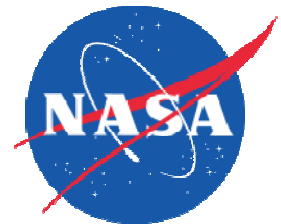


# Velocity Measurements in Unseeded Cryogenic Flows using FLEET

---

**Paul Danehy**  
**Senior Technologist for Adv. Meas. Systems**  
**NASA Langley Research Center**  
**Hampton, Virginia**

---



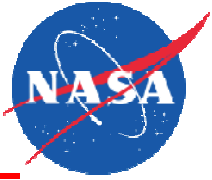
## **Collaborators:**

Ross Burns, Daniel Reese (National Institute of Aerospace, Hampton VA)  
Christopher Peters, Richard Miles (Princeton University, Princeton NJ)  
Naibo Jiang, Sukesh Roy, Josef Felver, Daniel Richardson, Mikhail Slipchenko  
(Spectral Energies LLC, Dayton OH)  
Jim Gord (AFRL, WPAFB, Dayton OH)



*50<sup>th</sup> JSASS Fluid Dynamic Conference*  
*Miyazaki Japan, July 4-6, 2018*



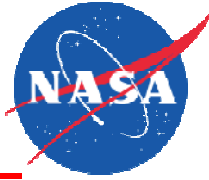


# Outline of Presentation

---

- Background
- Introduction of FLEET Concept
- Example of a FLEET measurement: Airfoil
- 3 related techniques: FLEET, PLEET and STARFLEET
  - Signal Intensity Scaling (with T, P)
  - Lifetime Scaling (with T, P)
  - Accuracy Assessment
  - Precision Assessment
- Summary of FLEET, PLEET, STARFLEET

# Role of Advanced Measurement Techniques in Aerospace Vehicle Development



Evaluate new concepts: Tailcone Thruster



Planned X-plane: QueSST



## Measurement Needs:

- Force + Moment
- Flow visualization
- Shape, Deflection
- Surface Pressure
- Surface Temperature
- Surface Shear Stress
- Off-body (gas)
  - Velocity
  - Density
  - Pressure
  - Temperature
  - Concentration

- Inability of computational methods to reproduce ground test results (wind tunnel)
  - Could be inflow conditions!
- Many of the models in these codes have not been assessed / validated at relevant conditions
- In some cases, detailed flow data are needed for physics based modelling:
$$\rho u'v', T'\chi_i'$$
- Requirements drive spatial, temporal resolution, multi-parameter measurement

## Design based on Computational Fluid Dynamics (CFD)

### Computational Methods predict:

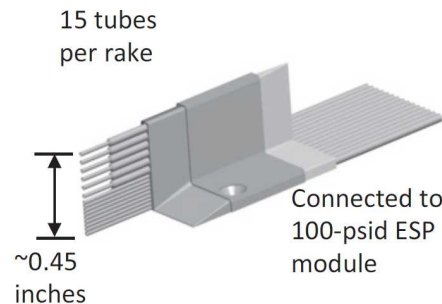
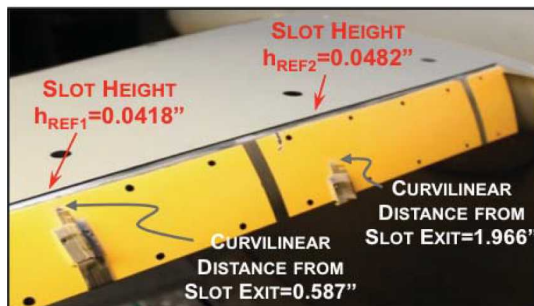
- Cruise at Mach 0.85
- Turbulence
- Flow separation
- Boundary layer (BL) transition
- Shock BL Interaction
- Aeroelasticity
- Plumes / Jet flows
- Fuel-air mixing
- Combustion

# Background: Cryogenic Wind Tunnel Testing

- High-pressure, cryogenic tunnels allow ground testing at flight-accurate Reynolds and Mach numbers
  - National Transonic Facility (NTF) and 0.3-m Transonic Cryogenic Tunnel at NASA LaRC
- Challenging testing environment: Optical measurement techniques difficult to conduct
- Current method for measuring flowfield data in NTF:



Launch Abort System model in the National Transonic Facility

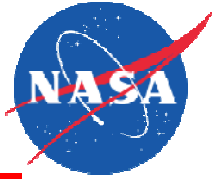


Milholen, Jones, et al, 2013



NASA Langley 0.3-m TCT

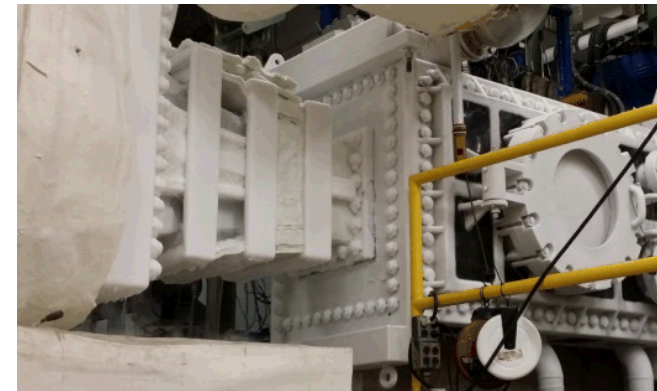
# Background: Cryogenic Wind Tunnel Testing



- High-pressure, cryogenic tunnels allow ground testing at flight-accurate Reynolds and Mach numbers
  - National Transonic Facility (NTF) and 0.3-m Transonic Cryogenic Tunnel at NASA LaRC
- Challenging testing environment: Optical measurement techniques difficult to conduct
- Limited application of optical diagnostics in cryogenic tunnels at NASA LaRC
  - Pressure & Temperature sensitive paints (Watkins, 2009, 2015, ongoing)
  - Rayleigh scattering (Herring/Shirinzadeh, 1999, 2002, 2015)
  - Schlieren/shadowgraph (Snow, 1982)
  - Laser Doppler velocimetry (Gartrell, 1981)
  - Laser transit anemometry (Honaker, 1985)



Launch Abort System model in the National Transonic Facility

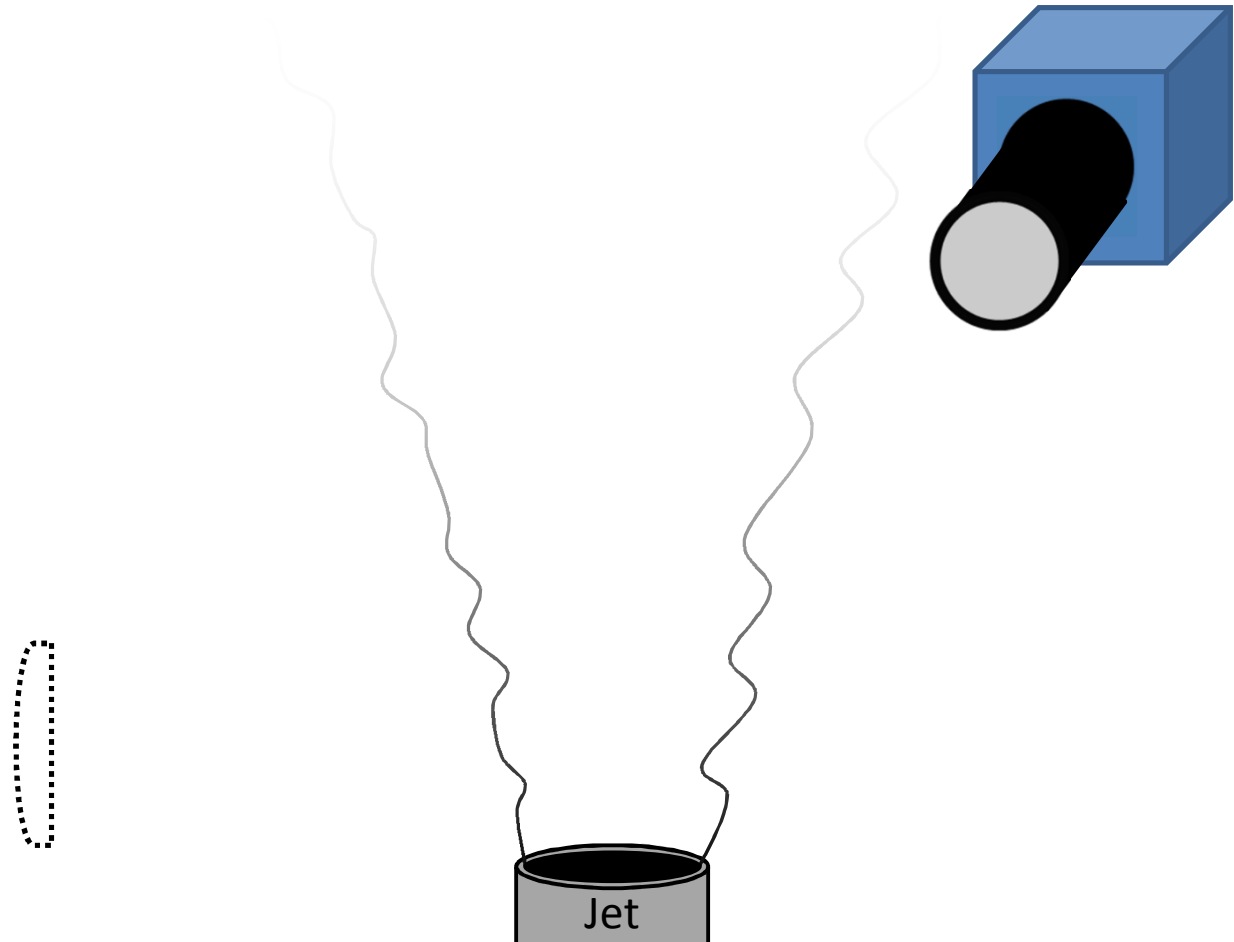


NASA Langley 0.3-m TCT

# Basic Concept: FLEET Velocimetry

FLEET (Femtosecond Laser Electronic Excitation Tagging) velocimetry (Princeton)

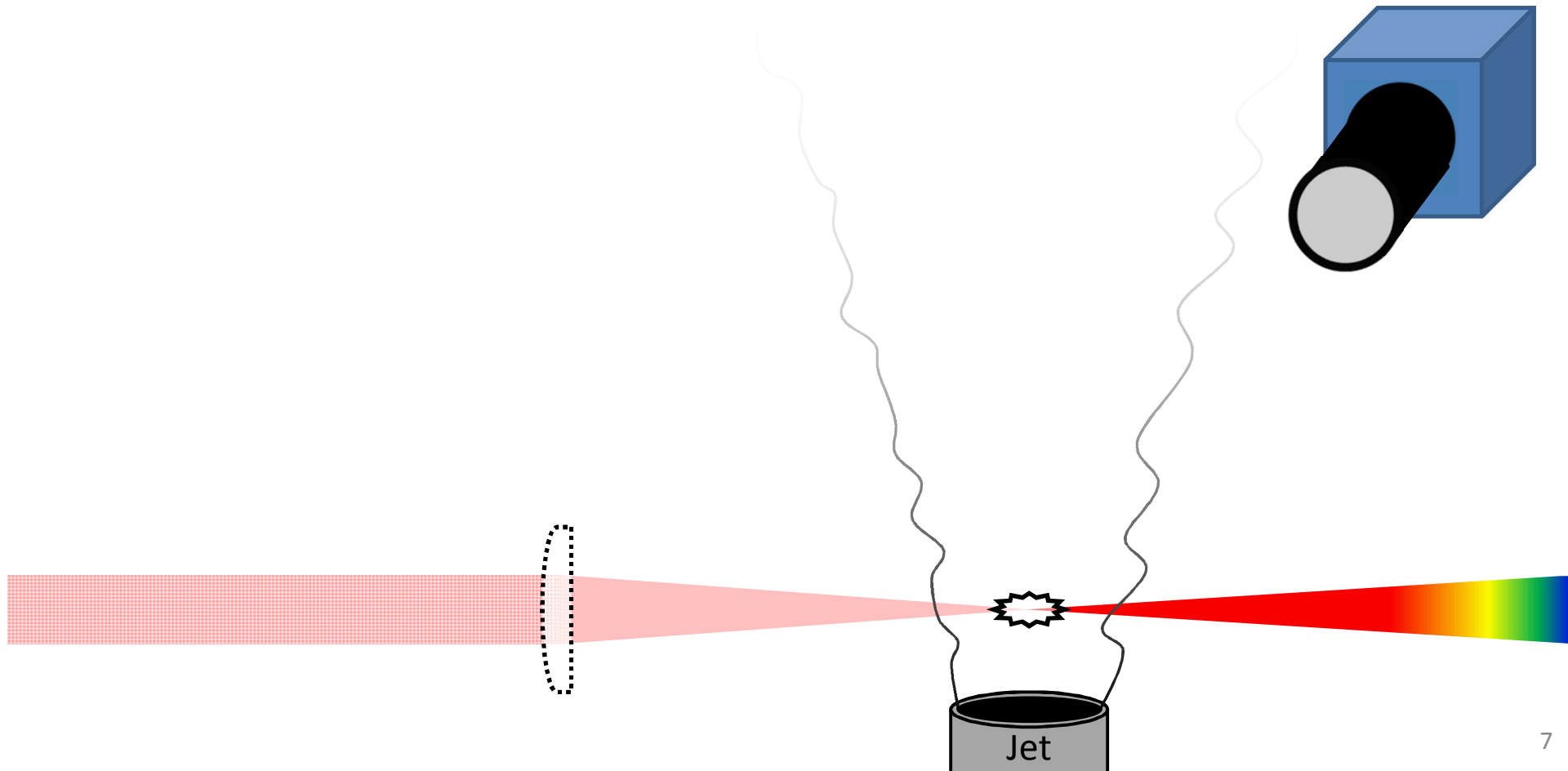
- Unseeded optical velocimetry technique
- Femtosecond laser focused to dissociate/ionize molecular  $N_2$



# Basic Concept: FLEET Velocimetry

FLEET (Femtosecond Laser Electronic Excitation Tagging) velocimetry (Princeton)

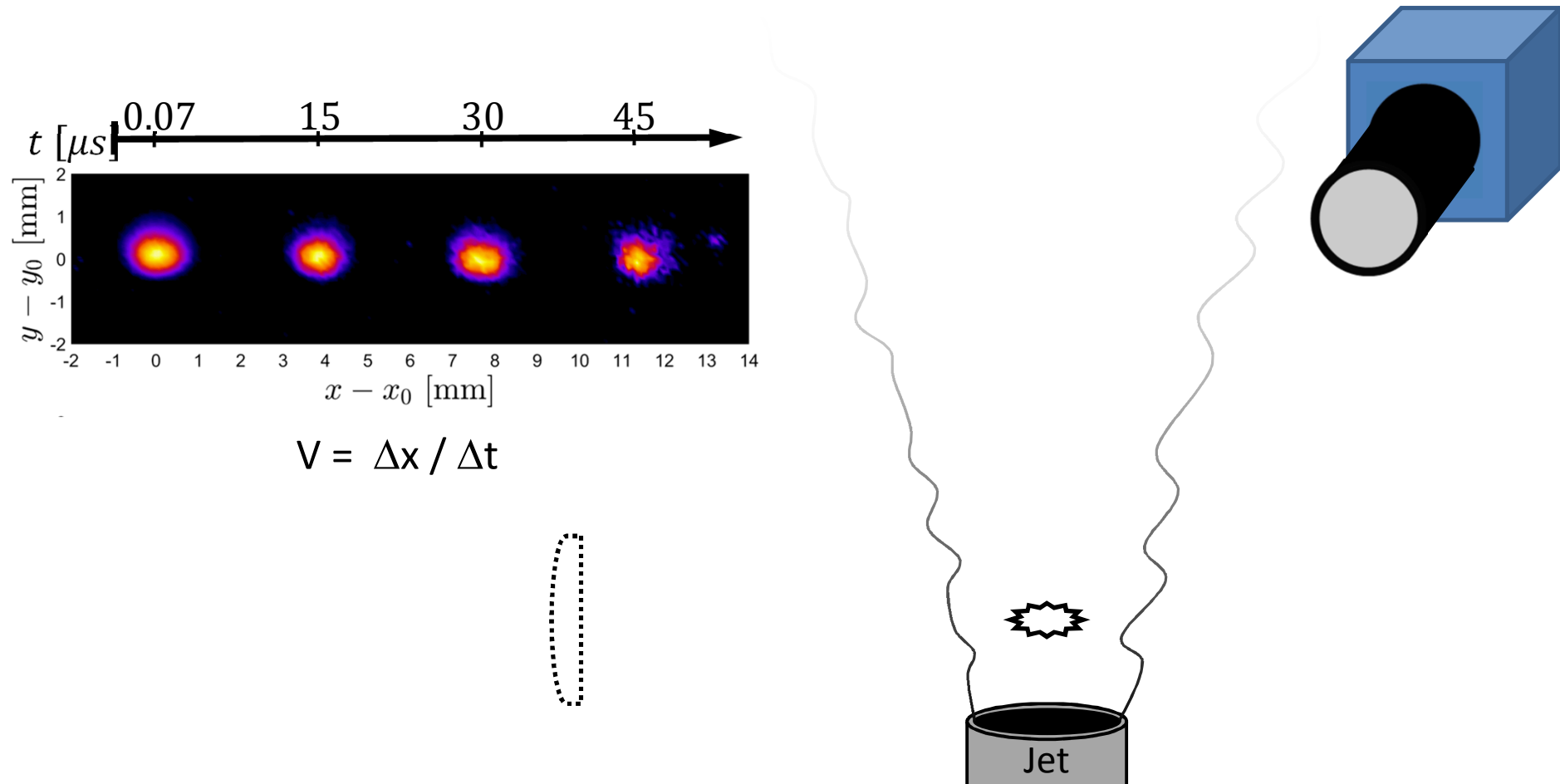
- Unseeded optical velocimetry technique
- Femtosecond laser focused to dissociate/ionize molecular  $N_2$

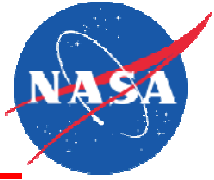


# Basic Concept: FLEET Velocimetry

FLEET (Femtosecond Laser Electronic Excitation Tagging) velocimetry (Princeton)

- Unseeded optical velocimetry technique
- Femtosecond laser focused to dissociate/ionize molecular  $N_2$
- Perturbation advects with flow, motion tracked through sequential imaging





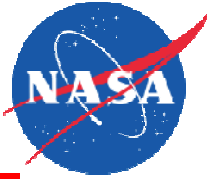
# Some features of FLEET

---

- Measure gas velocity and acceleration
- No seeding required
  - Air, N<sub>2</sub> or other gases (e.g. R-134a [Zhang, 2018])
  - We found signal increases with density: great for Cryo tunnels
- Visible excitation (800 or 400 nm) & detection (400-900 nm)
- Single-laser, single-camera required for 2 component measurement
  - Ti:Sapphire fs Laser is turn-key (in theory)
  - 3 components using 2<sup>nd</sup> camera (Danehy, 2014)
- Multi-parameter measurement possible
  - Concentration (Halls et al 2017, Peters et al. 2016)
  - Density (Burns et al. 2017, 2018)
  - Temperature (Edwards et al, 2013; Calvert et al, 2015; Jiang, et al, 2016)

But...

- High power laser: perturbs flow; can damage model or tunnel
- Only a point or line or cross measurement, only 1 kHz
- Spatial resolution not as fine as other methods



# Outline of Presentation

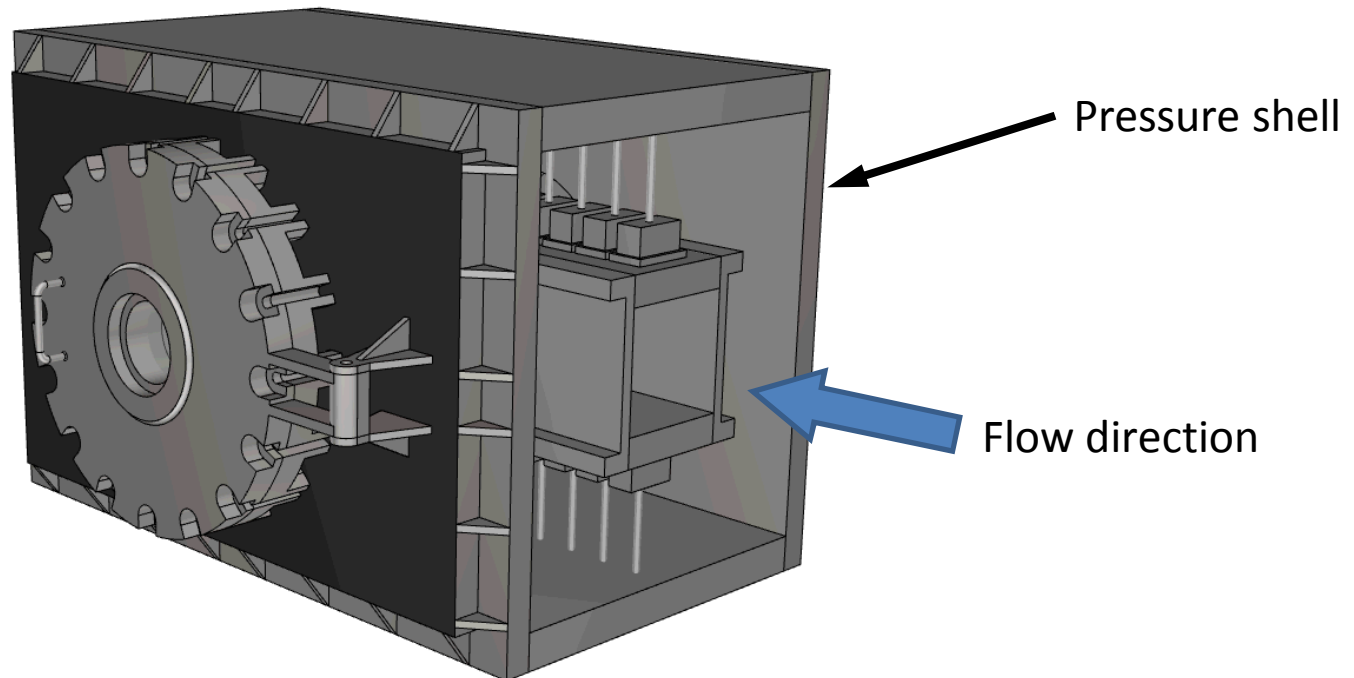
---

- Background
- Introduction of FLEET Concept
- Example of a FLEET measurement: Airfoil
- 3 related techniques: FLEET, PLEET and STARFLEET
  - Signal Intensity Scaling (with T, P)
  - Lifetime Scaling (with T, P)
  - Accuracy Assessment
  - Precision Assessment
- Summary of FLEET, PLEET, STARFLEET

# Test Facility

## NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT)

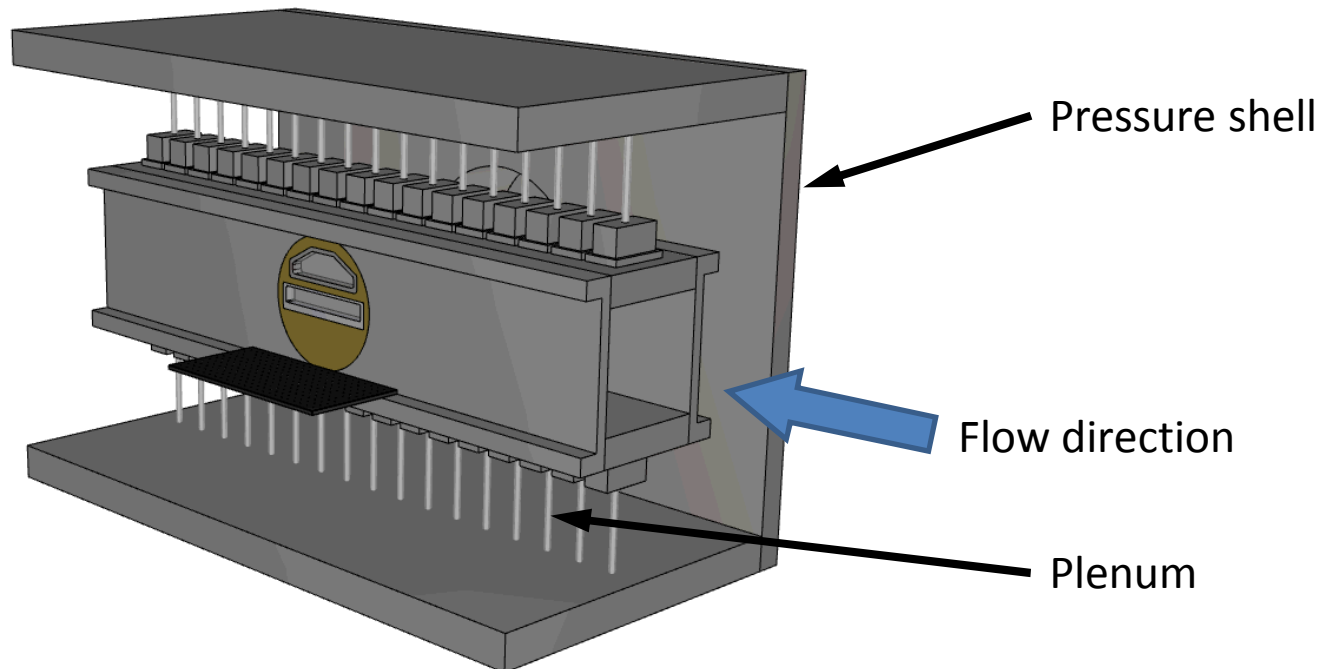
- Continuous, closed-circuit wind tunnel operating with  $N_2$
- Mach number range: 0.2 to 0.9
- Total pressure range: 100 kPa to 500 kPa
- Total temperature range: 95 K to 320 K
- Double-shelled construction



# Test Facility

## NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT)

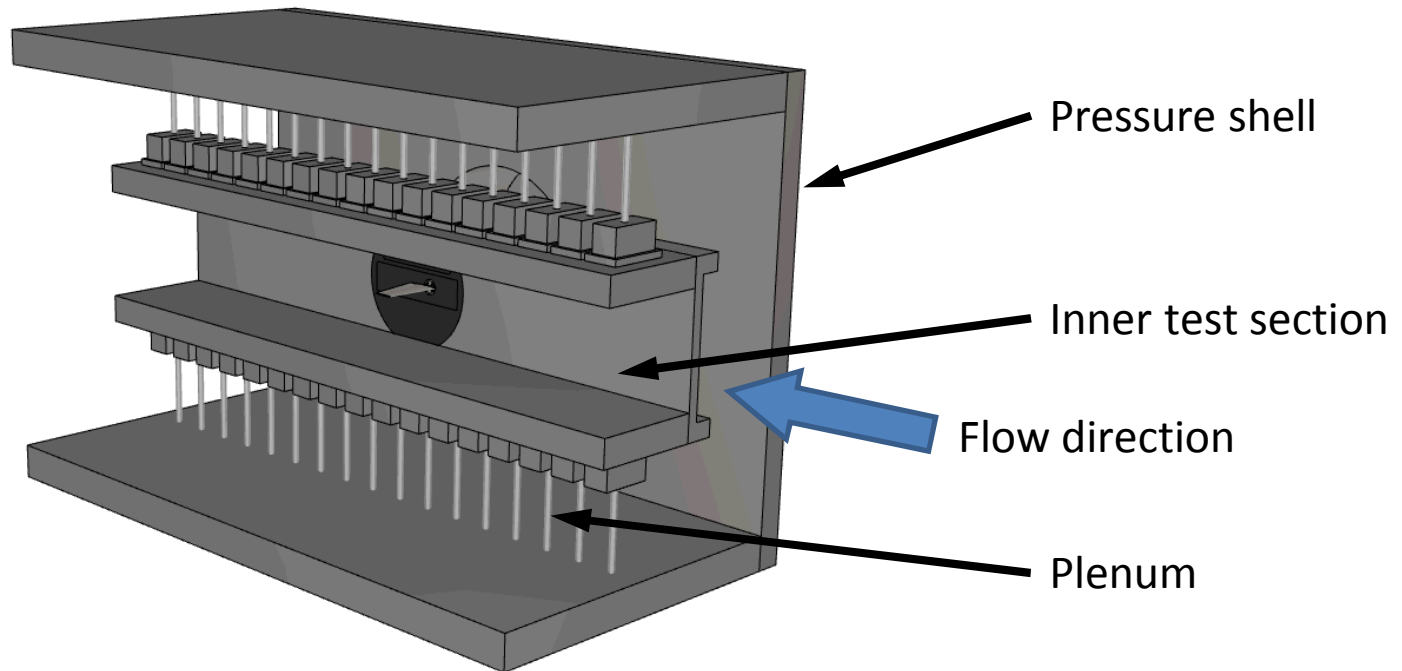
- Continuous, closed-circuit wind tunnel operating with  $N_2$
- Mach number range: 0.2 to 0.9
- Total pressure range: 100 kPa to 500 kPa
- Total temperature range: 95 K to 320 K
- Double-shelled construction



# Test Facility

## NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT)

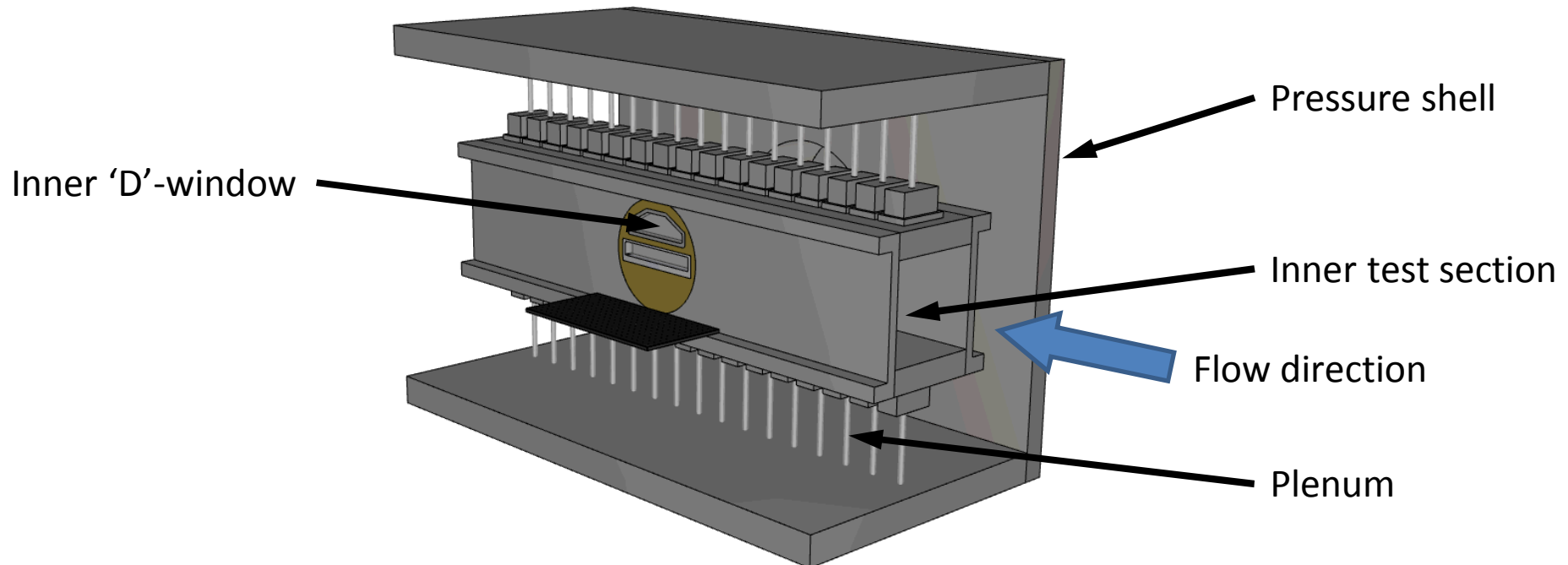
- Continuous, closed-circuit wind tunnel operating with  $N_2$
- Mach number range: 0.2 to 0.9
- Total pressure range: 100 kPa to 500 kPa
- Total temperature range: 95 K to 320 K
- Double-shelled construction



# Test Facility

## NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT)

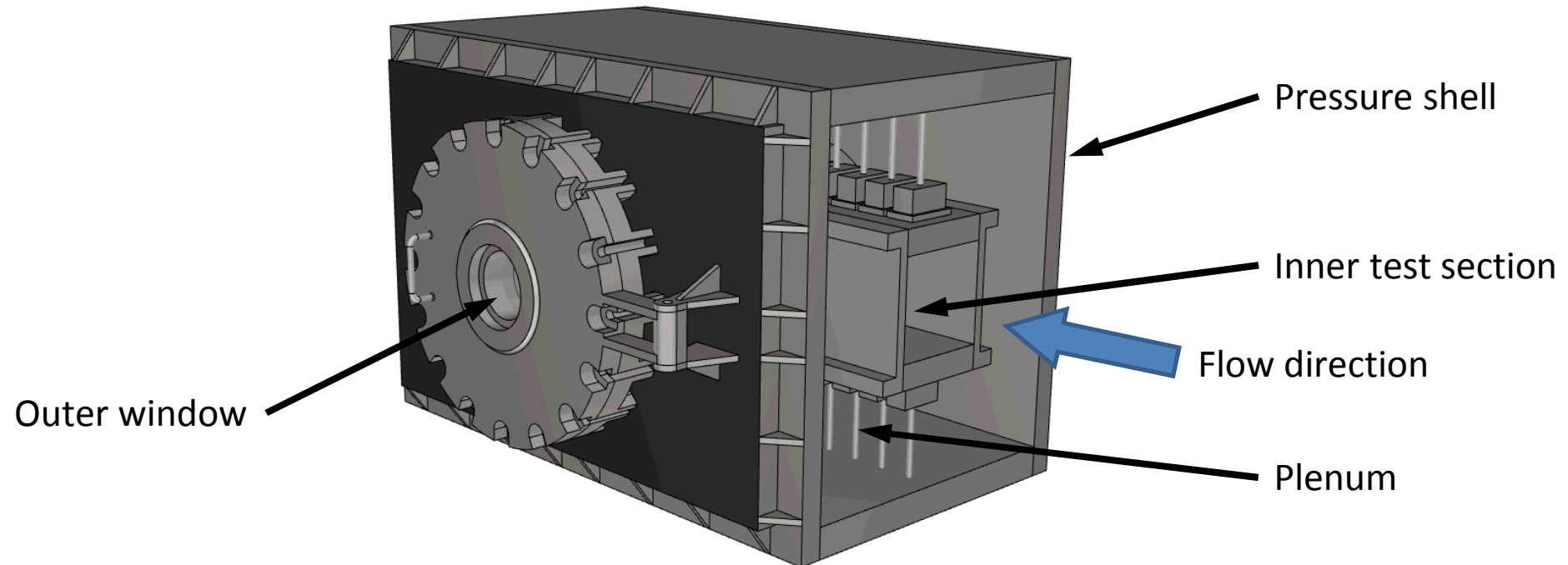
- Continuous, closed-circuit wind tunnel operating with  $N_2$
- Mach number range: 0.2 to 0.9
- Total pressure range: 100 kPa to 500 kPa
- Total temperature range: 95 K to 320 K
- Double-shelled construction
- Optical access: outer pressure shell window + window in turntable



# Test Facility

## NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT)

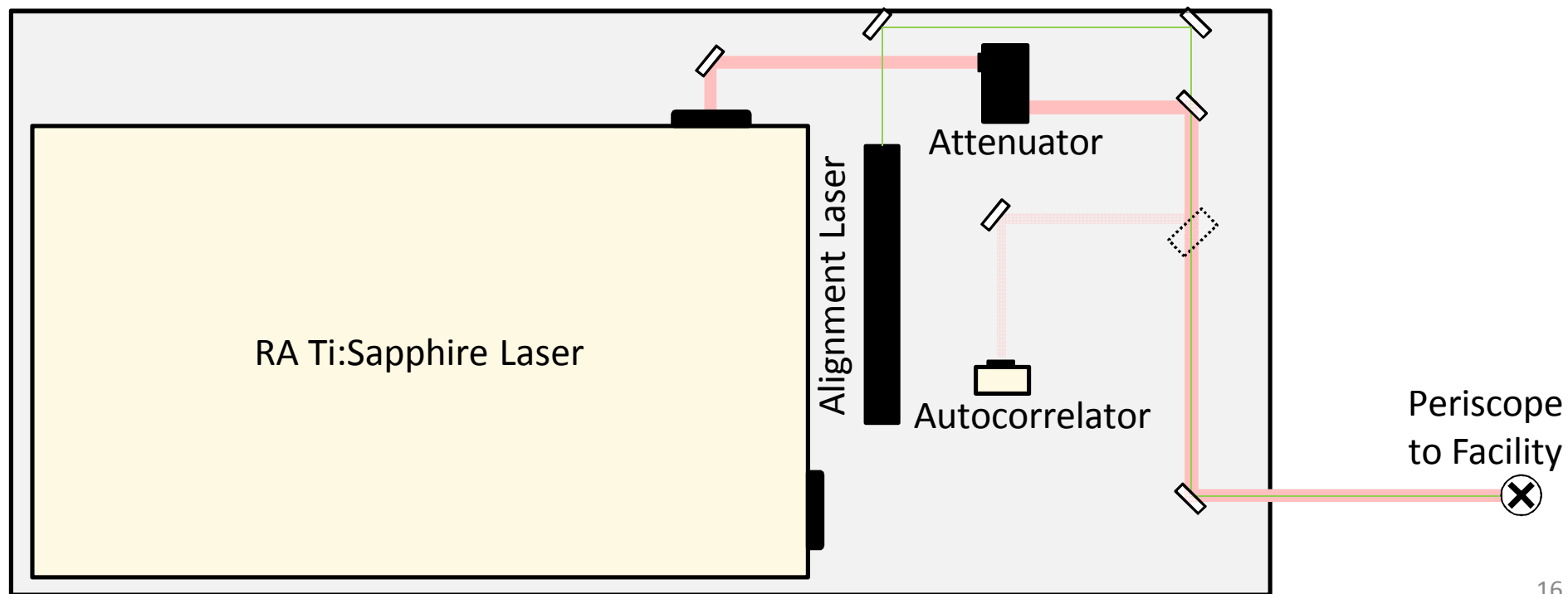
- Continuous, closed-circuit wind tunnel operating with  $N_2$
- Mach number range: 0.2 to 0.9
- Total pressure range: 100 kPa to 500 kPa
- Total temperature range: 95 K to 320 K
- Double-shelled construction
- Optical access: outer pressure shell window + window in turntable



# Experimental Program – Laser and Optical Systems

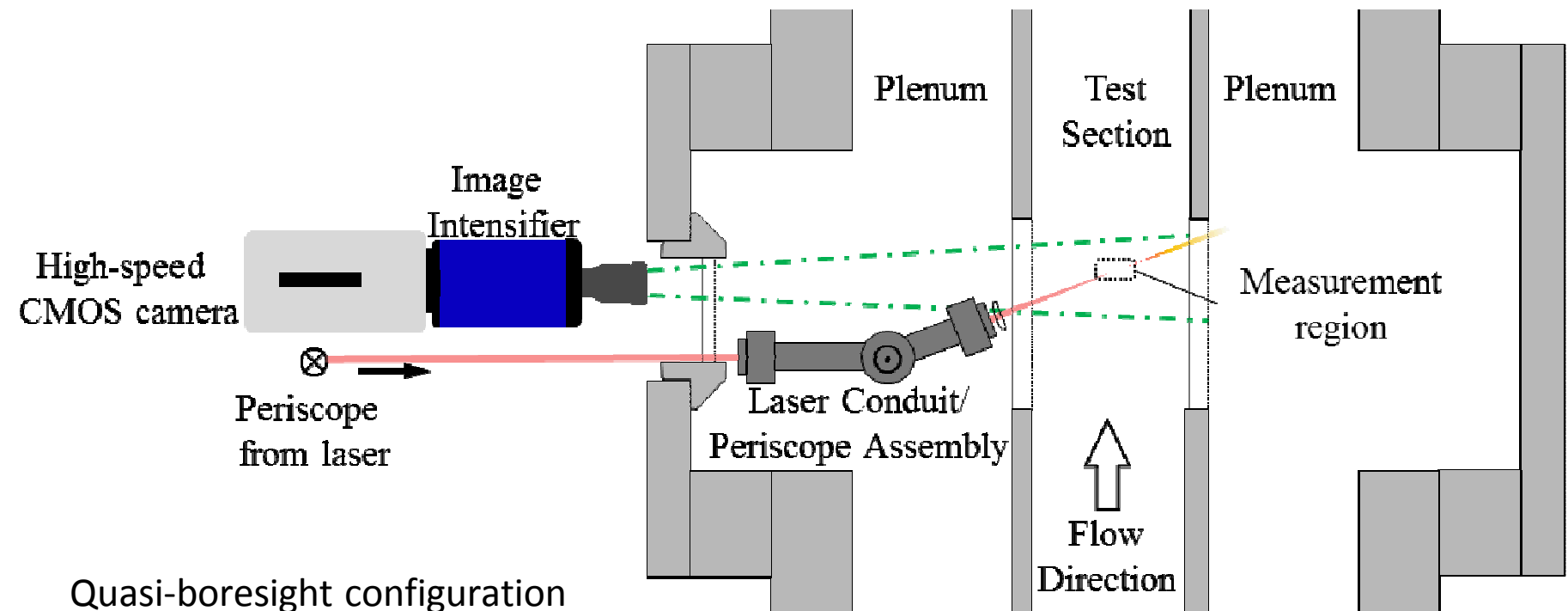
## Optical Systems – Femtosecond Laser

- Regeneratively-amplified Ti:Sapphire laser
- Output wavelength: 800 nm
- Output bandwidth: 20 nm
- Pulse duration:  $\sim 70$  fs
- Pulse energy: 3.5 mJ but used only 1 mJ (0.5-0.7 mJ at measurement location)

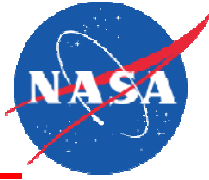


# Laser and Optical Systems

- Beam routed through series of actuated vertical and horizontal periscopes
  - Maintain alignment during facility contraction
- Beam focused with a simple spherical lens (+250 mm) for FLEET
- Data obtained with Phantom High Speed camera (SA-X2) with LaVision HS-IRO intensifier with s25 photocathode and P46 phosphor.
  - Typically acquisition rate of 200 kHz (5 usec delay between images; 1 usec gate)
  - EMCCD shown for Rayleigh scattering measurement (not described herein)

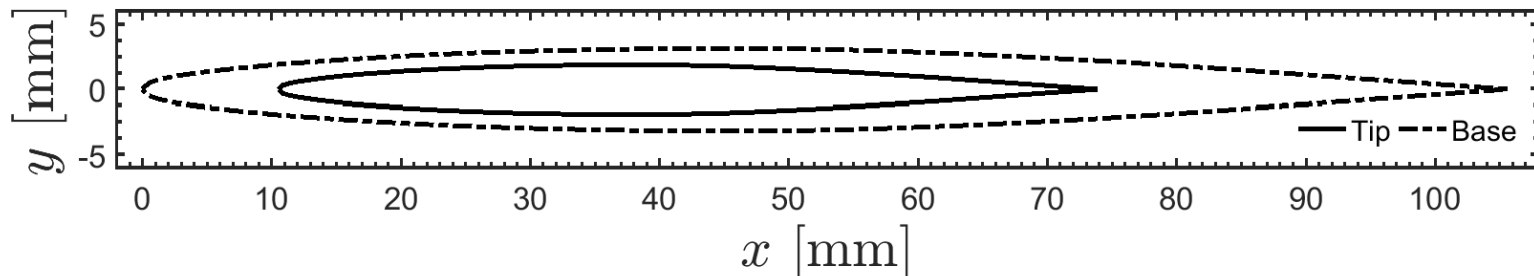
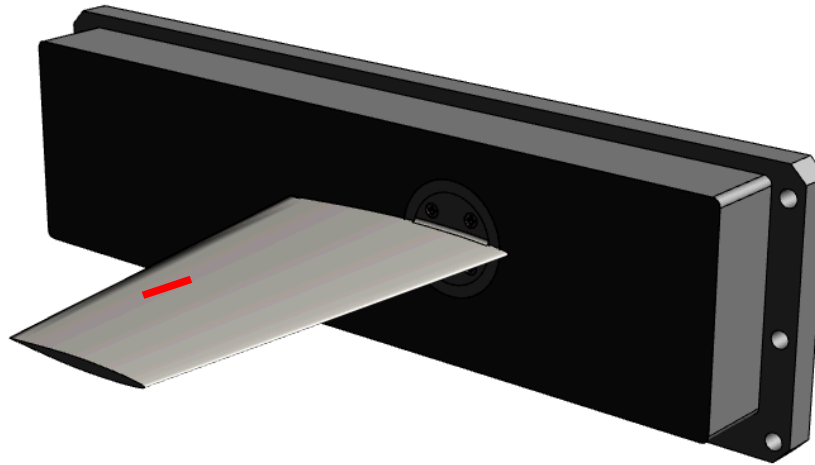


# FLEET Measurement on an Airfoil Model



Tested in NASA Langley's 0.3-m TCT facility

- Assessed practical performance of FLEET velocimetry
  - Made mean and fluctuating velocity measurements in wake and on surfaces of a transonic airfoil at different Mach numbers and angles of attack

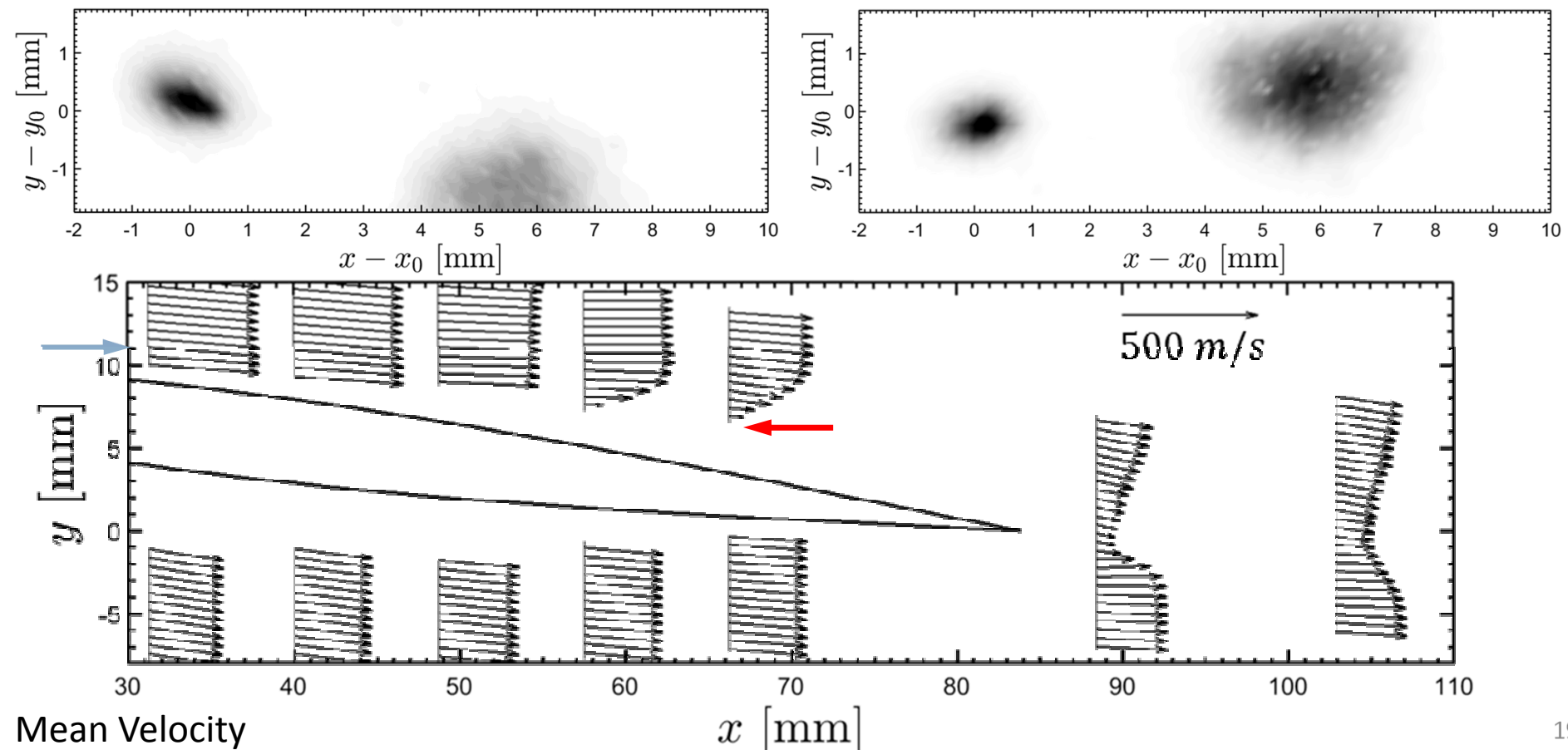


Tapered NACA 0006

# FLEET Measurement on an Airfoil Model

Tested in NASA Langley's 0.3-m TCT facility

- Assessed practical performance of FLEET velocimetry
  - Made mean and fluctuating velocity measurements in wake and on surfaces of a transonic airfoil at different Mach numbers and angles of attack

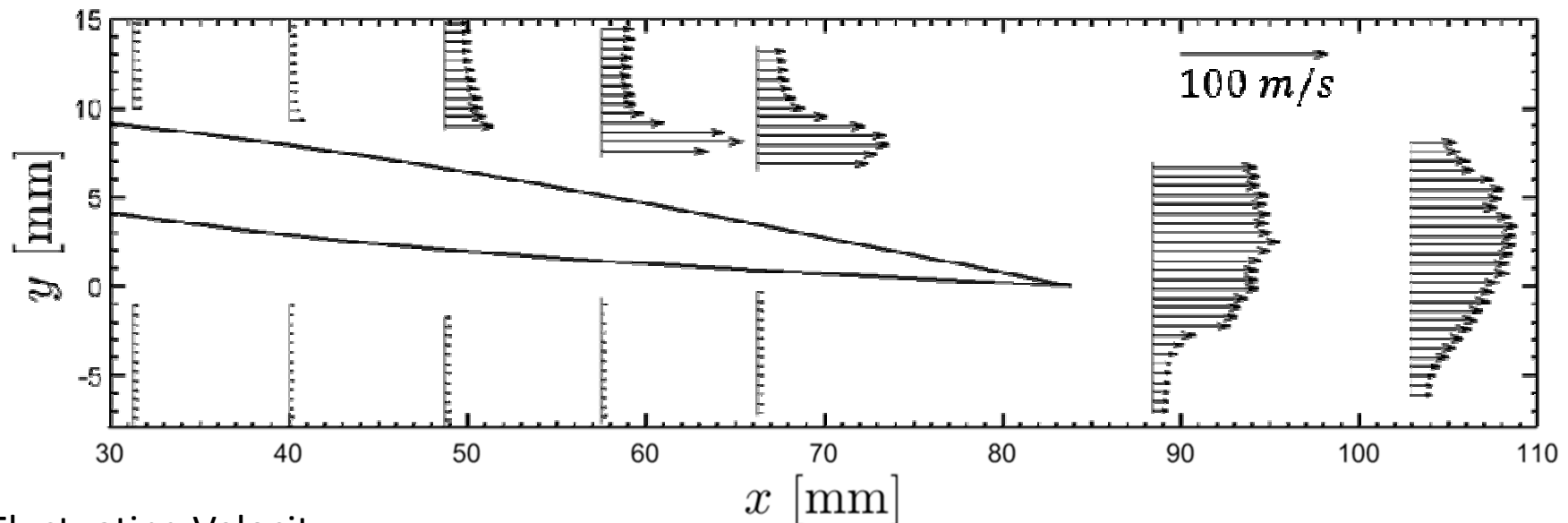


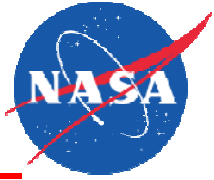
# FLEET Measurement on an Airfoil Model

Tested in NASA Langley's 0.3-m TCT facility

- Assessed practical performance of FLEET velocimetry
  - Made mean and fluctuating velocity measurements in wake and on surfaces of a transonic airfoil at different Mach numbers and angles of attack

(Burns and Danehy, AIAA Journal, 2017)

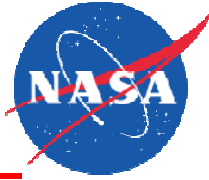




# Outline of Presentation

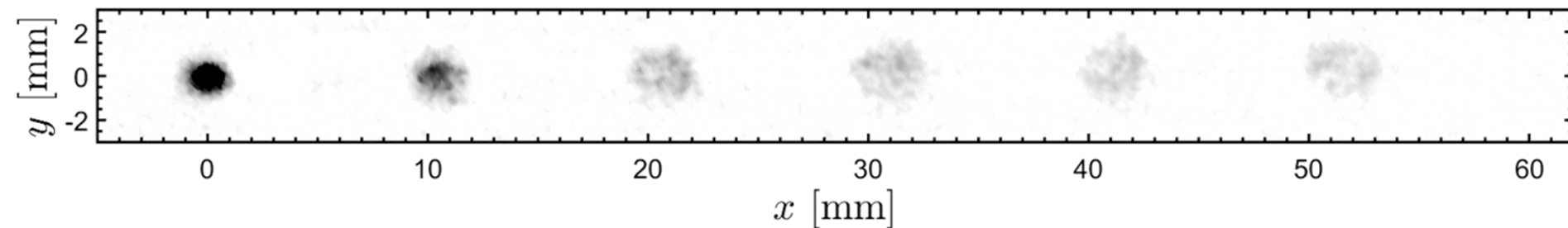
---

- Background
- Introduction of FLEET Concept
- Example of a FLEET measurement: Airfoil
- 3 related techniques: FLEET, PLEET and STARFLEET
  - Signal Intensity Scaling (with T, P)
  - Lifetime Scaling (with T, P)
  - Accuracy Assessment
  - Precision Assessment
- Summary of FLEET, PLEET, STARFLEET



# PLEET: Higher Speed (100 kHz) Measurements

- FLEET currently limited to 1 kHz or slightly faster
- Pulse burst laser technology (Spectral Energies LLC) can run at  $\geq 100$  kHz
- Use 100 picosecond seed laser (Jiang et al, 2017) at up to 100 kHz excitation
  - Picosecond Laser Electronic Excitation and Tagging (PLEET)
- PLEET Experiment performed at 0.3 m TCT in collaboration with Spectral Energies
  - Laser rep rate: 25 kHz
  - Camera acquisition rate: 100 kHz
  - 10 msec Burst sequence of 250 pulses.
  - Single image has fluorescence from multiple laser pulses



- Could be problematic in highly unsteady / recirculating flows

(MST Manuscript (under review): Burns, Danehy, Jiang, Slipchenko, Felver, Roy, "High-Speed, Unseeded Velocimetry for Transonic Cryogenic Tunnels Using Pulse-Burst PLEET.")

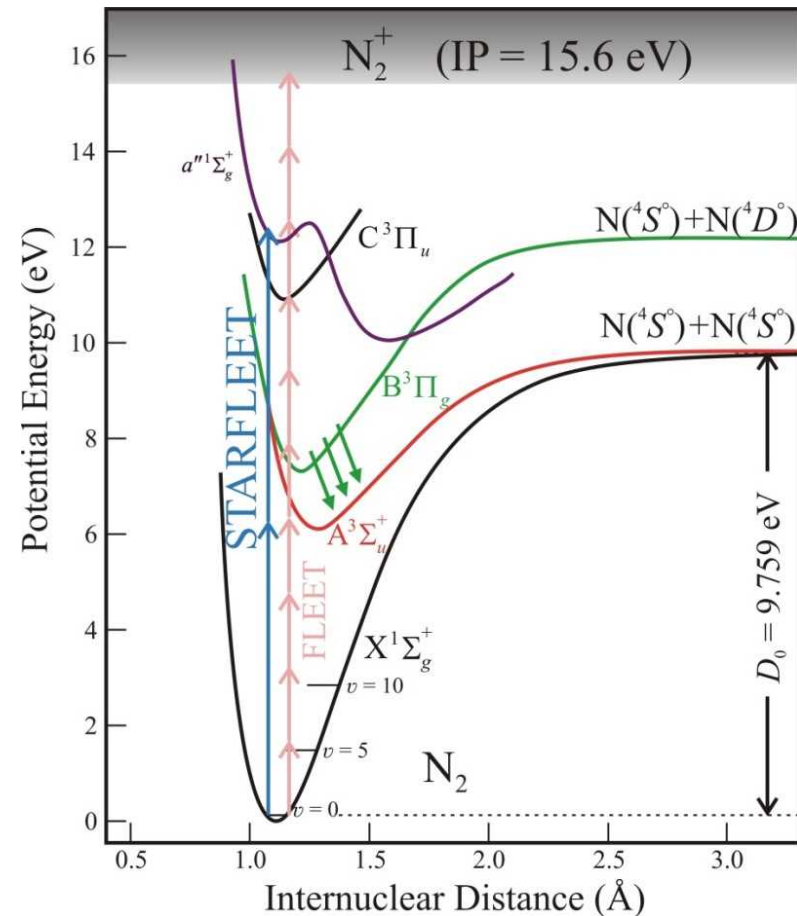
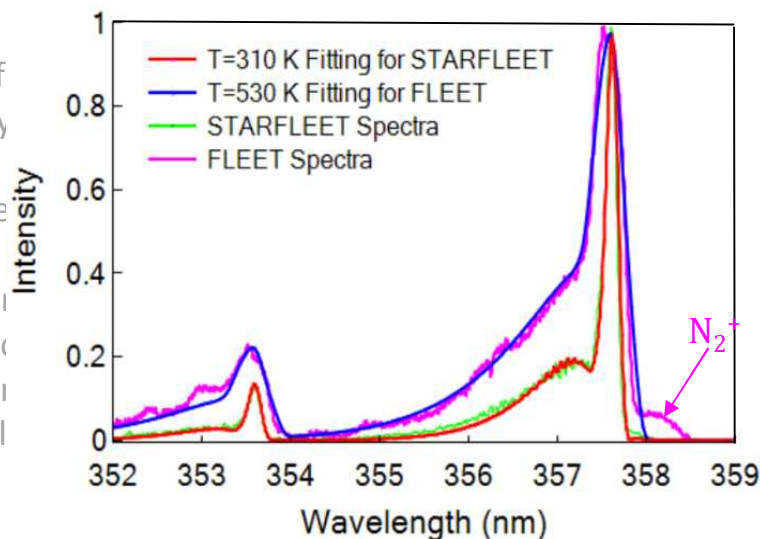
# STARFLEET: Less perturbative measurement

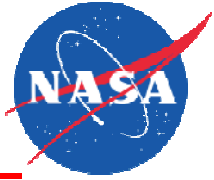
STARFLEET (selective two-photon absorptive resonance FLEET) uses  $1/30^{\text{th}}$  the energy

- Spectral Energies LLC (Jiang et al, 2017)
- Same velocity measurements as FLEET with less thermal perturbation
- Potential for spectroscopy-based temperature measurement

- Direct resonant excitation of the  $a''^1\Sigma_g^+ \leftarrow X^1\Sigma_g^+$  transition in  $N_2$  ( $\sim 202.5$  nm); minimize ionization
- Wavelength produced by FHG of fs laser
  - BUT: need  $MgF_2$  windows and mirrors are poor at this wavelength for fs laser

Jiang, Halls, Stauff  
Danehy, Gord, Roy  
"Selective two-photon absorptive resonance femtosecond-laser electronic-excitation tagging velocimetry" Optics Letters, Vol 41, No. 10, 2016.



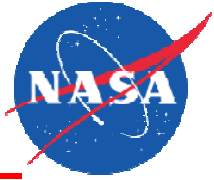


# Outline of Presentation

---

- Background
- Introduction of FLEET Concept
- Example of a FLEET measurement: Airfoil
- 3 related techniques: FLEET, PLEET and STARFLEET
  - Signal Intensity Scaling (with T, P)
  - Lifetime Scaling (with T, P)
  - Accuracy Assessment
  - Precision Assessment
- Summary of FLEET, PLEET, STARFLEET

Measurements in known  
freestream flow (no model)  
using nitrogen test gas

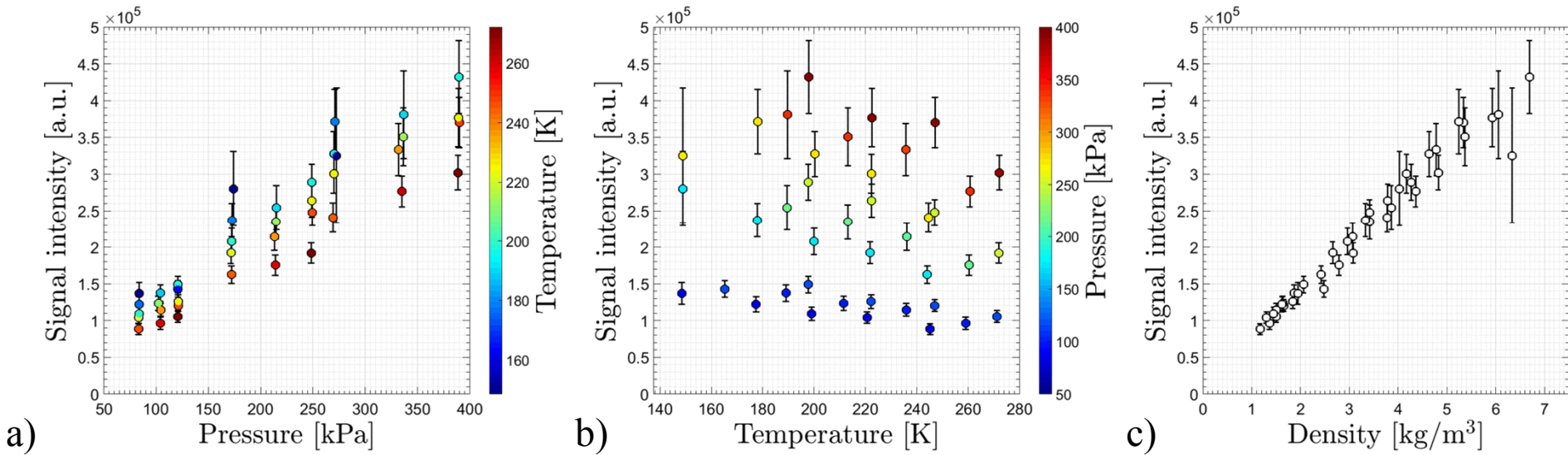


# Signal intensity, lifetime studies

---

- Signal intensity and lifetime was studied previously by others but at room temperature or elevated temperature
  - Observations:
    - Signal increases then decreases then increases with increasing pressure up to 1000 Torr (Deluca 2014, Edwards 2013)
      - Measurement location changes with laser intensity
      - Lifetime increases with laser energy
        - Dominated by atomic recombination into  $N_2$  B state.
    - Lifetime decreases with increasing pressure (several)
- Do these trends occur at lower temperature relevant to cryogenic (nitrogen) facilities? What about much higher pressures  $> 1$  bar?
  - What is the performance (accuracy, precision) at these conditions?
  - How about PLEET, STARFLEET? How do they behave?

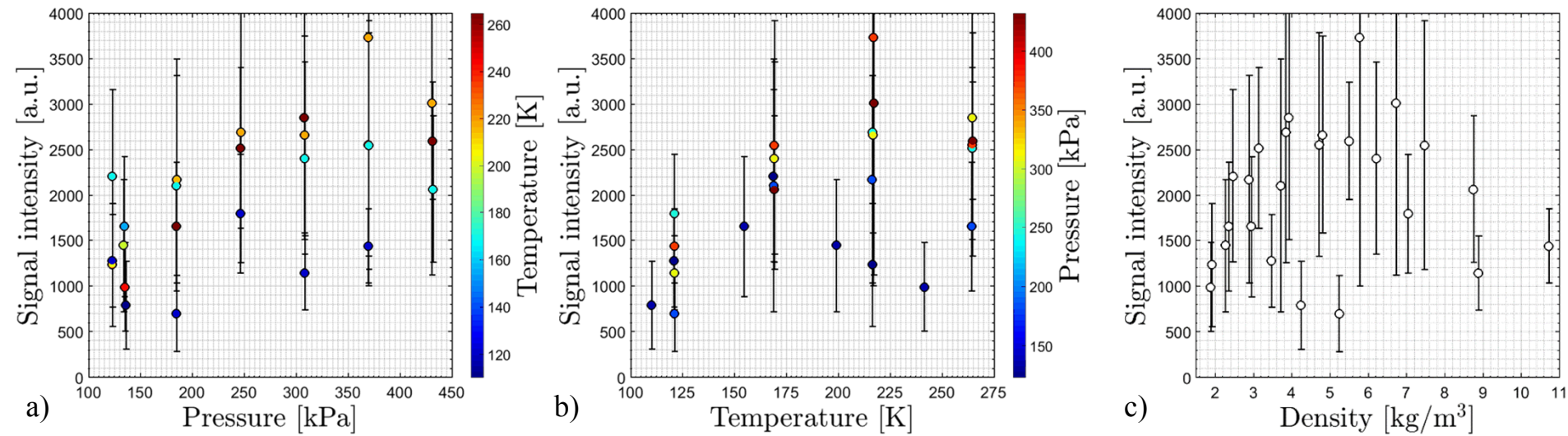
# Signal Intensity: FLEET



(Burns et al, MST, currently under review)

- FLEET Signal  $\sim \rho$  at least in range: ( $100 < T < 300$  K,  $100 < P < 400$  kPa)
  - Later we found that this doesn't always hold (shear)

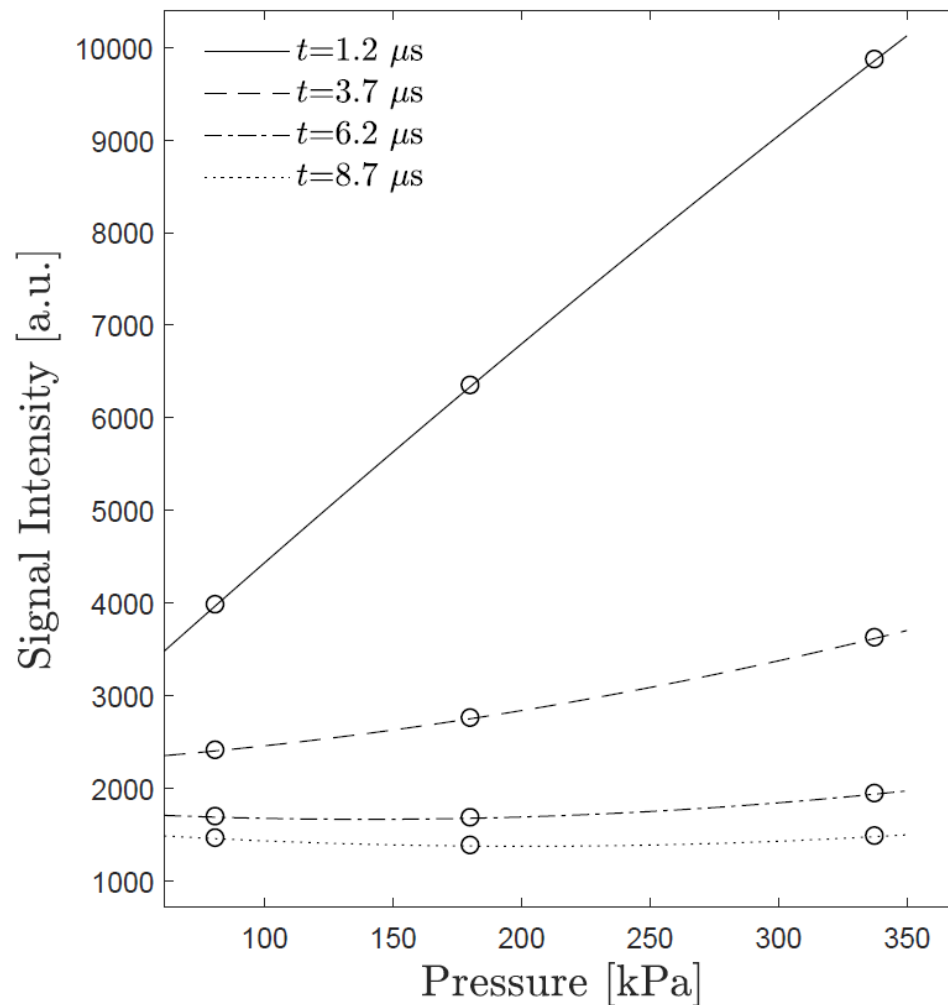
# Signal Intensity: PLEET



(Burns et al, MST, currently under review)

- No observed thermodynamic trends in PLEET Signal at least in range:  
( $100 < T < 300$  K,  $100 < P < 400$  kPa)

# Signal Intensity: STARFLEET



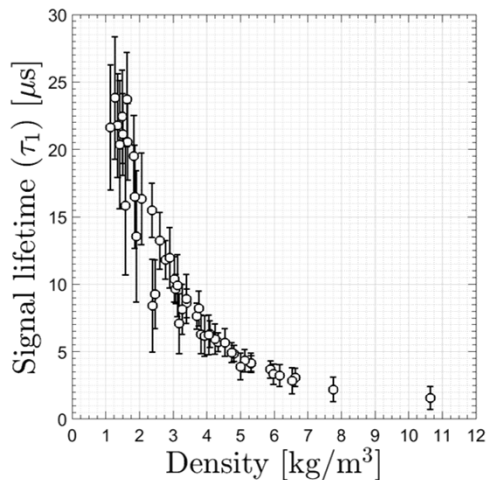
Room Temperature  
Measurements in  
0.3 meter cryo

(Reese et al, AIAA  
Aviation, 2018)

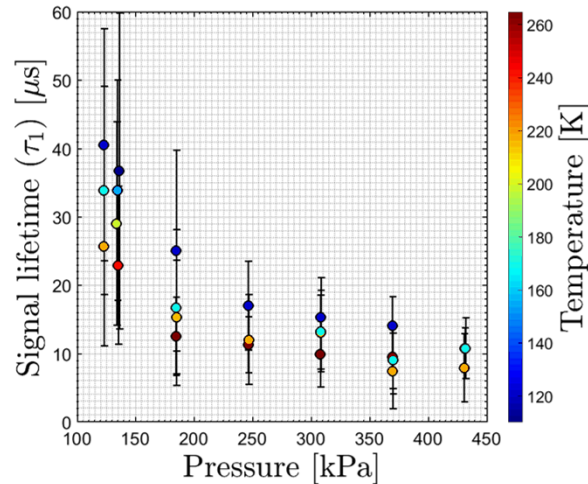
- STARFLEET Signal increases with pressure (for  $80 < P < 350$  kPa at 300K)

# Lifetime Assessment

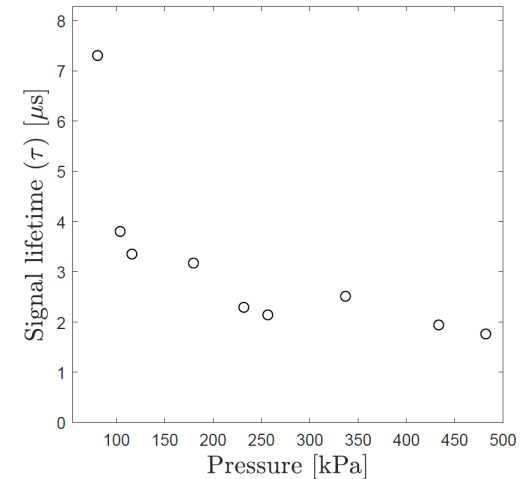
## FLEET



## PLEET



## STARFLEET

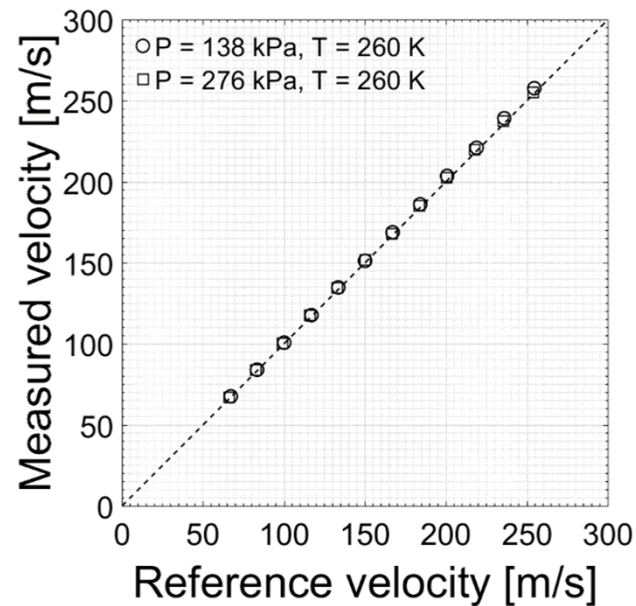


- Lifetime has implications for accuracy / precision
  - Could potentially use lifetime to measure something
- FLEET: strong inverse correlation with density
- PLEET: inverse correlations with both pressure and density
- STARFLEET: strong inverse correlation with pressure
- **Overall lifetimes: PLEET > FLEET > STARFLEET**

# Accuracy Assessment

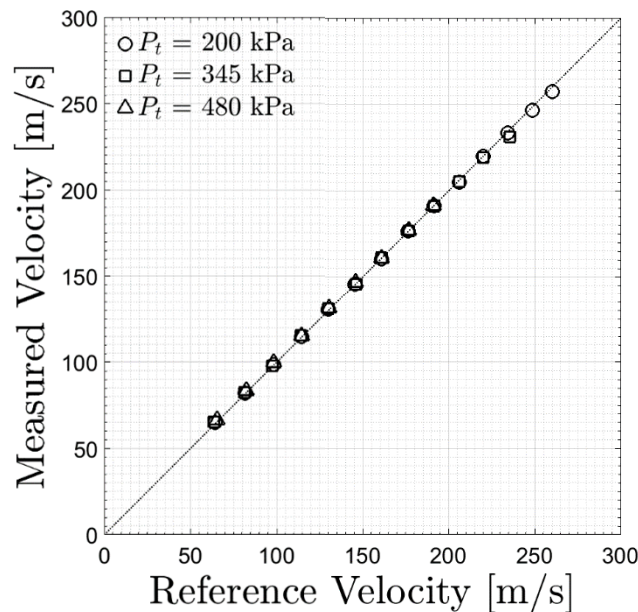
**Accuracy**  $\equiv$  how velocity differs from a known reference (facility data acquisition system)

## FLEET



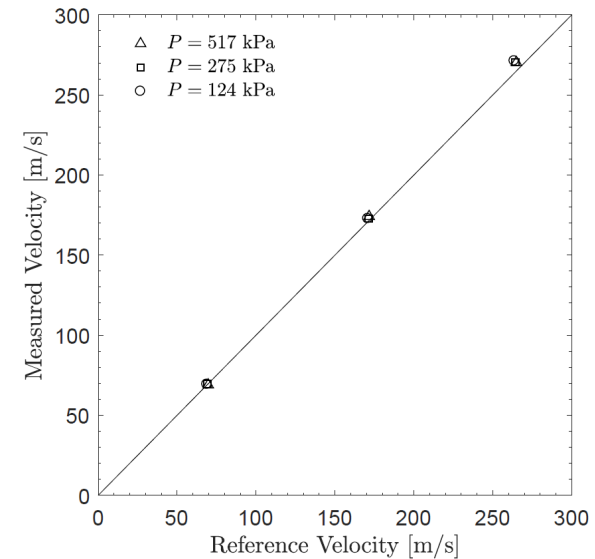
Accuracy : 0.5 to 1.5%

## PLEET



Accuracy : 0.6 to 1.2%

## STARFLEET



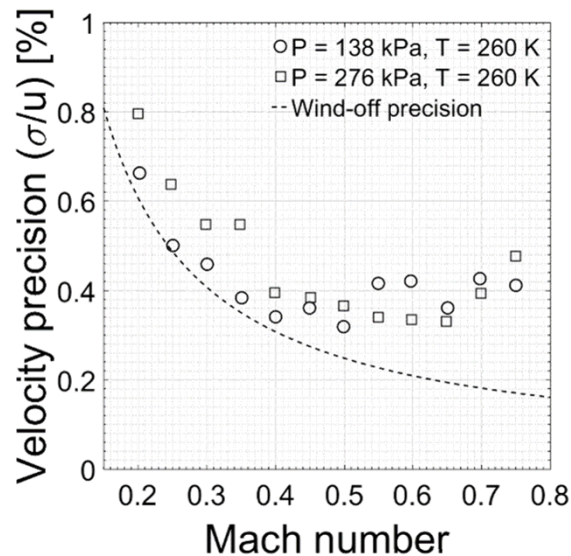
Accuracy : 1 to 2.9%

- Errors expected from calibration (magnification)

# Precision Assessment

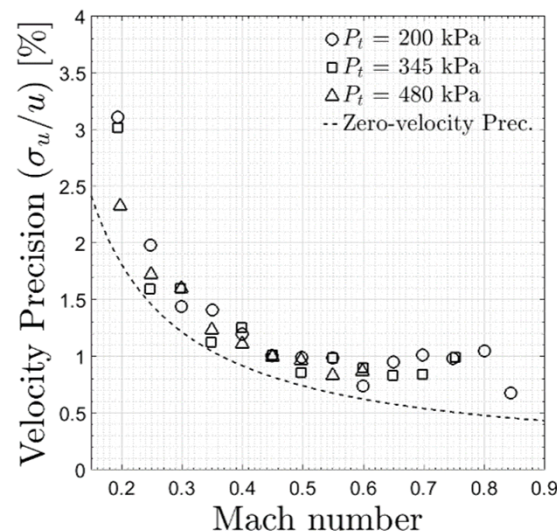
**Precision**  $\equiv$  1 standard deviation of an ensemble of measurements

## FLEET



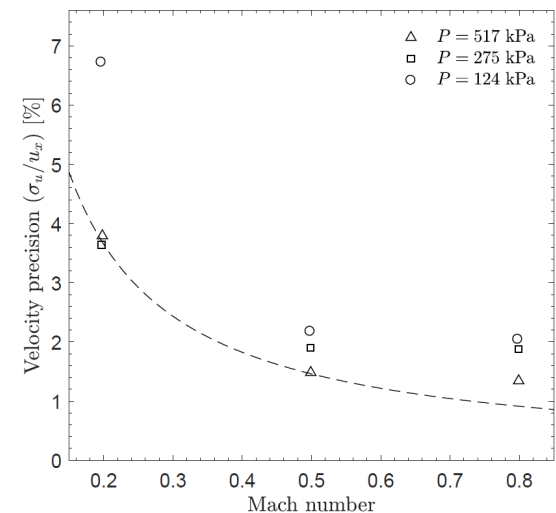
Precision as low as 0.4 m/s  
As good as 0.4% of V

## PLEET



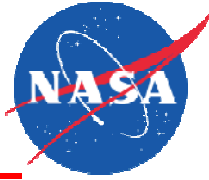
Precision as low as 1.2 m/s  
As good as 0.8% of V

## STARFLEET



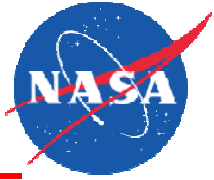
Precision as low as 3 m/s  
As good as 1.5% of V

- Dashed line is based on wind-off (zero velocity) precision
- At higher velocities may be resolving facility freestream fluctuations
- Precision Best- $\rightarrow$ Worst: FLEET  $\rightarrow$  PLEET  $\rightarrow$  STARFLEET



# Summary

| Criteria                                                                                                         | FLEET                    | PLEET                    | STARFLEET                   | Comment           |
|------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------|-----------------------------|-------------------|
| Laser pulse duration                                                                                             | 70 fs                    | 100 ps                   | 100 fs                      |                   |
| Laser repetition rate                                                                                            | 1 kHz                    | 10-100 kHz               | 1 kHz                       |                   |
| Excitation wavelength                                                                                            | 800 nm                   | 1064 nm                  | 202.25 nm                   |                   |
| Typical energy used /pulse                                                                                       | 0.5-2 mJ                 | 10-40 mJ                 | 10-30 uJ                    |                   |
| Temperature perturbation from energy deposition (DT) at STP using energy to generate comparable signal intensity | 230 K with 1.1 mJ        | 250 K with 10 mJ         | 10 K with 30 uJ             | Jiang et al, 2017 |
| Average Measurement Accuracy (error) in 0.3 TCT                                                                  | <1% of measured velocity | ~1% of measured velocity | ~2% of measured velocity    |                   |
| Zero-velocity measurement precision (1 s) in 0.3 TCT                                                             | 0.4 m/s                  | 1.2 m/s                  | 3 m/s                       |                   |
| Spatial resolution in as implemented in 0.3 m TCT                                                                | 3 mm, single point       | 3 mm, single point       | 3 mm, 5 points              |                   |
| Suitable test media                                                                                              | Nitrogen, Air, R134A     | Nitrogen                 | Nitrogen                    | Zhang et al, 2018 |
| Thermodynamic dependence of signal intensity for typical TCT conditions (100 < T < 300 K, 100 < P < 500 kPa)     | Intensity ~ $\rho$       | none                     | Intensity ~ P (for T=300 K) |                   |



# Conclusions

---

- Three different MTV techniques evaluated in the NASA Langley 0.3-m TCT facility
  - FLEET
  - PLEET
  - STARFLEET
- Viable single-shot images acquired over full operational envelope of this cryogenic transonic wind tunnel
  - Suitable for mean velocity and velocity statistics, though 3 mm spatial res.
  - Also can measure density with Rayleigh scattering (Burns and Danehy, 2018)
- Accuracies and precisions on the order of 1% of measured velocities
  - FLEET and PLEET appear to perform better than STARFLEET
  - STARFLEET susceptible to window/mirror losses resulting in low signals
- Which technique to use? Depends on the application.
- Currently implementing the FLEET technique in NASA Langley's NTF

# Questions?

---

