COE CST Tenth Annual Technical Meeting

Task 325: Optical Measurements of Rocket Nozzle Thrust and Noise

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FAA Technical Monitor: Nick Demidovich

Agenda

- Team Members
- Challenges and Motivation
- Task Description
- Test Facilities
- Nozzle Design & Instrumentation
- Measurements
- Schedule and Milestones
- Conclusions and Future Work

Team Members

Team

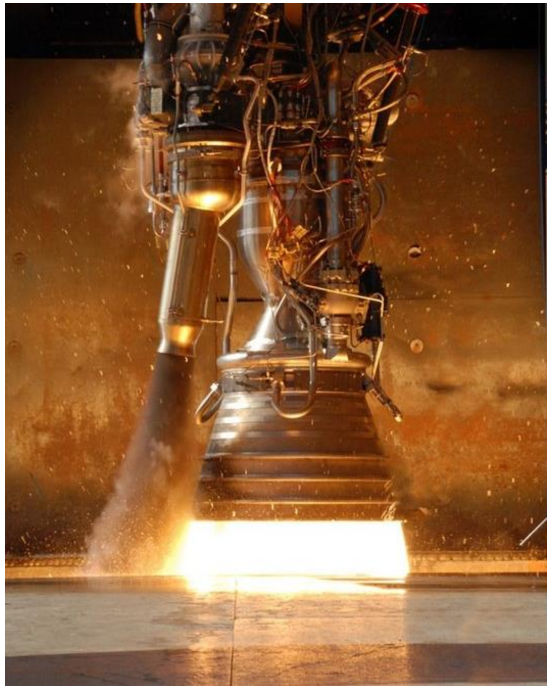
- Rajan Kumar & Farrukh Alvi
- Jonas Gustavsson, Michael Sheehan
  - Rohit Vemula, Nikhil Khobragade

  Samuel Lee, Timothy Willms, Vikas Bhargav, Yogesh Mehta (Post-doc)

Organizations Involved

- FSU / FCAAP
- Space Florida
- SpaceX

Challenges & Motivation



70% accidents in aerospace missions are due to engine malfunction or propulsion system failures!!

Rocket propulsion studies are limited (only National Labs. & big corporations)

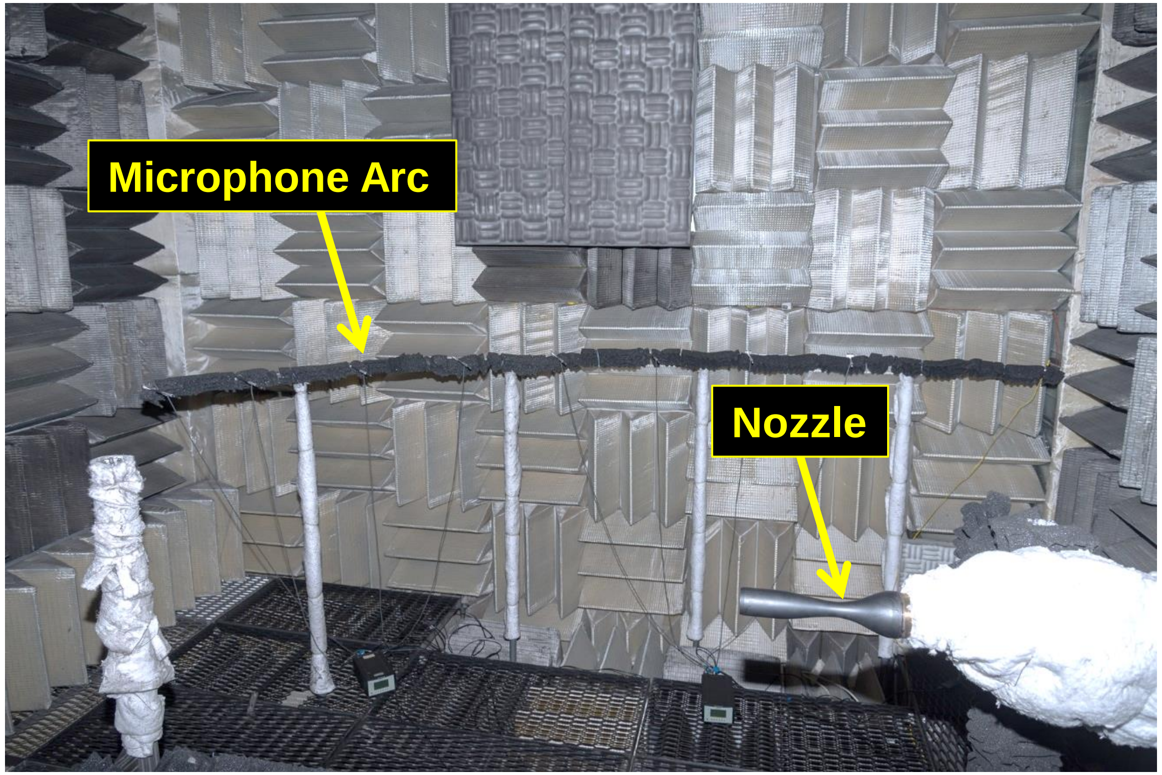
- High temperature and pressure environment
- Complex chemistry – unstable fuels
- Large scale tests are expensive & require specialized rigs

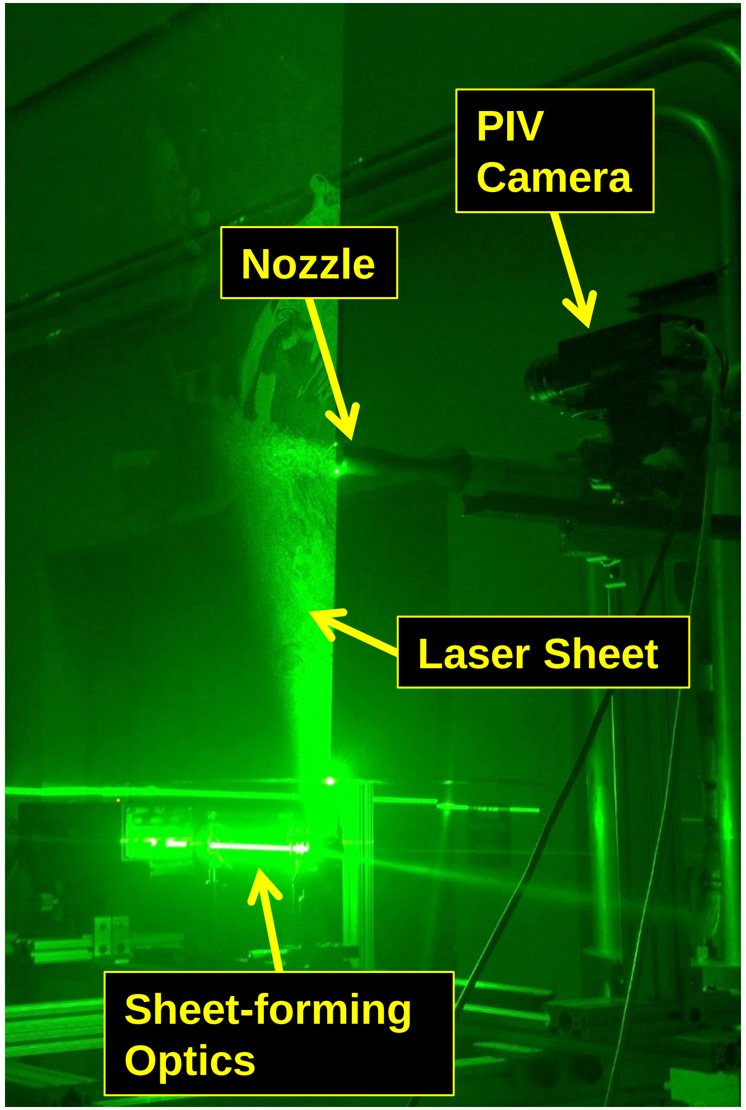
- Need to develop high temperature pressure sensors – activity initiated under COE-CST
- Measure steady and transient loading on the nozzle and ground surface – material characterization
- Jet plume development and flow field analysis
- Nearfield & farfield noise measurement and prediction tools
- Study of next generation hybrid fuels

Tasks Description

- Development of a research plan based on state-of-art thrust and noise measurement techniques.
- Discussion with NASA /commercial launch engineers to ensure the transition of technology from laboratory to full-scale implementation.
- Design of a scaled nozzle and simulate realistic temperature and pressure conditions of the jet exhaust in the FSU jet facility
- Design and develop advanced optical techniques for thrust measurements and characterize its performance at controlled conditions.
- Refine and test measurement techniques over a wide range of test conditions.
- Optical measurement of thrust using PIV and pressure distribution at the nozzle exhaust. The measured thrust using optical method compared to thrust measurement using load cell thrust stand.
- Noise measurements in the FSU hot jet anechoic facility over a range of nozzle pressure conditions.
- Flow control system implemented and tested over a wide range of test conditions.
- Simulate take-off and landing conditions of a rocket engine as impinging jet on a launch/landing surface.

Test Facilities

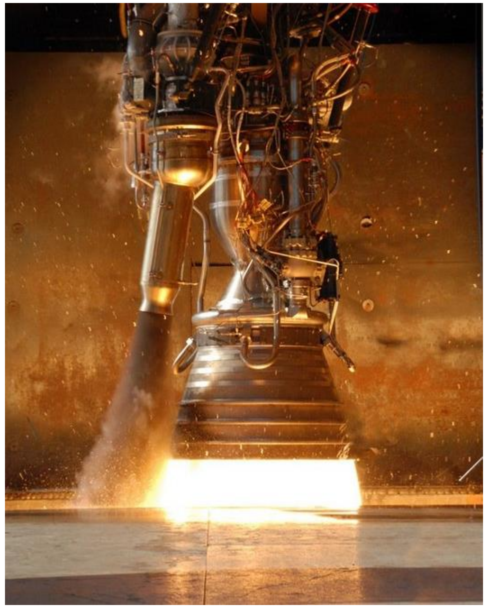




Operational/Test Capabilities

- *Mach Number = 0.5 - 2.5*
- T_o *= 70 - 2000 F*
- D_{Jet} *= 25.4 – 76.2 mm*
- *NPR = Under-ideal-over expanded*
- *Anechoic chamber: 5.8 m x 5.2 m x 4.0 m, Calibrated to 100 Hz*

Thrust Measurements

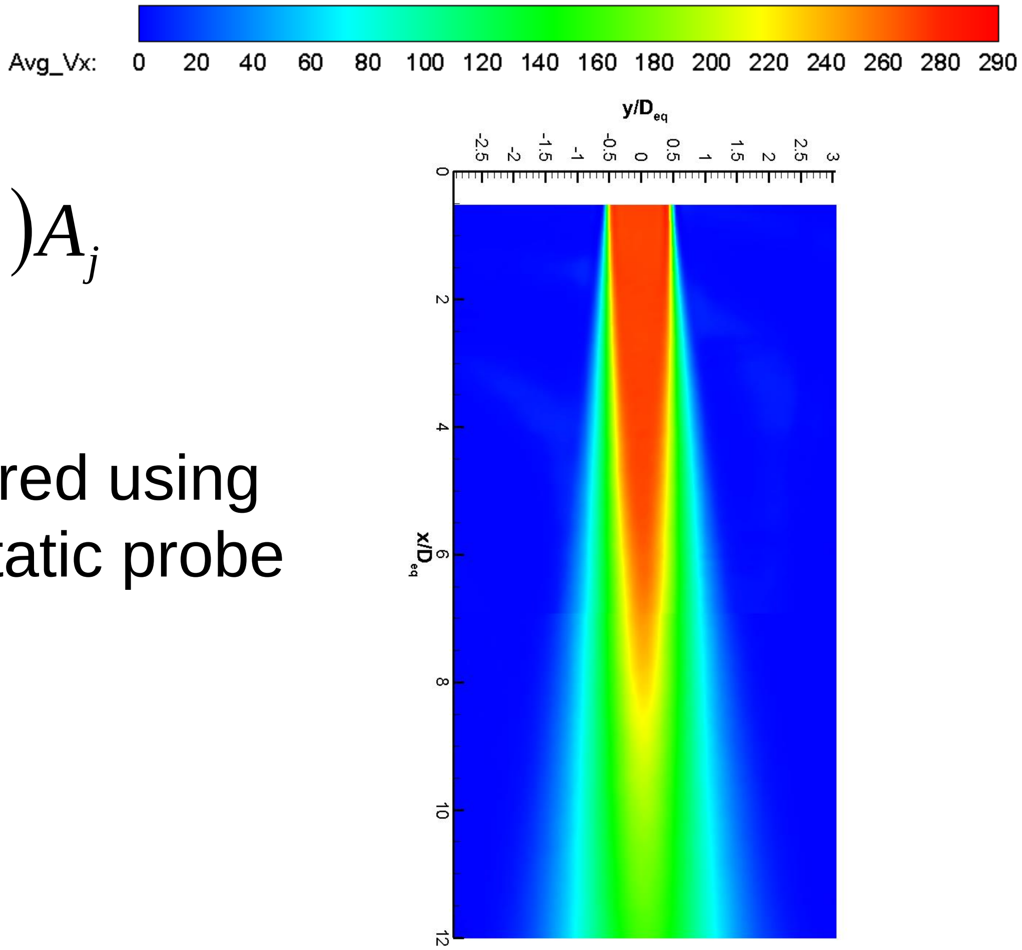


$$F = F_m + F_p$$

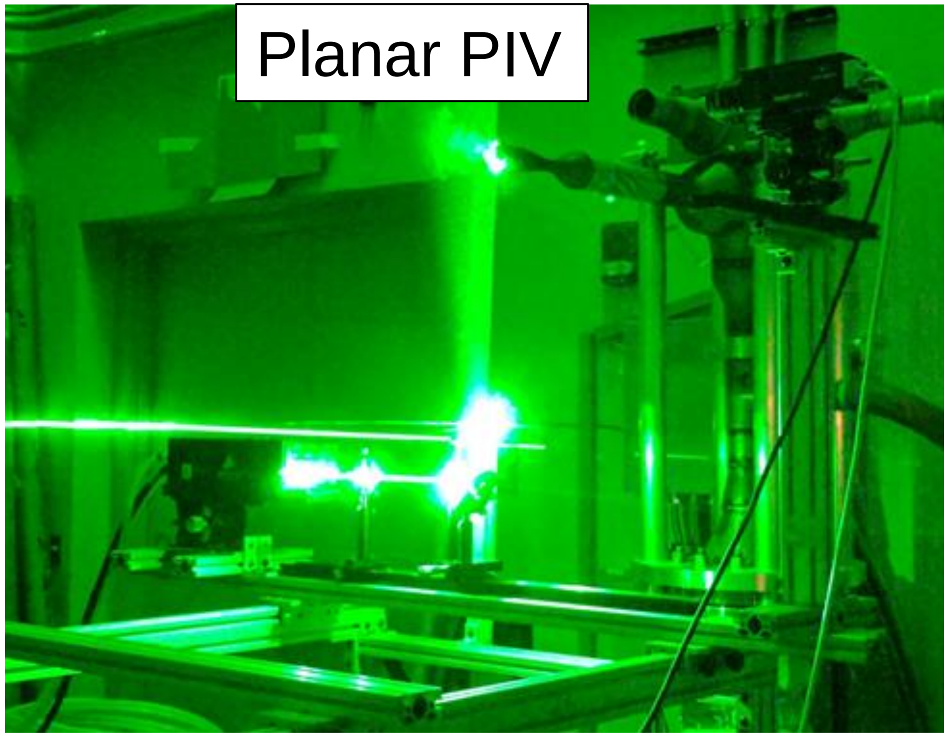
$$F = \dot{m}u_j + (p_e - p_a)A_j$$

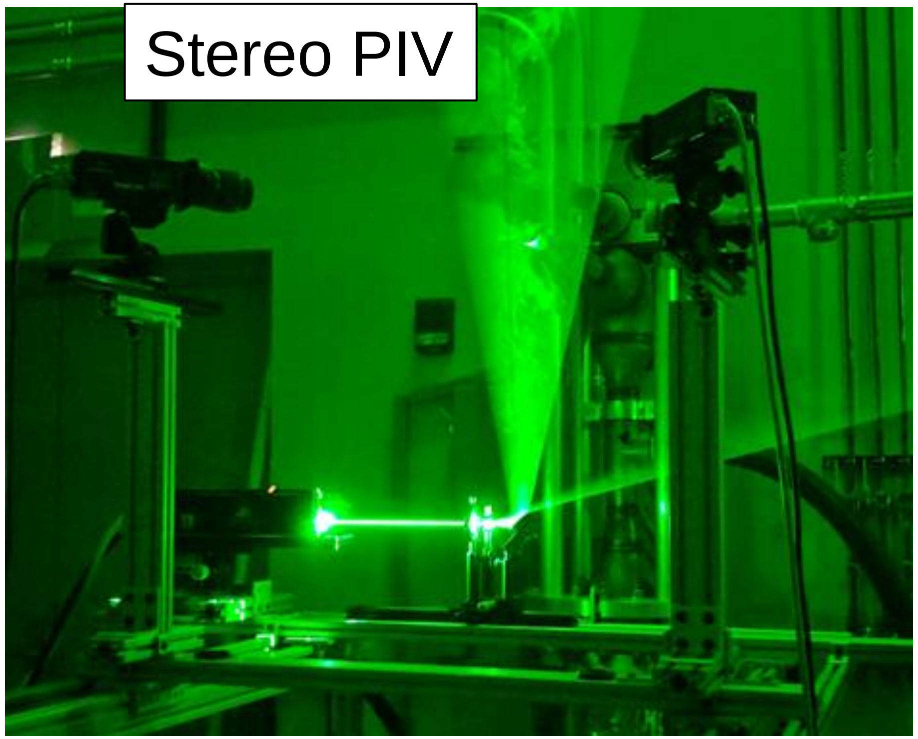
Measured using PIV

Measured using Pitot-static probe



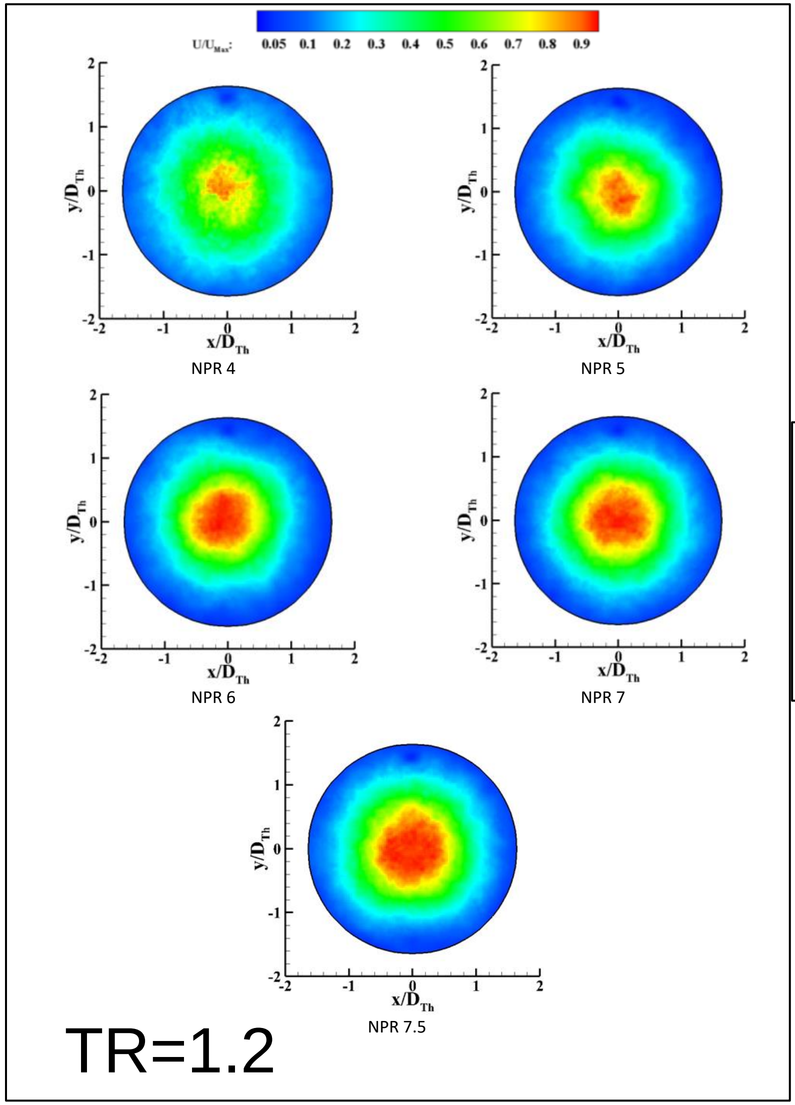
Particle Image Velocimetry



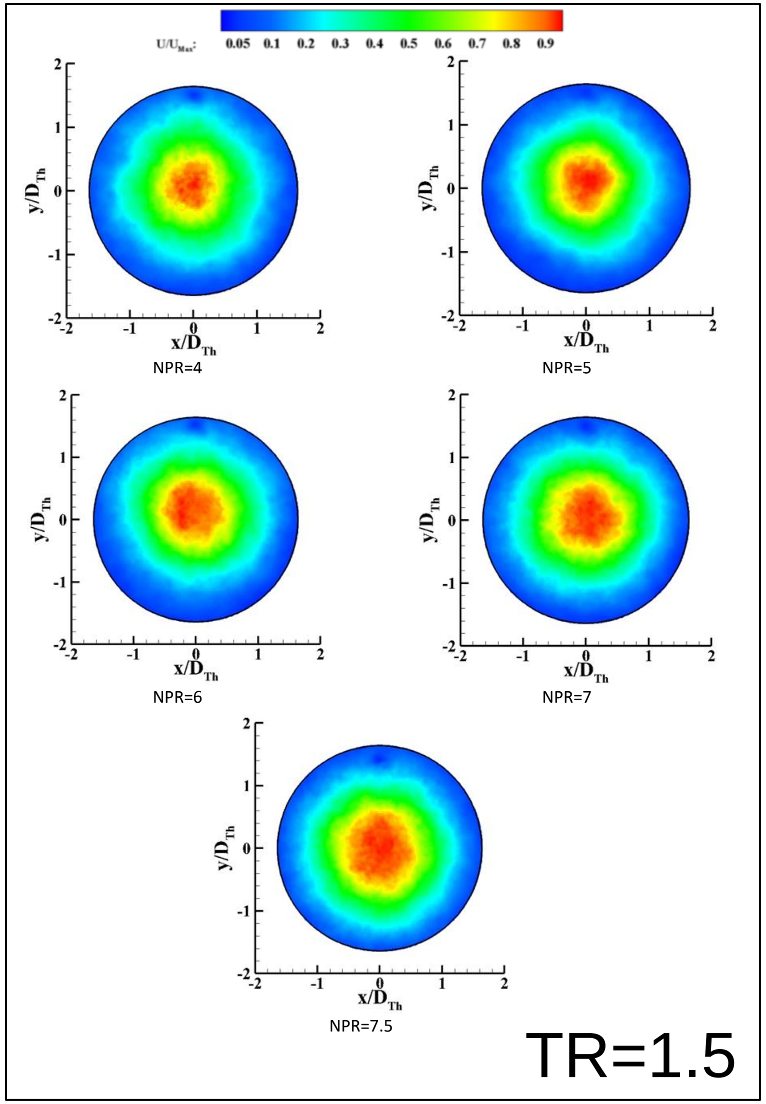


Planar: Downstream development of plume
Stereo: Velocity distribution over exit plane

Mean Velocity Field – NPR/TR

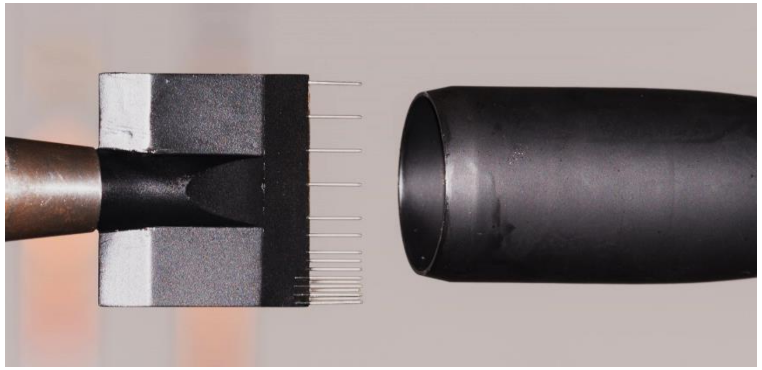


Velocities increase with TR and NPR. Overall shapes have some varying unsteadiness with NPR.



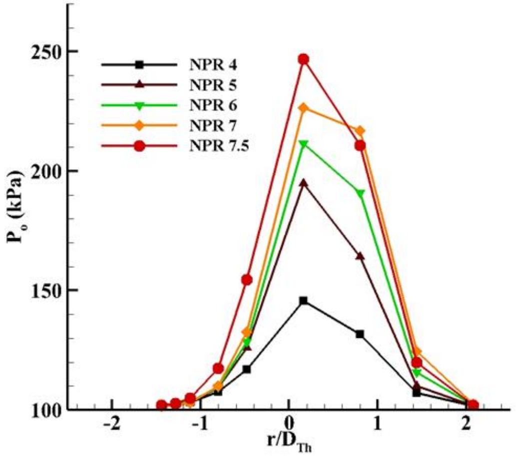
Pressure Rake Measurements

To capture density and static pressure needed for calculation of thrust from flowfield measurements, PIV measurements were complemented with pressure rake measurements of stagnation pressures at the nozzle exit.

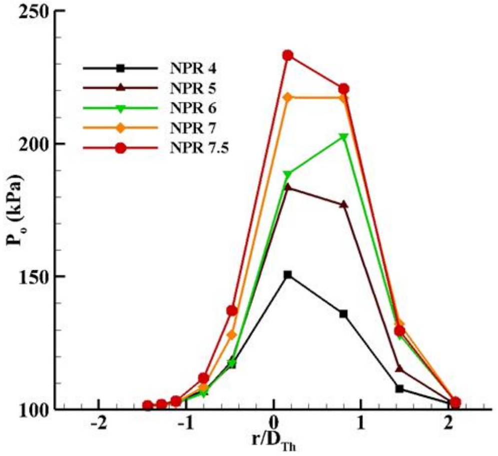


Boundary layer rake with 16 ports connected to ESP scanner 30 psid

Vertical (0°) profiles shown



TR=1.2

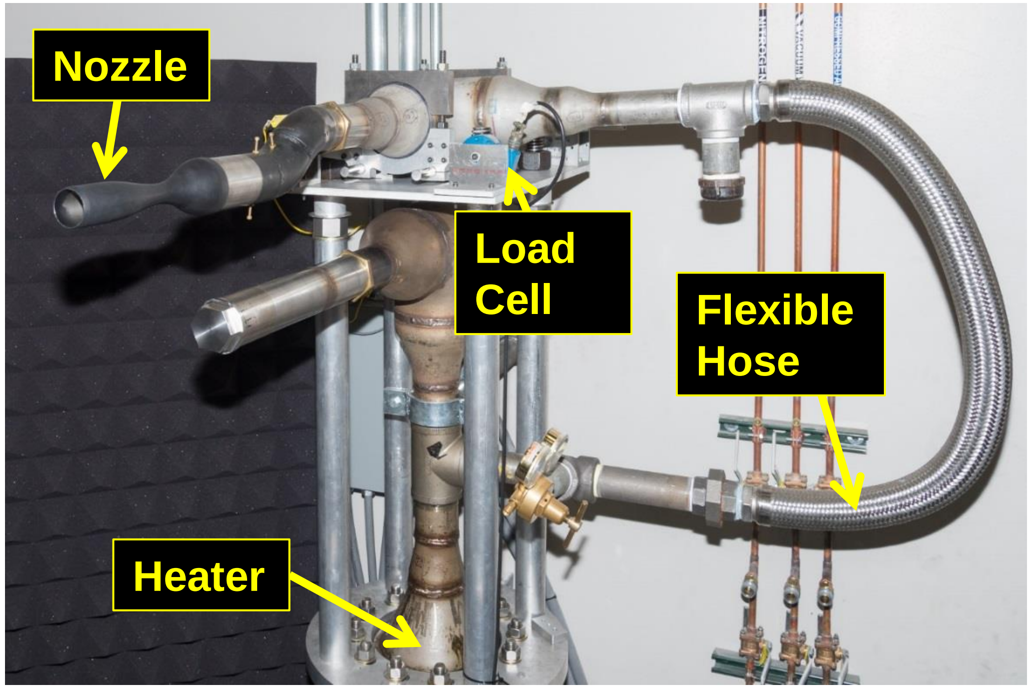


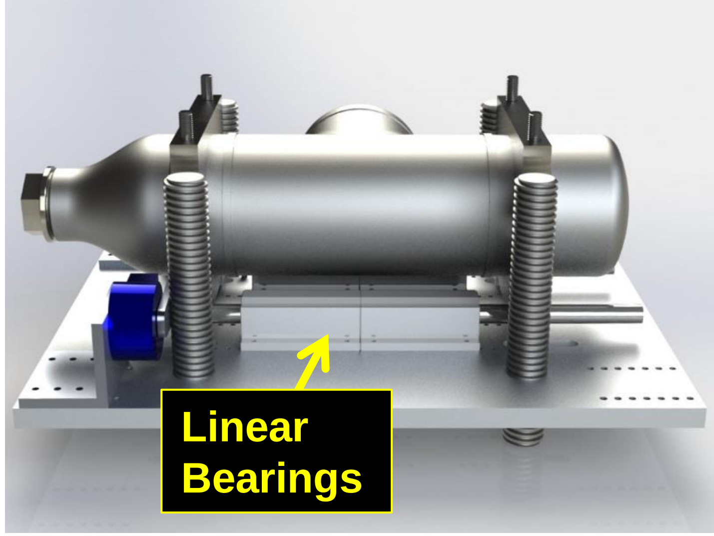
TR=1.5

Rake was rotated to 0, 45, 90, 135° azimuthal orientation. Axisymmetry verified, but radial resolution low – need dedicated rake and traverse.

Thrust Measurements

A thrust measurement system was designed that allowed the nozzle stagnation chamber to traverse axially on linear bearings. Heated air was supplied from the side through a flexible hose, allowing all axial loads to be captured by the load cell.





Design by William McCormack

Thrust Calculation

The PIV and pressure rake measurements are combined with stagnation pressure and temperature from the stagnation chamber to calculate the thrust.

Thrust equation: $F = \dot{m}u + (P - P_a)A$

Rewriting using P_0 & M:

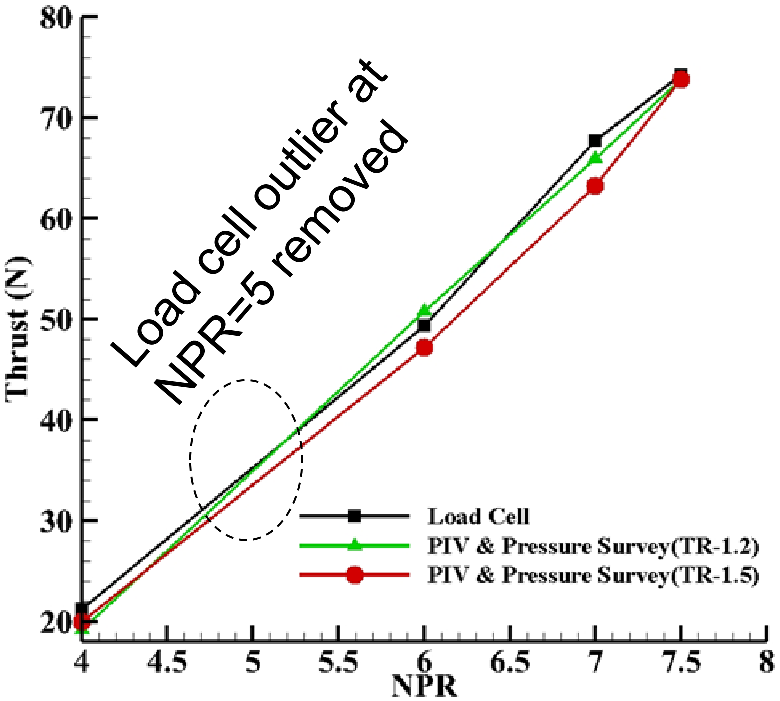
$$F = \iint_A \frac{P_0}{\left(1 + \left(\frac{\gamma - 1}{2}\right) M^2\right)^{\frac{\gamma}{\gamma - 1}}} (\gamma M^2 + 1)\ dA - P_a A$$

Pressure rake (P_0); Ambient (P_a)

Mach number is obtained from:

$$M^2\left(1 - \left(\frac{\gamma - 1}{2}\right)\frac{u^2}{\gamma R T_o}\right) = \frac{u^2}{\gamma R T_o}$$

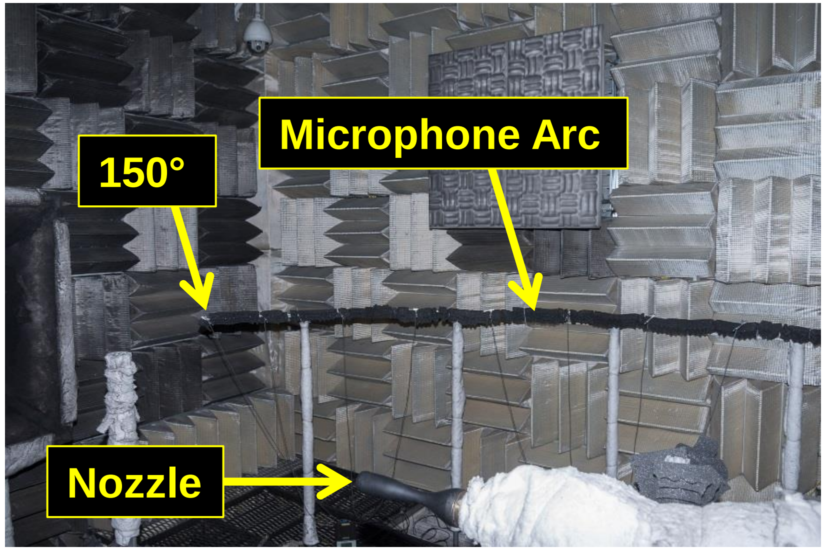
PIV (u^2); Stag. Ch. (T_o)

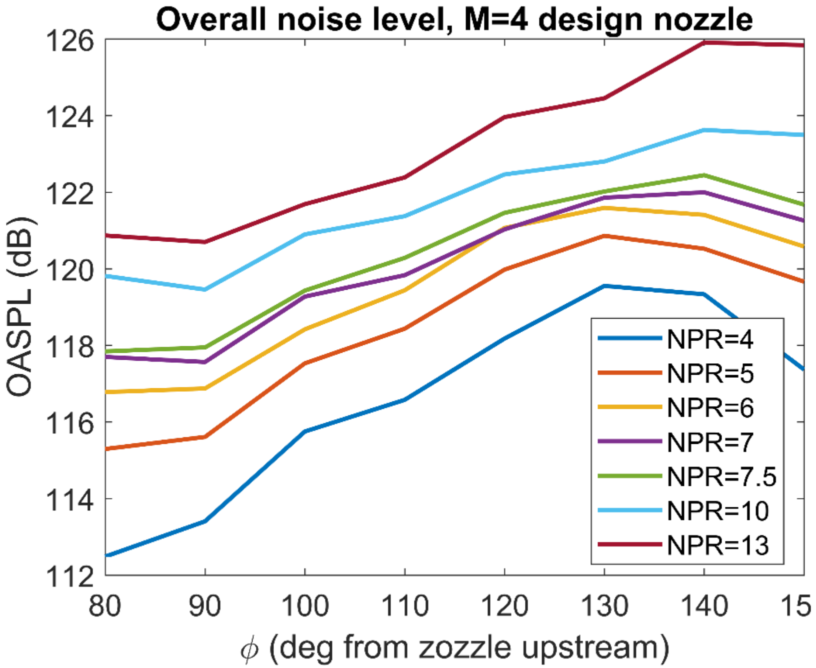


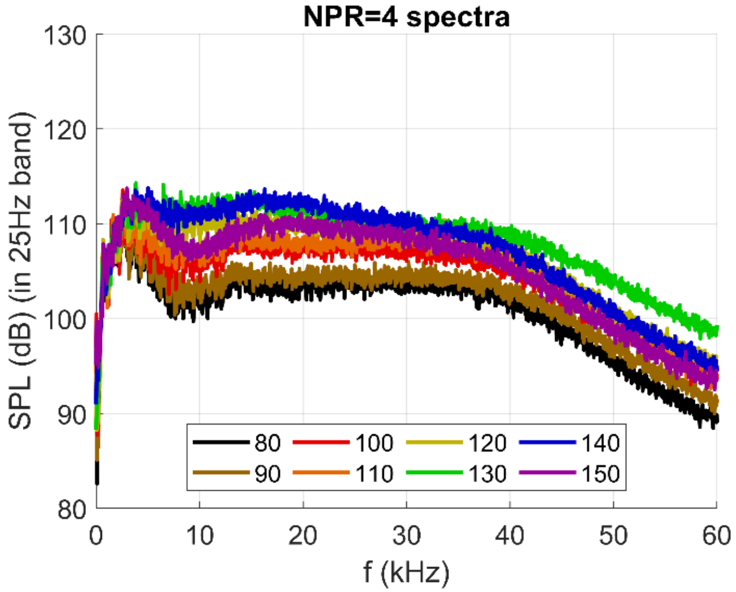
- Thrust increases linearly with NPR
- Excellent agreement indirect-direct thrust measurement

Noise Measurements

Noise measured for an isothermal jet (TR=1.0) at a wide range of NPR (4-13) in the FSU/FCAAP HotJet facility's anechoic chamber. Microphones were placed on an arc 200D* from the nozzle exit at 80-150 degrees from the nozzle upstream axial direction.





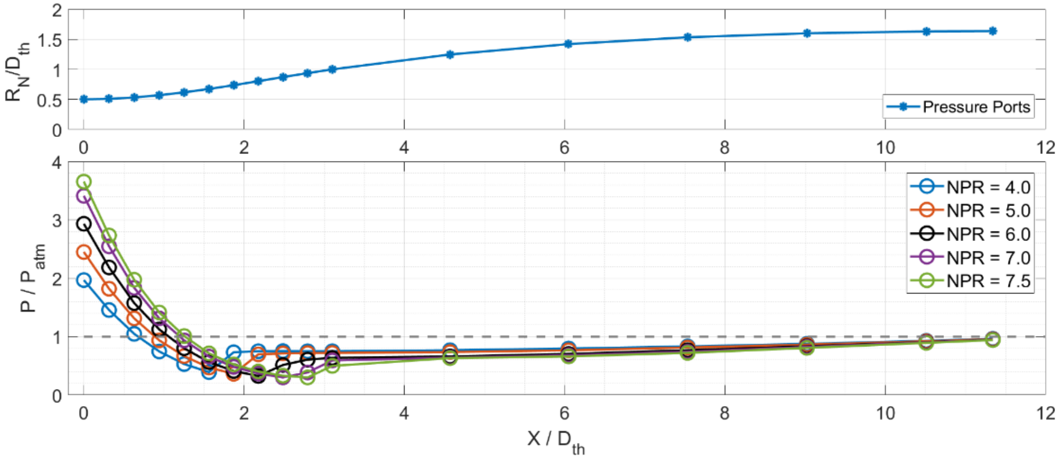


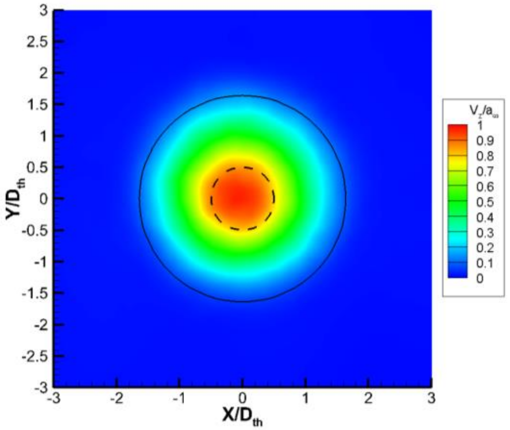
OASPL increases with NPR and has a maximum at 130-140°

- Low-frequency hump near 3 kHz strong at large angles and high NPR

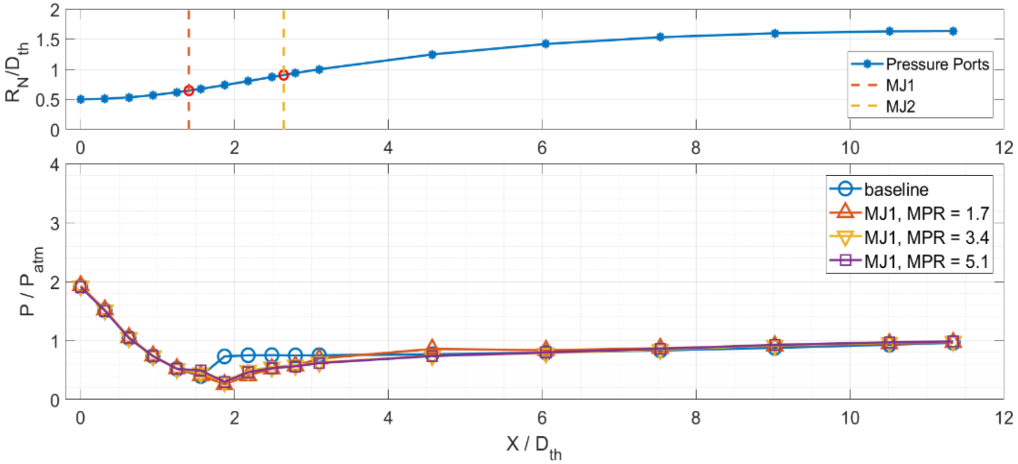
Pressure Measurements Inside Nozzle

Rocket nozzle with pressure taps and a sketch of a cross-section indicating locations of pressure ports and microjet arrays



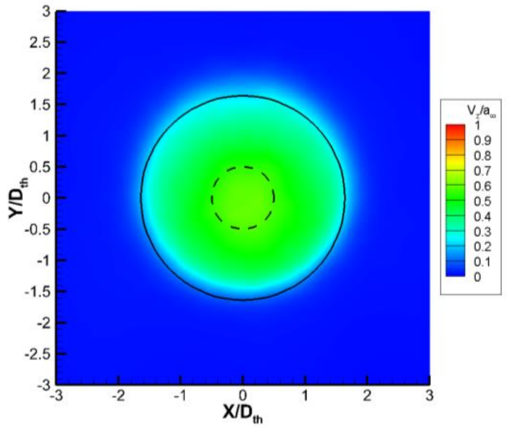


Baseline jet

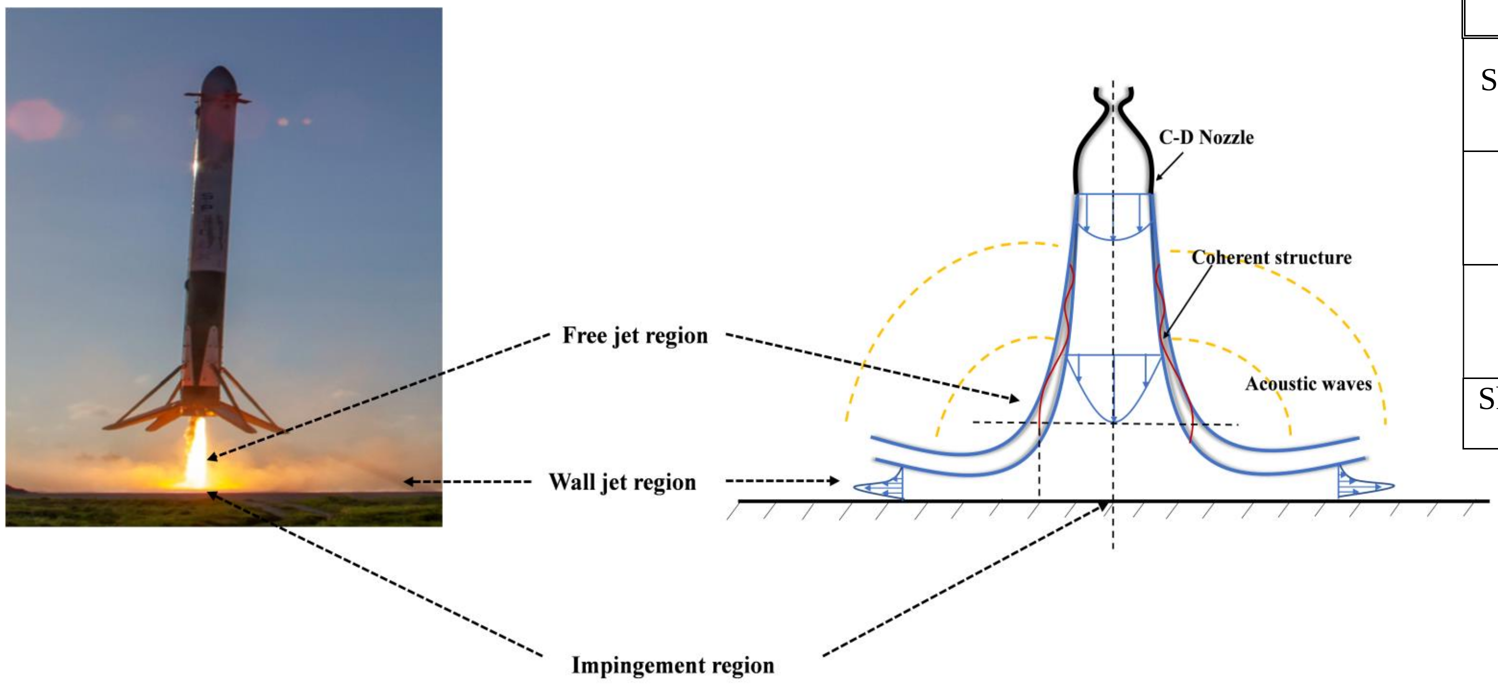


- **Delay in flow separation with microjet control.**
- **Reduction in core velocity, increase in jet diameter and better stability of the jet plume with microjet control**

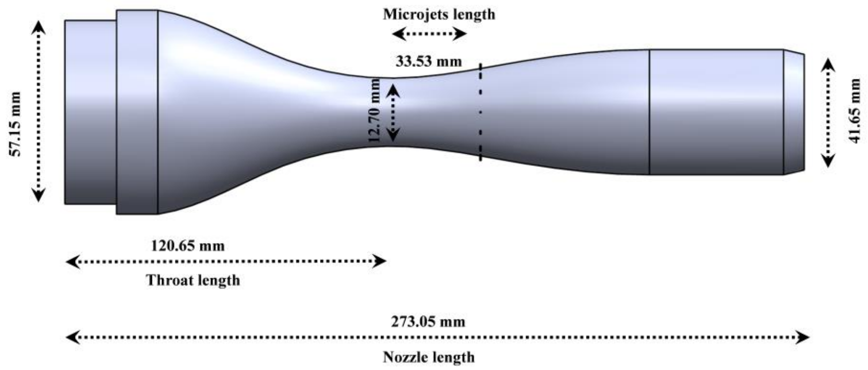
With microjet control



Characterization and Control of an Impinging Jet Issued from a Rocket Nozzle

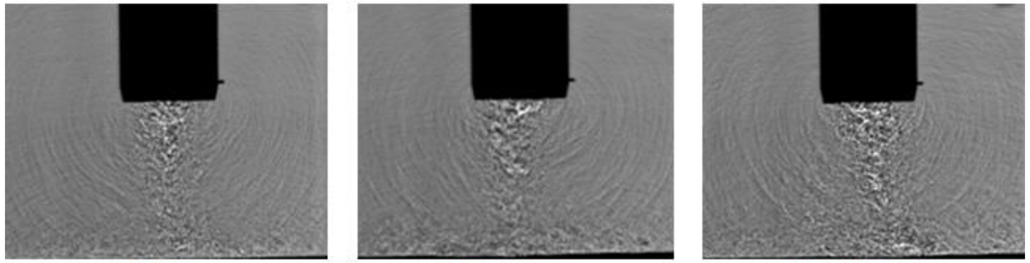


Measurement	TR	NPR	h/d_t	Measurement location
Static pressure	1	4, 5, 6	2, 3, 4, 5, 6, 8, 10, 12	Ground plane R/d_t = 0 to 7.5
Unsteady pressure				Ground plane R/d_t = 0 to 4.25
Nearfield acoustics				Microphone R = $30d_t$
Shadowgraphy				-



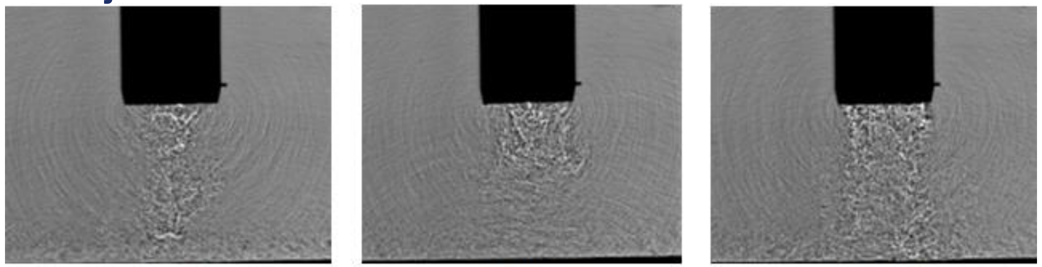
Impinging Jet Results

Baseline jet

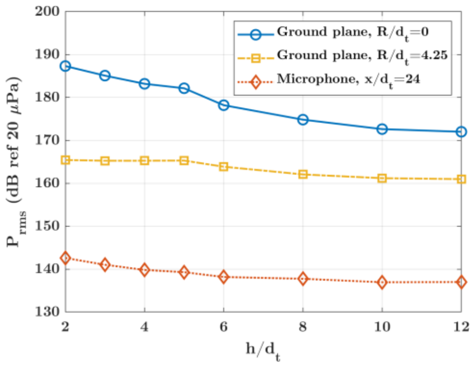


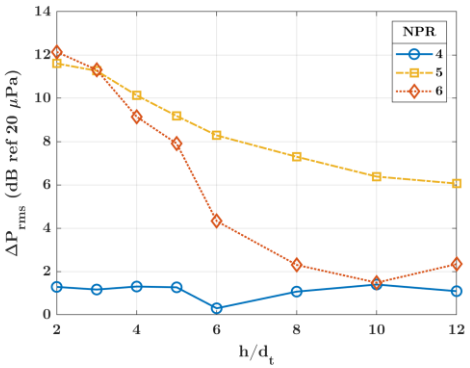
(a) NPR = 4 (b) NPR = 5 (c) NPR = 6

Microjet Control

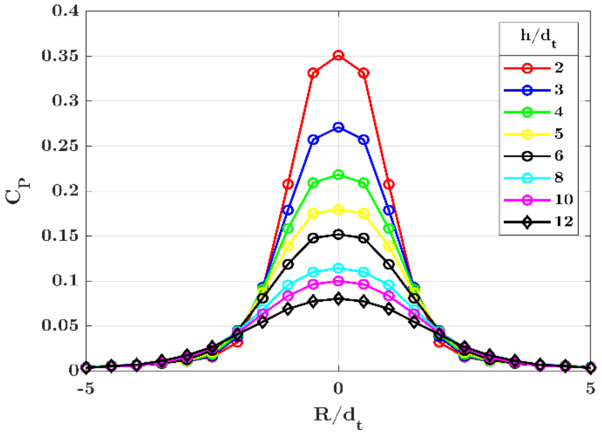


(a) NPR = 4 (b) NPR = 5 (c) NPR = 6

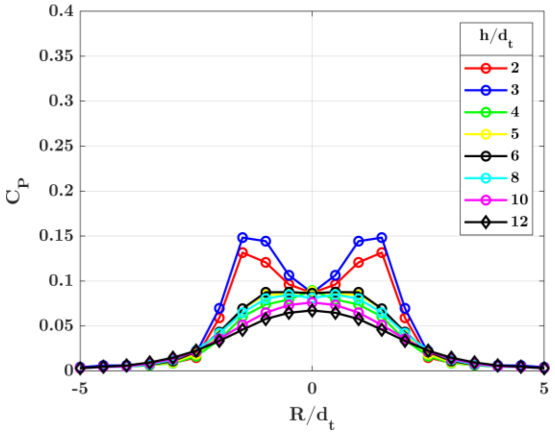


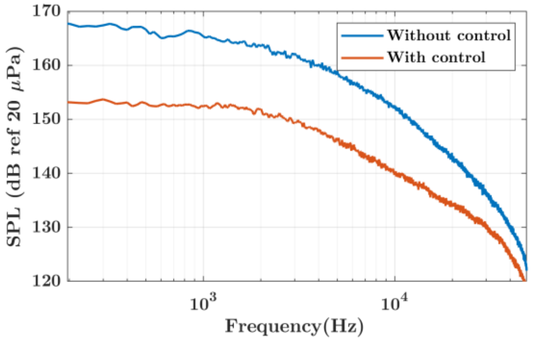


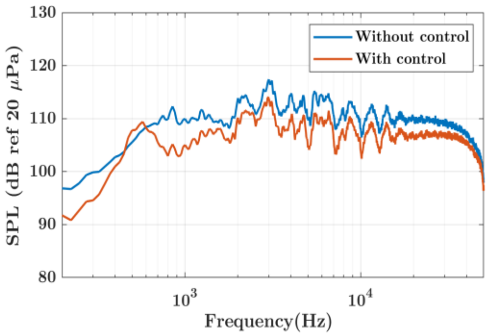
Baseline jet



Microjet Control



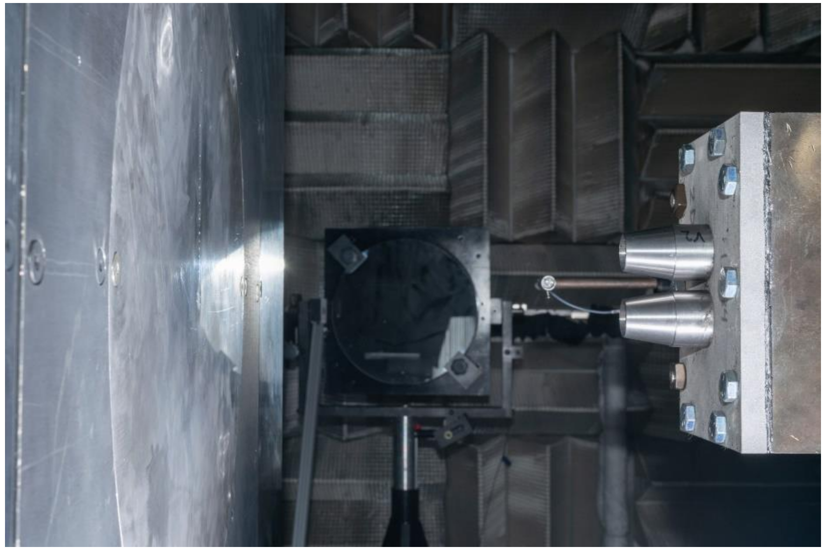




1) **Microjet flow control alters the global flow field thereby reducing both the pressure fluctuations on the ground and acoustics in the nearfield region.**
2) **Effectiveness of control is sensitive to the position of microjets to the flow separation location inside the nozzle, suggests that if the flow separation location of a rocket nozzle operating at a certain condition is known a priori, one can tailor the position of microjet flow control for maximum effectiveness.**

Conclusions and Future Work

- Conclusions
  - Method of measuring thrust indirectly using flowfield data has been validated against load cells.
  - Microjet based flow control implemented. The surface static pressure distributions are modified and flow separation is significantly delayed with the implementation of microjet based flow control.
  - Measured noise in the FSU hot jet anechoic facility over a range of nozzle pressure conditions
  - Simulated rocket take-off and landing condition as impinging jet and measured loading on the surface
- Future Work
  - Conduct velocity field measurements for impinging jet using PIV
  - Measure acoustic and unsteady loading for twin impinging jets.
  - Design and develop microjet based flow control method.
  - We will develop scaling laws and perform system integration studies for large scale implementation at SpaceX /NASA facilities



Schedule and Milestones

Task	3/20	5/20	7/20	9/20	11/20	1/21	3/21	5/21	7/21	9/21	11/21	
Single Impinging Jet Experiments												
Twin Impinging Jet Experiments												
Impinging Jet velocity measurements												
Side load measurements												
Develop scaling laws												

Publications, Presentations, Awards, & Recognitions

PUBLICATIONS

1. Mehta, Y., Bhargav, V. N., and Kumer, R. (2020) Experimental Characterization and Control of an Impinging jet Issued from a Rocket Nozzle. Submitted to *New Space Journal*.
2. Khobragade, N., Wylie, J., Gustavsson, J. & Kumar, R. (2019) Control of Flow Separation in a Rocket Nozzle Using Microjets. *New Space Journal*, Vol. 7, No. 1, pp31-42, doi: 10.1089/space.2018.0037
3. Vemula, R. C., Gustavsson, J. & Kumar, R. (2018) Rocket Nozzle Thrust and Flowfield Measurements using Particle Image Velocimetry. *New Space Journal*, Vol. 6, No. 1, 37- 47, doi: 10.1089/space.2017.0045.
4. Daniel L. Bradley, Alexander M. Sharp, and Rajan Kumar (2018) "Student-Designed Liquid Rocket Engine From Concept to Completion", 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4865) https://doi.org/10.2514/6.2018-4865
5. Vemula, R. C., Valentich, G. & Kumar, R. (2017) Flow Field Characteristics of Non-Axisymmetric Jets at High Temperatures, AIAA SciTech, 55th AIAA Aerospace Sciences Meeting, 9-13 January 2017, Grapevine, Texas, AIAA 2017-1888
6. Vemula, R. and Kumar, R. (2016) Measurement of Rocket Nozzle Thrust and Noise. 2016 National Space & Missile Materials Symposium (NSMMS) & Commercial and Government Responsive Access to Space Technology Exchange (CRASTE), Westminster, CO, June 20-23, 2016