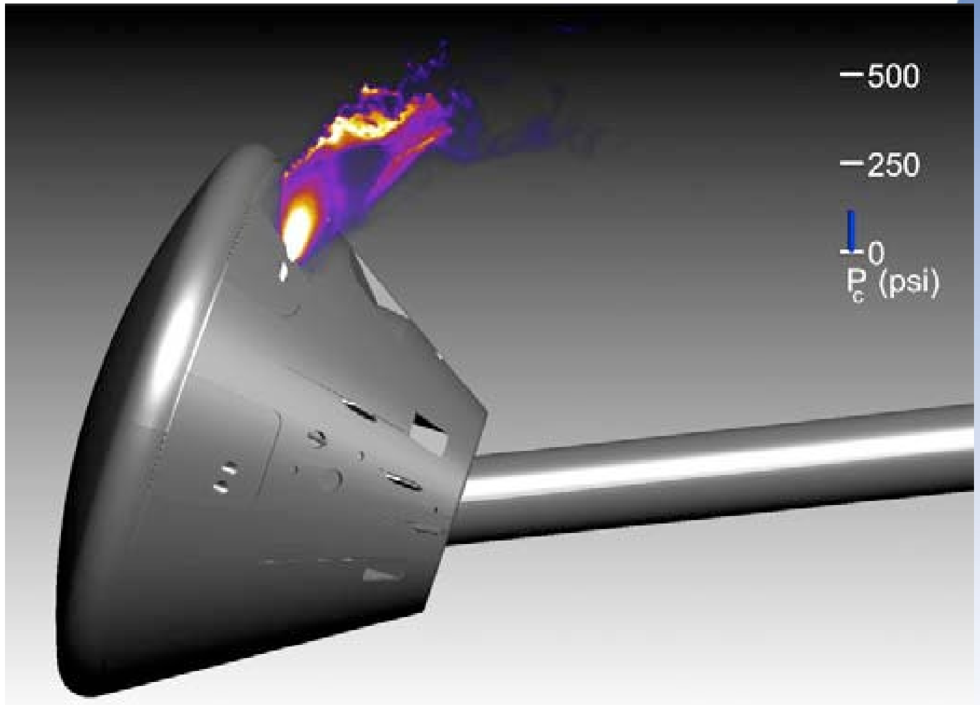


IRVE Models: Greg Buck

Camera's Field of View

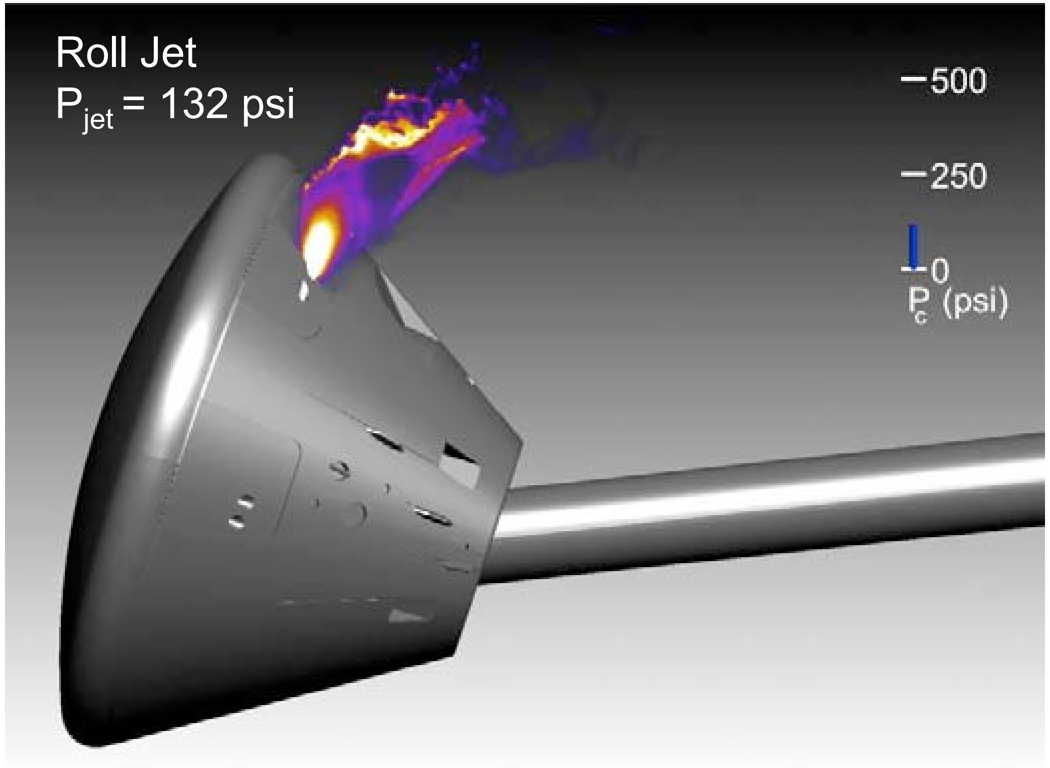
Seeding Methods

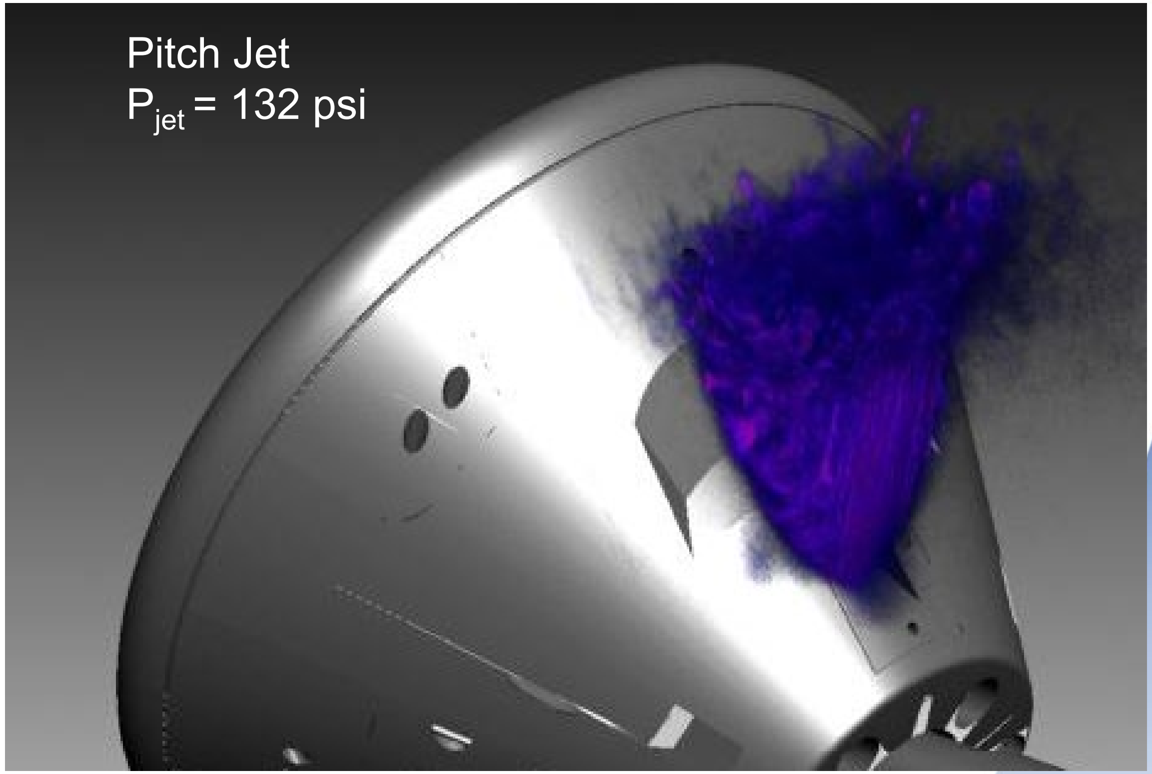
- Need to seed nitric oxide (NO) into this blowdown Mach 10 air facility
  - NO is toxic, corrosive, can react with O_2 or H_2O and release heat, must be seeded, detected for safety
  - NO absorbs and fluoresces at convenient wavelengths, strong fluorescence, well understood spectroscopy
- Want to be minimally perturbative for many types of experiments
  - Low flowrate (0.1-5 slpm) pure NO seeded plumbed to model
  - Boundary layers
    - Flow over trips, cavities
  - Hypersonic vehicle wake flows
- Flow control applications are trying to perturb the flow
  - Blowing to transition a boundary layer to turbulence (X-43)
  - Reaction control system (RCS) Jets
  - High flowrate, high pressure (500 psi) 1-5% NO seeded in N_2
    - Pathfinder tests using Apollo geometry
      - Tests 400, 419, 438, 467 (2005, 2996, 2007, 2009)
      - Model developed by Greg Brauckmann
    - Orion Crew Exploration Vehicle (CEV)
      - Tests 438, 454, 455 (2007, 2008)
      - Model developed by Greg Buck



Orion CEV RCS Roll Jet visualization

Imaging Methods: Planar versus Volumetric

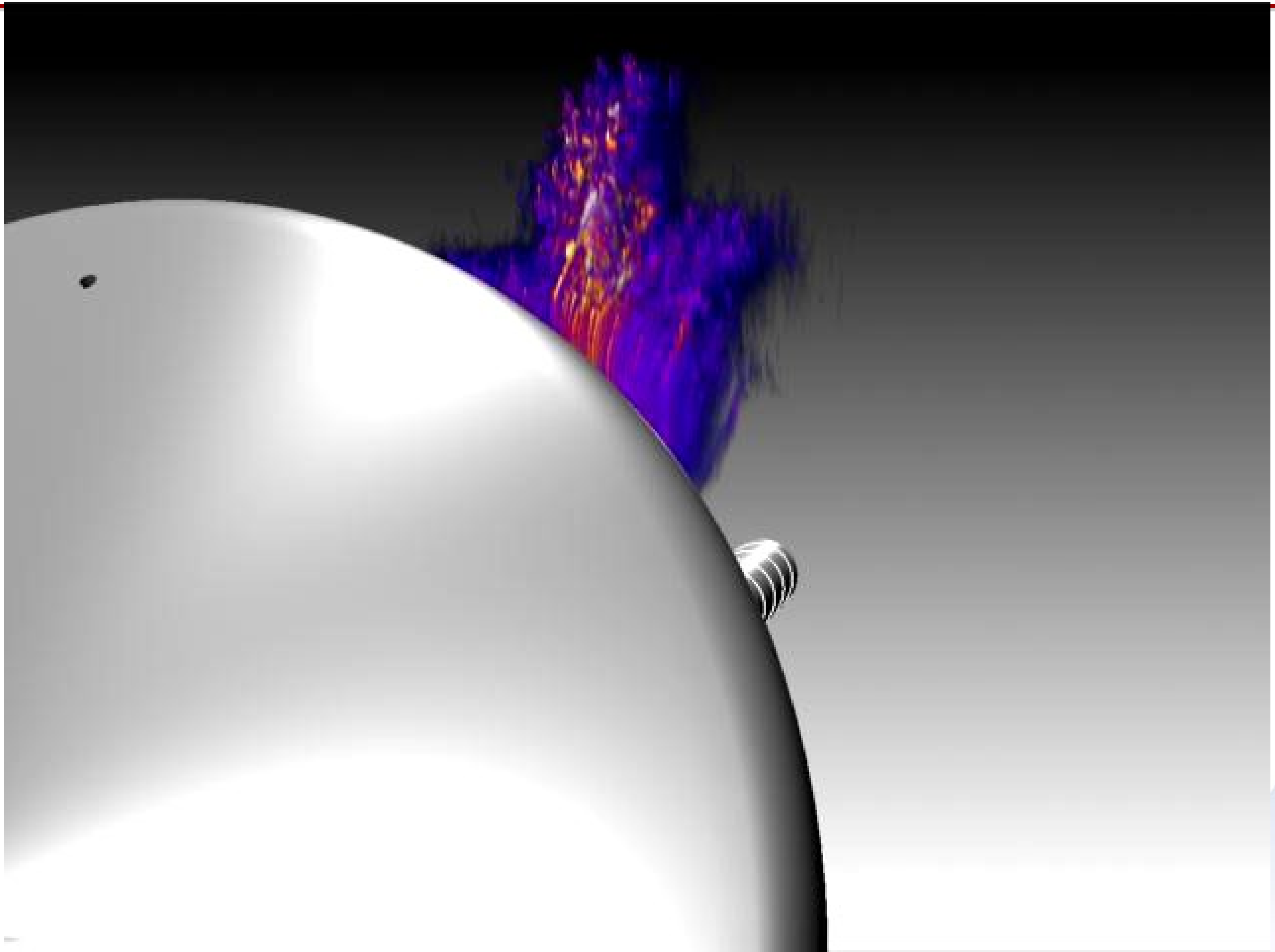




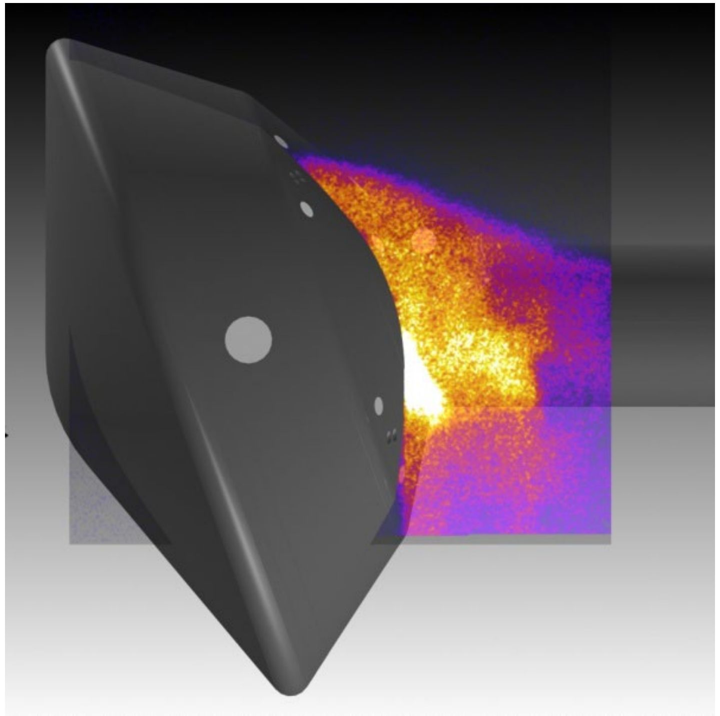
- 1 minute runs in the 31-Inch Mach 10 Air facility
- Single shot images of NO-seeded RCS jet fluid; spatially scan laser sheet
- Multiple images displayed simultaneously to show 3D trajectory of jet: *quasi*-volumetric imaging

J. A. Inman, P. M. Danehy, et al. AIAA Journal Vol. 47, No. 4, April (2009) 14

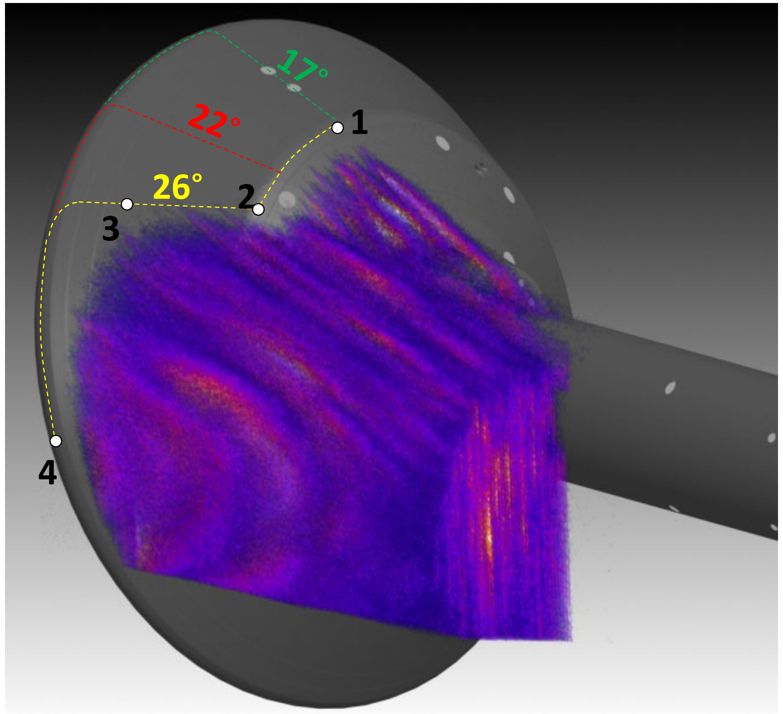
Visualization of 3D flow structures: Roll Jets



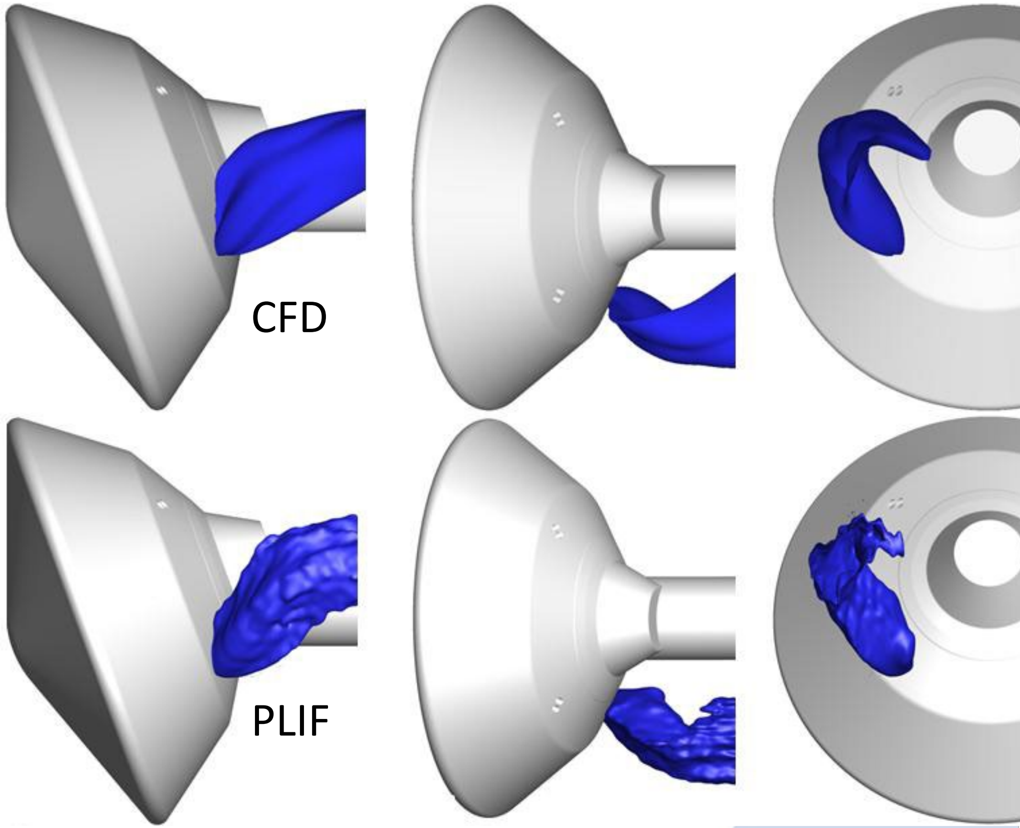
Mars Science Laboratory: Wake Flow Separation, RCS



NO Seeded into MSL Wake

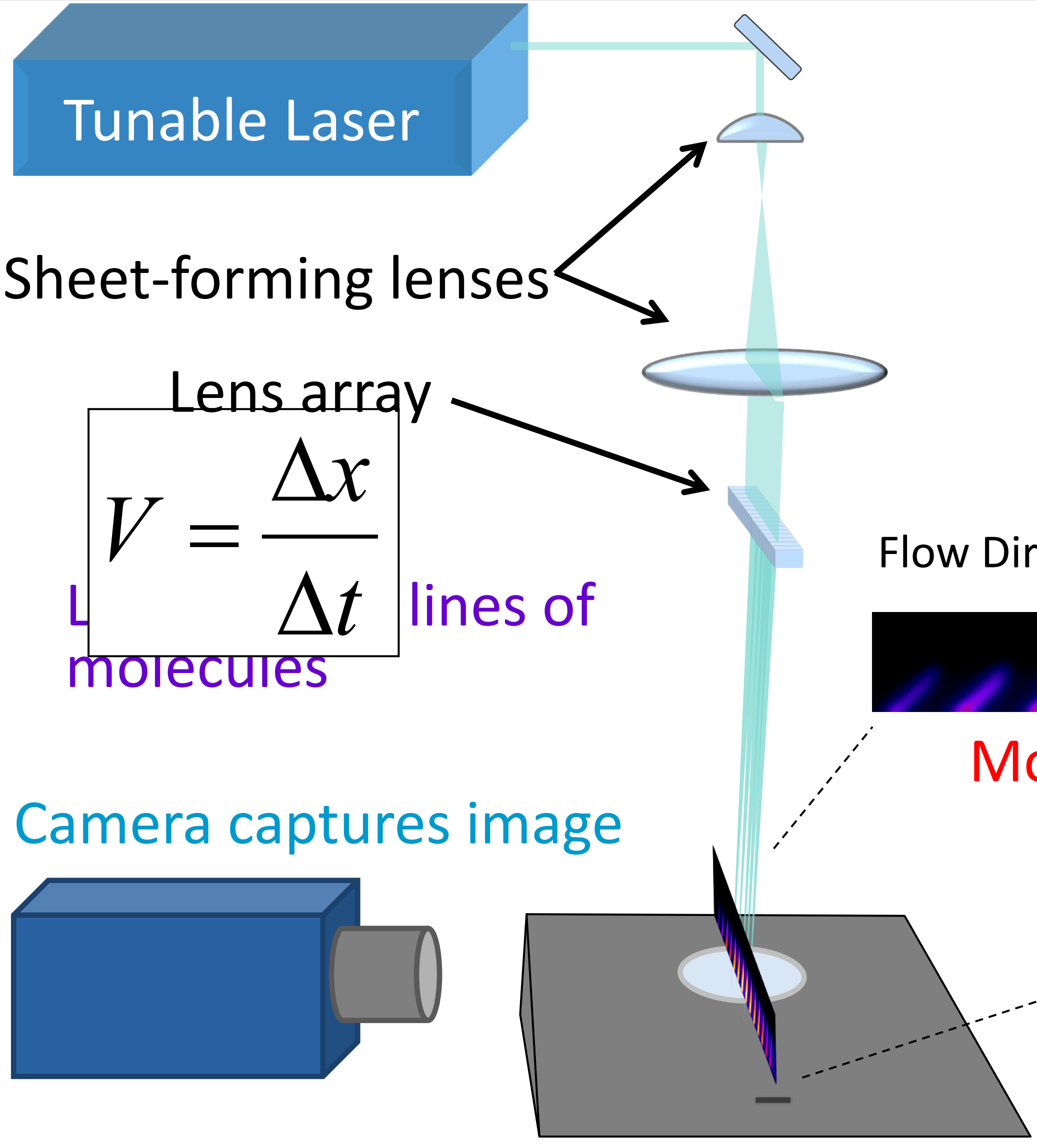


Superposition of NO PLIF images

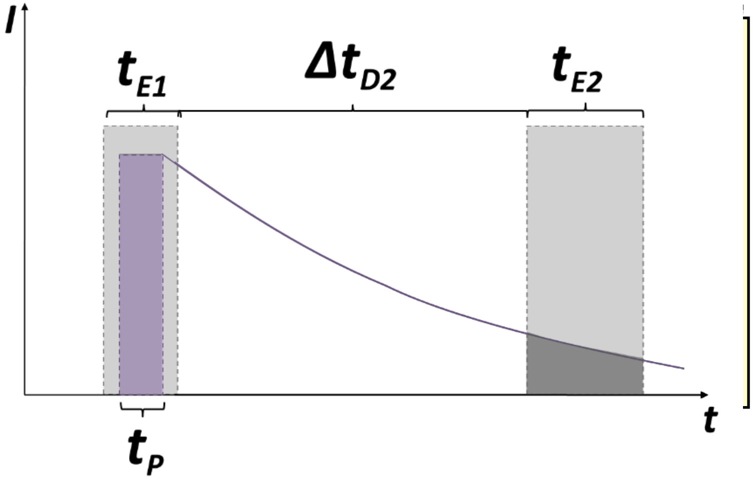


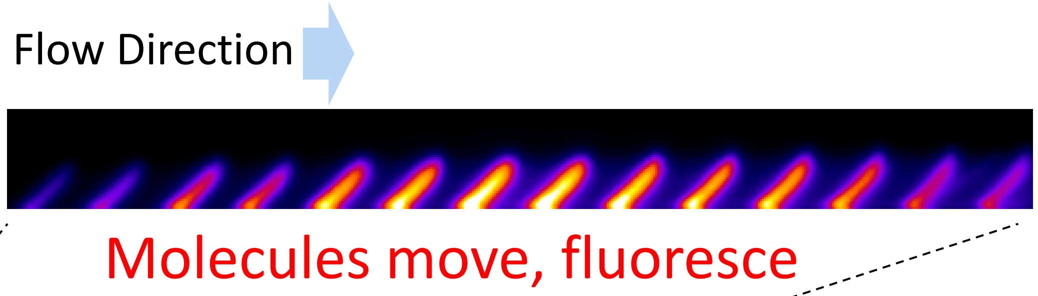
- Johansen used PLIF wake flow images to study flow separation on MSL aft body and computed RCS trajectories and compared both with OVERFLOW CFD.
  - C. T. Johansen, L. Novak, B. F. Bathel, S. W. Ashcraft, and P. M. Danehy, "Mars Science Laboratory Reaction Control System Jet Computations with Visualization and Velocimetry," Journal of Spacecraft and Rockets, (2013)

Single-laser Molecular Tagging Velocimetry (MTV)



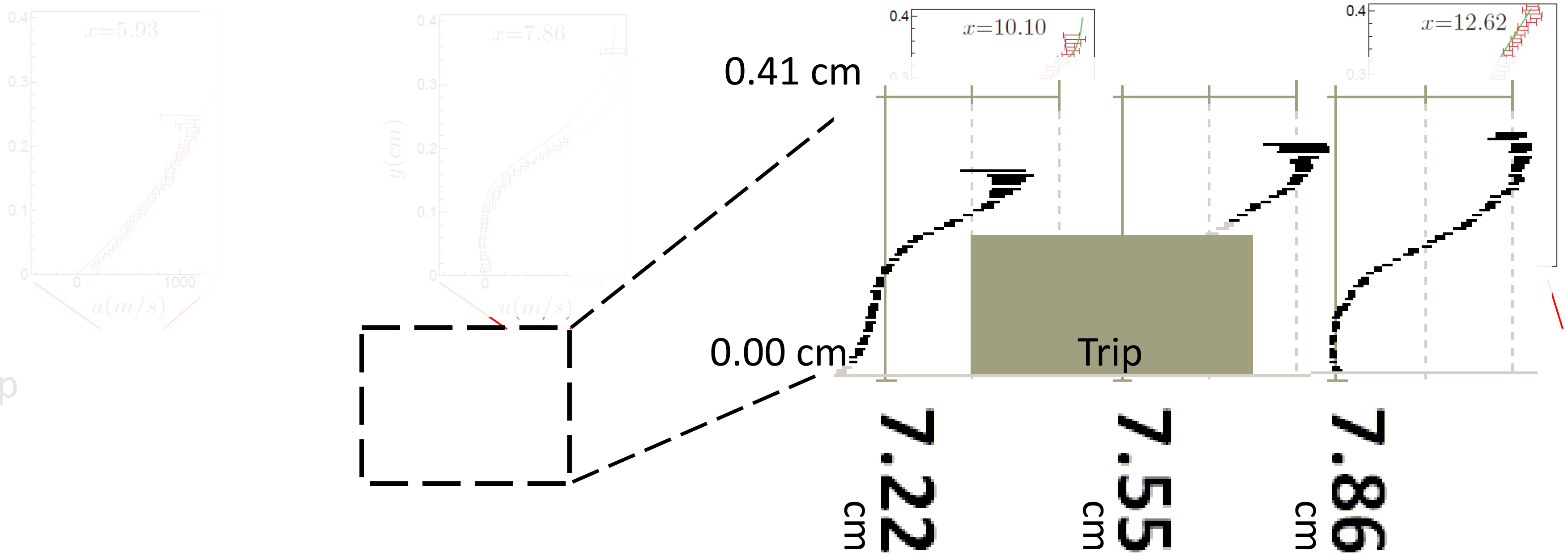
$$V = \frac{\Delta x}{\Delta t}$$





BF Bathel, et al, AIAA journal 49 (9), 1883-1896, 2011

NO MTV (and Comparison with CFD)



$M_e \approx 8.1$

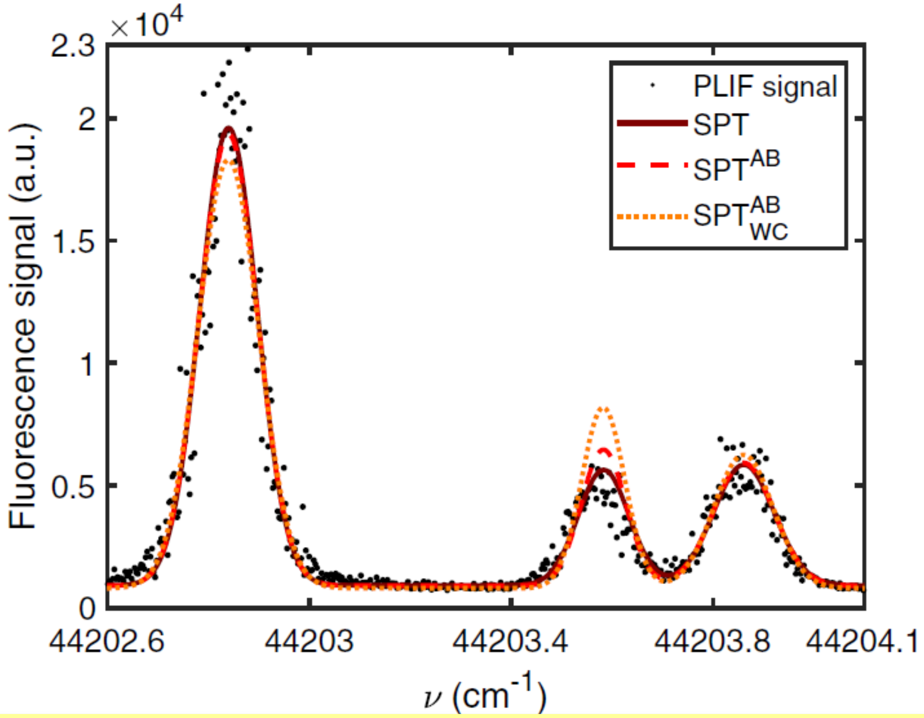
- **Velocity Measurement**
  - Single-component
  - Developed thorough uncertainty analysis methodology
  - Data used in subsequent CFD study by Iyer et al. of Univ. of Minnesota (AIAA 2011-566)

Bathel et al also performed NO_2 MTV (more precise)
See Neil Rodrigues talk later this week for NO PLIF MTV on LOFTID Model
- 25→ 75 lines in the Langley 31 Inch Mach 10 facility

BF Bathel, et al, AIAA Journal 49 (9), 1883-1896, 2011

Rotational PLIF Thermometry

- Approach: scanned laser over three transitions of nitric oxide to measure rotational temperature by fitting.
- Measurement was performed in laminar boundary layer flow on a flat plate.



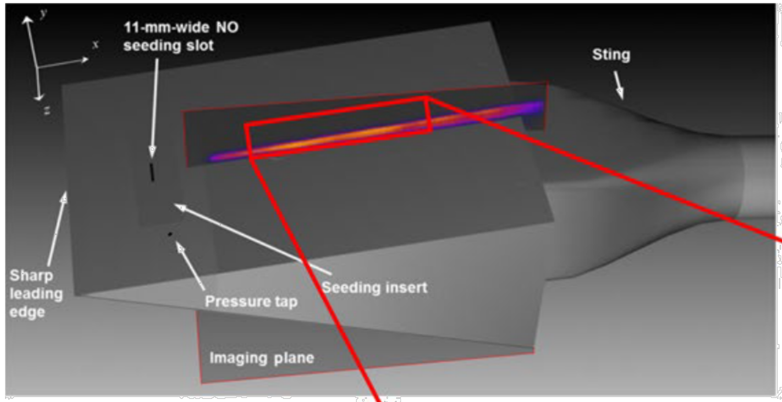
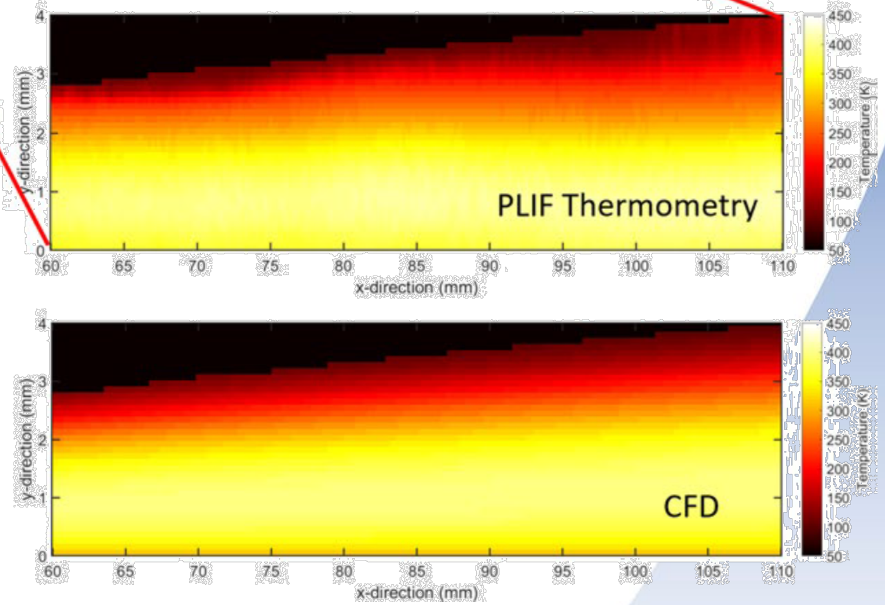


Fig. PLIF thermometry temperature field in the boundary layer of a Mach 10 wedge flow compared to CFD temperature predictions from the literature.

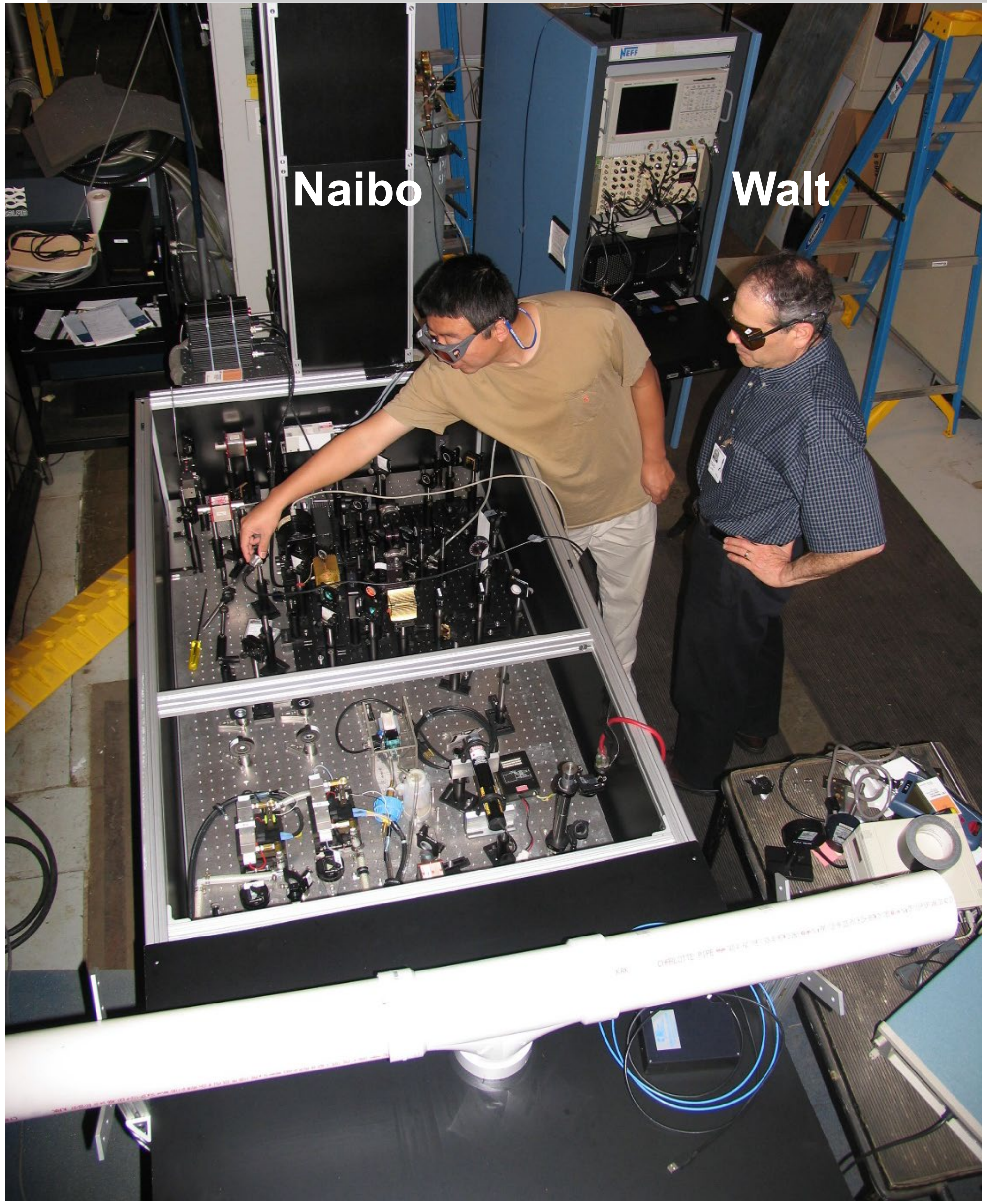


Current efforts: 2-line instantaneous PLIF thermometry

McDougall, C.C., Hinman, W.S., Johansen, C.T., Bathel, B.F., Inman, J.A. and Danehy, P.M., 2020. Evaluation of nitric oxide laser-induced fluorescence thermometry techniques in a hypersonic boundary layer. Experiments in Fluids, 61(4), p.102.

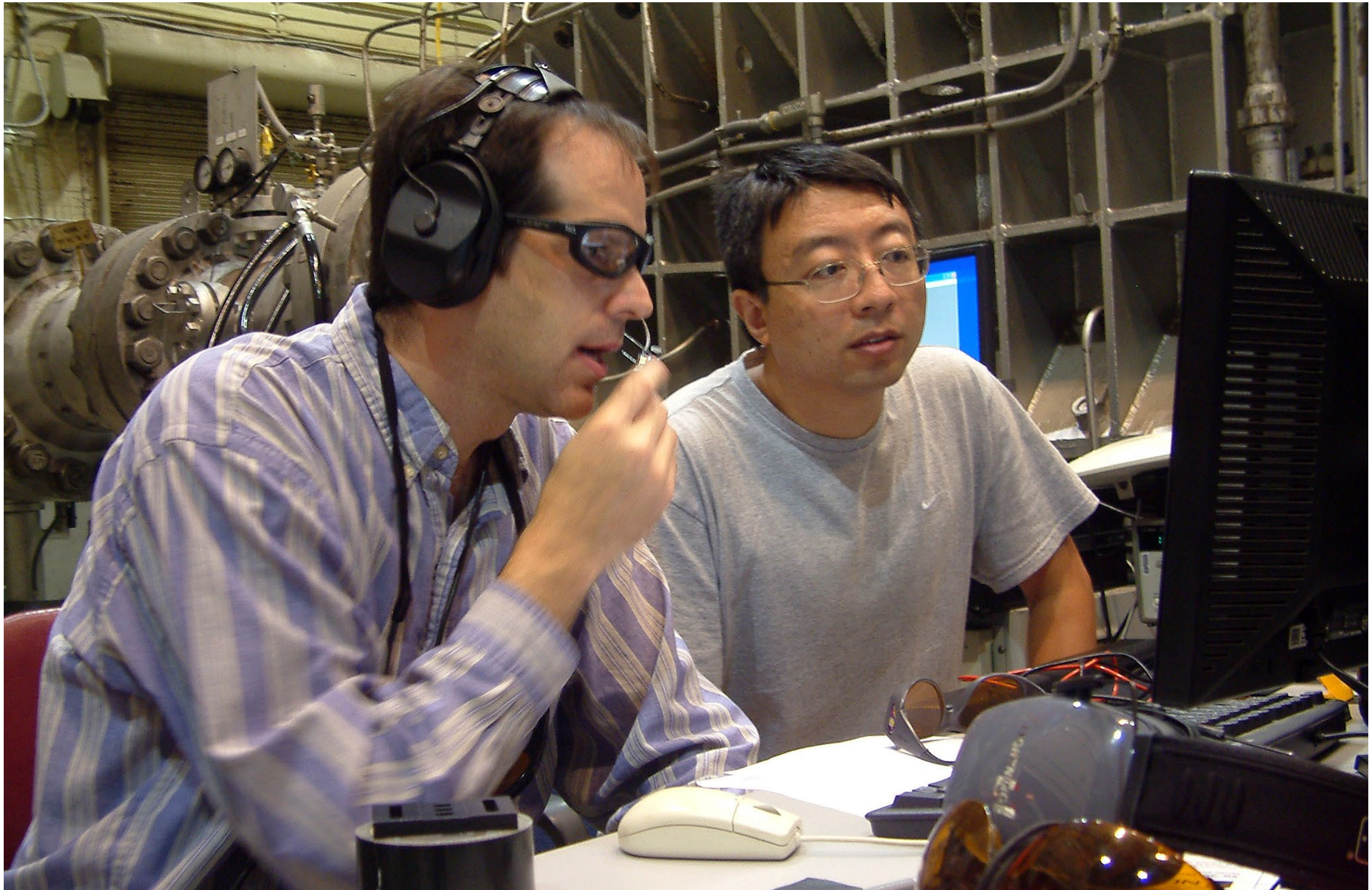
C. J. Arisman, C. T. Johansen, B. F. Bathel and P. M. Danehy, “Investigation of Gas Seeding for Planar Laser-Induced Fluorescence in Hypersonic Boundary Layers” AIAA Journal, Vol.53: 3637-3651 (2015).

Collab. with OSU & ISU (NRA 2007-09) **& SE** (SBIR 2010)

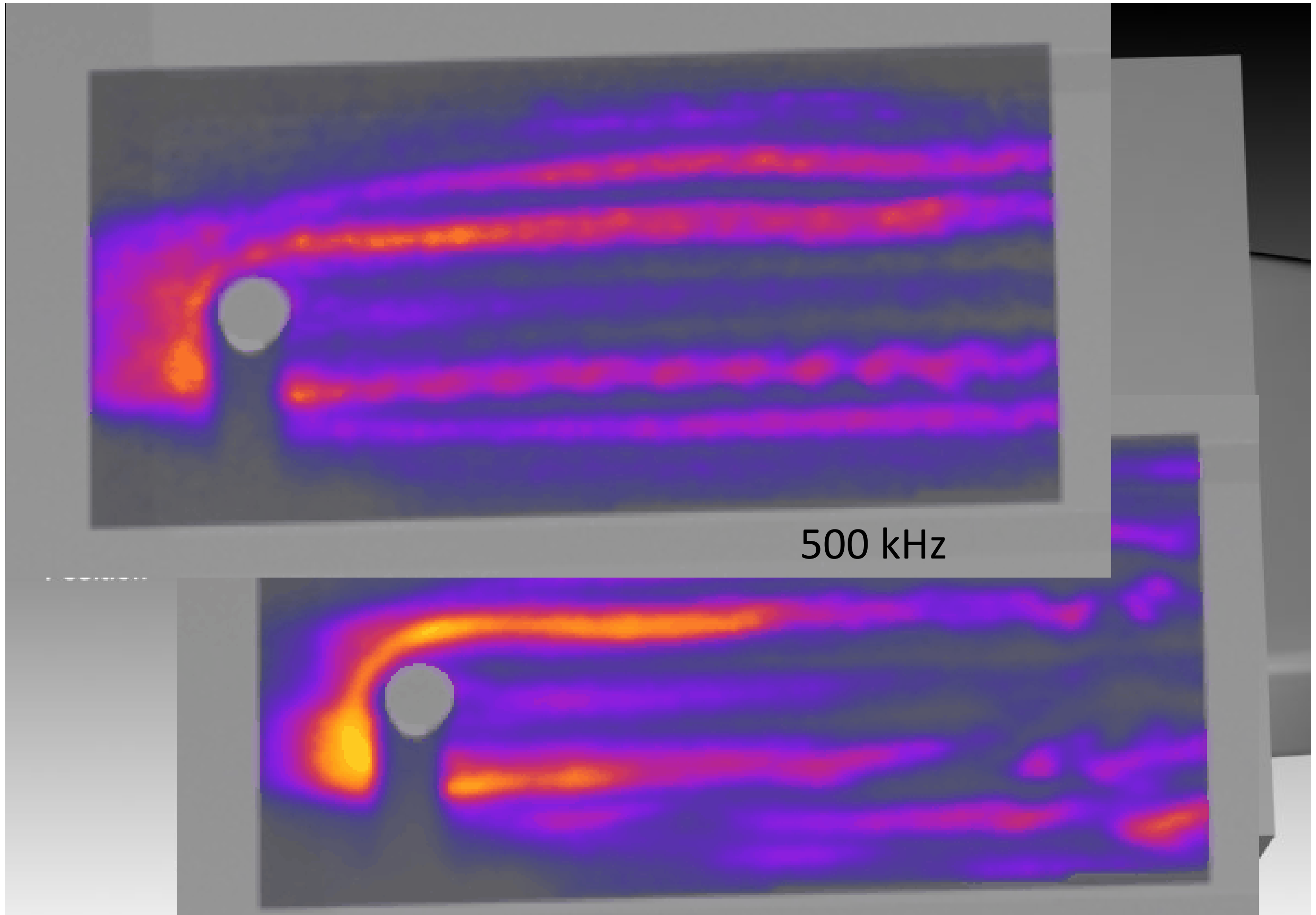


High Speed NO PLIF

Collab. with OSU & ISU (NRA 2007-09) **& SE** (SBIR 2010)

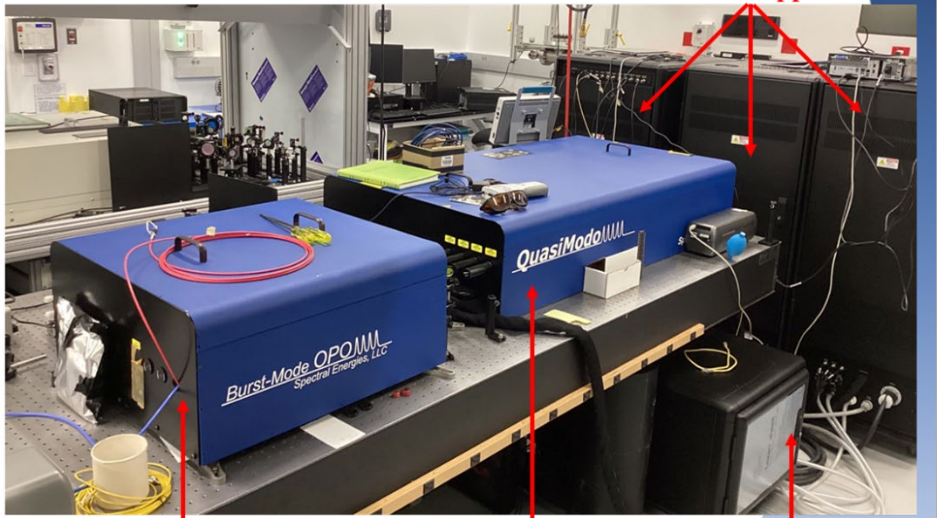


1 MHz NO PLIF System



Jiang et al, Applied Optics Vol. 50, Issue 4, pp. A20-A28 (2011)

NASA PB OPO System



- 1 million FPS – time resolve these flows, compare with time resolved CFD
- More coming soon: NASA just procured a similar system through SBIR program (Spectral Energies, Dayton OH)

22

Summary and Outlook

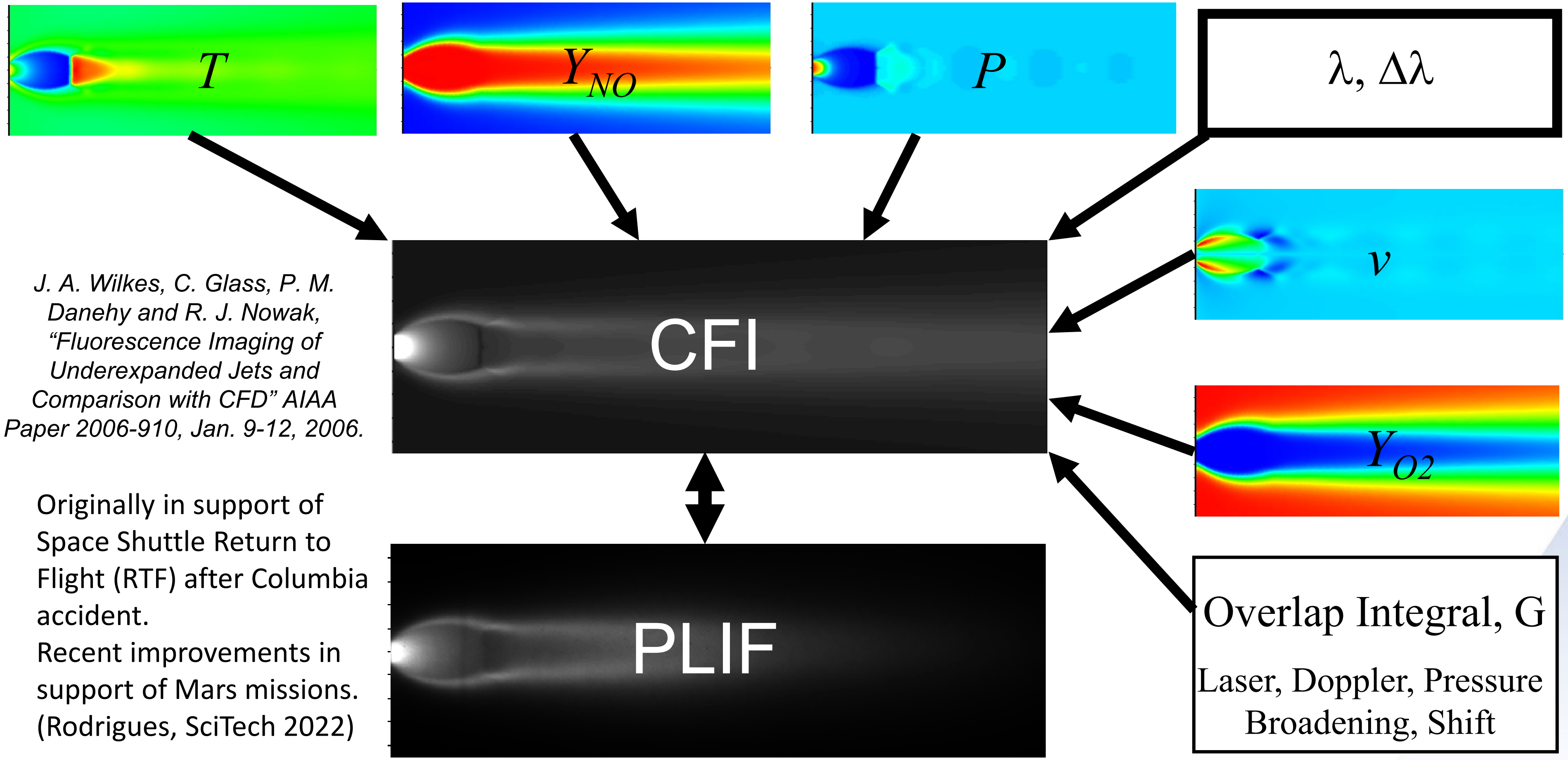
- Described NASA's mobile PLIF system, Ohio State's high-speed system, Personnel
- Seeding methods (minimally intrusive vs flow control) with Planar and Volumetric Measurements
  - Flat plate experiments: protuberances (including Space Shuttle Flight Orbiter Experiment, Cavity)
  - Wake flows (IRVE, LOFTID, MSL)
  - Reaction Control Systems (Orion, MSL)
- Quantitative Methods
  - Molecular Tagging Velocimetry
  - Thermometry
- High Speed Visualizations (Ohio State)
- Outlook for the future
  - Upcoming entry vehicle wake flow studies (LOFTID-like configurations)
    - Support from NASA's Space Technology Mission Directorate (STMD), Game Changing Development (GCD), Entry Systems Modelling (ESM) Project; collaborating with Experimental and Computational Fluid Dynamics Team (Langley and Ames) for code validation.
    - More accurate velocity, 2D velocity, 2D temperature
  - Recently purchased a pulse burst laser OPO system from Spectral Energies LLC
    - Plan to implement at Mach 10 for NO PLIF at 100s of kHz.

Work was supported by NASA :
Aeronautics (Hypersonics),
Space (Shuttle, Orion) and
Science (MSL)

Backup

Computational Flow Imaging (CFI)

- Compute PLIF Images based on CFD and spectroscopic data (broadening, shift, quenching)
  - More direct comparison between PLIF and CFD



J. A. Wilkes, C. Glass, P. M. Danehy and R. J. Nowak, "Fluorescence Imaging of Underexpanded Jets and Comparison with CFD" AIAA Paper 2006-910, Jan. 9-12, 2006.

- Originally in support of Space Shuttle Return to Flight (RTF) after Columbia accident.
- Recent improvements in support of Mars missions. (Rodrigues, SciTech 2022)