New Sensors and Techniques for Aircraft Engine Health Monitoring

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NASA Glenn Research Center

Kent State University Aeronautics Safety Day
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Introduction

Mark R. Woike

- Research Engineer at the NASA Glenn Research Center, Ohio
- 31 years at NASA

- Current area of expertise
  - Advanced instrumentation and techniques for propulsion health monitoring
  - Optical Instrumentation for flow field diagnostics

- 11 years - Research Engineer
- 6 years - Test Project Manager at Plum Brook Station
- 14 years - Test Engineer & Technical Lead in the Wind Tunnel Test Facilities

- MSEE and BSEE from Cleveland State University…many years ago! ☺

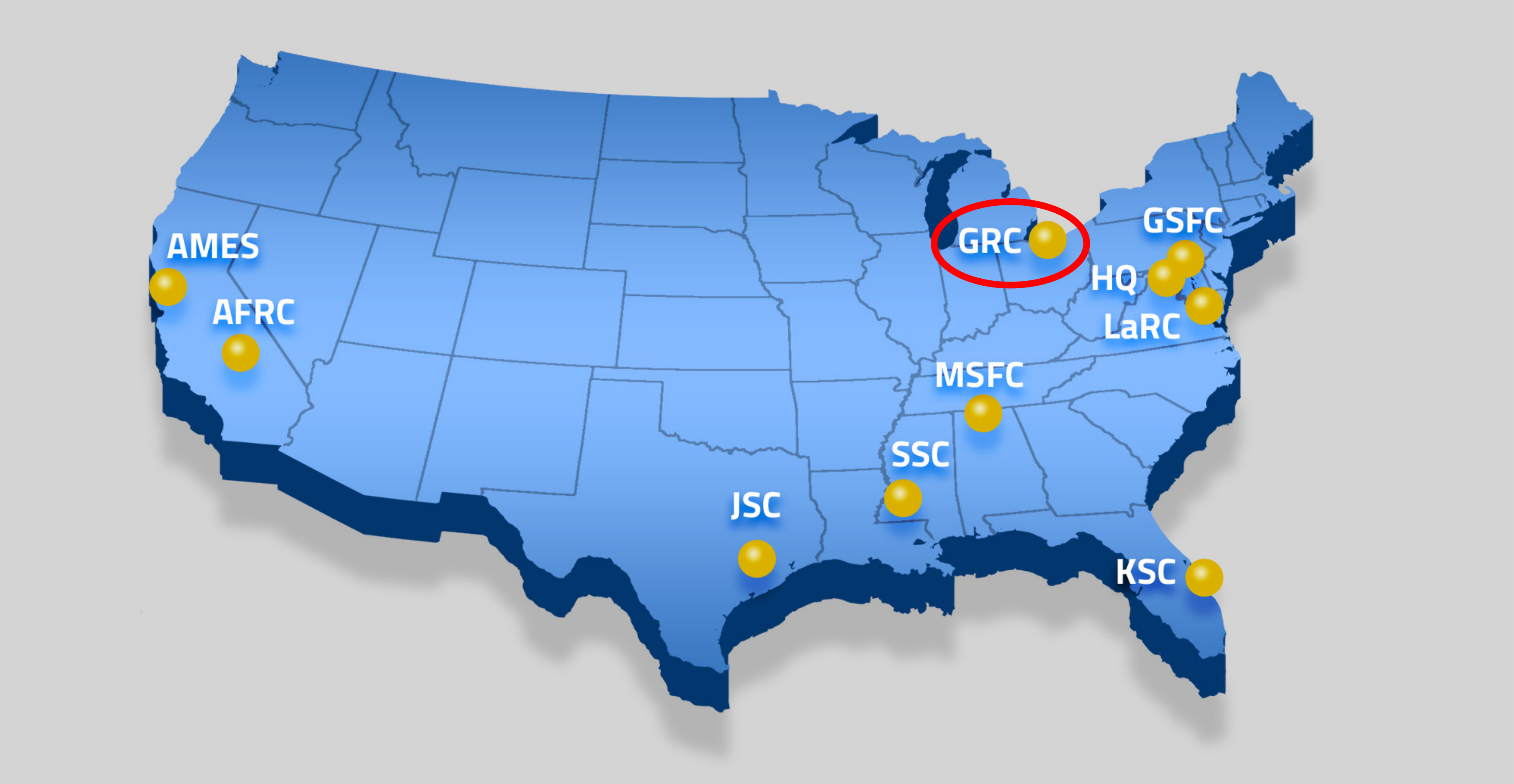
Overview

- Overview of the NASA Glenn Research Center
- NASA Aeronautics Research & Test Facilities
- New Aircraft Engine Sensor Technologies and Techniques
- Advanced Aeronautical Evaluation and Test Facility Instrumentation
- Student Opportunities at NASA Glenn

NASA Glenn Research Center

National Aeronautics and Space Administration

- 1 of 10 NASA field centers located across the US.



NASA Glenn Campuses

Lewis Field (Cleveland)

- 350 acres
- ~1561 civil servants and ~1476 contractors

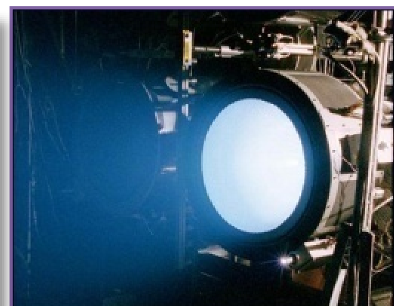
Plum Brook Station (Sandusky)

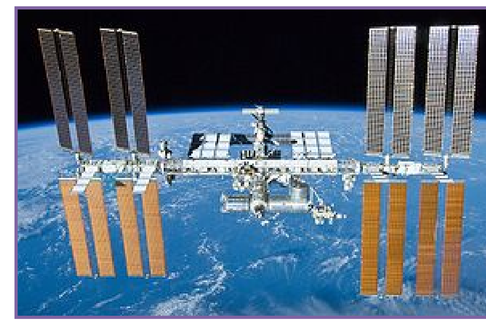
- 6500 acres
- ~18 civil servants and ~89 contractors

NASA Glenn Missions

Glenn's Mission:

We drive research, technology, and systems to advance aviation, enable exploration of the universe, and improve life on Earth.





Glenn Core Competencies

Air-Breathing Propulsion

In-Space Propulsion and Cryogenic Fluids Management

Physical Sciences and Biomedical Technologies in Space

Communications Technology and Development

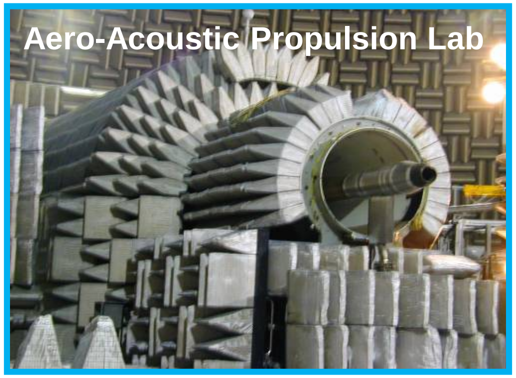
Power, Energy Storage and Conversion

Materials and Structures for Extreme Environments

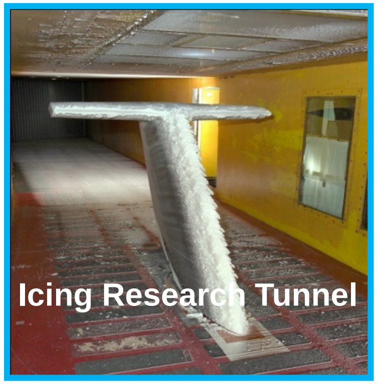
NASA Glenn Unique Aeronautics Test Facilities

Subsonic Propulsion Wind Tunnel
- Noise suppression
- Inlet/Airframe integration
- STOVL hot gas ingestion

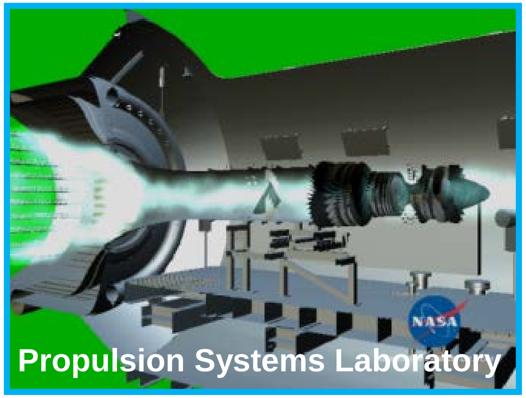
Transonic and Supersonic Propulsion Wind Tunnels
- Advanced propulsion concepts
- Inlet/Airframe Integration
- Internal/external aerodynamics



Engine Acoustic Research Facility
- Fan/nozzle acoustics research
- Simulate hot engine nozzles in flight
- Aerodynamic and Aeroacoustic measurements capabilities



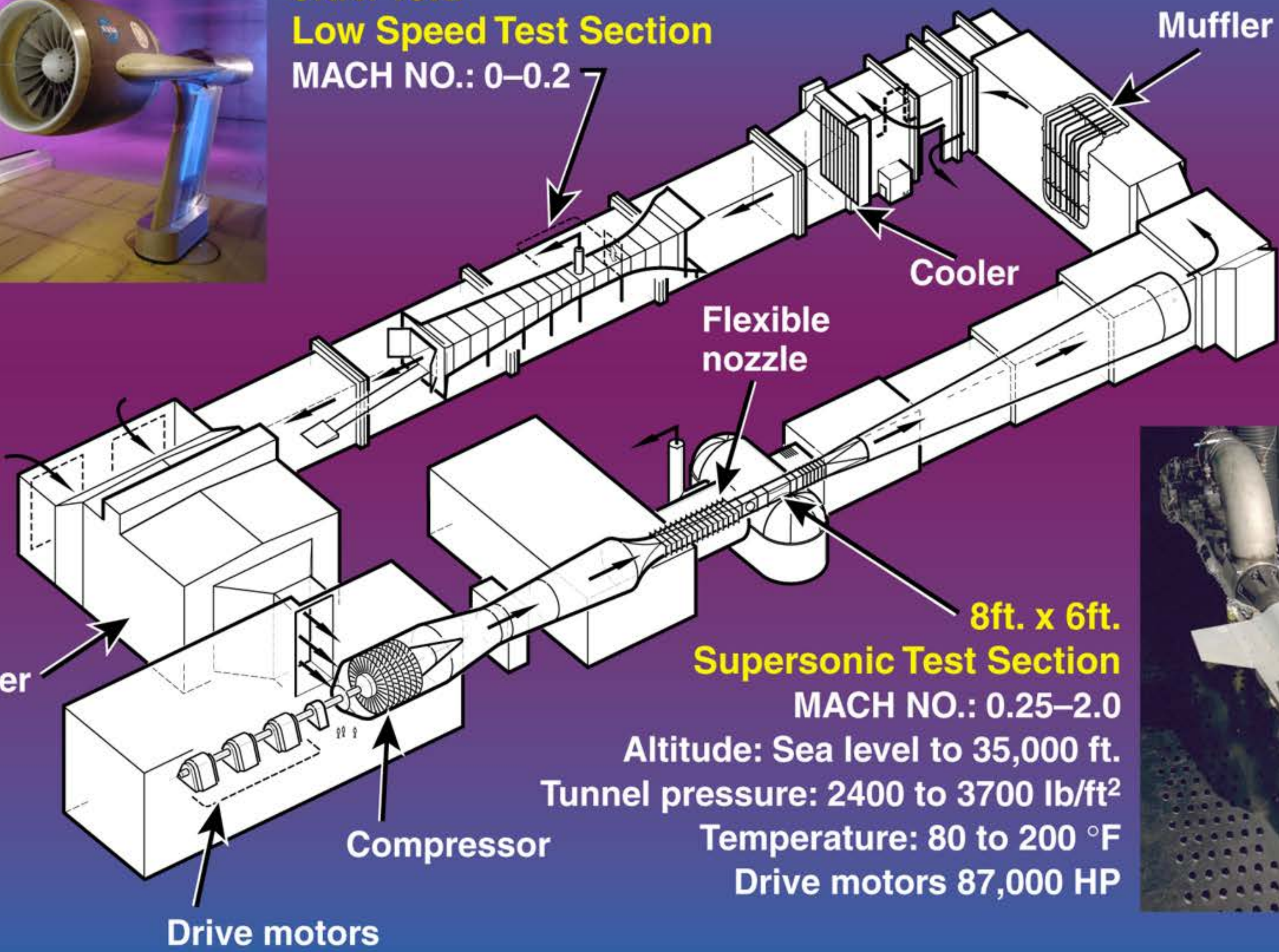
Largest Icing Tunnel in US
- Aircraft icing certification
- Ice protection systems development
- Icing prediction/code validation



NASA's only altitude full-scale engine facility
- Jet Engine Icing Research
- Engine operability/performance
- Nozzle-engine integration

Over 50 Versatile Engine Component Facilities
- Combustor and Heat Transfer
- Compressor and Turbine
- Inlets and Nozzles

8x6 SWT/9x15 LSWT Wind Tunnel Complex

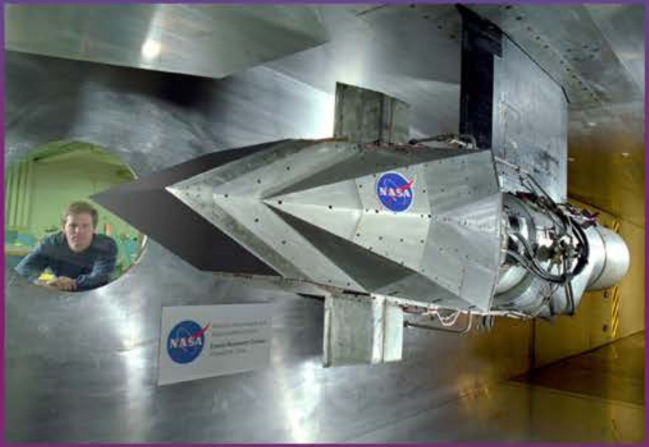


CD-98-77052

10x10ft. Supersonic Wind Tunnel

Test Section
10ft.x10ft.x40ft. long

Supersonic and Subsonic test modes
Aerodynamic–Closed loop
Propulsion–Open loop



Mach No.: 2.0 to 3.5
and 0 to 0.4 (240 knots)
Altitude: 50,000 to 150,000 ft.
Temperature: 60° to 680°F
Fuels: Liquid JP, hydrogen and oxygen
Continuous Operation: 250,000 hp drive motors
Remotely accessible real-time data display

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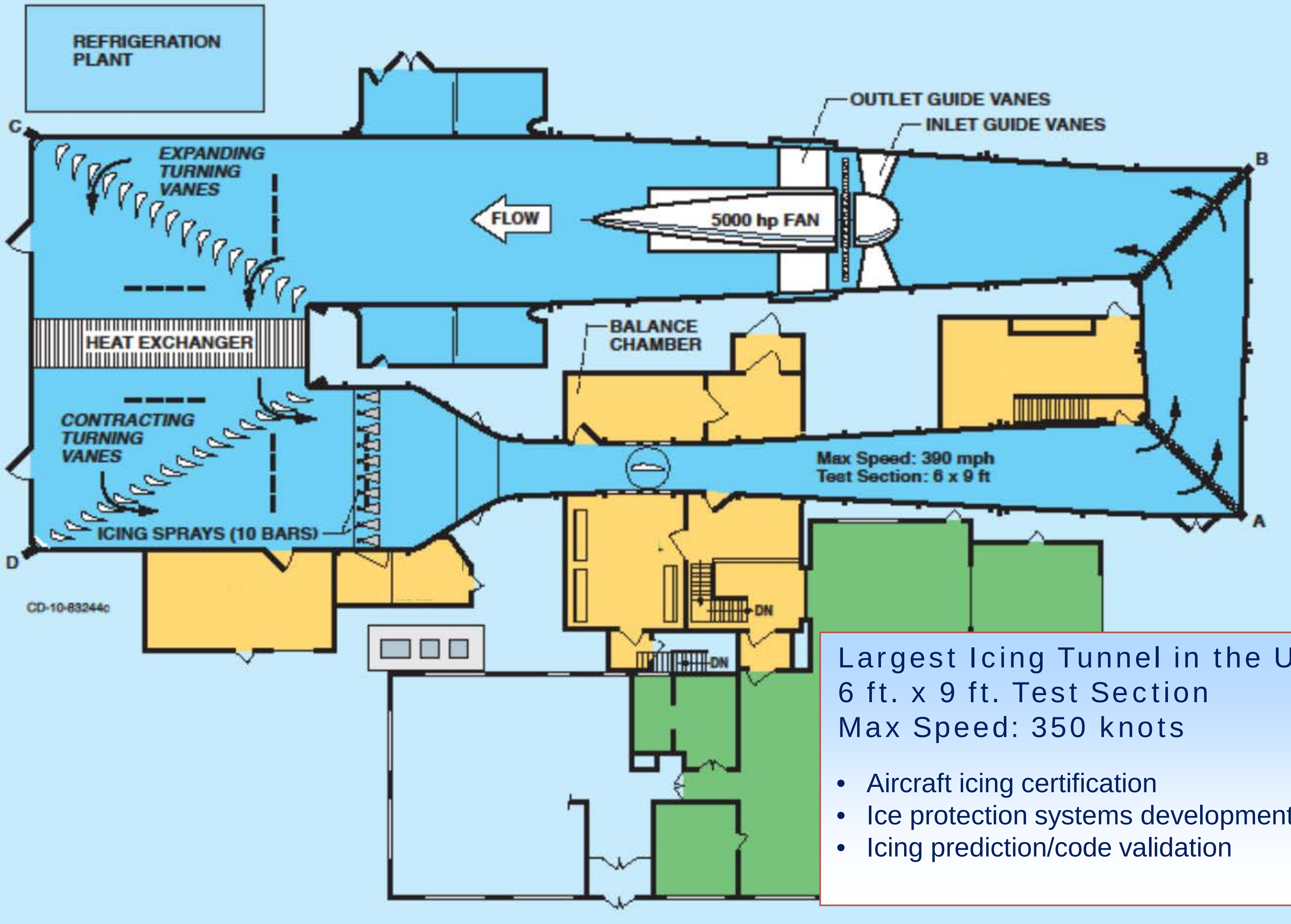
Icing Research Wind Tunnel



Largest Icing Tunnel in the US
6 ft. x 9 ft. Test Section
Max Speed: 350 knots

- Aircraft icing certification
- Ice protection systems development
- Icing prediction/code validation

Propulsion Systems Laboratory (PSL)

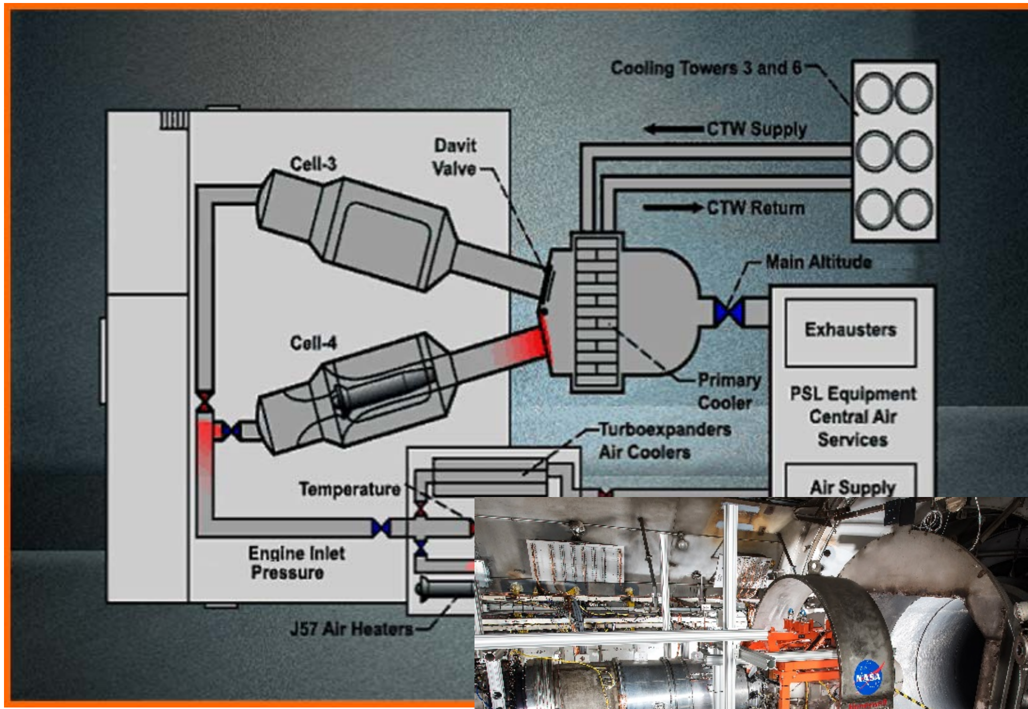
NASA PSL is one of the Nation's Premier Direct Connect Altitude Simulation Facilities for Full-Scale Gas Turbine Engine and Propulsion System Research

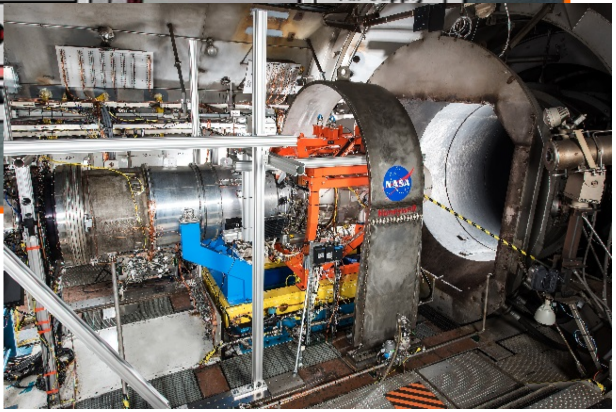
<u>**Capabilities/Applications**</u>

- **Continuous Flow at Full Flight Envelope up to Mach 4, 90,000 ft (-90 F)**

- Engine Operability and Stall Resistance
- High Altitude Performance
- General Aviation and Business Jets
- Engine Development
- Helicopter Turbo-shaft Engines

- <u>**Ice Crystal Research – Engine Icing Capability (new)**</u>



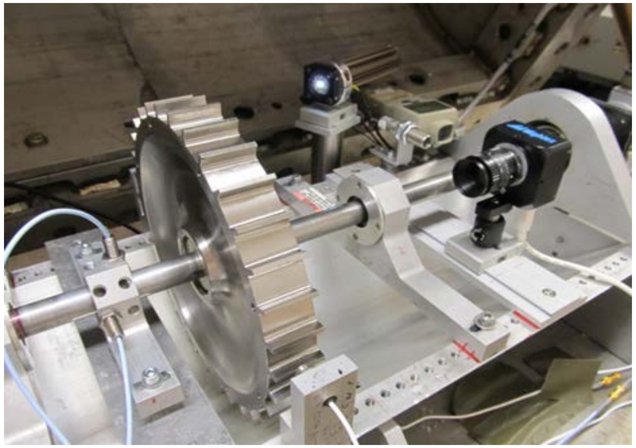


New Sensors and Techniques for Aircraft Engine Safety

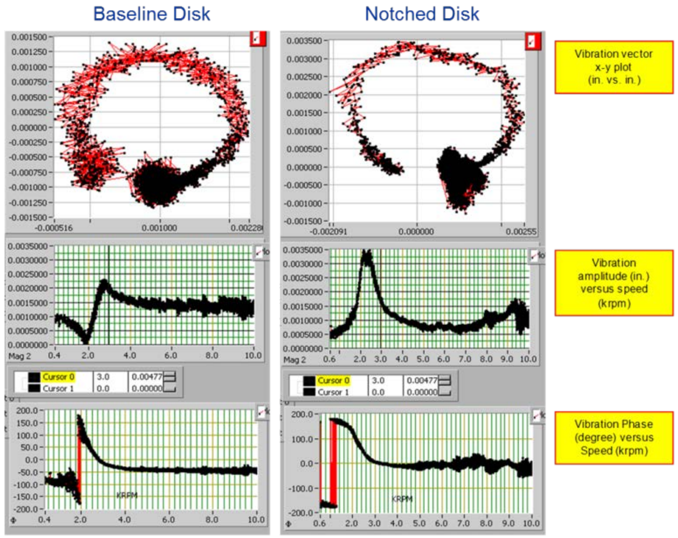
Motivation – Aviation Safety

- **NASA Aviation Safety Related Programs & Technologies**
  - Integrated Vehicle Health Management Project (IVHM)
  - Vehicle Safety Systems Technology Project (VSST)
  - ***Transformational Tool & Technologies (T3) Project***
- **Enhance & Improve Aviation Safety**
  - Typical practice is to rely on schedule-based inspection & maintenance
  - ***Goal is to develop new instrumentation and techniques that can detect pre-cursors to events in order that actions can be taken to prevent failures***

Turbine Disk Failure – June 2, 2006



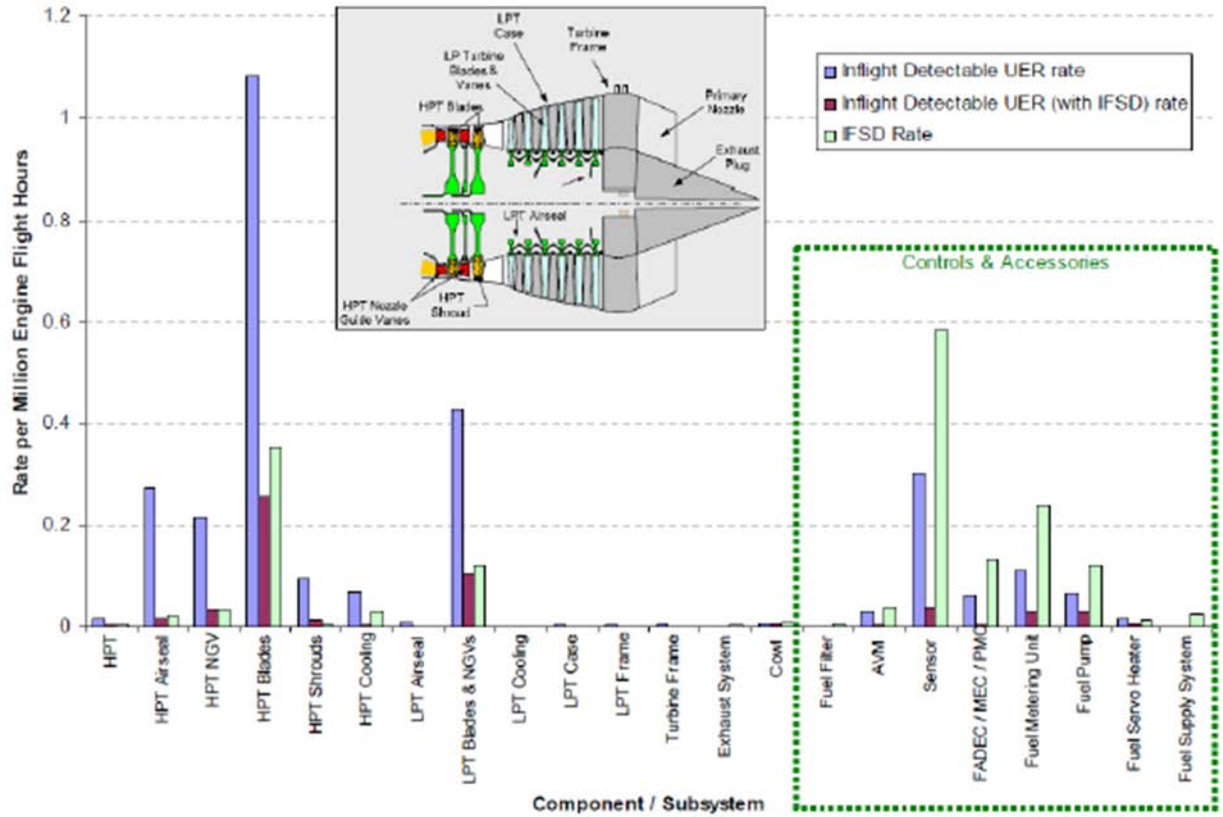
Crack Detection Experiments in GRC Rotordynamics Lab



Crack Detection Experiment Results

Motivation – Aviation Safety

- FAA Report AR-08/24 “Engine Damage Related Propulsion System Malfunctions”
- Damage in the HPT and HPC sections
  - **~32%** of damage events that caused engine removal for unscheduled maintenance
  - **~12%** of “in flight shut down” events

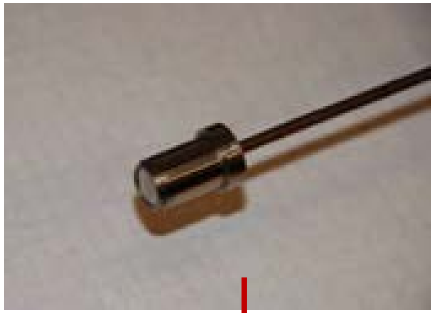


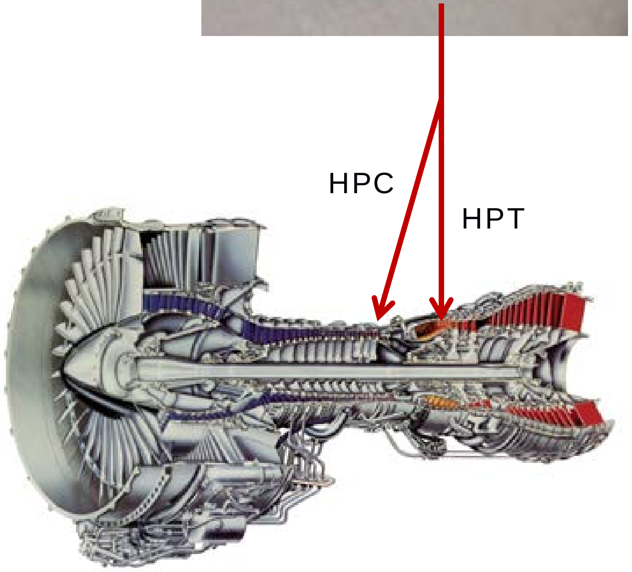
Steve Clark, Grace Balut Ostrom, and Sam Clark, Engine Damage-Related Propulsion System Malfunctions, DOT/FAA/AR-08/24, December 2008.

New Sensors - Microwave BTC Sensor

- Targeting sensors in the High Pressure Turbine (HPT) and High Pressure Compressor (HPC) sections
  - In-situ structural health monitoring for gas turbine engines
    - **Blade tip clearance to monitor growth & wear**
    - **Blade Tip Timing to monitor deflection & vibration**
  - Active closed loop turbine clearance control
    - **For every ~25um (~0.001)” decrease, SFC decreases ~0.1%, EGT decreases ~2 deg. F**
  - Key discriminator of microwave sensor technology……**Operation and Survivability at High Temperature**
- ***New sensors need to “buy” their way onto the airplane…need strong justification.***

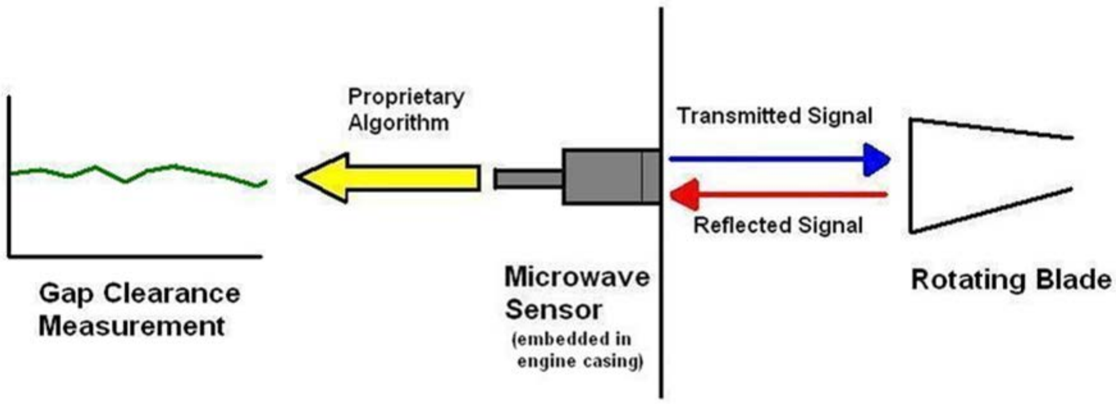
24 GHz Microwave Blade Tip Clearance Sensor (Meggitt)



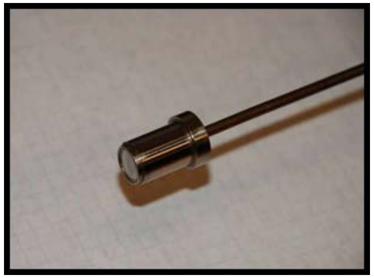


MWBTC Theory of Operation

- Theory of Operation
  - Probe operates as a field disturbance sensor
    - Probe is both a transmitting and receiving antenna
  - The sensor sends a continuous microwave signal towards a target and measures the reflected signal
  - The motion of the blade phase modulates the reflected signal
    - Changes in amplitude & phase directly correspond to distance between the blade and the sensor
    - The time interval of when the blade passes through the field is measured to provide timing

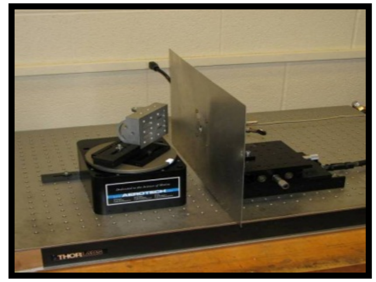


MWBTC Sensor History & Usage at NASA GRC



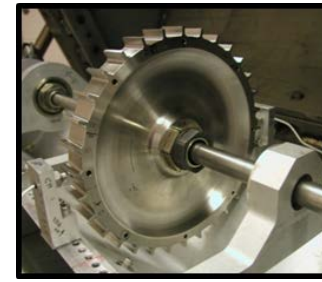
Microwave Clearance Sensor

Sensor Evaluation on High Pressure Burner Rig



Sensor Calibration Rig

Clearance Evaluation on Large Axial Vane Fan



Rotordynamics & Fault Detection in Lab Testing

- Microwave tip clearance sensors developed by **Meggitt** (formerly Radatec **)** through the NASA Small Business Innovation Research (SBIR) Program and other commercial R&D contracts
  - **2007-2008, First Generation, 5.8 GHz probes & system via Phase III SBIR**
  - **2009-2010, Second Generation, 24 GHz probes & system via commercial contracts**
  - **2011-2015, Follow-on contracts additional probes & hardware developed**

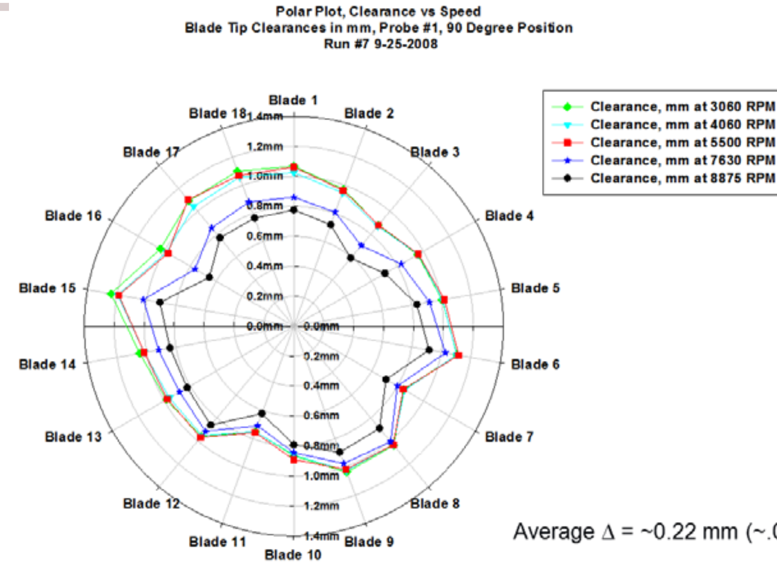
Clearance & Timing Evaluation on NASA Turbofan

- Several evaluation experiments have been accomplished at NASA GRC from FY08 to present
  - **Successfully demonstrated microwave BTC sensors on an on-wing engine ground test on a large air transport vehicle at the NASA Armstrong Flight Research Ctr.**
  - **In the process of developing its use for engine health monitoring.**

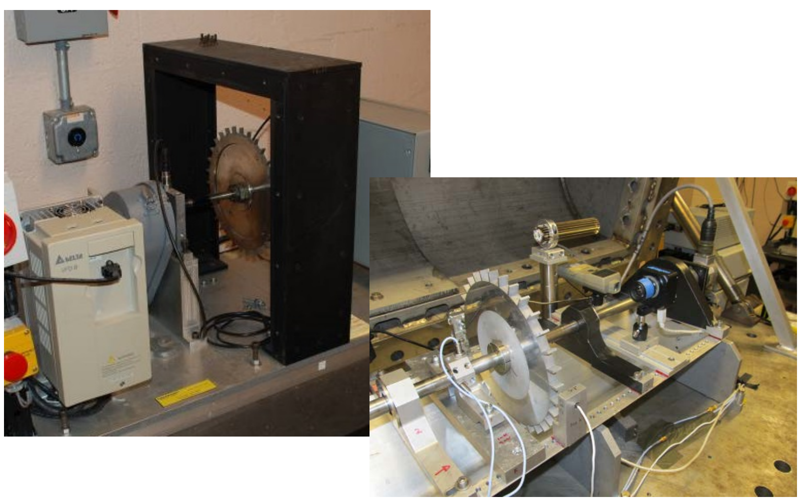
VIPR Engine Ground Test

Key Experiments to Date

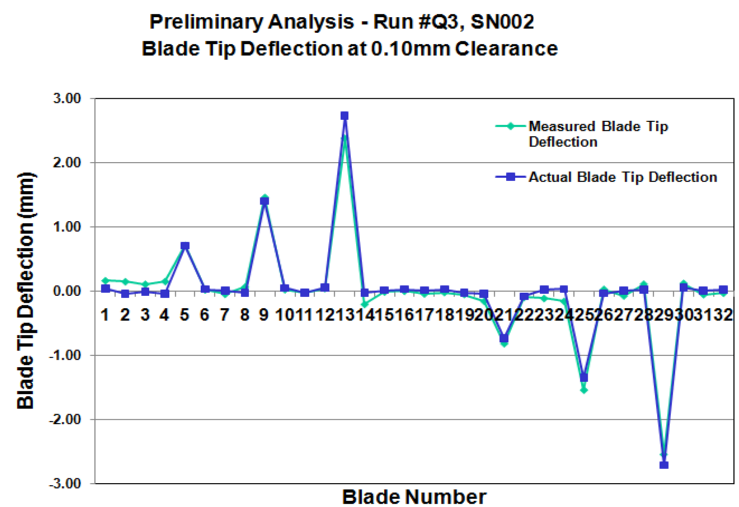
Blade Tip Clearance Evaluation on NASA Turbofan



Average Δ = ~0.22 mm (~.009")



Blade Tip Timing Evaluation on GRC Spin Rigs

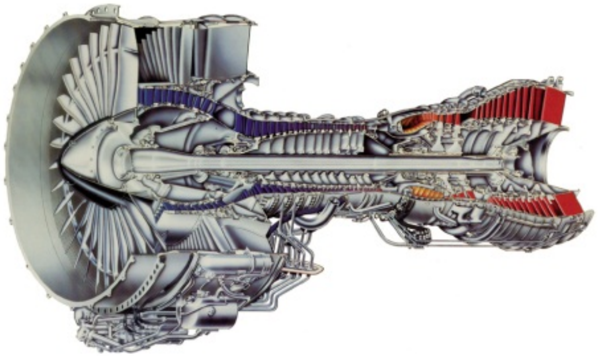


Vehicle Integrated Propulsion Research (VIPR) Test Entries

– Series of on-engine tests for the evaluation of new propulsion heath monitoring / structural health monitoring sensor technologies

– Test Summary
  - 2011
    - **Successfully EMI/EMC cleared microwave sensors for use on the engine**
  - 2013
    - **1 microwave sensor was installed on an engine**
    - **Successfully survived acceptance run.**
    - **Preliminary data acquired**
  - 2015
    - **2 microwave sensors installed in the HPT of an engine**
    - **Acquired both blade tip clearance and timing data for engine health monitoring.**

Boeing C-17 Globemaster III



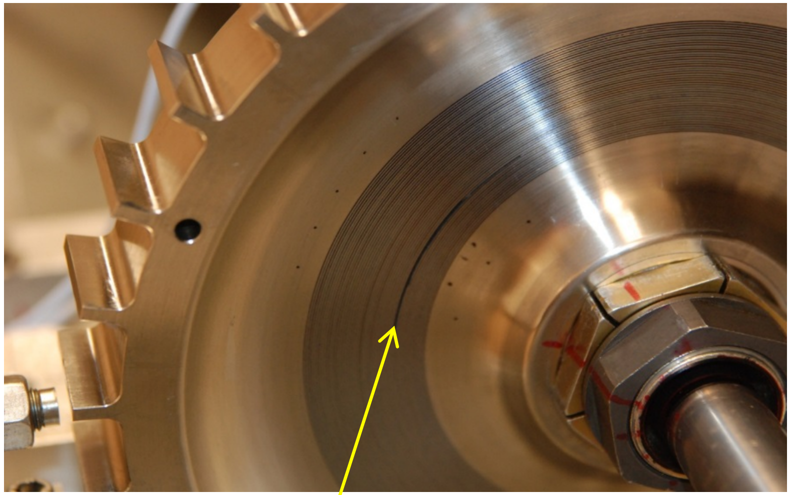
Pratt & Whitney F117 Turbofan Engine

New Techniques – Vibration Based Crack Detection

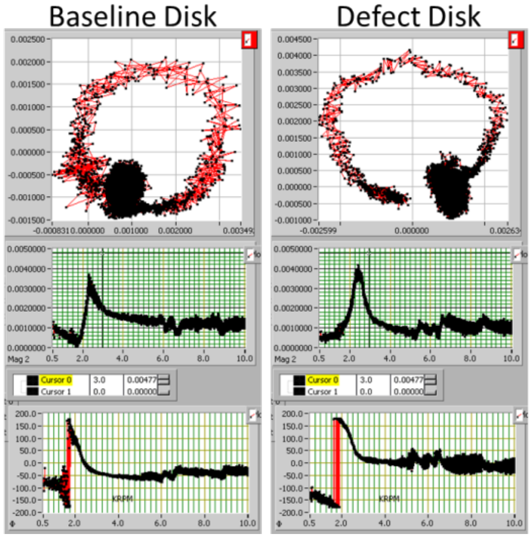
- Development and validation of new in-situ health monitoring and fault detection techniques for gas turbine engines

- *Vibration sensor based crack detection technique*
  - To determine if a defect such as a crack could be detected by analyzing the vibration response of a disk as it was operated at speeds up to 12 000 rpm

Simulated Turbine Disk with Defect



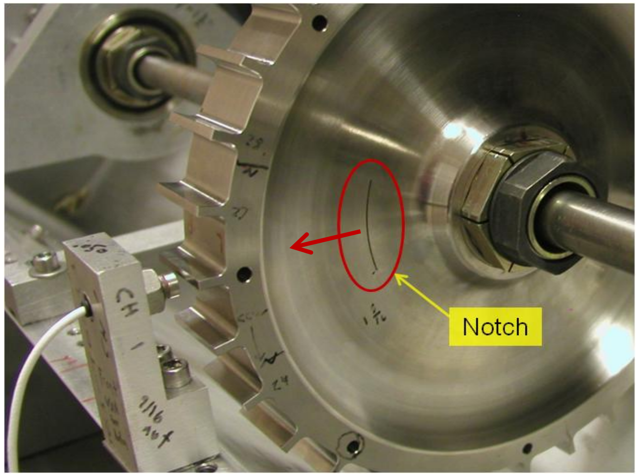
2" Long Notch



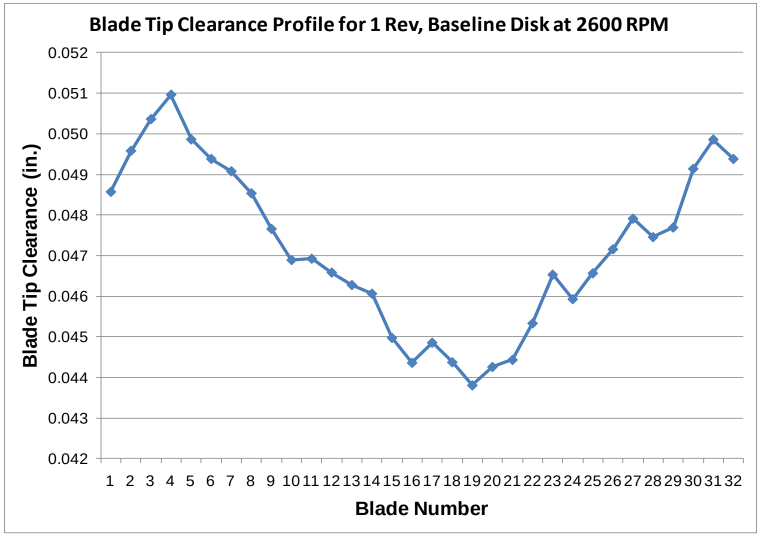
Vibration Response Data – 10K rpm

Vibration Based Crack Detection - Theory

- A crack creates minute deformations in the disk as it is being rotated
  - Opens up due to centrifugal loading
- This deformation creates a speed dependent shift in the disks center of mass
- This shift can be detected by analyzing the vibration response (radial motion) of the disk-rotor system as it is operated over a range of speeds
  - ***Synchronous whirl of disk-rotor system***
  - Amplitude and phase of the synchronous (first harmonic) component of the radial displacement
  - Measured by blade tip clearance sensors for 1 revolution varies as a f(x) or speed



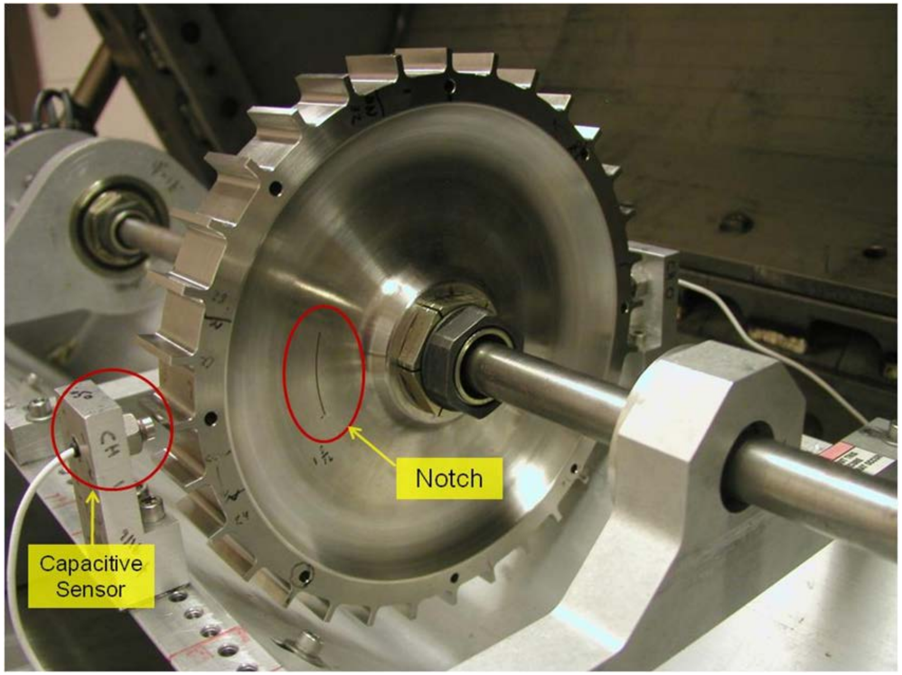
Notched Disk



Vibration Based Crack Detection – Experimental Setup

- Introduced a 2” (50.8mm) long notch on a simulated engine disk to imitate a crack
- Vibration response (radial motion) was measured using blade tip clearance sensors
- Two disks were tested
  - Clean “undamaged” baseline disk
  - Defect disk with notch
- Operated disks at speeds up to 12000 RPM on our High Precision Spin Rig to simulate rotational speeds in an engine.

Notched Disk



Disk Specifications:

Material	**Haynes-X-750**
Diameter	**9.25” (235 mm)**
Rim Thickness	**1.25” (31.75 mm)**
Bore Thickness	**1.00” (25.4 mm)**
Web Thickness	**0.10” (2.54mm) at thinnest point**
Weight	**10.75 lb (4.88 kg)**
32 Blades	**1.25” w x 1/8” t x 1/3” h (31.75mm w x 3.30mm t x 8.38mm h)**

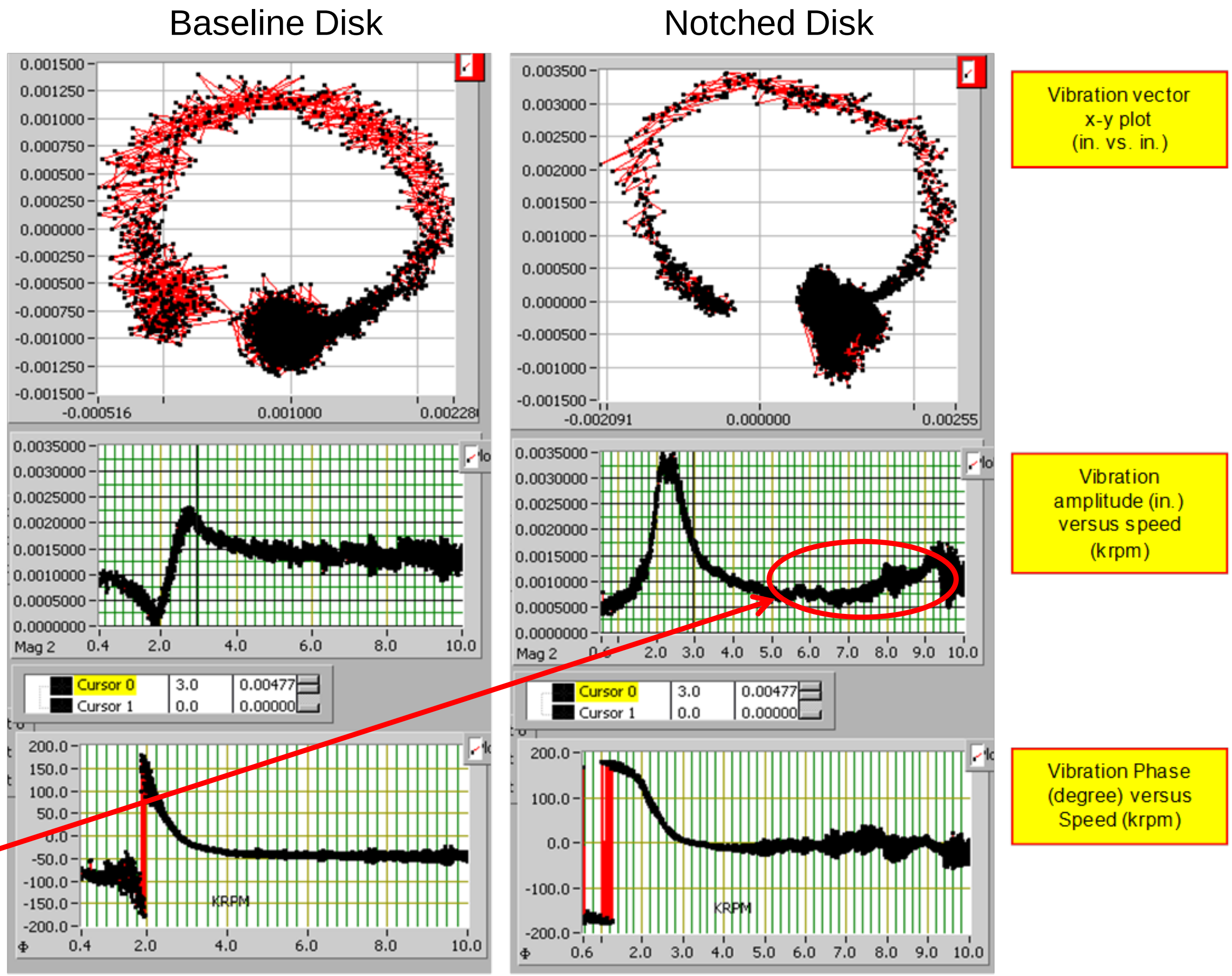
Vibration Based Crack Detection – 10000 RPM Multiple Cycle Test Run

Baseline disk results

- Based on Jeffcott rotor model
- Amplitude peaks and the phase shifts 180 degrees as the system goes through the first critical speed
- Amplitude and phase values stabilizes in the post-critical regime
- The combined disk-rotor system is rotating about a common center of mass

Defect disk results

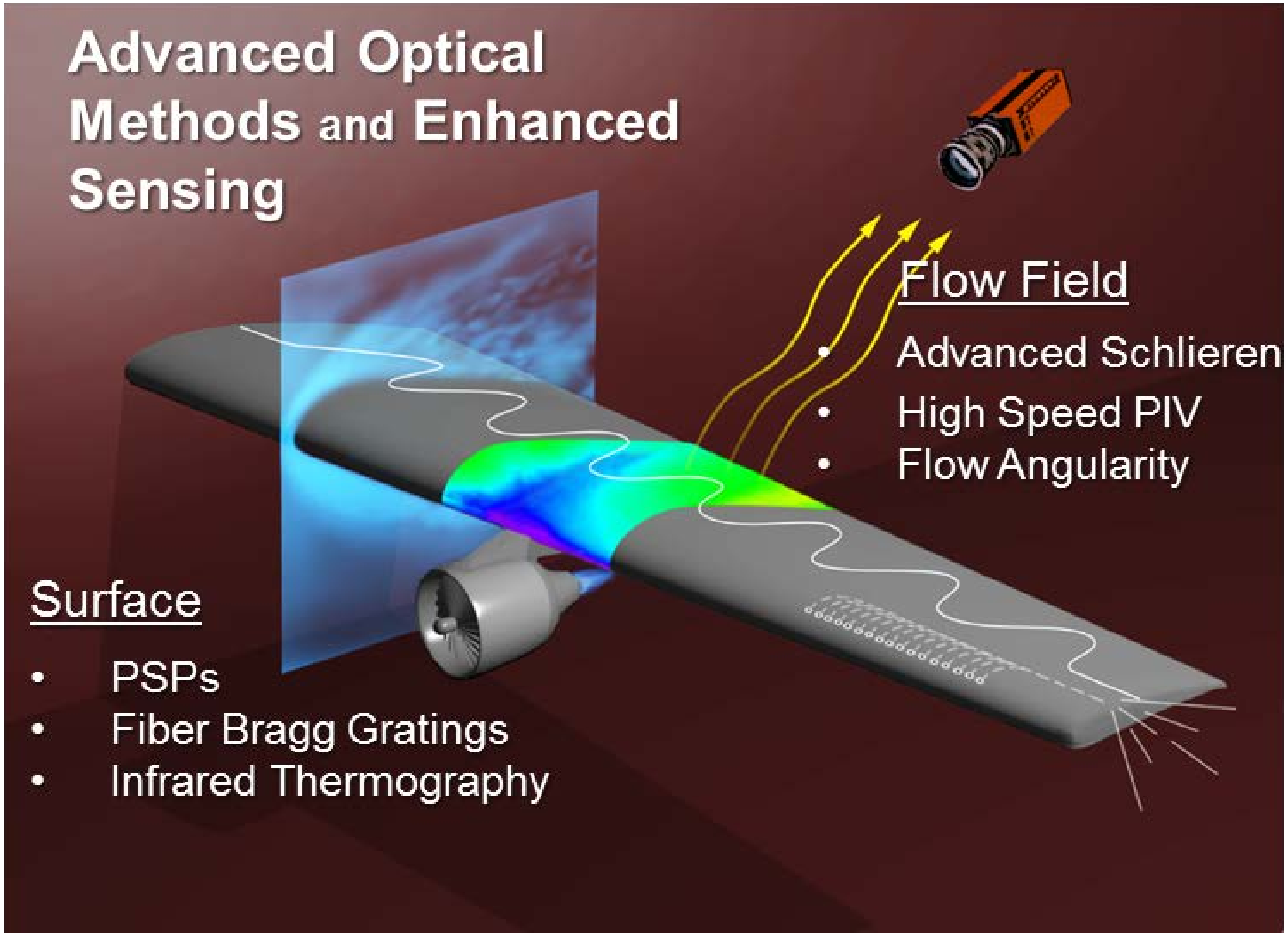
- In the post-critical region the crack induced shift in the disks center of mass grows and starts to dominate the overall vibration response
- Expect speed dependent change in amplitude in the post critical speed region {f (ω^2)}
- Expect variation in vibration vector orbit



10000 rpm Multi-Cycle Results

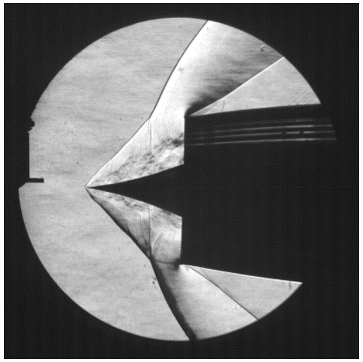
Advanced Measurement Techniques for Aeronautical Evaluation and Test Facilities

Optical techniques are everything!!



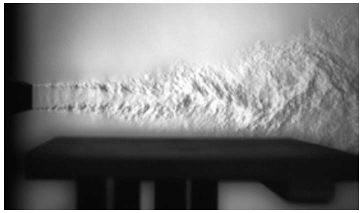
Schlieren Flow Visualization Technology at GRC

- **Conventional Schlieren**
  - Employs traditional mirror, knife edge cut-off set up with through optical access in the test facility
  - Conventional Systems are available in the in 8x6 SWT, 10x10 SWT, 1x1 SWT and 15cmx15cm SWT



Large Scale Low Boom Inlet Test - 8x6 SWT

- **New Advanced Techniques in development (more robust, more portable, greater viewing capability)**
  - Background Oriented Schlieren (BOS)
  - Focusing Schlieren

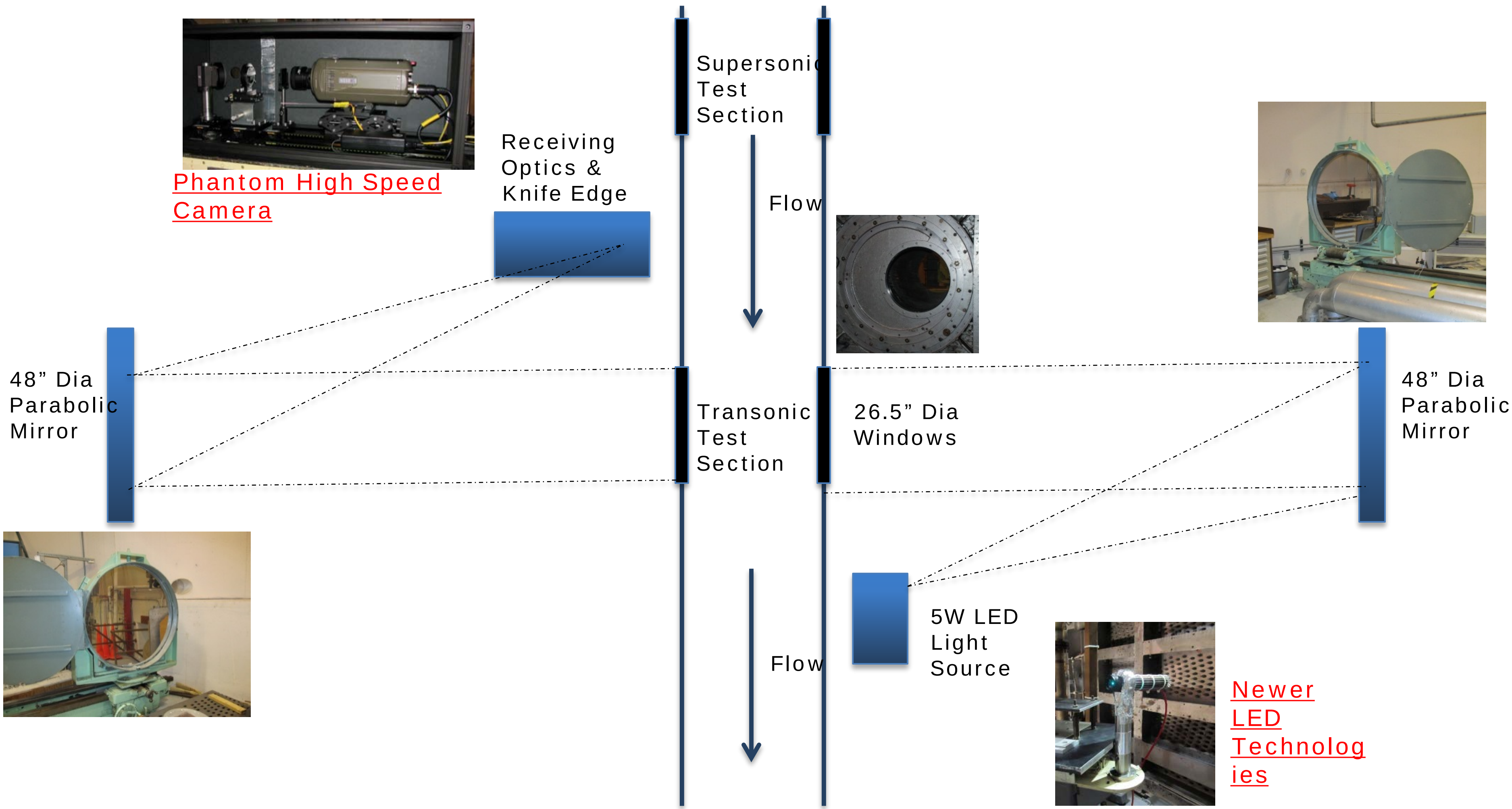


Jet Surface Interaction Tests – Engine Research Bldg

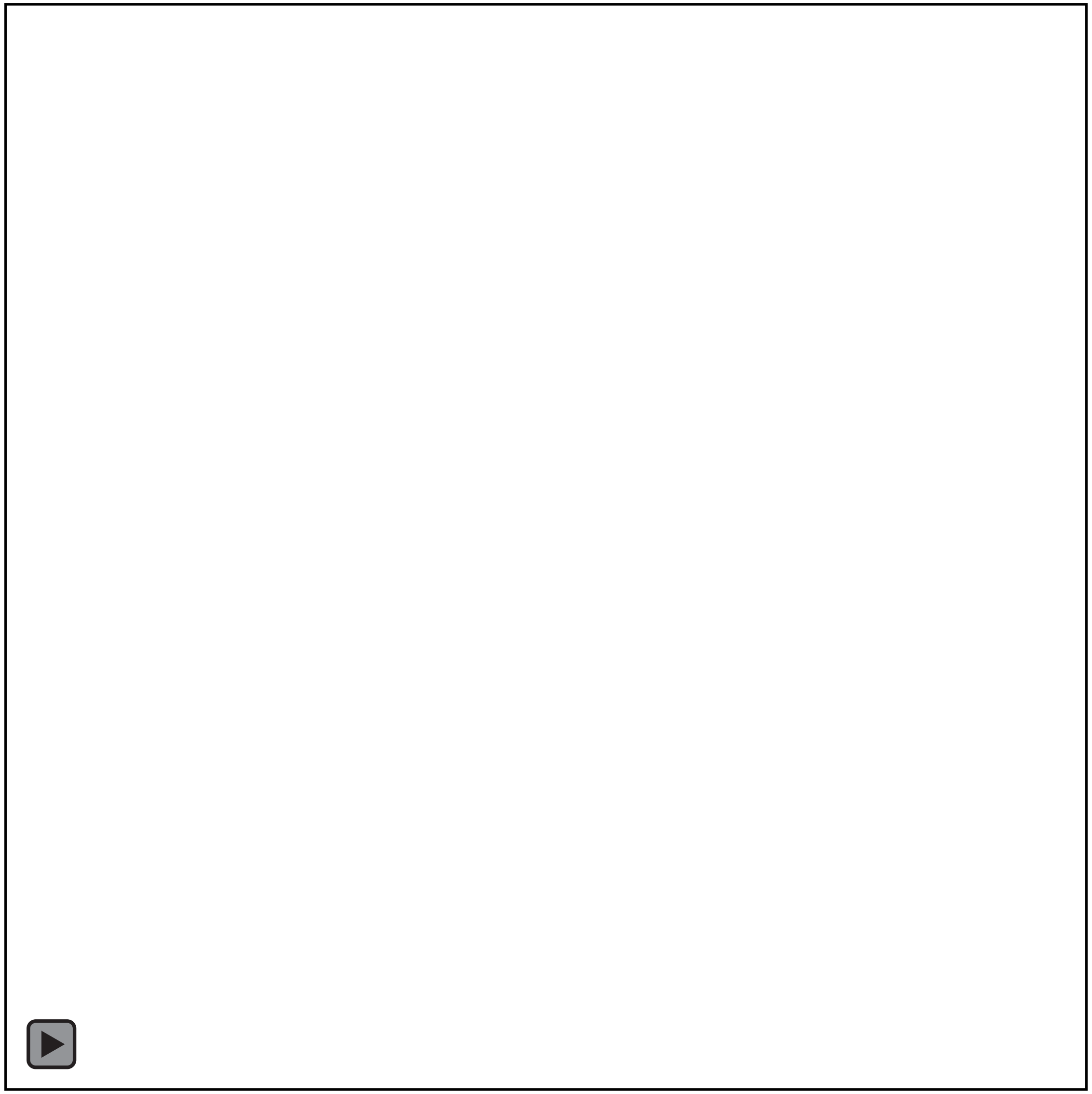
- **Overall Goal**
  - **Transition schlieren from a flow visualization to a quantitative flow measurement tool**
  - **Allow better simulation, measurement and validation of flight conditions that a "vehicle" is experiencing in our test facilities**

Conventional Schlieren - 8x6 SWT

- Conventional Knife Edge Schlieren System - Horizontal Z-Configuration

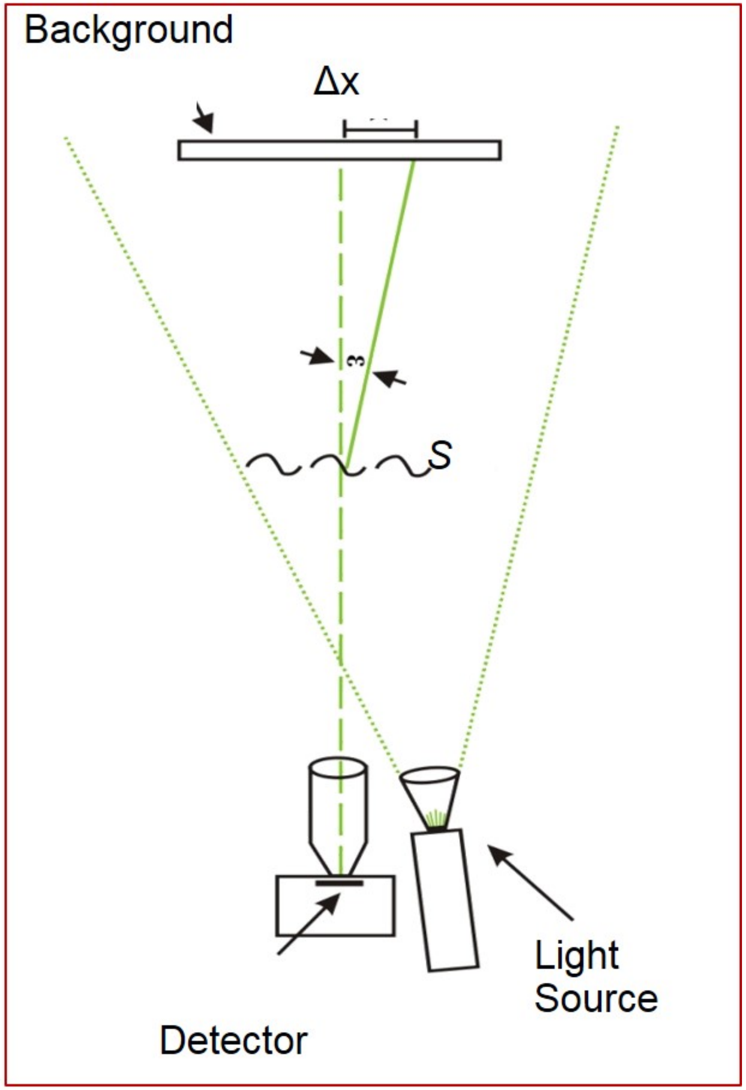


Conventional High Speed Schlieren
Large Scale Low Boom Inlet Test – 8x6 Supersonic Wind Tunnel



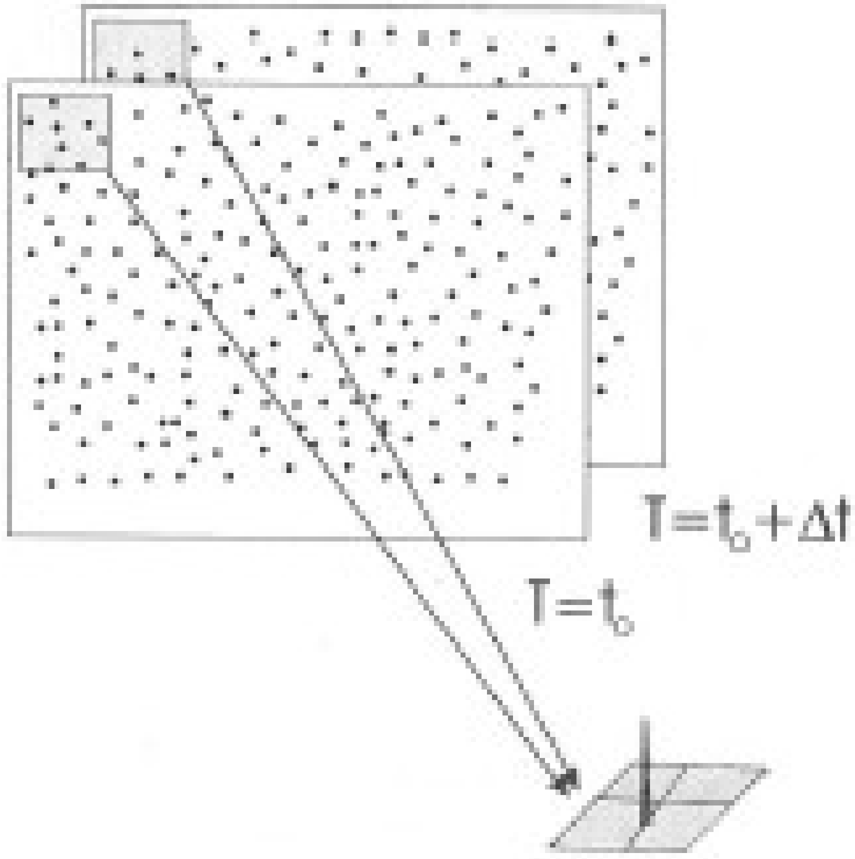
Background Oriented Schlieren (BOS)

- BOS is a more recent development of the schlieren and shadowgraph techniques used to non-intrusively visualize density gradients.
- Based on an apparent movement of the background when imaged through a density field onto a detector plane.
- BOS captures the density field but only requires a CCD camera, light source, and a high-contrast background.



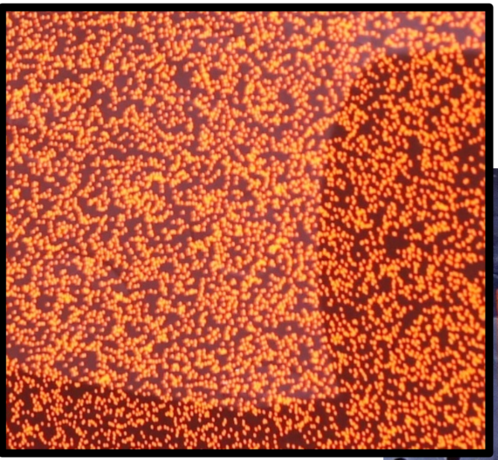
BOS

Theory: BOS Cross-Correlation Processing

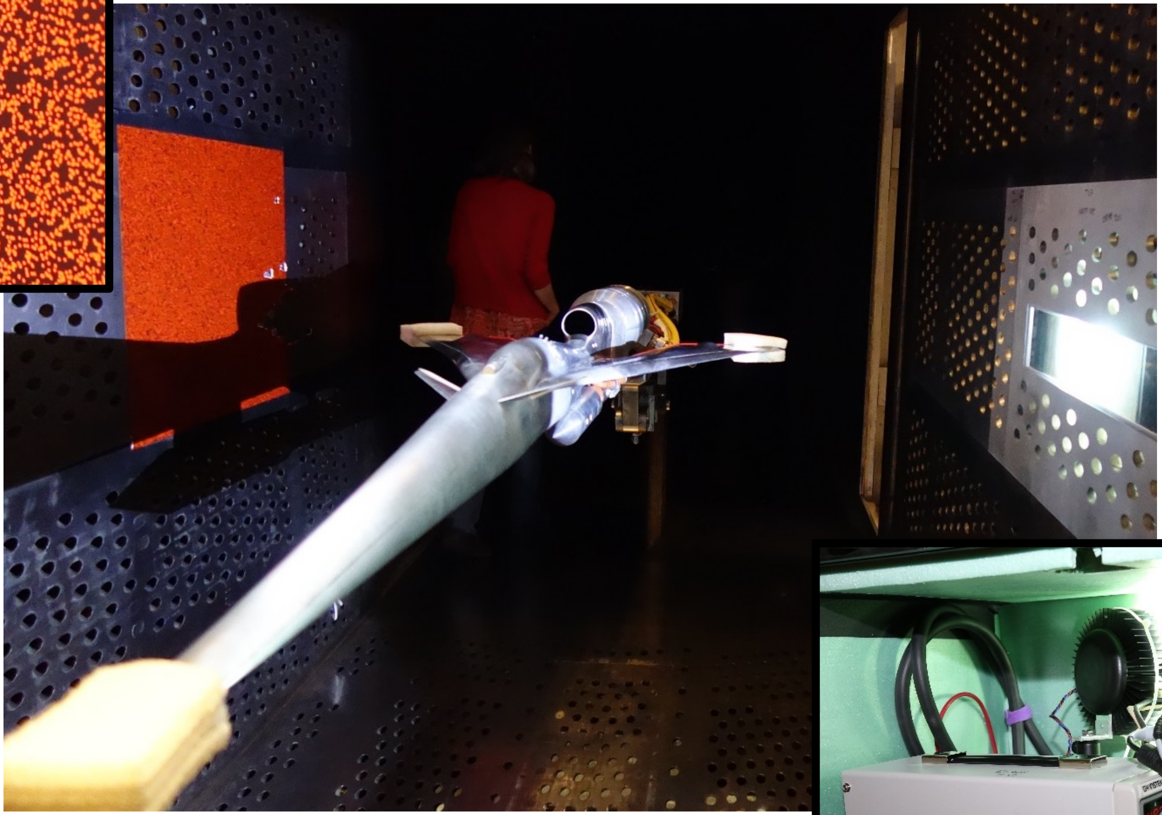


- It is necessary to take a reference (or Wind-Off) image
- Wind-On images are compared to the reference image via cross-correlation algorithms
- Both the reference image and the Wind-On images are divided into sub-images
- Via Cross-Correlation, the apparent displacement of the background pattern due to diffraction can be calculated for each sub-image and a displacement vector field is produced
- The resulting vector field can be used to produce an image of the flow field's density changes akin to conventional Schlieren.

BOS Setup: NASA QueSST (Low Sonic Boom) Test

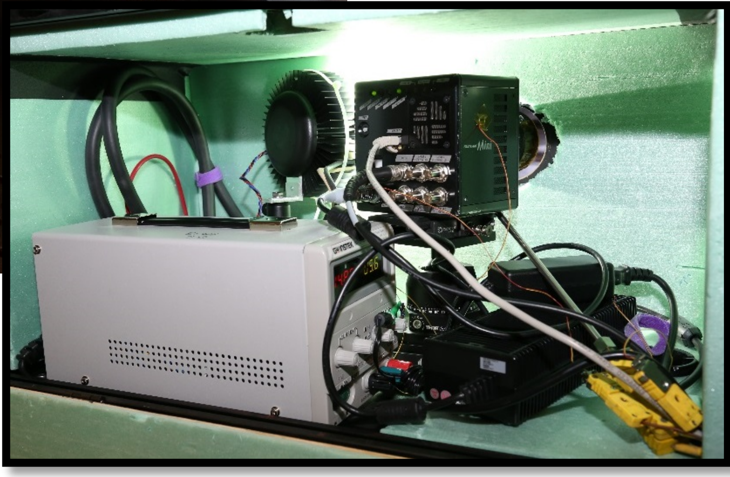


Background Pattern

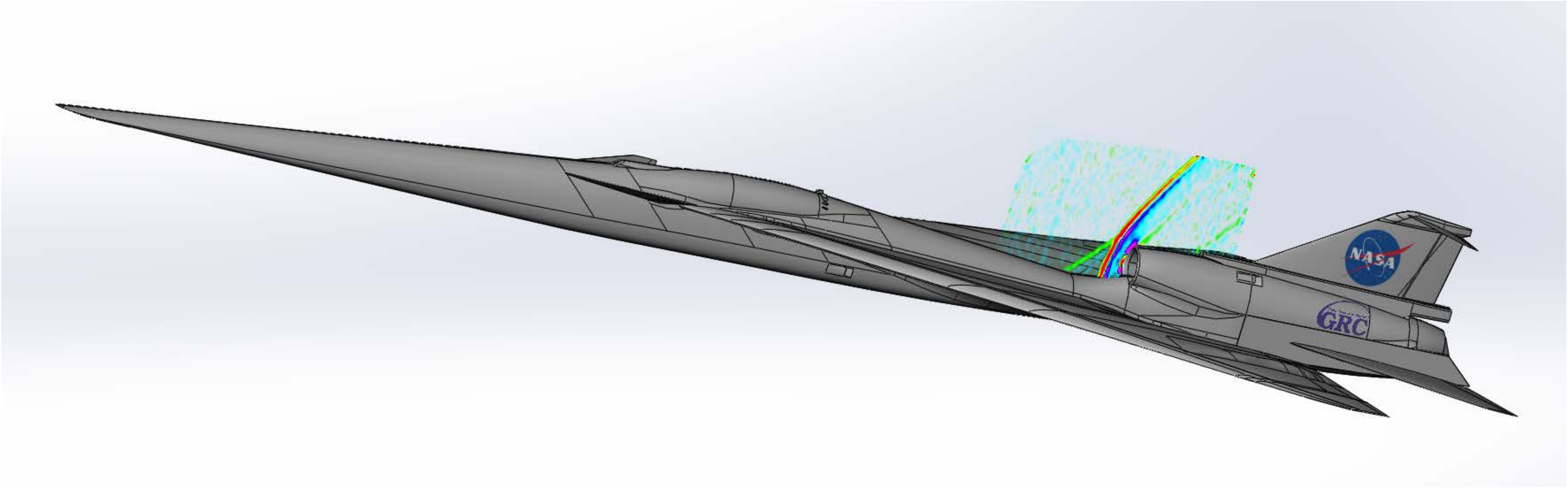


BOS installed in 8’ x 6’ SWT during QueSST testing

Camera and high-output LED installed in cooled box, mounted to exterior of tunnel wall

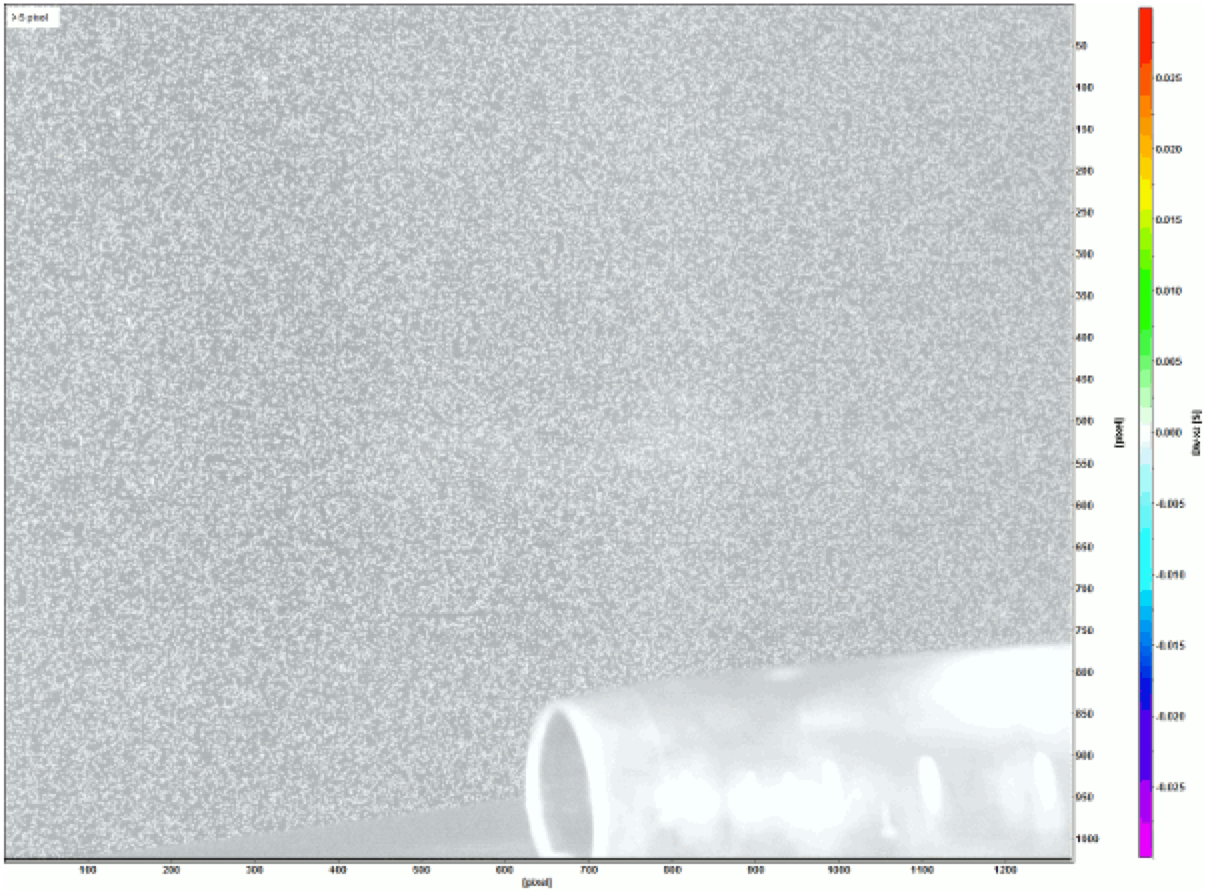


BOS: NASA QueSST Test Results



BOS produced flow image shown with QueSST CFD surface model

BOS: NASA QueSST Test Results



Mass Flow Plug sweep at Mach 1.4

Light Extinction Tomography

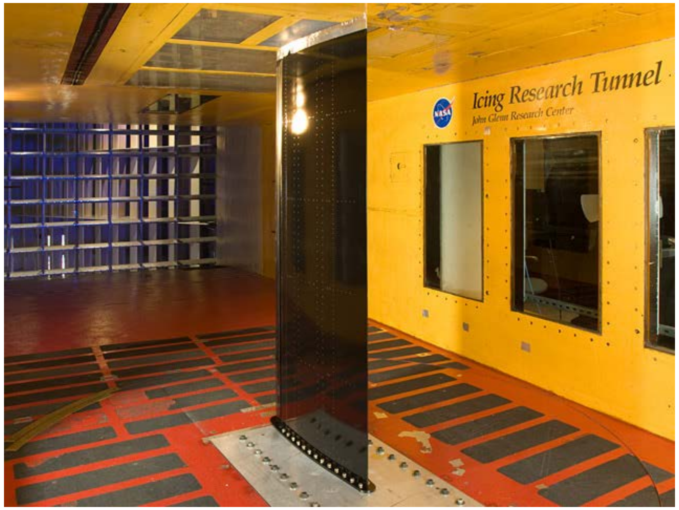
- New measurement technique developed to measure Icing Clouds used in the GRC Icing Test Facilities
  - Icing conditions are used to study the effects of ice on air vehicles, wings, aero surfaces, aero engines.
  - Light Extinction Tomography measures density and uniformity of these icing clouds

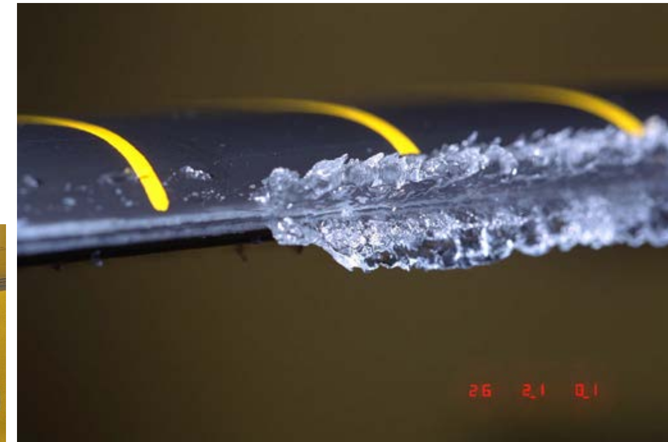
- Propulsion Systems Laboratory (PSL) – Icing effects on engines
- Icing Research Tunnel (IRT) – Icing effects on wings, tails, aero surfaces, etc.

Focus on Safety

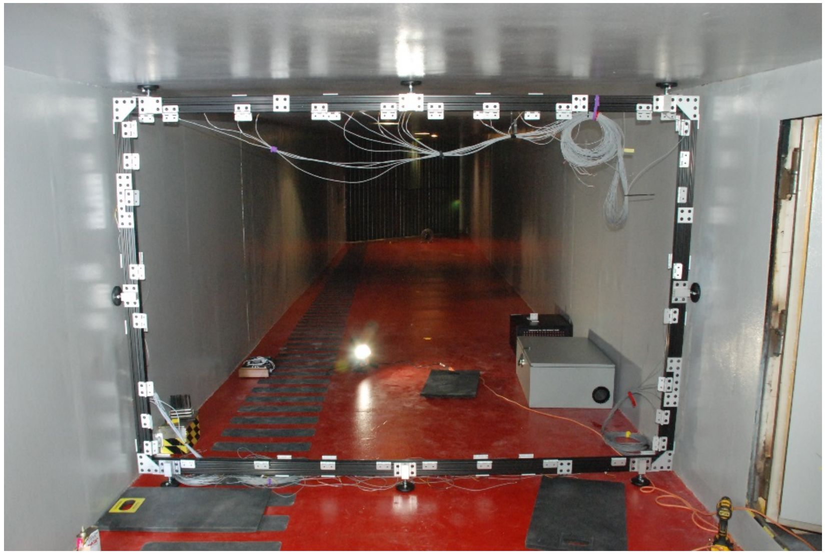
- **What happens during icing conditions?**
- **How to prevent or mitigate effects of icing?**

Icing Research Tunnel – Typical Experiments





IRT Icing Tomography System



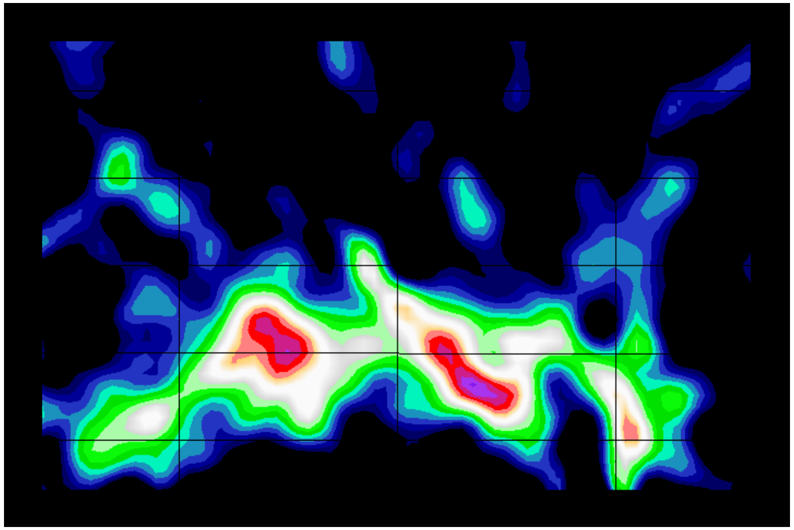
- Light extinction tomography
  - One light source fires, many detectors measure light extinction due to cloud/particles in the optical path from the lasers to the detectors
  - Sequential firing of light sources located around the periphery yields a 2D reconstruction of the cloud
  - Utilizes tomographic reconstruction techniques

- Prototype System Developed for the Icing Research Tunnel
  - 6’ x 9’ Square geometry
  - 60 light sources and 120 detectors

IRT Icing Tomography System - Results

Video of a typical icing cloud spray

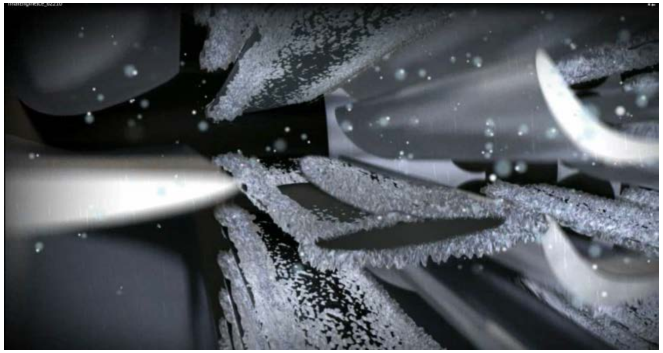
2D tomographic reconstruction of icing cloud spray



Propulsion Systems Laboratory (PSL)– Engine Icing

Aviation Safety Issue – Studies conclude there are over 140 loss of thrust control incidents thought to be a result of operating in high altitude ice crystal environment

NASA Aeronautics Test and Aviation Safety programs have invested in researching engine icing at NASA Glenn's Propulsion Systems Laboratory (PSL)



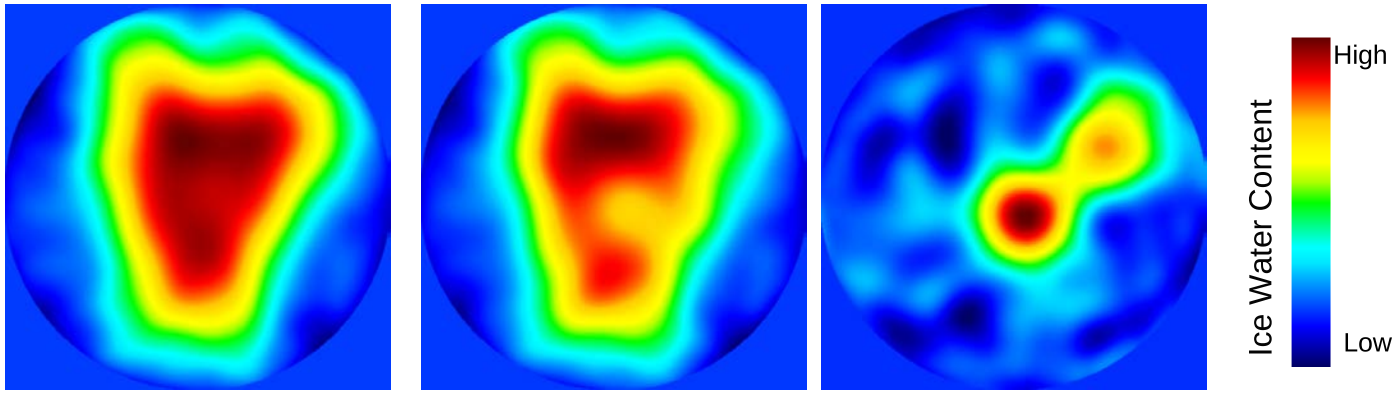
Ice Crystal System Capabilities		
	Min	**Max**
Alt. (ft)	4,000	40,000
Total Temp. (°F)	-60	15
Mach #	0.15	0.80
Flow (pps)	10	330
IWC (g/m³) (icing water content) Cloud Density	0.5	9.0
MVD (μ) (median vol.dia.)	40	60
Run Time	Continuous	

Understand, predict & mitigate effects of icing on engines

PSL Light Extinction Tomography Results

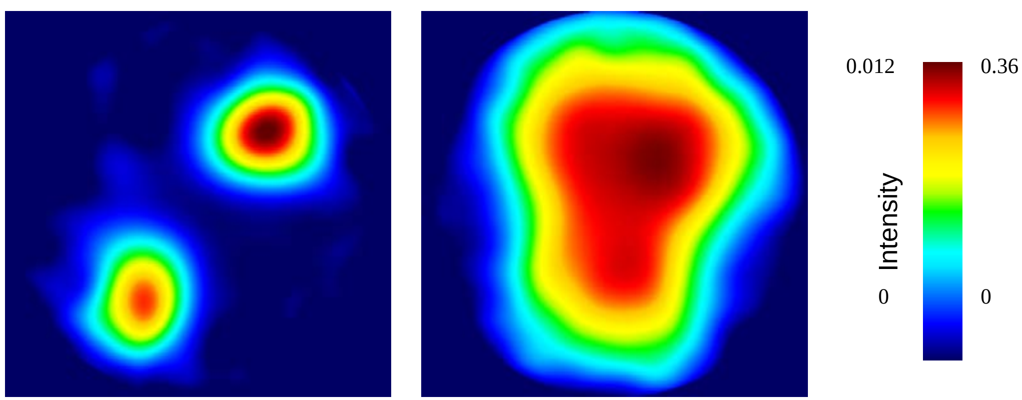
PSL Icing Tomography System

Icing spray nozzle diagnostic monitoring capability



30 Nozzles | 28 Nozzles | Difference

Extremes of spray system water flow

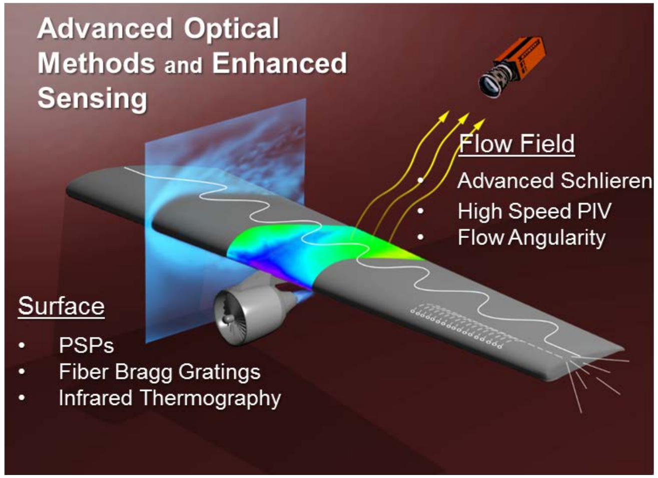


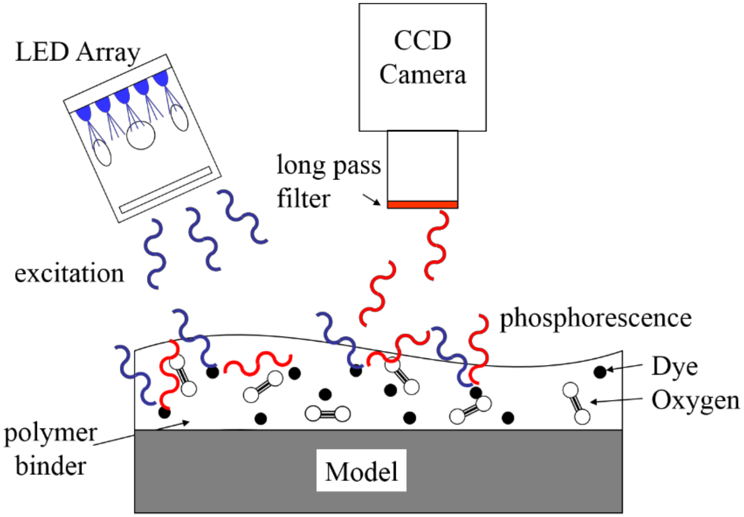
0.08 GPM | 8.2 GPM

Pressure Sensitive Paint (PSP) Measurement Technique

- Motivation: To achieve non-intrusive global pressure measurements on an aerodynamic surface
  - Image based technique
  - O2 sensitive fluorescent dye in a O2 permeable (polymer) binder
    - When a dye molecule is excited, it recovers to a ground state by emitting a photon of longer wavelength
    - In some materials, O2 interacts with molecule causing a non-radiative transition. Hence, known as O2 quenching
    - The rate at which this happens is a f(x) of partial pressure of O2
      - Higher pressure = Higher O2 = Higher quenching = Lower intensity of returned light
  - Intensity is related to pressure by the Stern-Volmer equation:

$$\frac{P}{P_{REF}} = A + B\,\frac{I_{REF}}{I}$$

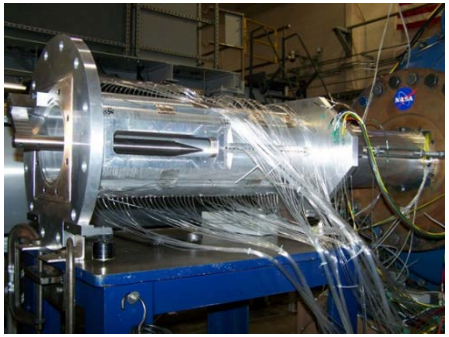




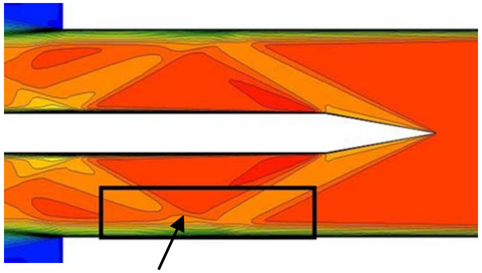
Pressure Sensitive Paint Measurement Technique

Pressure Sensitive Paint (PSP) - Examples

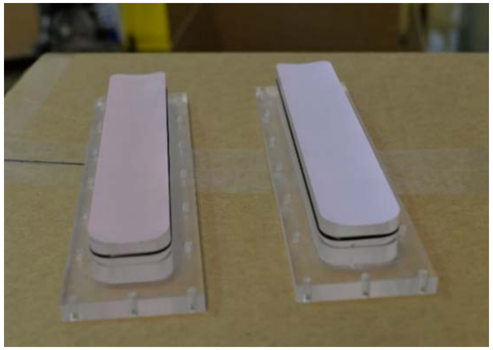
Shockwave Boundary Layer Interaction Experiment



Axisymmetric test section with shock generator installed



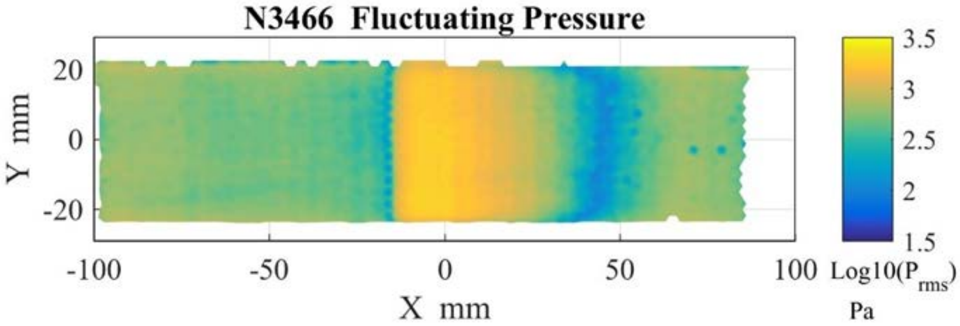
Shock wave boundary layer interaction area of interest



Fast PSP Windows

- The goal of this validation experiment was to better characterize the shock wave boundary layer interaction region with more refined and detailed measurements in order to better understand the this phenomena.

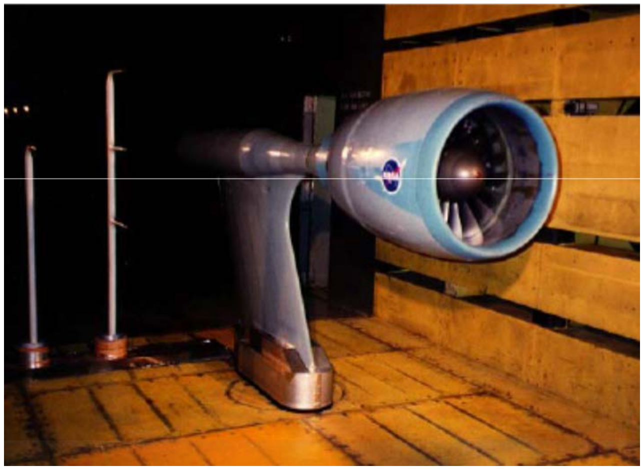
- PSP was applied to the inner flow surface side of specially made windows and imaged from the backside looking through the window to make unsteady pressure measurements (intensity based technique)



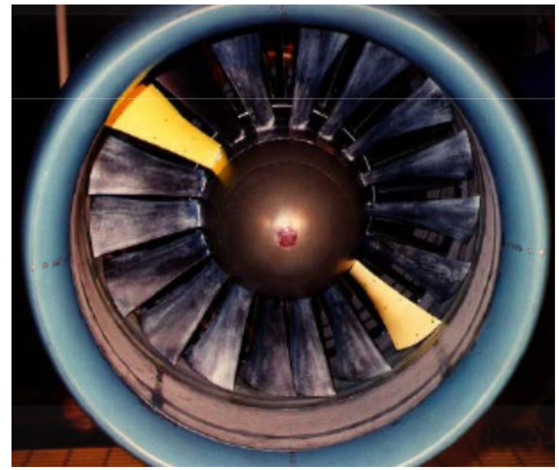
Mach 2.5 with 13.5 deg. shock generator at Reynolds numbers of 5E6:

Pressure Sensitive Paint (PSP) - Examples

Rotating PSP on 22” Turbofan Test Article – 9x15 LSWT

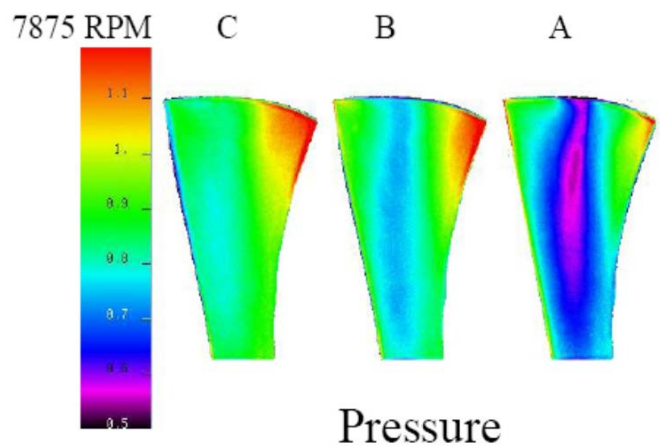


22” Diameter Turbofan – 9x15 LSWT



Painted Blades for PSP/TSP

- Rotating acquisition application, pulsed camera and lights synchronized to rig speed
- Usually acquire both temperature (using TSP) and pressure (using PSP). Temp data used to correct pressure data.



Blade pressure profiles for 3 different test conditions

Future of Aeronautics

- New Air Vehicle Designs (i.e. Blended Wing Body, etc.)
- Electric Propulsion / Hybrid Electric Propulsion
- Autonomous / Unmanned Air Vehicles
- Urban Air Mobility (UAM)

Student Opportunities at NASA GRC

- Summer Internships

  https://intern.nasa.gov/

- NASA Pathways Intern Employment Program

  https://www.usajobs.gov/Search?k=glenn

Acknowledgement

- I would like to acknowledge the **NASA Transformational Tools and Technologies (T3) Project** and the **NASA Aeronautics Evaluation and Test Capabilities (AETC) Project** for supporting the technology that was discussed in this presentation.

Questions ??