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Adaptive Aerostructures for Revolutionary Civil Supersonic Transportation

2018 Technical Interchange (AIAA Aviation)

Dimitris C. Lagoudas, Texas A&M University

ATA ENGINEERING, INC. BOEING FIU FORT WAYNE METALS UH Princeton University A&M UNT UtahStateUniversity

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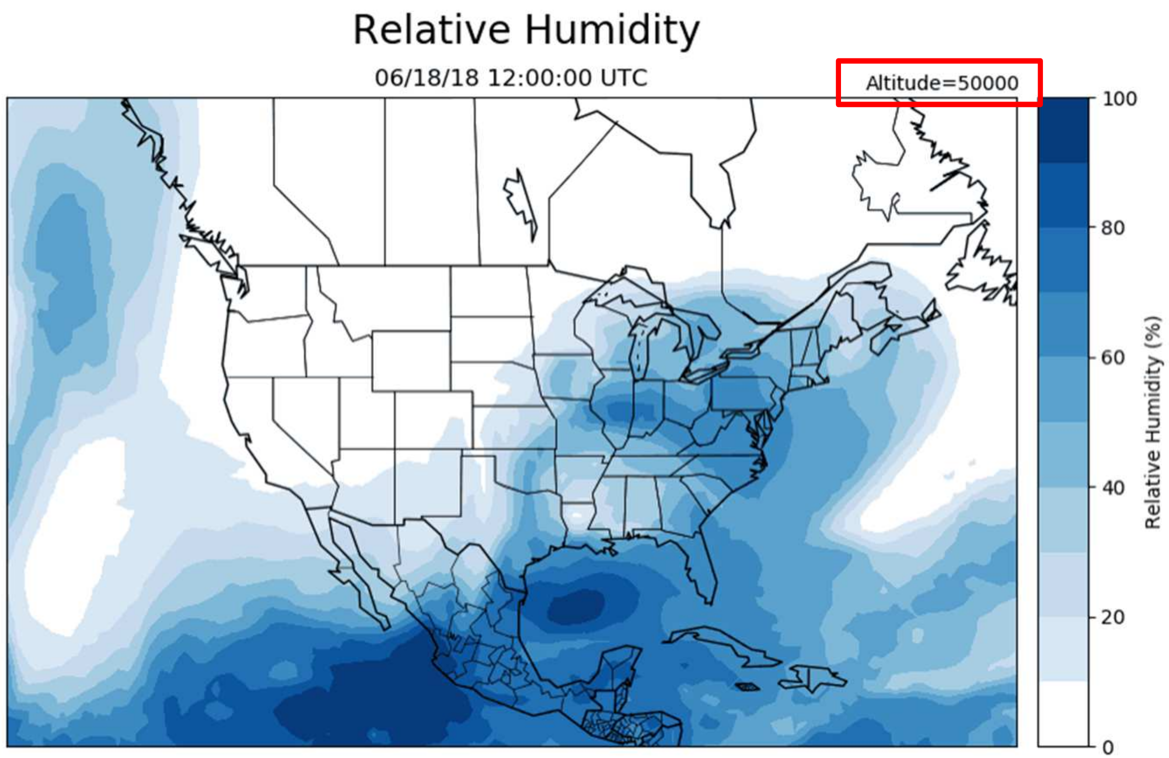
The Engineering Problem

- Propagation of sonic boom is strongly dependent on temperature, wind conditions, and *especially humidity* throughout the atmosphere

- These conditions vary drastically throughout the country and throughout the day



The Engineering Problem (Cont.)

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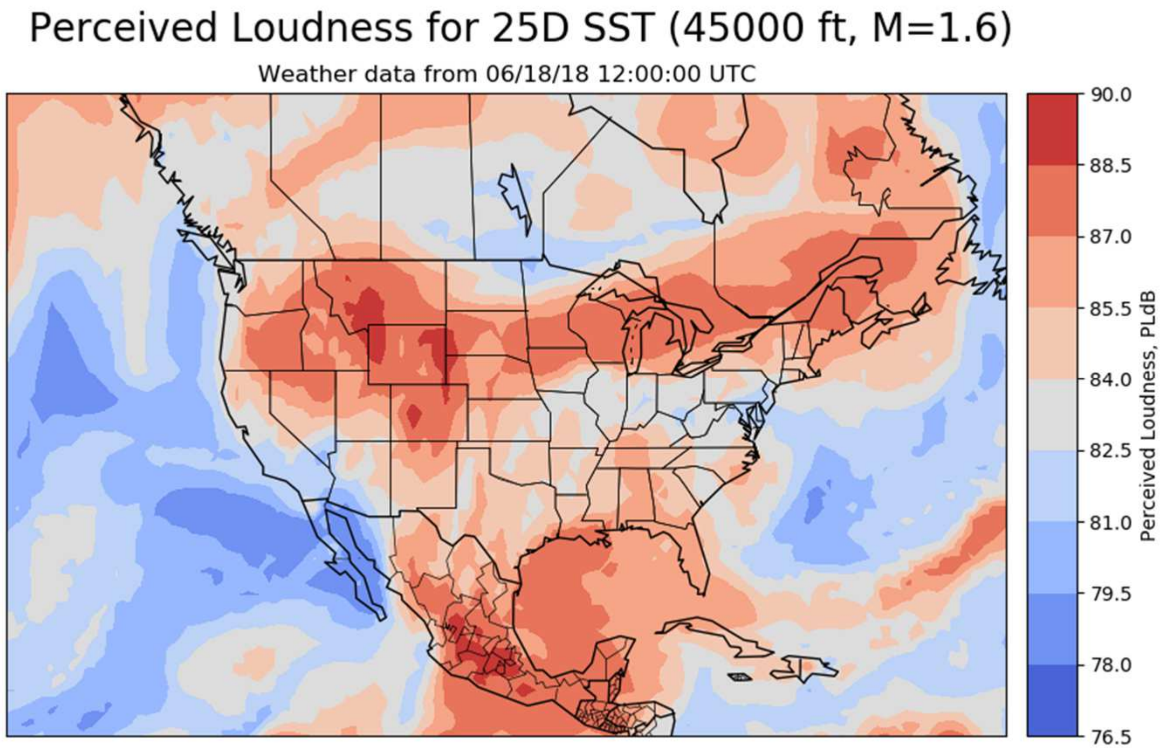
- Propagating identical near-field pressure signatures across the US resulted in wide range of PLdB values
  - ≈ 10 PLdB variation
- Low-boom supersonic aircraft must be able to adjust to these changing conditions



This is a complex multi-disciplinary engineering challenge

Adaptive Aerostructures for Revolutionary Civil Supersonic Transportation

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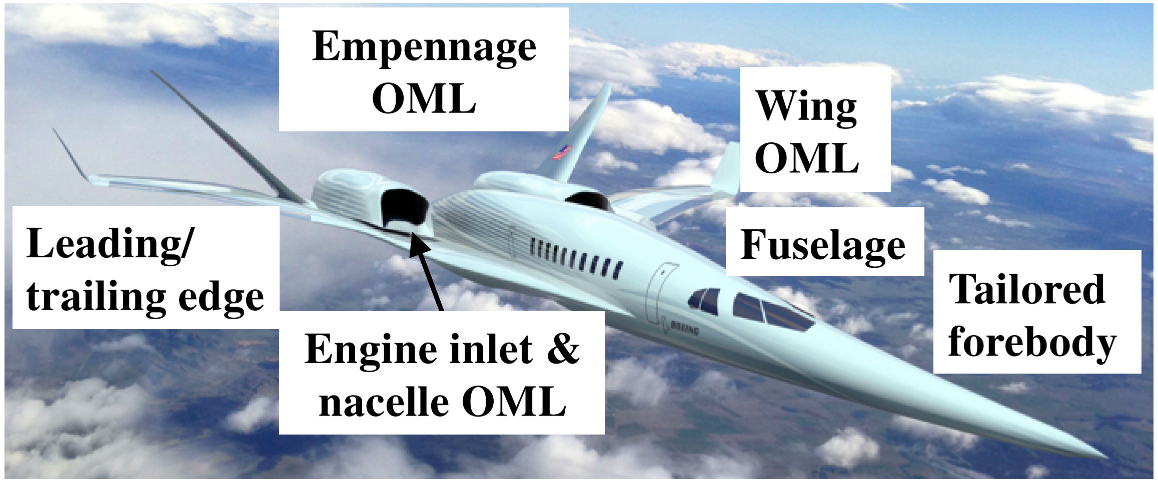
- To address the complex challenge of reliable/robust low-boom flight over land
  - Sense conditions between the aircraft and the ground (understand real-time atmospheric conditions)
  - Make small, distributed OML geometry adjustments to reduce boom for all flight conditions



Technical Approach

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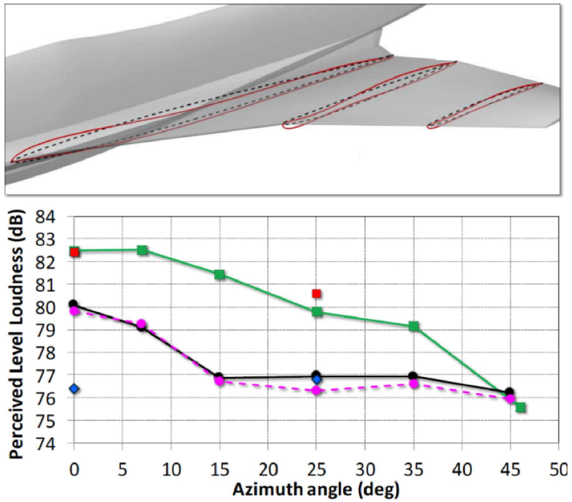
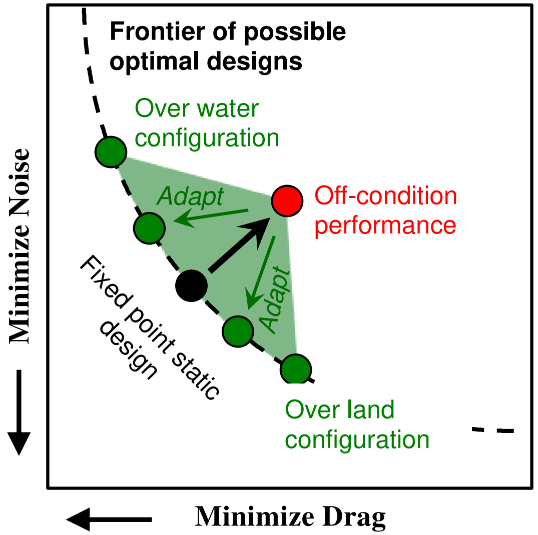


NASA research shows that small changes in local aircraft shape can significantly reduce *perceived loudness* of a sonic boom as flight conditions change

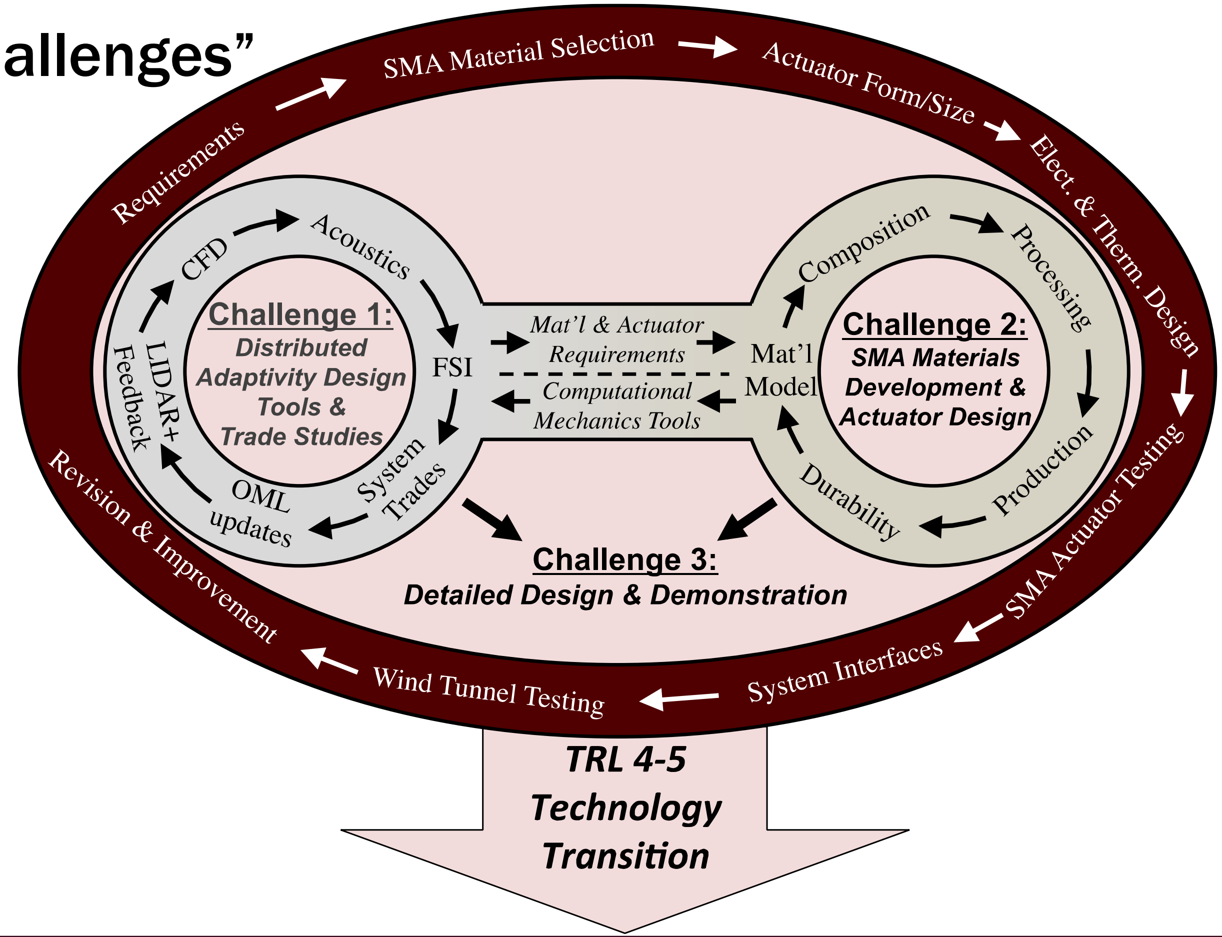


We will take advantage of these past findings to design and test *materials*, *actuators*, and the required *structural shape reconfigurations* to tune the aircraft throughout flight

Over the course of the next five years, our team will:

- **Demonstrate a 5dB reduction in perceived level loudness via outer mold line reconfiguration**
- **Prove that the new solid state material actuators enabling the structural reconfiguration are robust to 100k cycles**
- **Show that the fully coupled aero-thermo-mechanical modeling tools developed can be used to design a boom reduction solution to within 5% error**

Coupling of Three "Challenges"



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Multi-Disciplinary Expertise to Address the Challenge

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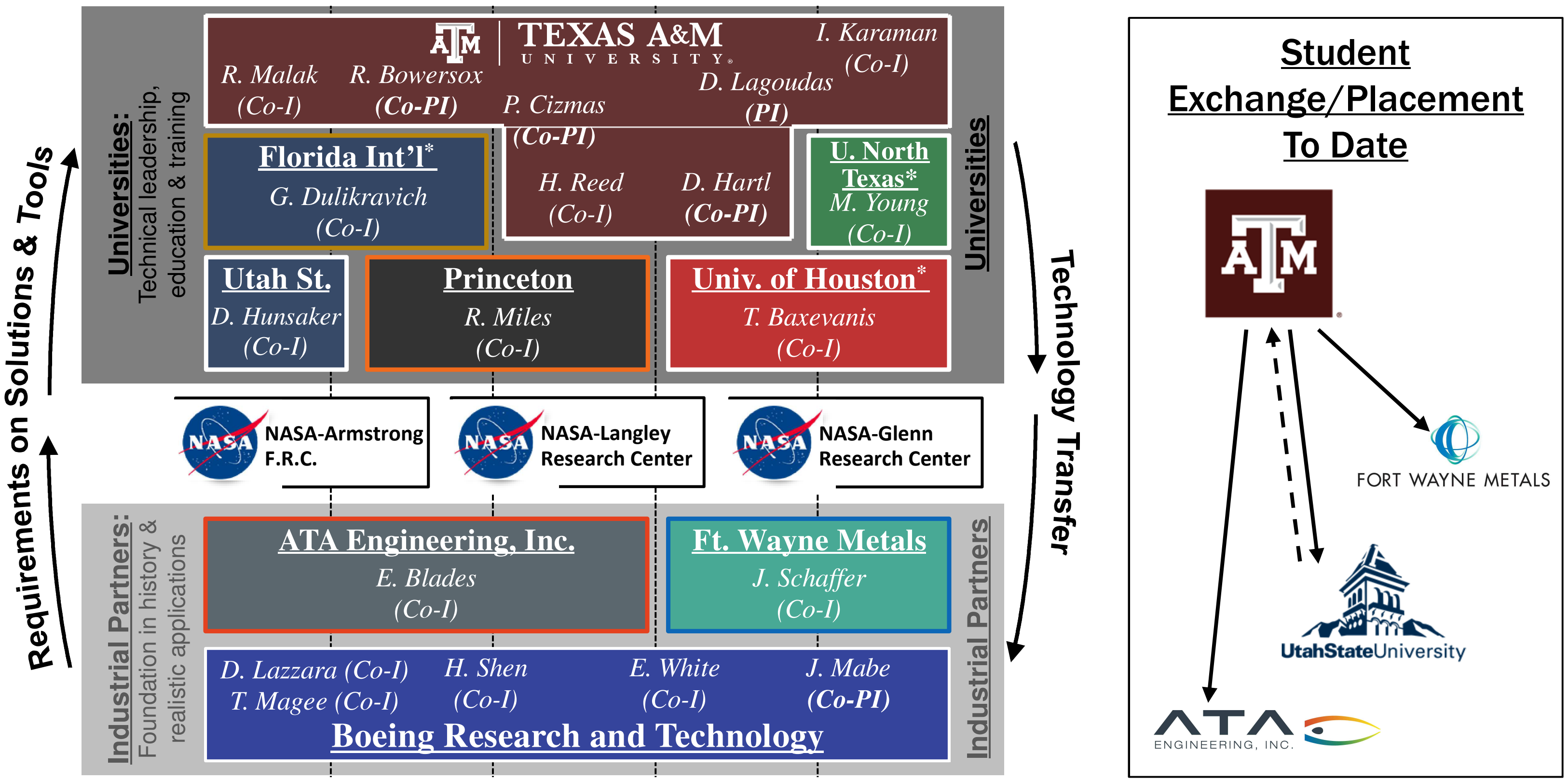

External Advisory Board

- Charbel Farhat — Aeronautics and Astronautics, Stanford University
- Luigi (Gigi) Martinelli — Mechanical and Aerospace, Princeton University
- Greg Reich — Aerospace Systems Directorate, Air Force Research Lab
- Sergio Lucato — Senior Materials Expert, Teledyne
- David Marshall — Aerospace Engr. Sciences, University of Colorado
- Jeff Brown — Vice President and SMA Expert, Dynalloy

Ensures technical focus and advancement to solve challenge

Overview of the Project Timeline

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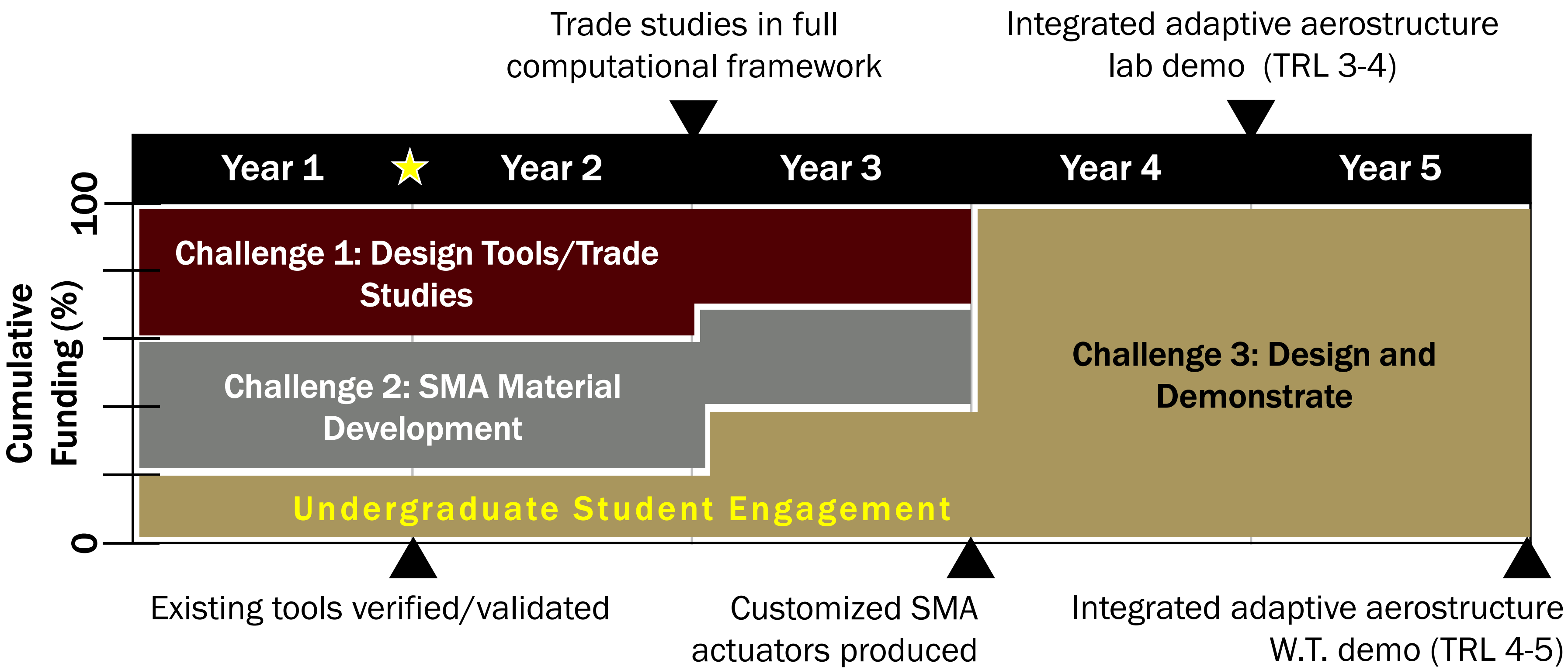

Challenge 1:
Distributed Adaptivity Design Tools Development & Trade Studies

ATA Engineering	Boeing	Florida Int'l Univ.	Princeton Univ.	Texas A&M Univ.	Utah State Univ.
E. Blades	D. Lazzara	G. Dulikravich	A. Dogariu	R. Bowersox	D. Hunsaker
	T. Magee		D. Miles	F. Carpenter	
	H. Shen		B. Goldman	P. Cizmas	
			S. Reuter	A. Gerakis	
			M. Shneider	C. Limbach	
				R. Malak	
				H. Reed	
				N. Tichenor	

Low-Boom Configurations for Preliminary Studies

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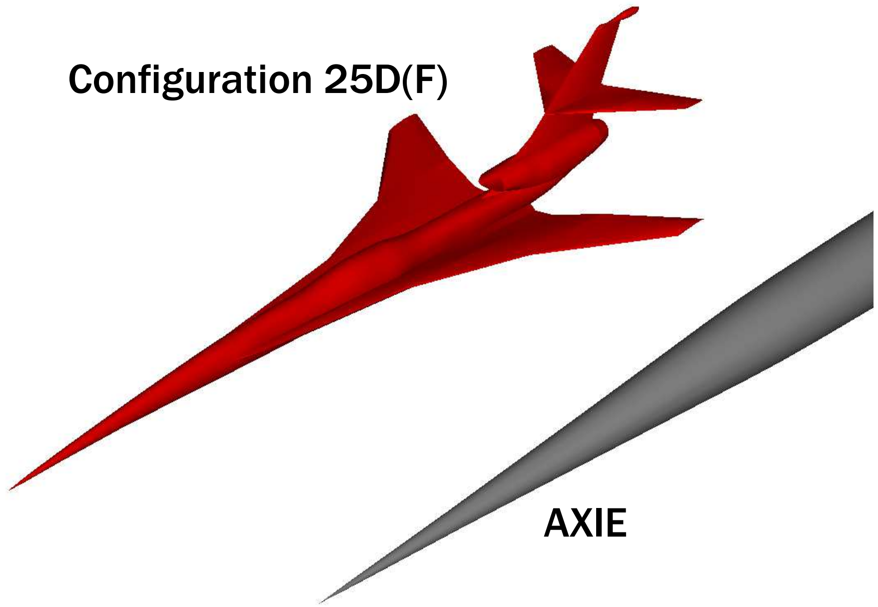
1. NASA Configuration 25D with flow through nacelle

2. NASA axisymmetric body (AXIE)
   - Gives equivalent near field pressure signature as Configuration 25D(F)



Chosen due to wide use in literature and availability of geometry and data (e.g., 2nd AIAA Sonic Boom Prediction Workshop in 2017)

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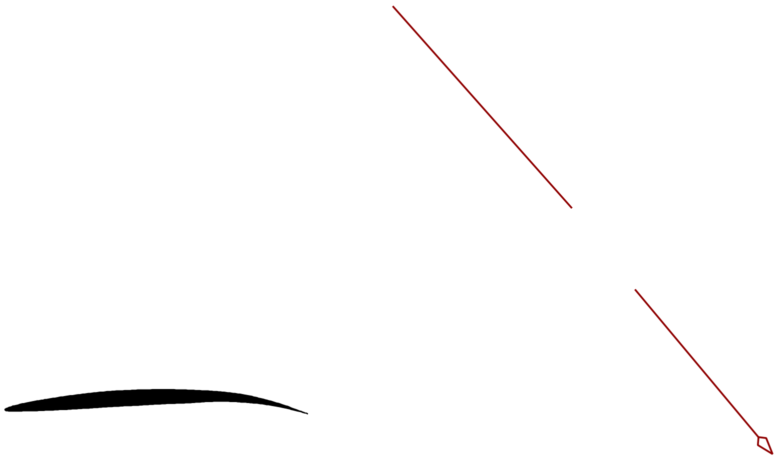
Boom Propagation Toolset to Date



- Near-field key parameters
  - Aircraft configuration
  - Angle-of-attack
  - Mach number
- Far-field key parameters
  - Temperature
  - Relative humidity
  - Wind
  - Atmospheric turbulence

Sensitivity: Mach Number & Angle-of-Attack

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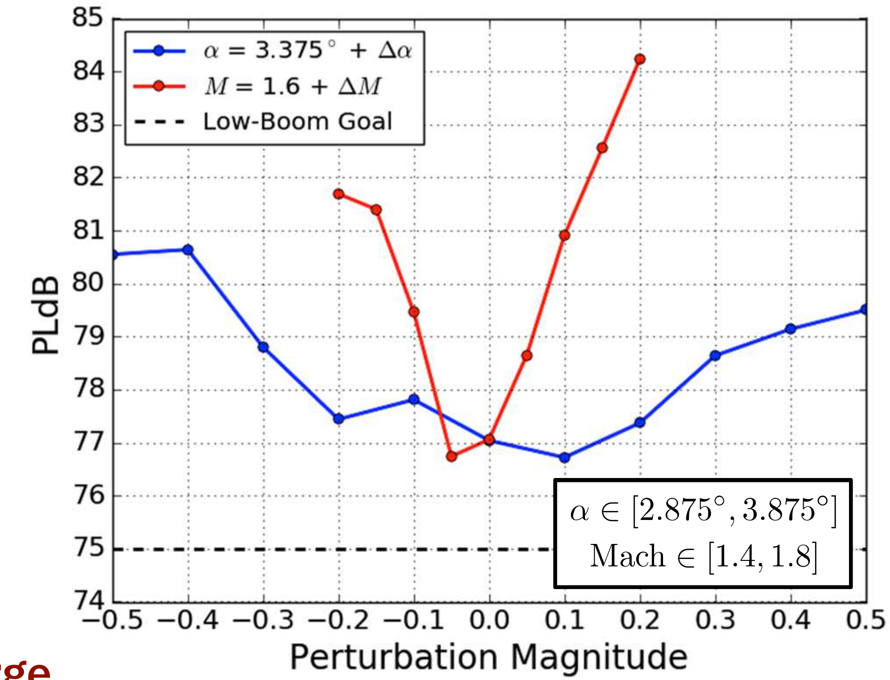
- Variations indicative of wind gusts or atmospheric turbulence

- NASA C25D(F) PLdB values most sensitive to changes in Mach number
  - MAX(ΔPL_M) ≈ 7.0 db
  - MAX(ΔPL_α) ≈ 3.5 db



Relatively-small perturbations may lead to large increases in PLdB

Sensitivity: Laminar-to-Turbulent Transition

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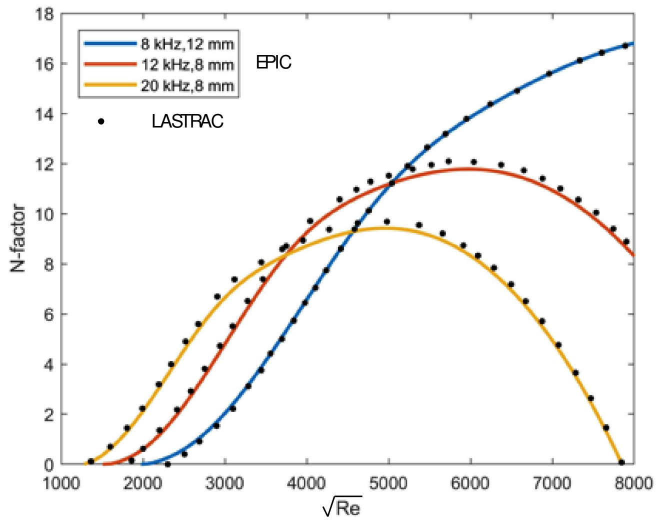
- How can laminar-to-turbulent transition be controlled to minimize boom?
  - Sonic boom noise, drag, and trim are coupled
- In-house stability tool EPIC compared to NASA stability tool LASTRAC
- Development path
  - Study laminar-to-turbulent transition characteristics of NASA 25D geometry
  - Determine effects of small OML geometry on laminar-to-turbulent transition



Ultimately perform trade study of laminar flow effects on sonic boom signature versus viscous drag

Sensitivity: Atmospheric Conditions

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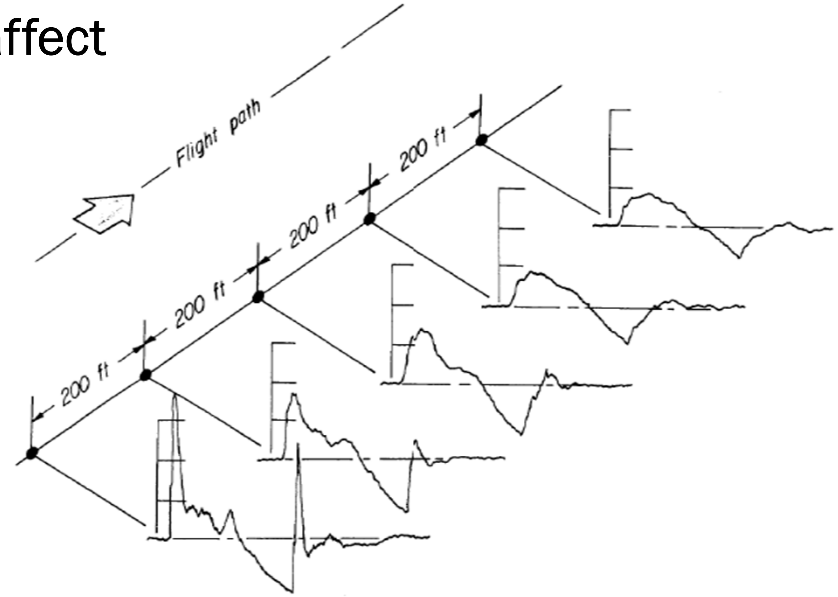
How do changes in atmospheric conditions affect perceived boom loudness at the ground?

- Two possible approaches to mathematically model acoustic propagation
  - Burgers equation:
    - Thermoviscous attenuation, geometrical spreading, atmospheric inhomogeneity, and <u>molecular vibration relaxation</u>
  - Khokhlov–Zabolotskaya-Kuznetsov (KZK) equation:
    - Adds diffraction, axial convection, transverse convection induced by <u>atmospheric turbulence</u>.

More complex, but may be necessary



Variation of boom N-Wave with atmospheric turbulence

Sensitivity: Atmospheric Conditions

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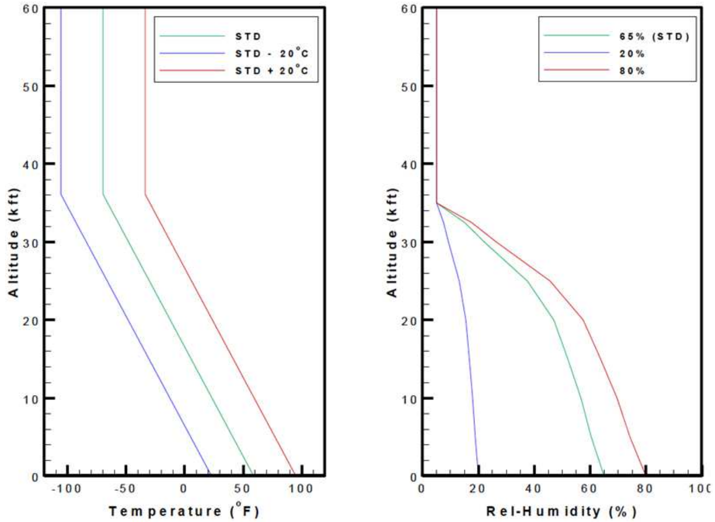
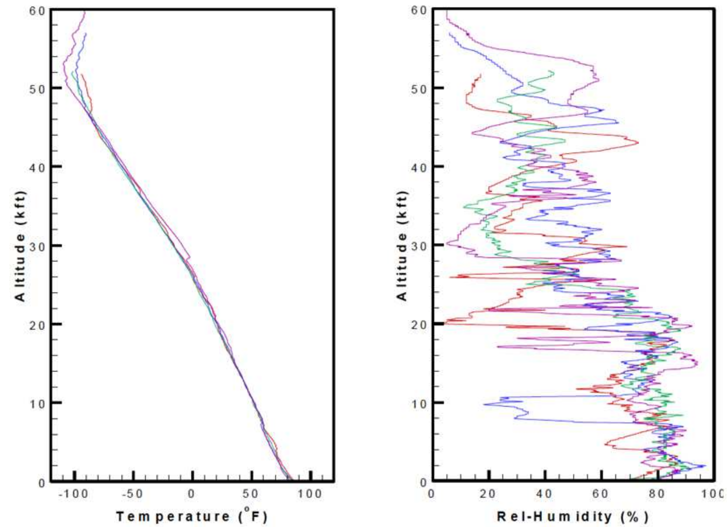
- Problem: Current design studies assume hypothetical profiles
- Real atmospheric profiles are significantly more complex

Hypothetical Profiles



Real Profiles: Cloudy and Humid



Sensitivity: Atmospheric Conditions

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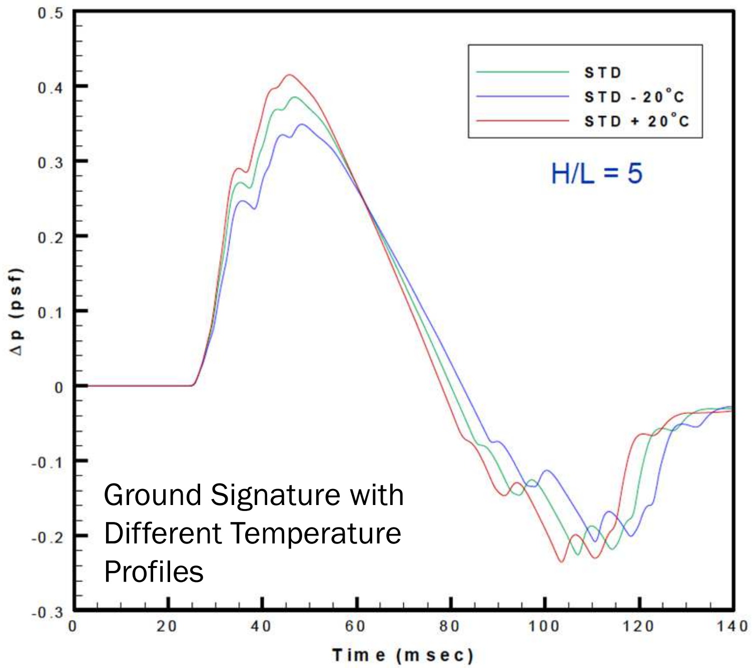
- Ground signature estimated using hypothetical atmospheric profiles



Ground Signature with Different Temperature Profiles

Perceived Loudness, varying temperature:

- STD 76.70 PLdB
- STD-20°C 76.48 PLdB
- STD+20°C 77.09 PLdB

Perceived Loudness, varying humidity:

- 65% (STD) 76.70 PLdB
- 20% 73.54 PLdB
- 80% 77.22 PLdB

Loudness shows sensitivity to both temperature and humidity profiles

Sensitivity: Atmospheric Conditions

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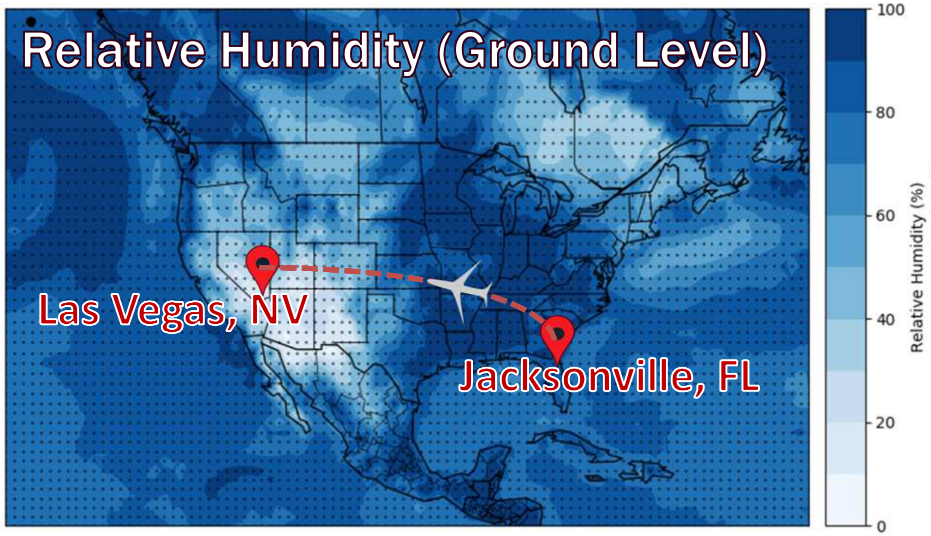
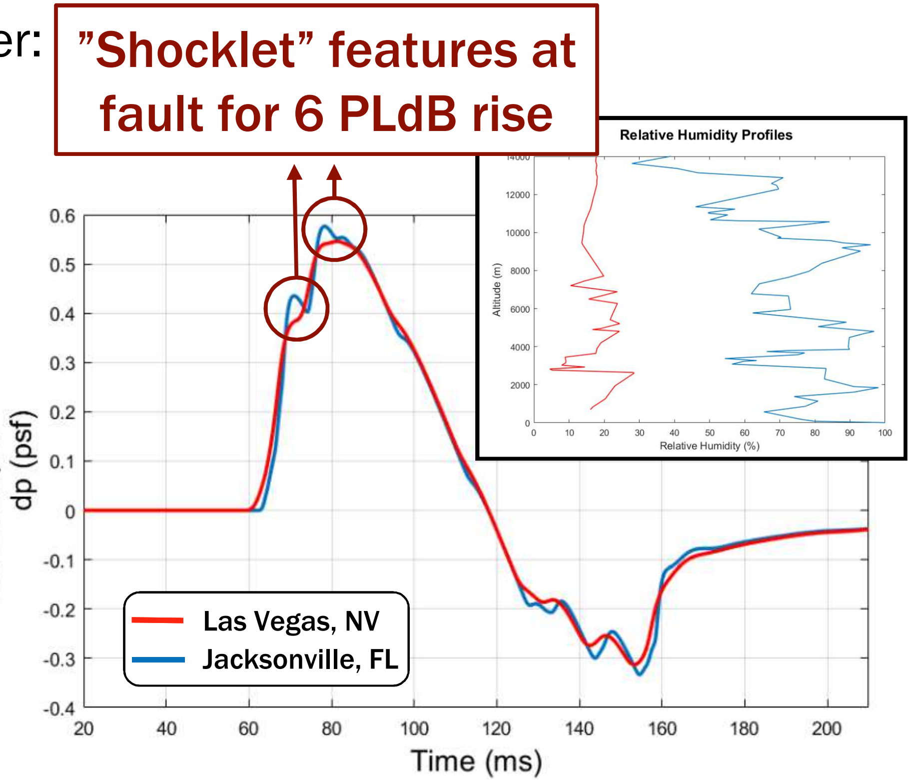
- Propagation in wet and dry climates can result in large differences in PLdB
- Consider the 25D configuration flying over:
  - Las Vegas: 77.4 PLdB
  - Jacksonville: 83.4 PLdB





Measurement of Atmospheric Properties with LIDAR

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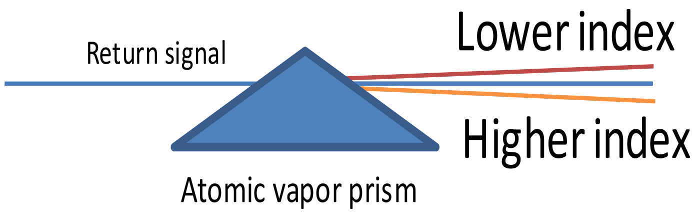
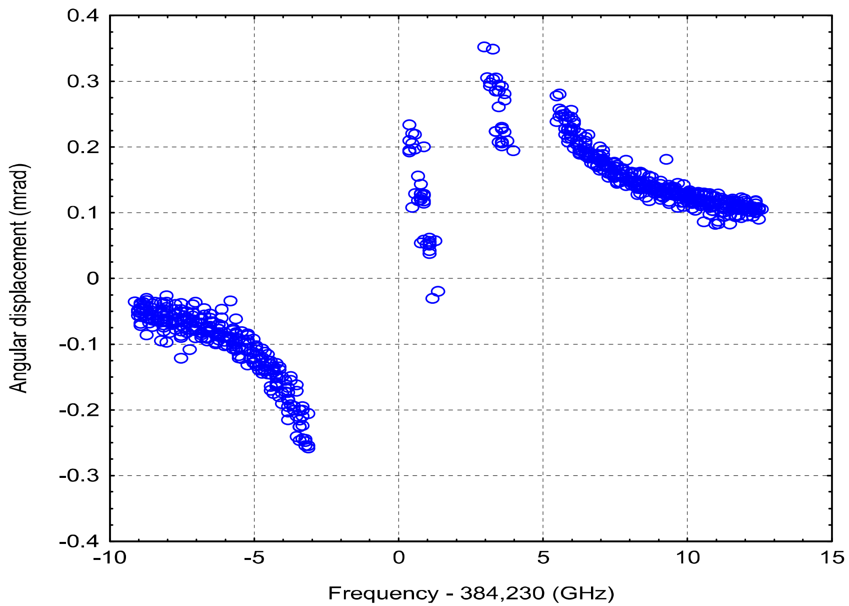
- **Wind speed (Mie scattering)**
- **Temperature (thermal broadening)**
- **Density (signal strength)**
- **Water vapor (line skirts)**

The spectrum is dispersed using a rubidium atomic vapor prism





Prism deflection angle

Look Down LIDAR

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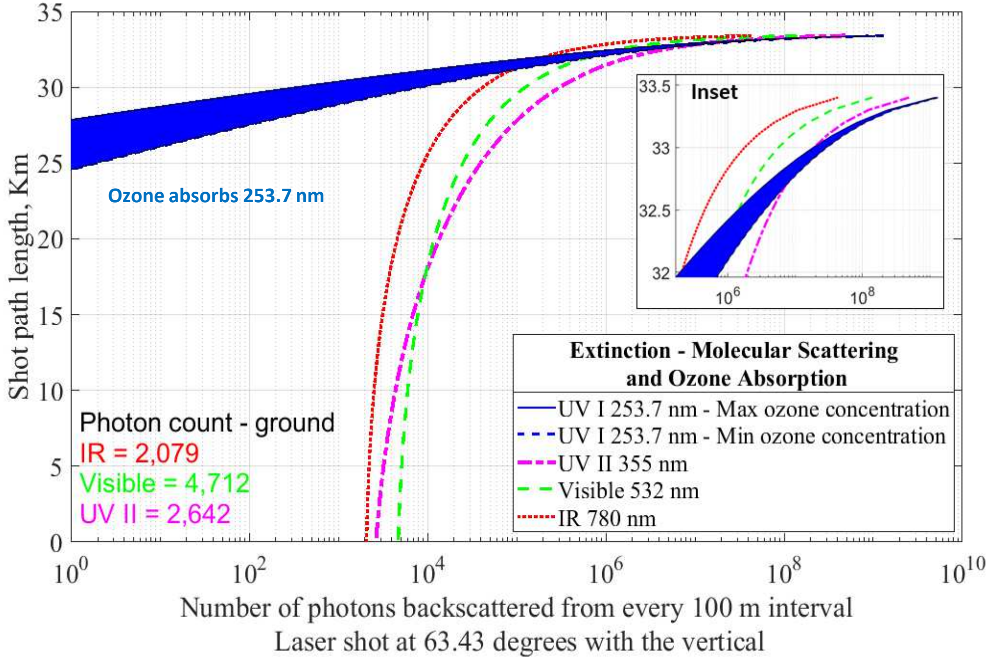
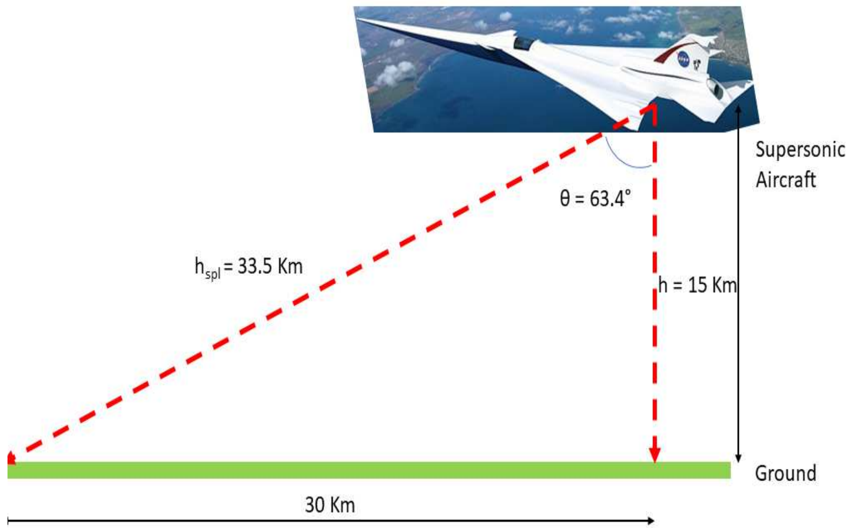
- Laser pulse is sent out and return signal is a combination of Rayleigh and particle scattering
- Return signal is passed through an atomic vapor prism which allows the Rayleigh spectrum to be measured





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Sensitivity: OML Geometry Reconfiguration
Offsetting Far Field Effects – Atmospheric Conditions

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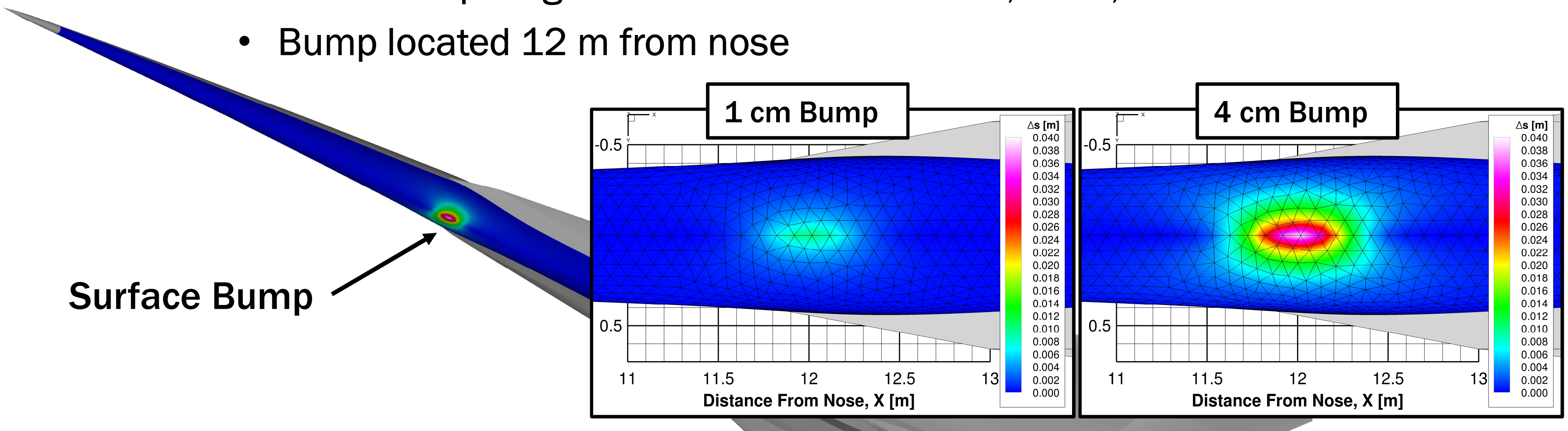
- Can small OML geometry changes lead to reduced boom signature?
  - Three-dimensional bump added to NASA C25D(F) underside about the plane of symmetry
    - Three bump heights were considered: 1 cm, 2 cm, and 4 cm
    - Bump located 12 m from nose



Sensitivity: OML Geometry Reconfiguration
Surface Geometry Source

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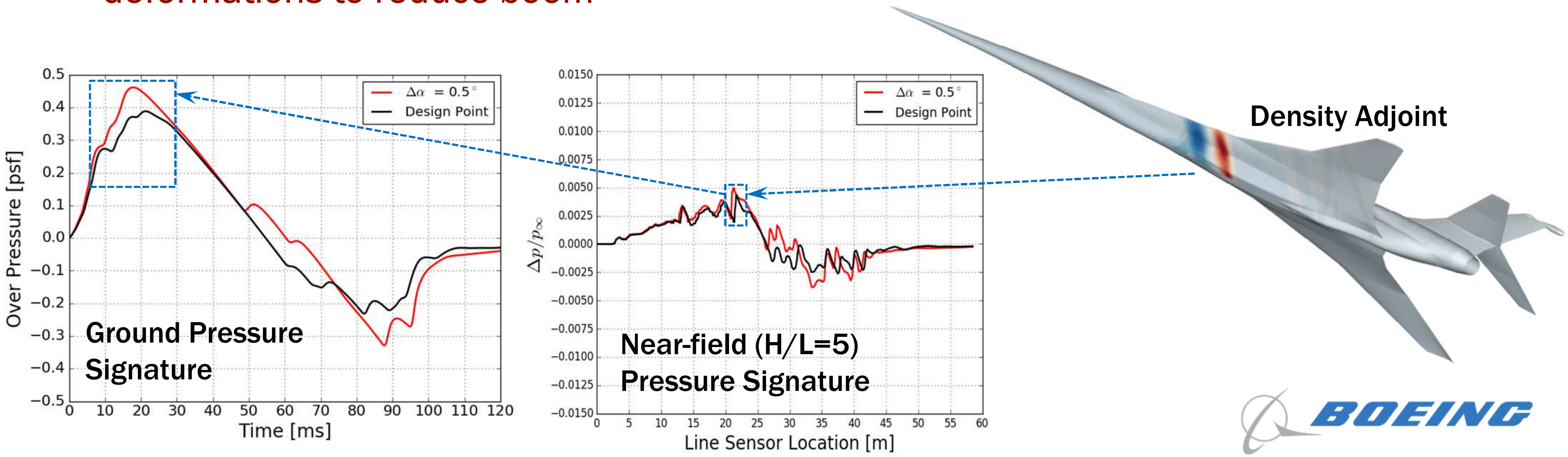
- Adjoint sensitivity analysis of CFD solutions spotlights surface regions responsible for highlighted signature variation
- Method provides opportunity to discover candidate locations for local surface deformations to reduce boom



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Sensitivity: OML Geometry Reconfiguration

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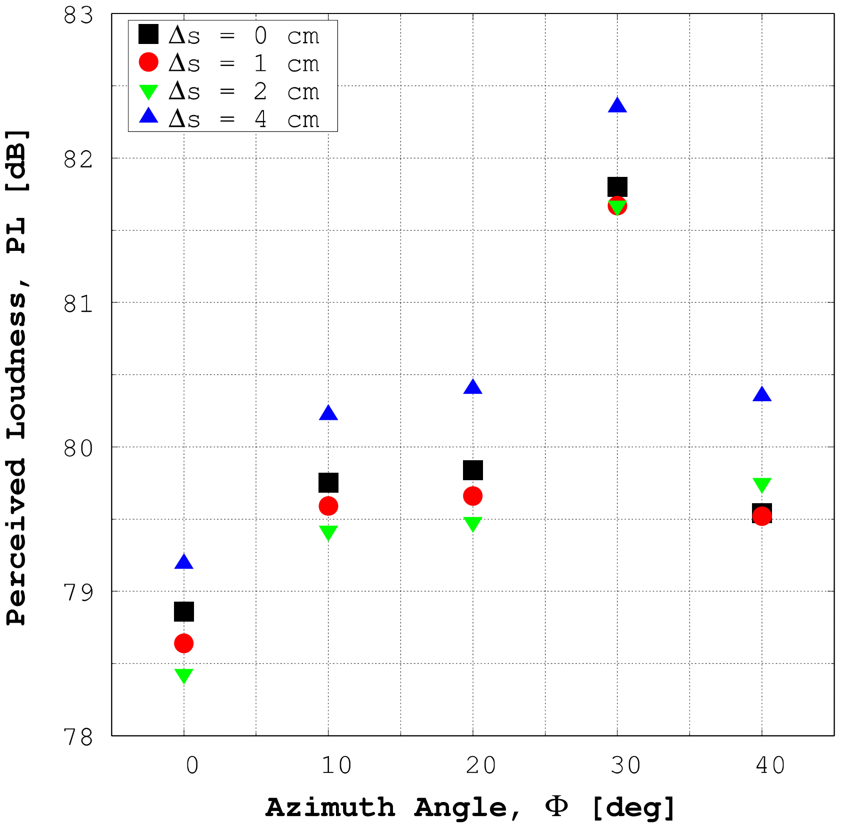
- Added surface bumps resulted in changes in PLdB across azimuth angle (Φ) sweep
- 1 cm and 2 cm bumps resulted in PLdB reduction up to Φ=30°
  - Max reduction along undertrack, ΔPL = −0.43 db
- Largest bump increased PLdB values across range of azimuth angle



Many-Objective Hybrid Optimization (MOHO)

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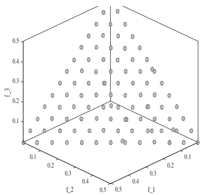
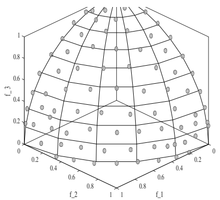
Non-Dominated Sorting Differential Evolution based on Reference Points (NSDE-R)

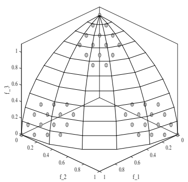
– Uses reference points to create a diverse set of optimum designs or aid in multi-criteria-decision-making

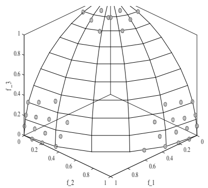
Uniform reference points → Uniformly distributed optimum designs

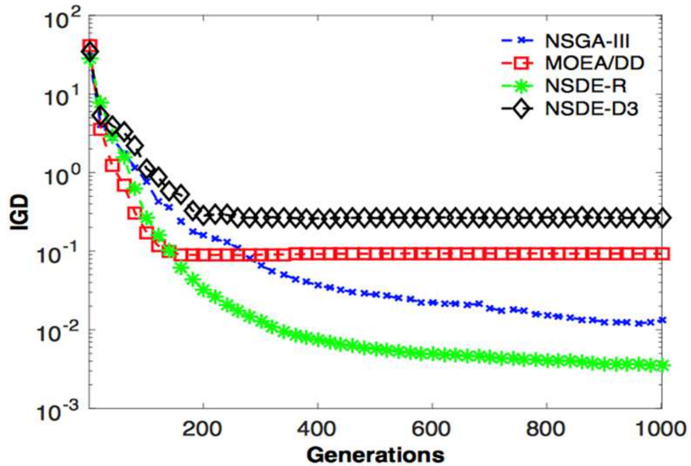




Biased reference points → Optimum designs biased in region of reference points







NSDE-R performs better than current state-of-the-art algorithms (NSGA-III) especially when solving problems with more than four objectives

Parametric Optimization

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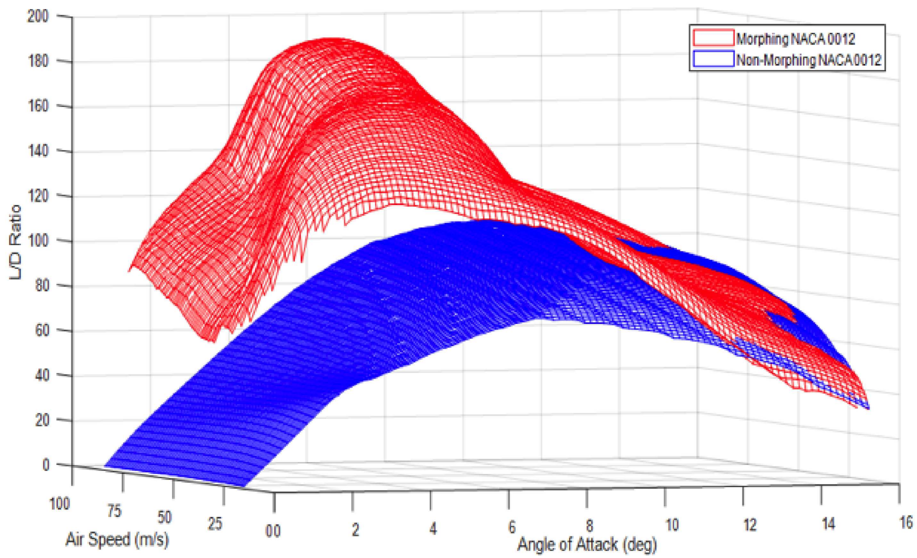
- Design tool that characterizes how optimal OML changes with flight conditions
- Allows lookup of optimal OML shape as flight conditions change & planning of morphing trajectory
- Based on integration of existing algorithm (P3GA) with aerodynamic and sonic boom analysis tools
- Current progress: P3GA integrated with XFOIL



NACA 0012 optimized for maximizing lift-to-drag (L/D) characteristics

Near-Field Lower-Fidelity Modeling: PANAIR

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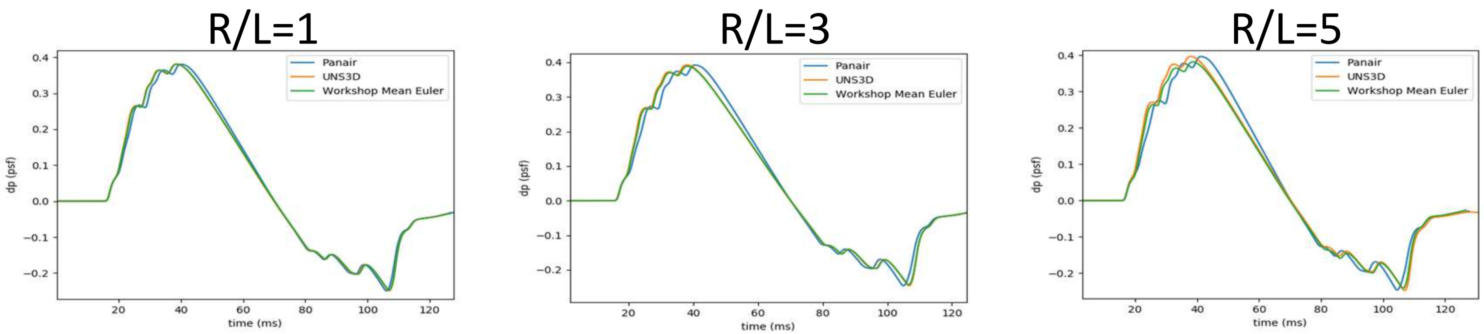
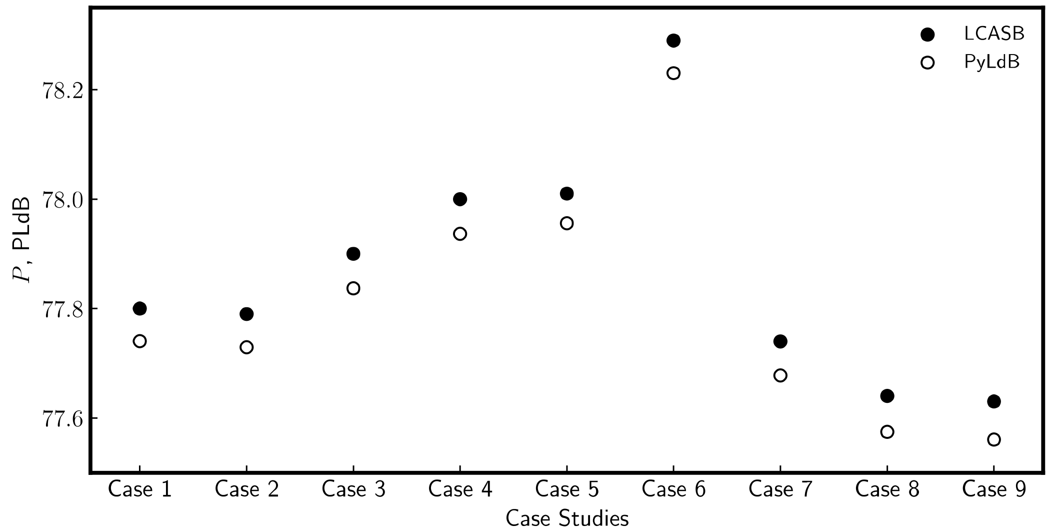
- Lower-fidelity modeling capability to couple into optimization framework
  - PANAIR and sBoom wrappers developed
  - PANAIR validation for AXIE case complete
- Propagated ground signatures for AXIE case using PANAIR, UNS3D, and mean of Boom Prediction Workshop results



PyLdB Loudness Code

- In-house code designed for seamless integration into the optimization framework
  - Written in Python for accessibility
  - Will be provided to the community

- Shows excellent agreement with NASA's LCASB in initial testing using AXIE ground signatures
  - 0.08% difference



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Challenge 2: Materials Development & Integrated Solid-State Actuation Design

Boeing
J. Mabe

Fort Wayne Metals
J. Schaffer

Univ. of Houston
T. Baxevanis

Texas A&M Univ.
D. Hartl
I. Karaman
D. Lagoudas
A. Solomou

Univ. of North Texas
M. Young

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Challenge 2:
Team Organization and Objectives

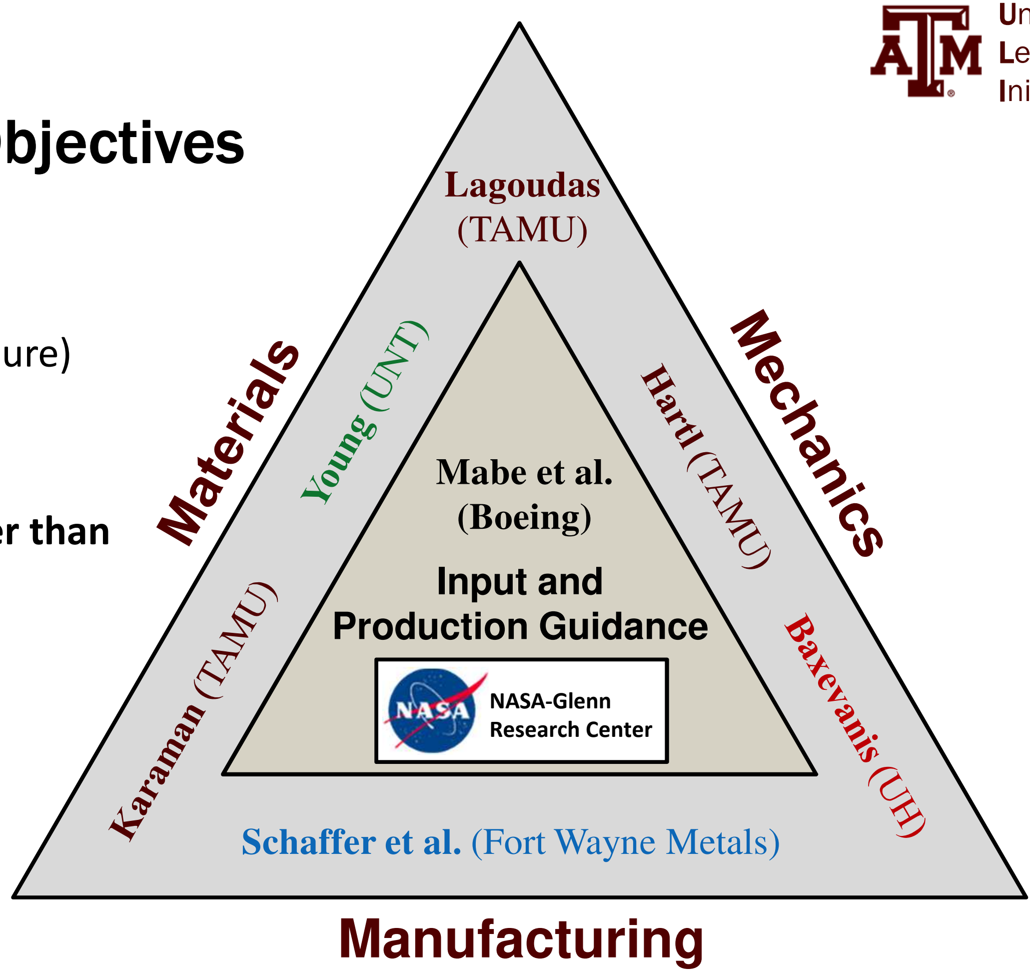
Develop SMA actuator materials

- composition (high and low temperature)
- processing
- forms

Demonstrate actuator durability greater than 100K cycles.

Demonstrate Scale up of material and actuator production.

Mechanics, Modeling, and Component Design for Durability.



Shape Memory Alloy (SMA) Actuation

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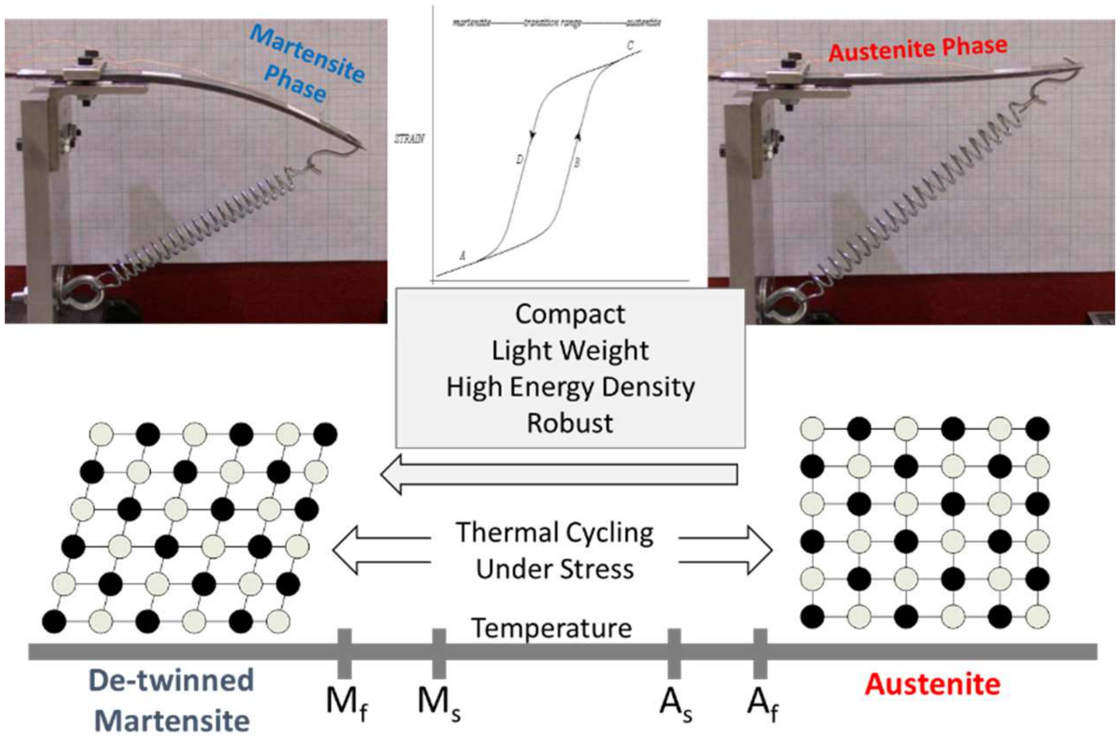
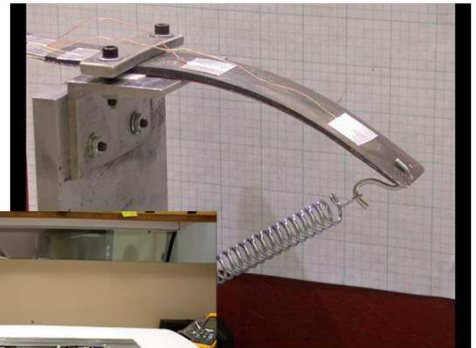
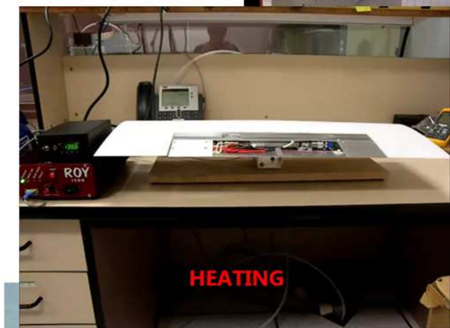
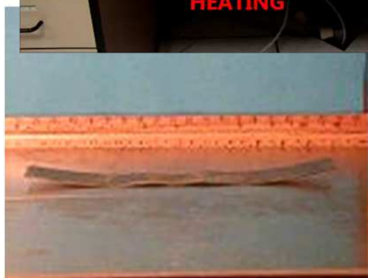


Bending Beam





Hinge Line Integrated SMA Tube



2D and 3D Morphing

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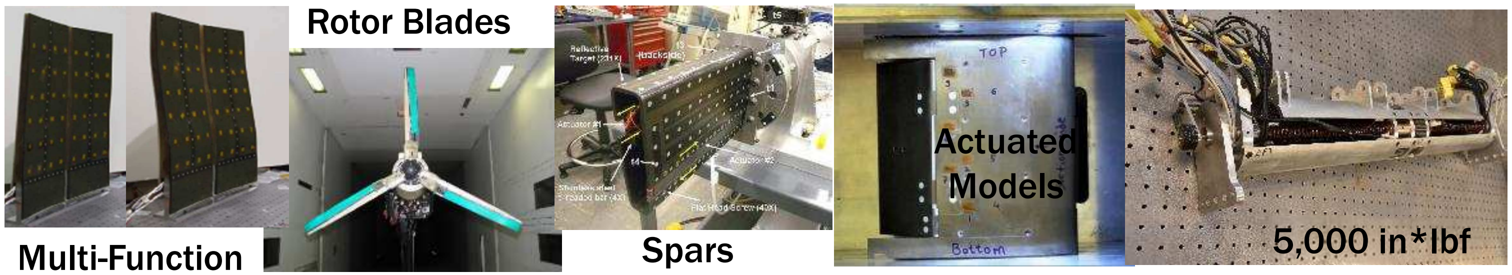
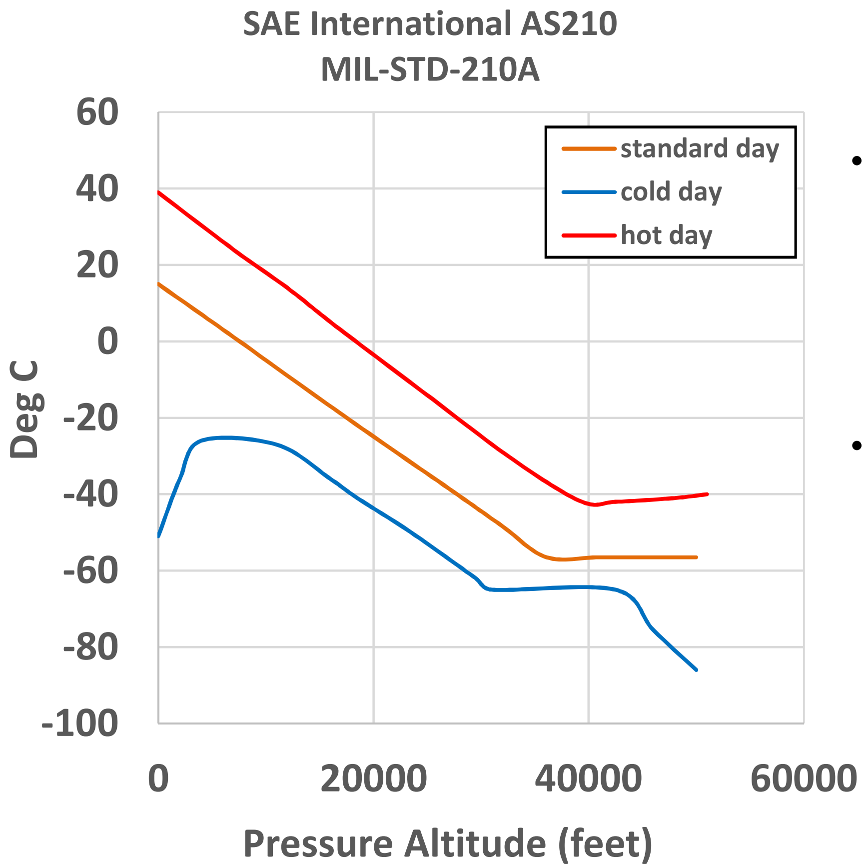
Flight Tests

Lab and Wind Tunnel Tests



SMA Forms



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Initially Two Shape Memory Alloys Targeted

- **Low Temperature for Autonomous Actuation**
  - **Actuation due to ambient temperatures, adapt between a take-off and landing configuration to a cruise configuration.**
  - ***Using AS210 and MIL-STD-210A for altitude and temperature models.***
- **High Temperature for World Wide Ambient Temperature.**
  - **SMA will not actuated due to hot ambient temperatures.**
  - ***RTCA DO-160 Type D2 Equipment, electronic equipment in non-pressurized areas.***

Currently specific applications and detailed requirements are TBD, but this work is laying the ground work for potential applications.

SMA Property Mapping and Development of SMA Selection Criteria for Solid State Actuators in Supersonic Flights

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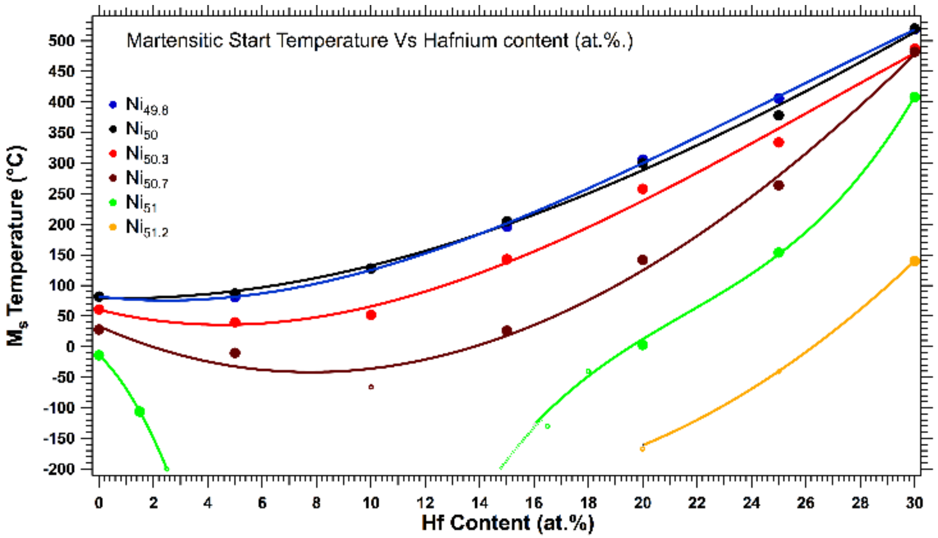
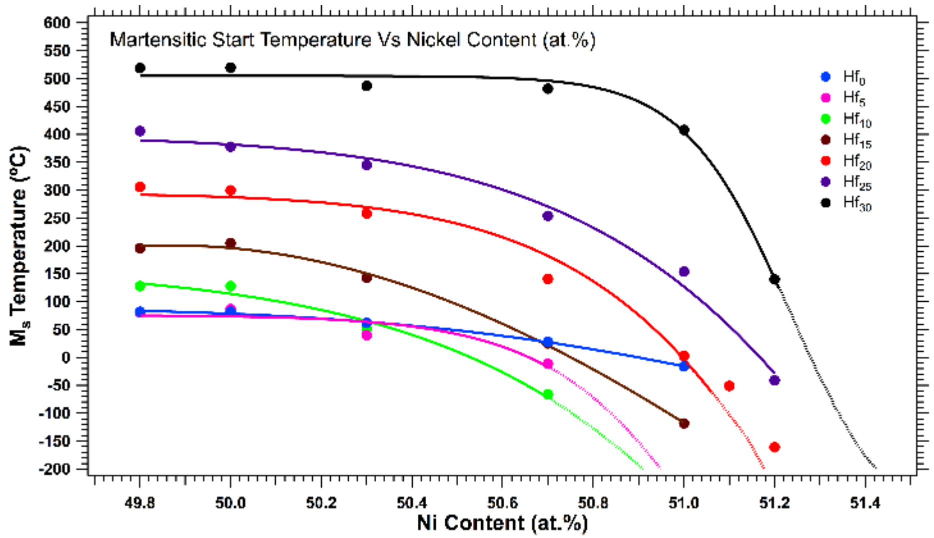
<u>TARGET</u> : High temperature SMA to actuate at temperatures above 85°C

Nickel, Titanium, and Hafnium melt ratios varied and temperature response evaluated

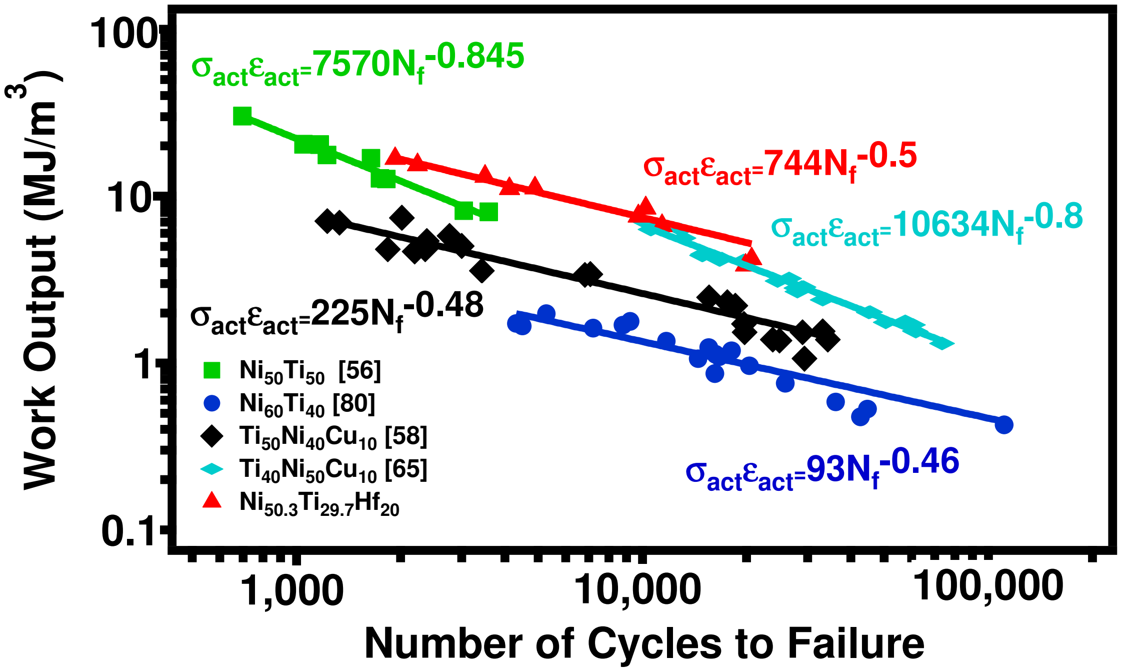




Primary Challenge:
100K Actuation Cycles Before Failure

Alloy selection and processing is being developed to meet a range of material, actuation, and performance requirements:

- Transformation Temperature
- Maximum Work Output
- Stable Performance
- High Durability
- Fracture and Fatigue Toughness



Maximize work output while maintaining 100K cycle lifetime.

Exploring Shape Memory Alloys using Novel *in situ and Conventional* Experimentation

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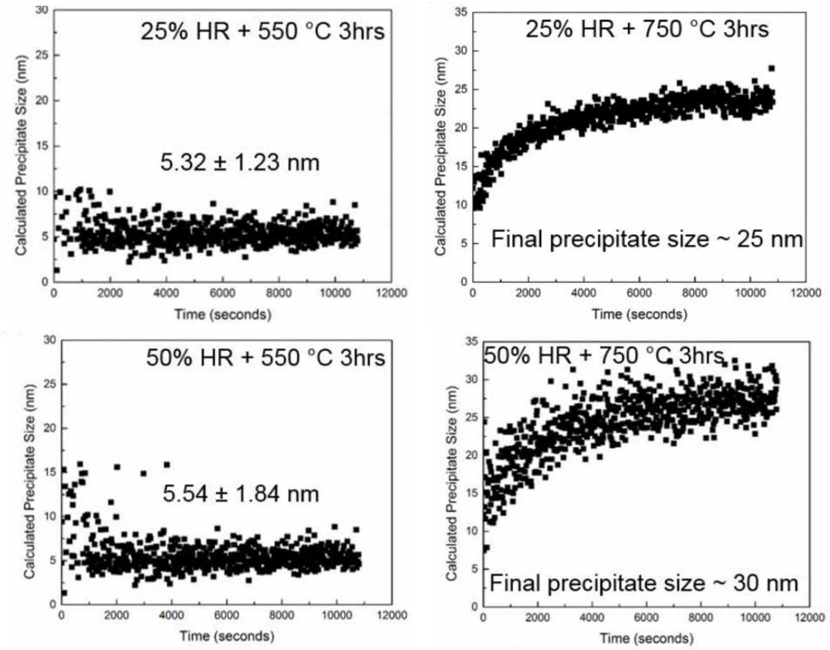
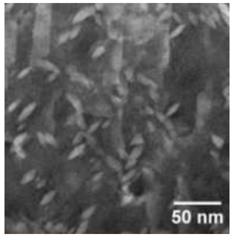
- SR-XRD in situ experiments used to examine effect of processing and heat treatment
- DSC, SEM, TEM, Vickers hardness experiments performed to characterize material's microstructure and response

Effect of processing & heat treatment on precipitates size

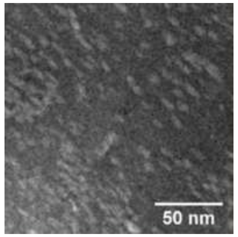


***in situ* SR-XRD experiments on $Ni_{50.5}Ti_{34.5}Hf_{15}$ (at. %)**

TEM Images



550 °C 25% HR



550 °C 50% HR

Fort Wayne Metals: From Specimens Toward Production

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- Constantly working to transition newly discovered/characterized SMA materials toward production scale
  - Provides critical capability needed for component testing

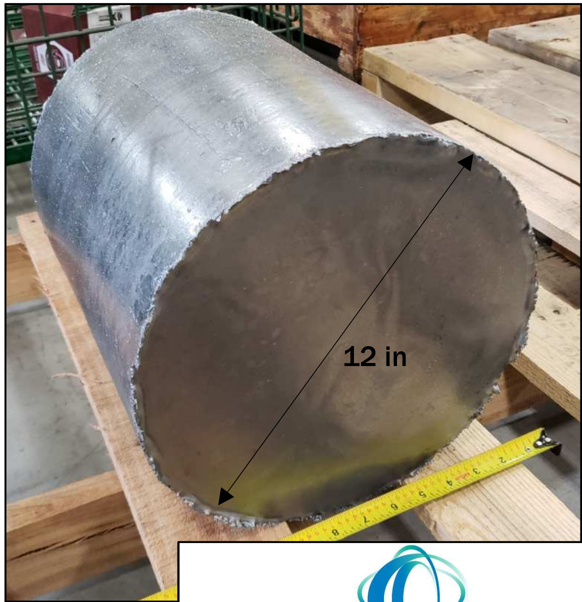
Vacuum arc melt SMA buttons

0.5in

SMA Bar

0.5in

PAM/VAR $Ni_{50.3}Ti_{29.7}Hf_{20}$ ingot at FWM (May 1, 2018)



FORT WAYNE METALS

Production Scale Up

Modeling of SMA Constitutive Response under Cyclic Loading

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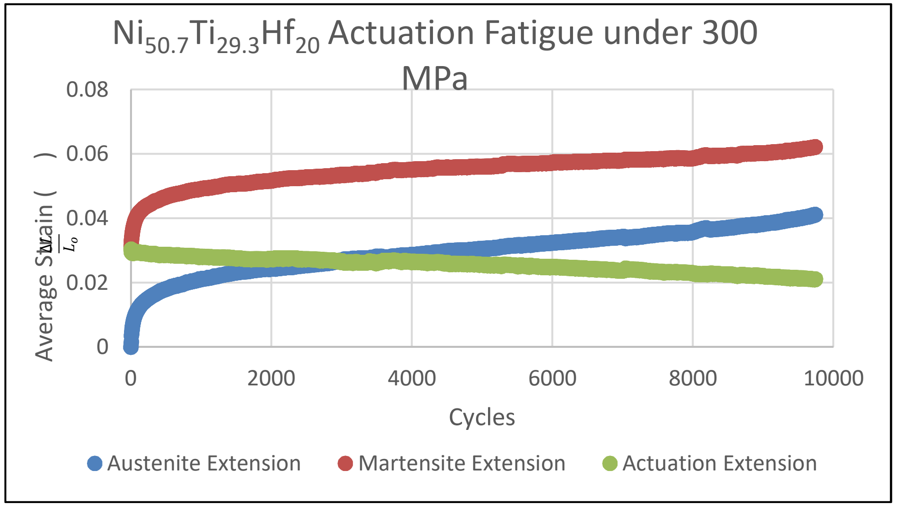
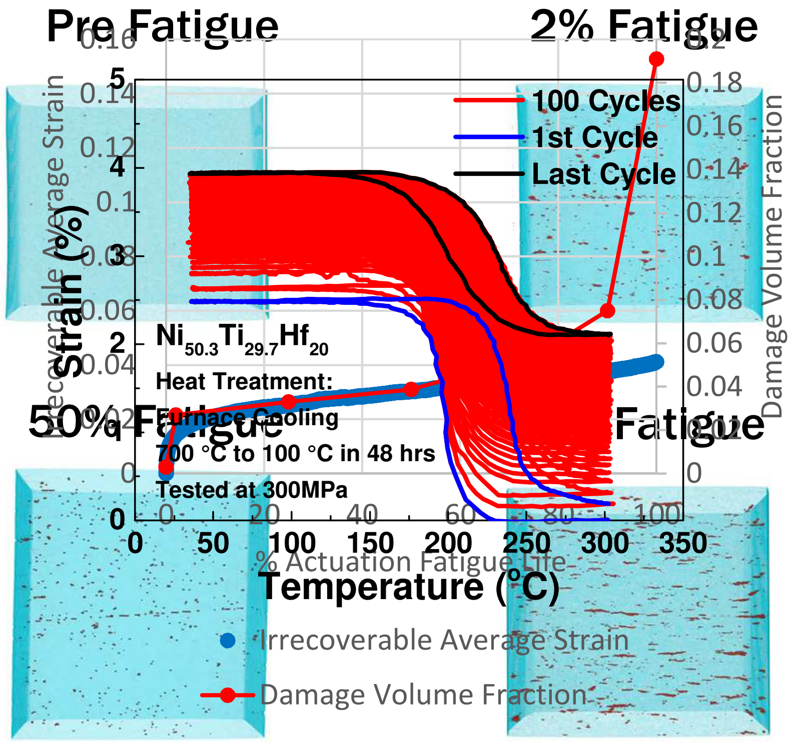


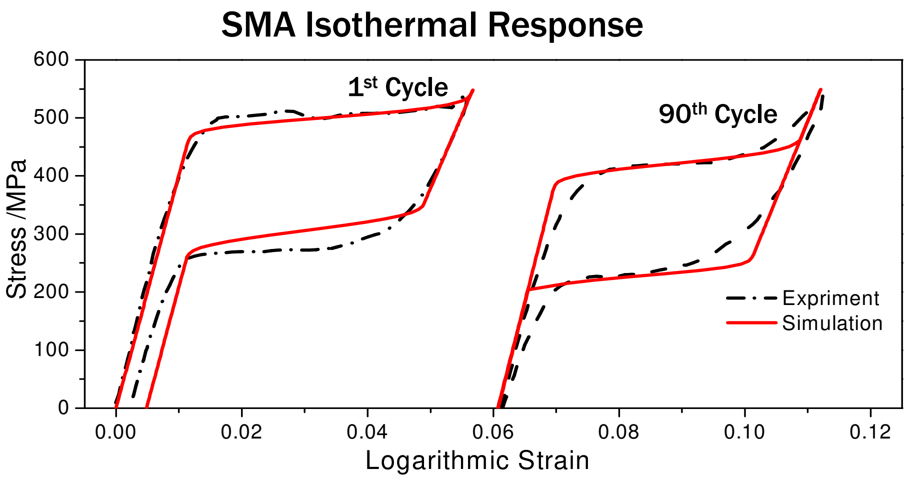


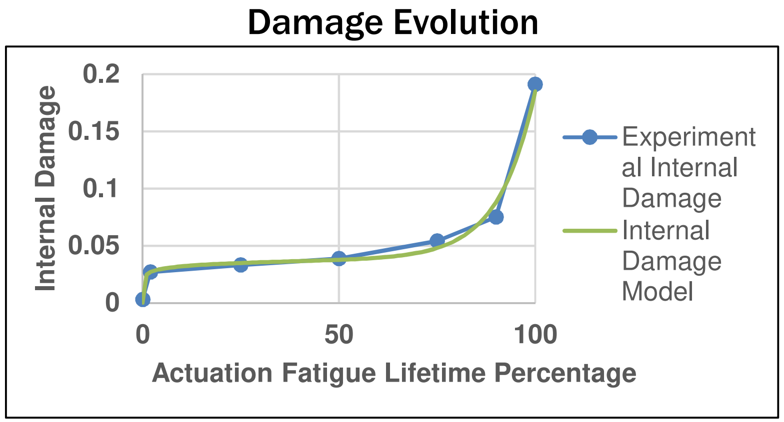
- SMA response is evolving during the actuation cycl
- Irrecoverable strains are accumulated due to evolution of damage and transformation induced plastic strains
- Models are needed in order to capture this complic and facilitate the design of SMA actuator compone

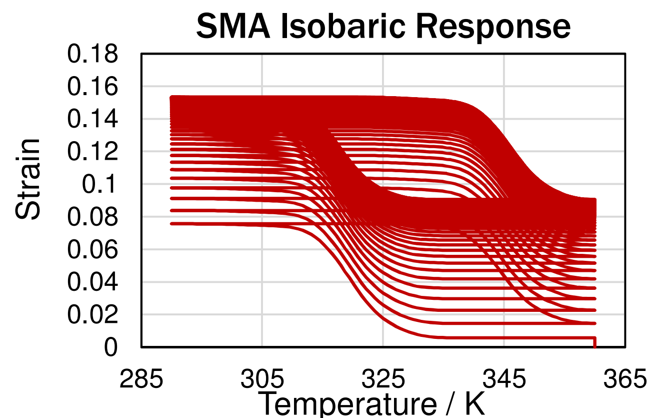
Note: Each scan is on a separate specimen

Modeling of Damage and Irrecoverable Strains Evolution

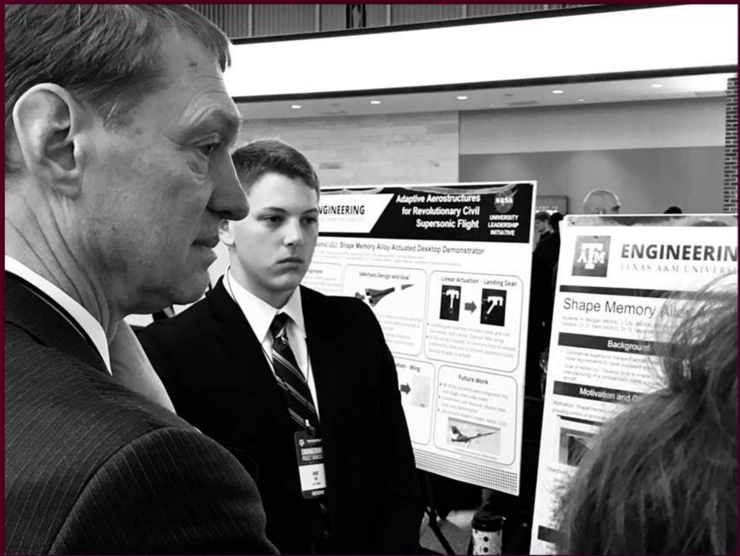
University Leadership Initiative







- **The developed models predict the evolution of materials response until failure by capturing:**
  - **The damage evolution**
  - **The irrecoverable strains accumulation**



ENGINEERING
TEXAS A&M UNIVERSITY

Challenge 3:
Detailed Design and Demonstration

Undergraduate Student Engagement
(Mabe, with Carpenter, Hartl, Lagoudas, & Tichenor)

ATA ENGINEERING, INC. BOEING FIU FORT WAYNE METALS Princeton University UNT UtahStateUniversity

Challenge 3: Undergraduate Student Participation

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- Three undergraduate teams were integrated into the ULI project as full participants
    1. Data mining for real time weather and flight condition across the US for flight path selection and weather impacts on boom signature.
    2. Design, build, and test of Shape Memory Alloy actuated desktop demonstrators of various forms of SMA actuation; torsion, tension, and bending actuators.
    3. Shape Memory Alloy Actuated Model in Supersonic Wind Tunnel using torsional actuation.

Challenge 3: Undergraduate Student Participation

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- Each team operated as an engineering course under the Aggie-Challenge program
  - Received credit for their participation
  - Presented status at weekly meetings to subject matter experts from the larger ULI program
  - Participated in Engineering Project Showcase sponsored by Texas A&M College of Engineering
- Freshman and Sophomore students committed to participation in following years
  - Laying the groundwork for improved student participation throughout program
- Wind tunnel model team is providing a platform for FSI model development and model validation
  - Abstract has been submitted for SciTech 2019
- Transitioning some efforts to *full Mechanical Engineering Senior Design* (Capstone) team for increased participation/leveraging of student creativity

Team 1: Visualization of Flight Conditions and Optimal Flight Paths/Parameters

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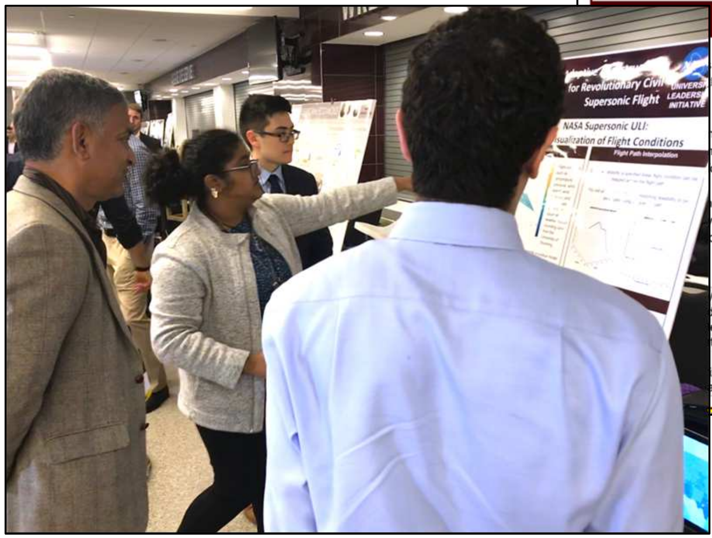
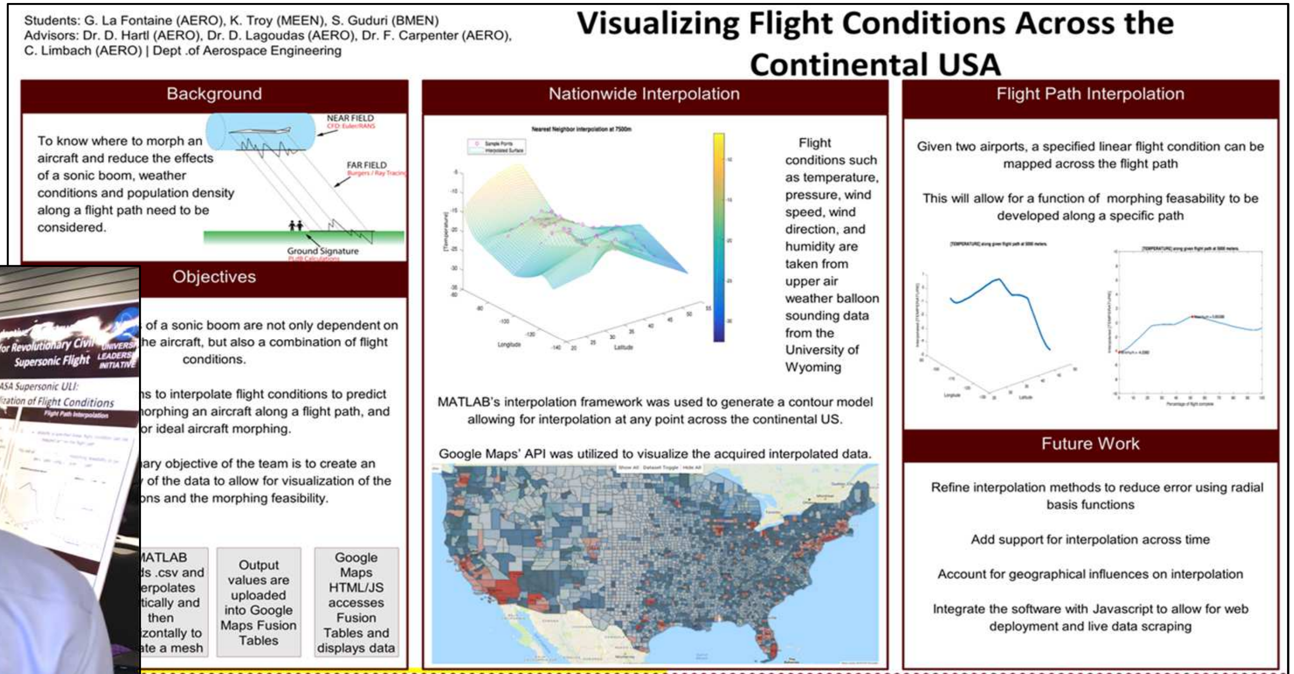
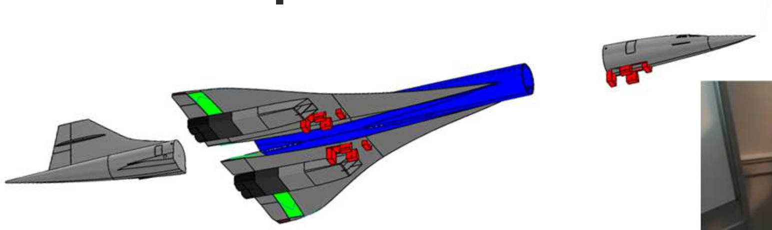
Team 1 students describe their progress to Dr. Koushik Datta, acting Deputy Director for the NASA Aeronautics Research Institute

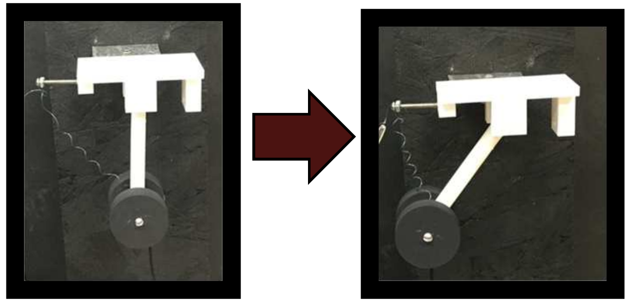




Poster presented at Texas A&M Engineering Expo event/competition

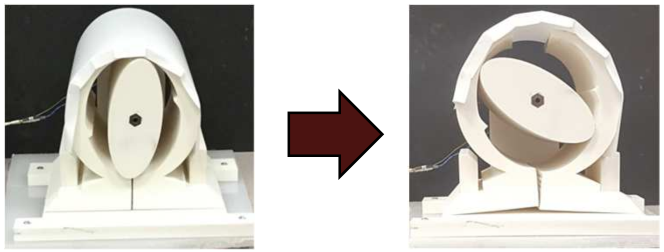
Team 2: Shape Memory Alloy Actuated Desktop Demonstrator



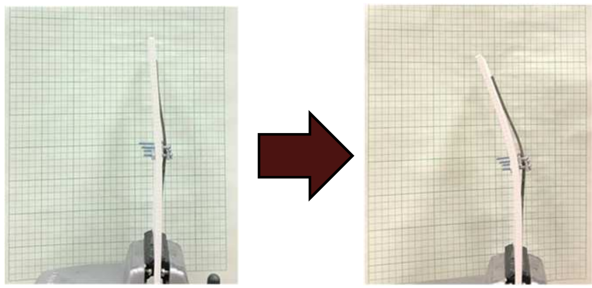


Linear Actuation

Student designed and built demonstrations of SMA actuation.



Torque Tube Actuation



Bending Actuation

Team 3: Shape Memory Alloy Actuated Model in Supersonic Wind Tunnel

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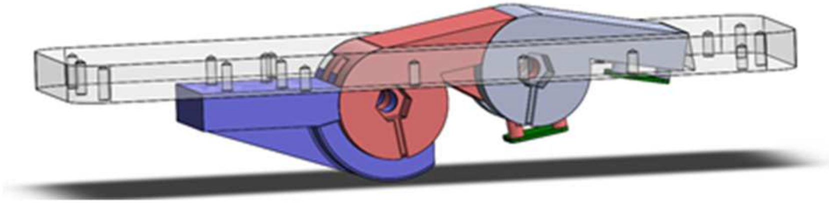
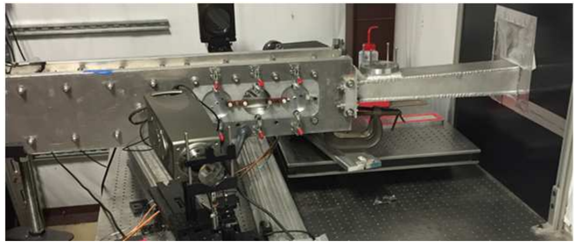
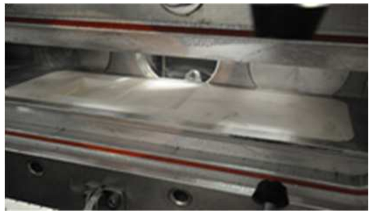


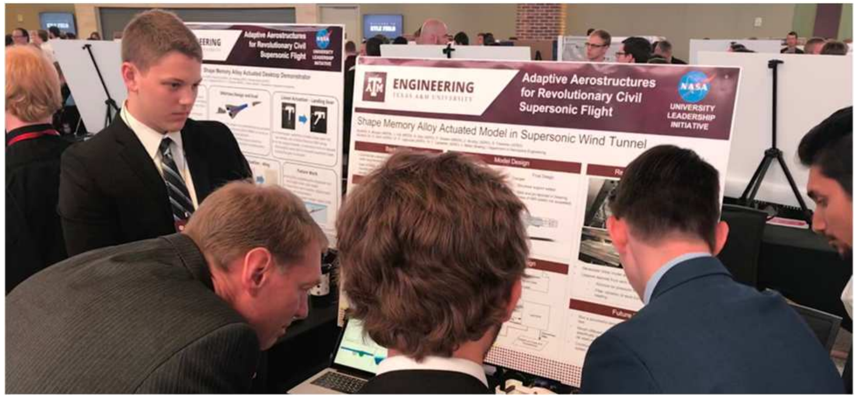
- SMA Actuation, sensors, and control system successfully demonstrated on the bench using ABS plastic.
- Tunnel fit check and preliminary testing.
- Improved design being built for wind tunnel testing.



Integrated into Supersonic Wind Tunnel

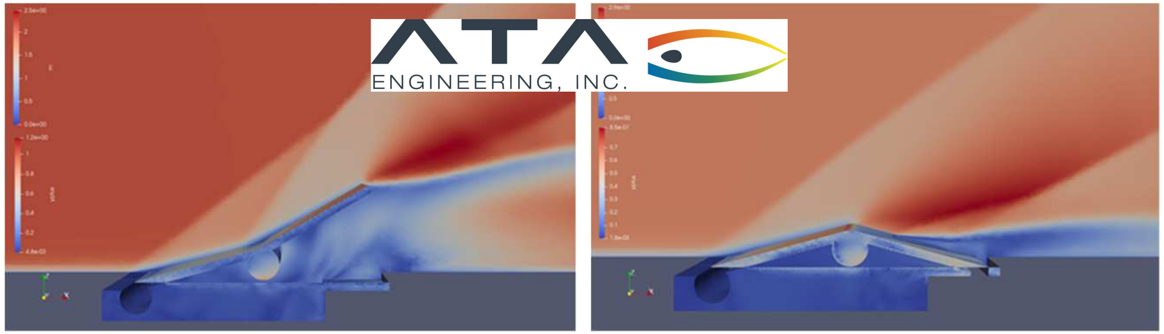


Team 3 students explain their approach to Dr. John Cavolowsky, TAC Program Director

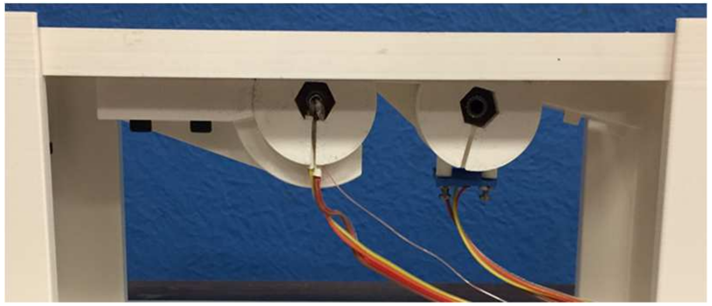


Team 3: An Example of Integration Across Project Participants

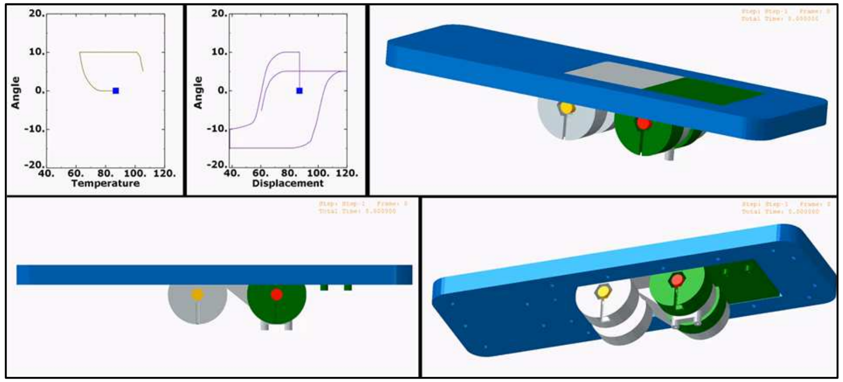
University Leadership Initiative



- Simple dual ramp wind tunnel model used for evaluation of integrated CFD and SMA tools.
- Simulations validated by actuated supersonic wind tunnel tests.
- Validated processes and method will be used for design optimization later in the program.



Student Built SMA Actuated Wind Tunnel Model
(Boeing Support, SMA and shock characteristics)



Texas A&M Abaqus UMAT

Thank you.

Questions?