Update on the NASA Junction-Flow Experiment: Methodology and Future Plans

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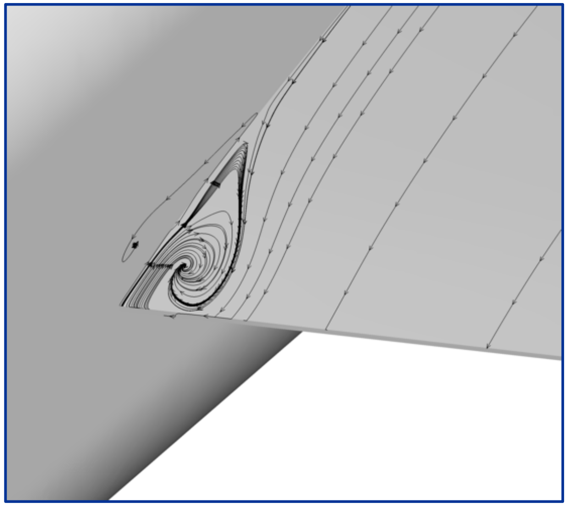
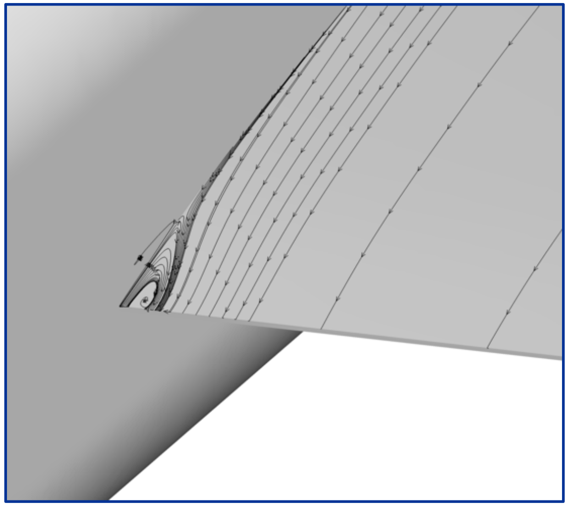
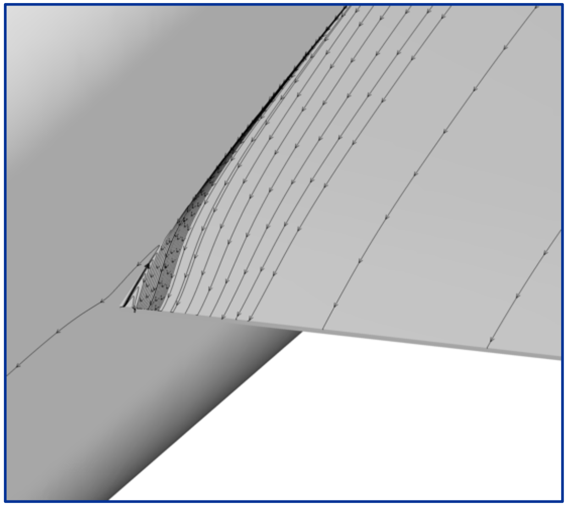
Introduction

- Junction flows are common features of practically all civil and military aircraft
- Junction flows typically exhibit regions of flow separation that adversely impact aircraft performance
- Wing-fuselage junctions often separate in the corner near the wing trailing-edge
- Turbulence models employed in RANS CFD are unable to reliably predict the onset and progression of the separated corner flow







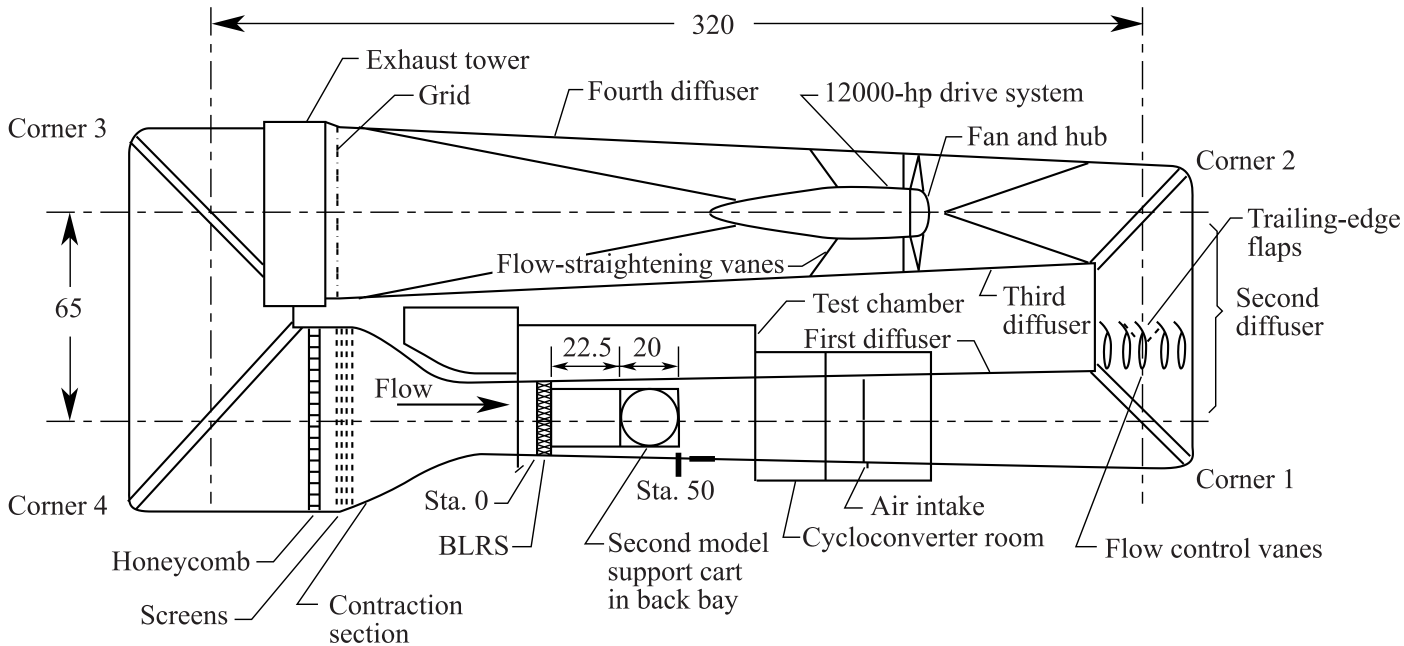
Introduction (cont.)

- Experimental validation-quality flow-field data in the junction region is needed to critically assess and improve upon existing turbulence models
- CFD validation experiment for a generic full-span wing-fuselage junction model at subsonic conditions
  - Detailed goals previously reported by Rumsey *et al*. (AIAA Paper 2016-1557)
- Ultimate goal is to provide a publicly-available flow field and surface data set with quantified boundary conditions, geometry, and measurement uncertainties
  - Allows for an unambiguous comparison between CFD calculations and experimental measurements
- First test entry with junction model conducted in Nov. 2017 – Mar. 2018
  - Initial report out of experiment details with sample results

Objectives

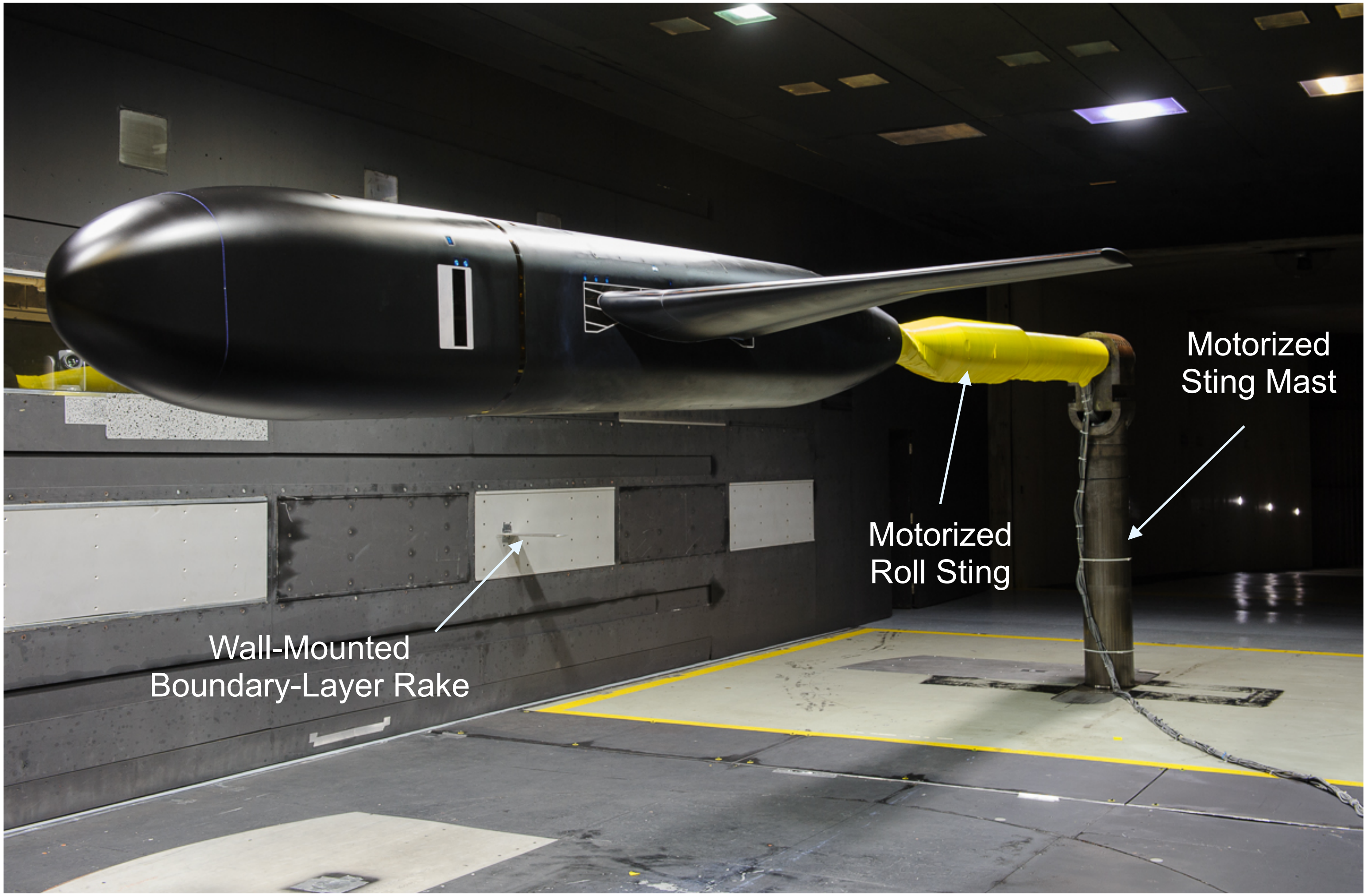
- Perform flow-field measurements via internally mounted laser Doppler velocimetry (LDV) systems
  - Mean velocities, Reynolds stresses, and velocity triple products
  - Measurements in the trailing-edge corner region of wing-fuselage junction
  - Measurements in the leading-edge region of the wing-fuselage junction
  - Measurements on the fuselage, upstream of the wing-fuselage junction
- Measure mean and dynamic pressures at selected locations on the wings and fuselage of the model
- Characterize boundary-layer transition on the model via infrared imaging
- Visualize surface topology of separated corner flow via oil-flow
- Characterize model and test-section geometry
- Measure test-section, diffuser, and boundary-layer rake pressures

14-by-22 Foot Subsonic Tunnel

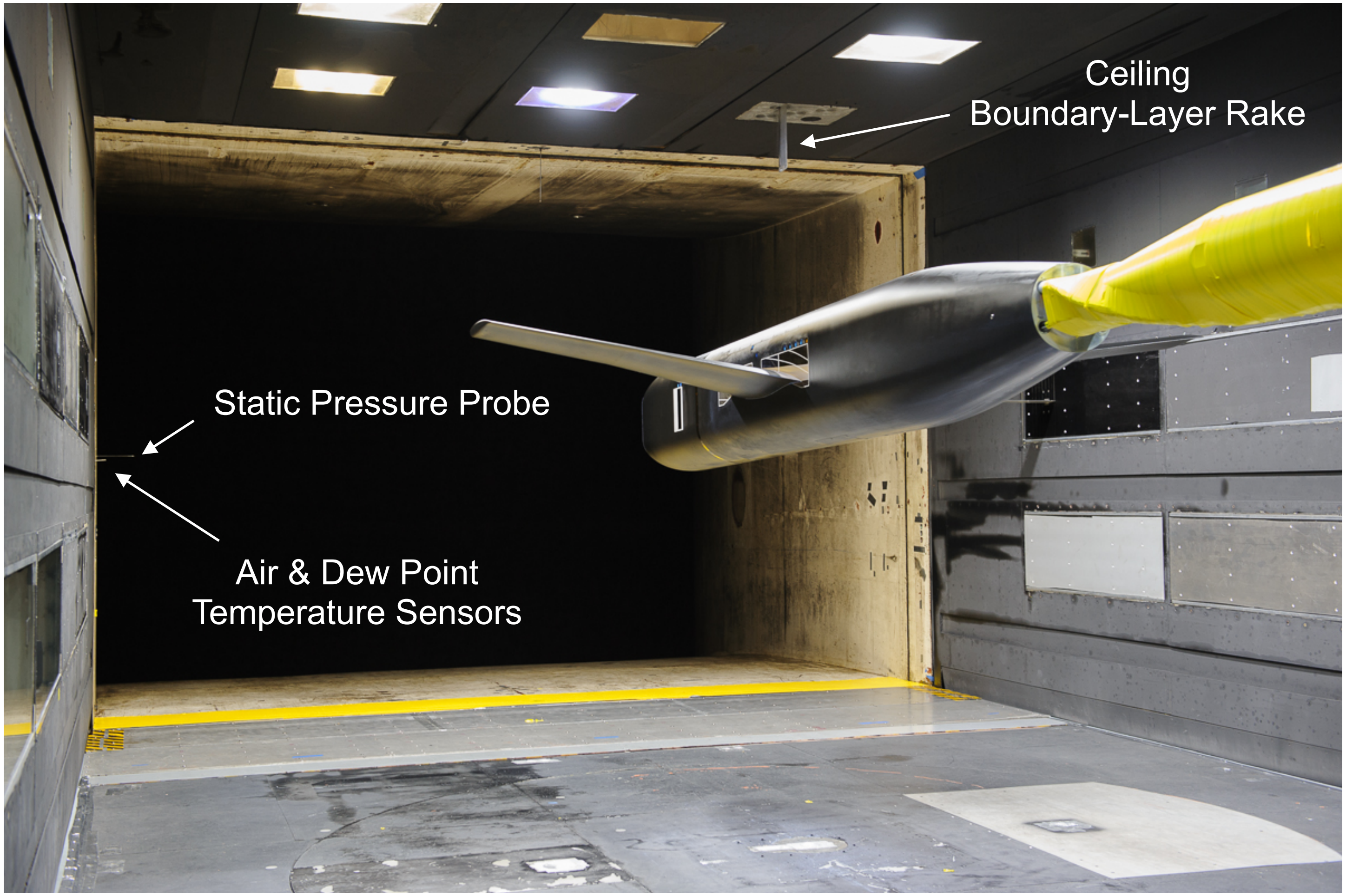


- Test section dimensions: 4.42 m high by 6.63 m wide by 13 m long
- Maximum freestream velocity: 103 m/s
- Free stream turbulence intensity: 0.07-0.08% at Q = 2.87 kPa (60 psf)
- Tunnel controller held chord Reynolds number fixed at 2.4 million
  - No temperature control, free stream velocity adjusted accordingly

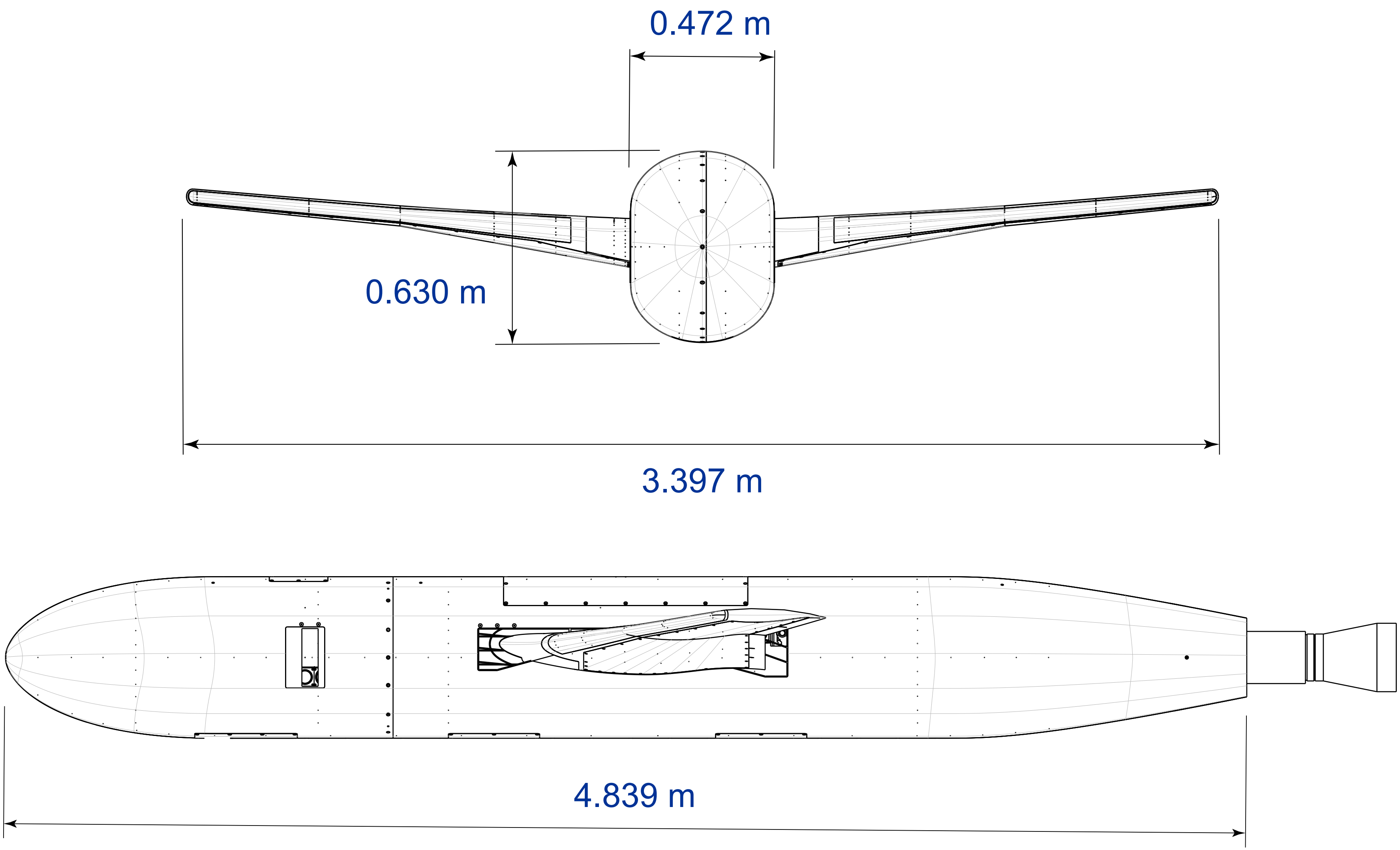
Wing-Fuselage Junction Model



Wing-Fuselage Junction Model

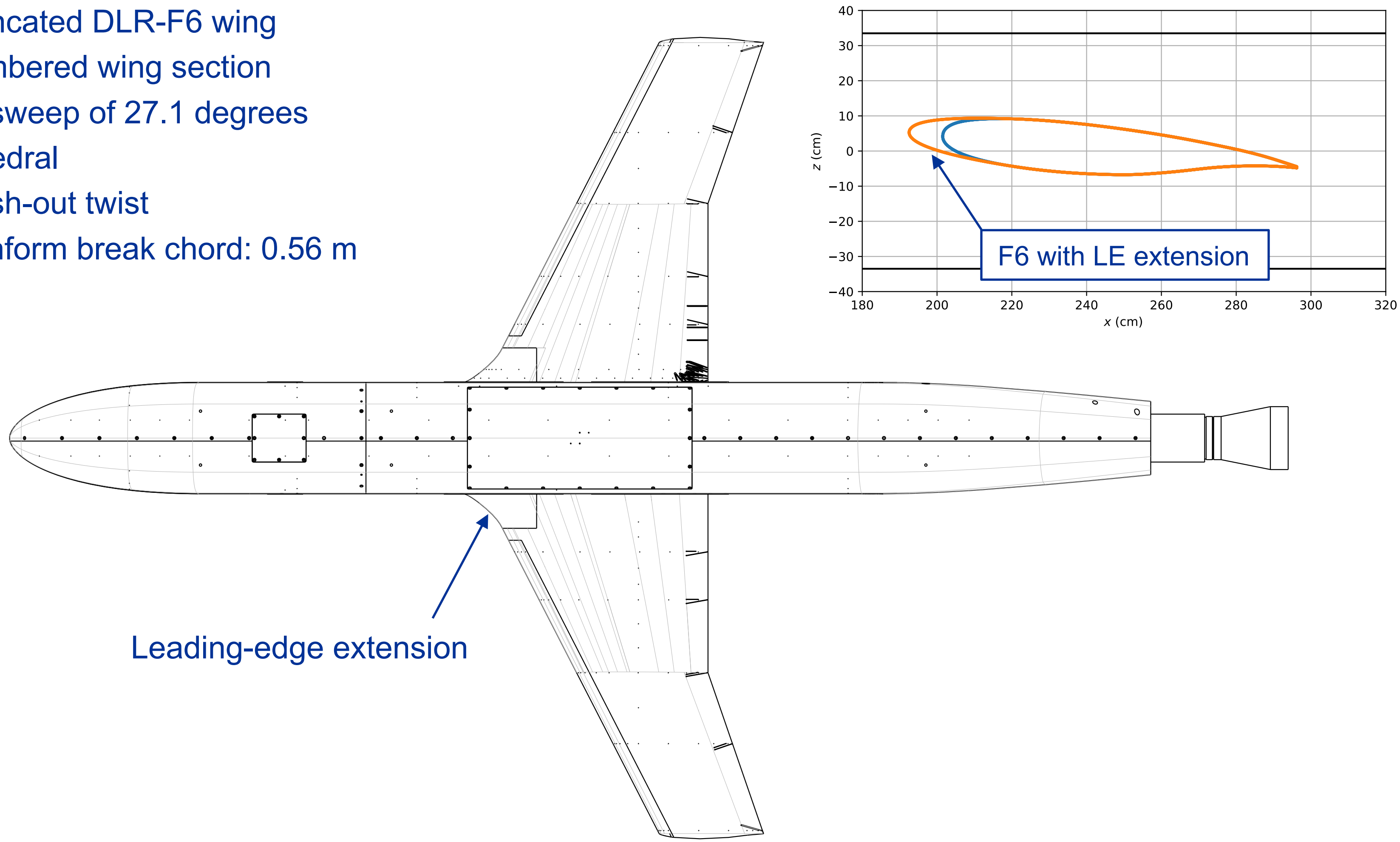


Front & Side View of the Junction Model

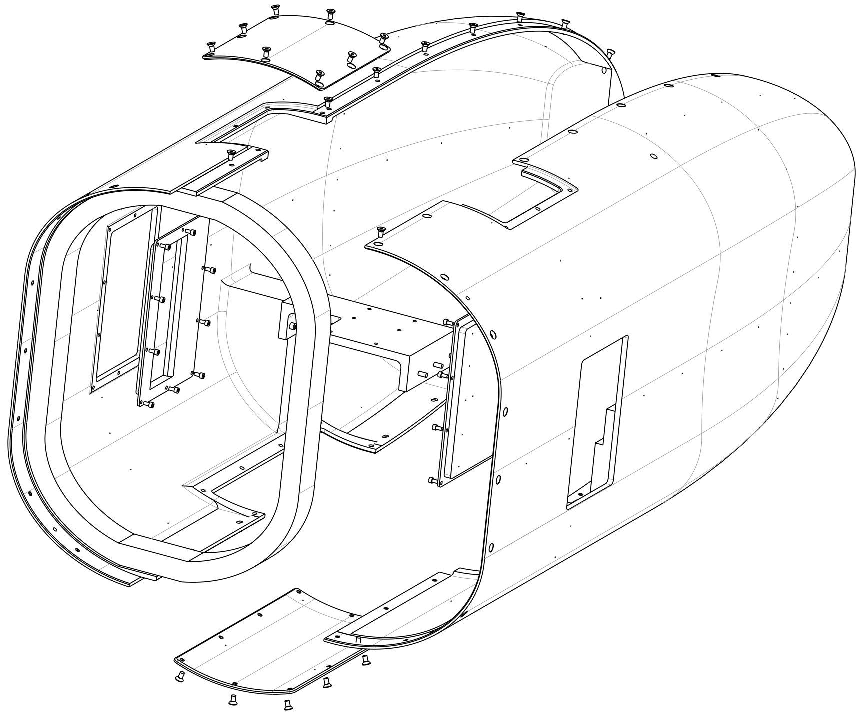


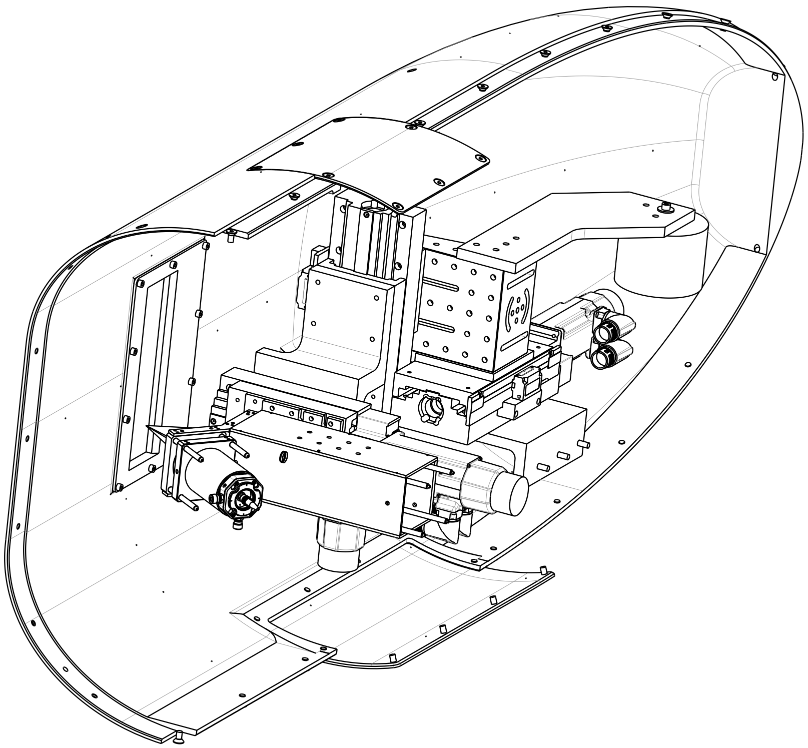
Top View of Wing-Fuselage Junction Model

- Truncated DLR-F6 wing
- Cambered wing section
- LE sweep of 27.1 degrees
- Dihedral
- Wash-out twist
- Planform break chord: 0.56 m



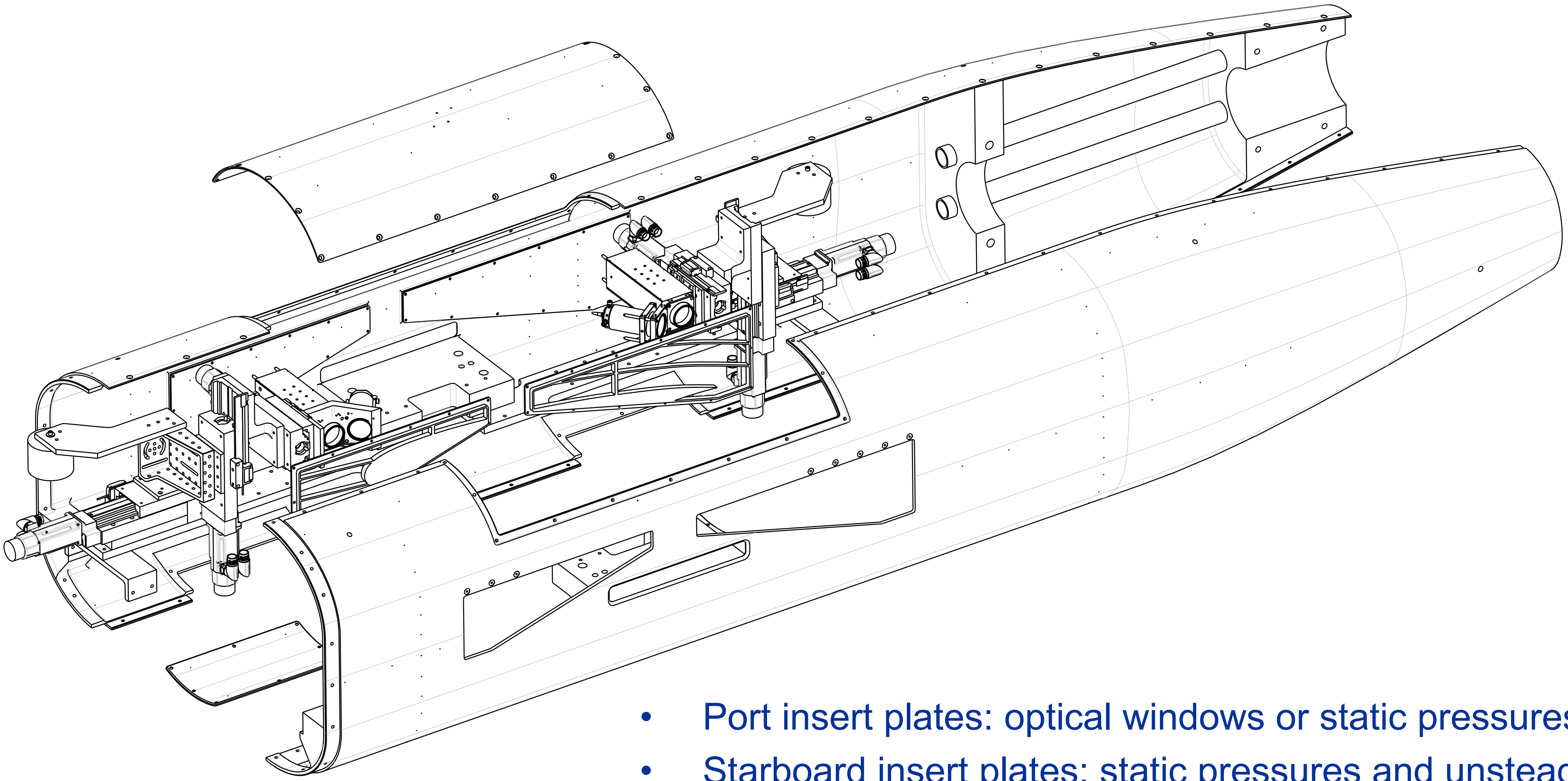
Fuselage Nose Section





- Insert plates on port and starboard side of fuselage nose section
- Insert plates instrumented with static pressure ports, unsteady pressure sensors, a Preston tube, a MEMS shear stress sensor or an optical window
- LDV system used to measure fuselage boundary layer

Fuselage Main Section



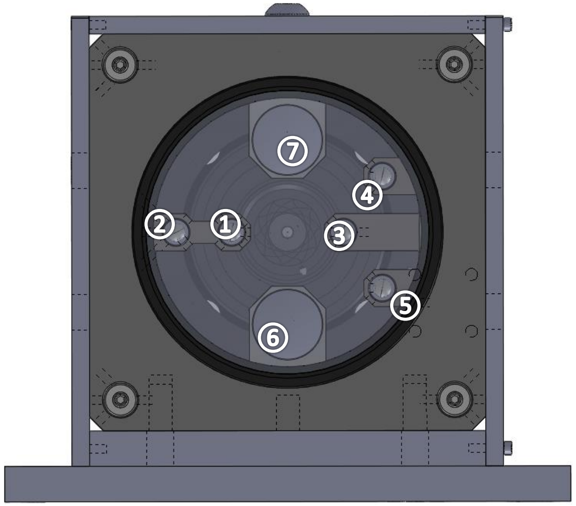
- Port insert plates: optical windows or static pressures
- Starboard insert plates: static pressures and unsteady pressures
- LDV system to measure fuselage BL near wing LE
- LDV system to measure corner-flow near wing TE

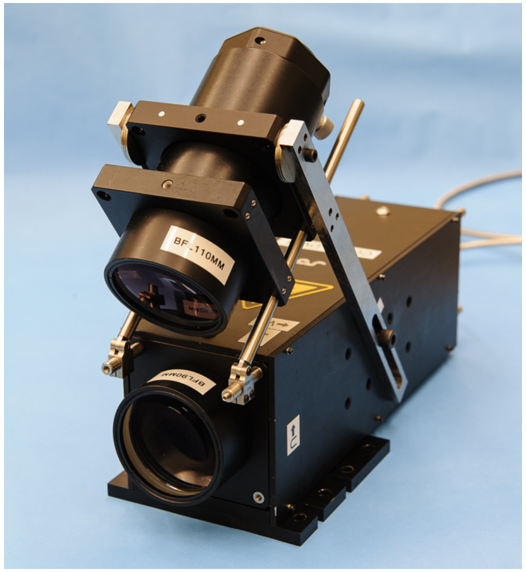
Laser Doppler Velocimetry (LDV) System

- Custom design delivered by Applied University Research, Inc. under a Phase III SBIR contract
- The LDV system yielded measurements of all three velocity components plus particle position within the measurement volume
  - Position information affords sub-measurement volume spatial resolution
- Two LDV systems were operated simultaneously
  - One system was used to measure the corner flow near the wing trailing edge
  - A second system was used alternately to measure the fuselage boundary layer upstream of and near the wing leading edge
- Each LDV system consisted of:
  - A photonics system that provided laser light to the LDV probe head
  - A fiber-optic based probe head with off-axis receiving optics
  - A set of photomultipliers to detect Doppler bursts
  - A DAQ computer with a high-speed A/D board and software for burst processing

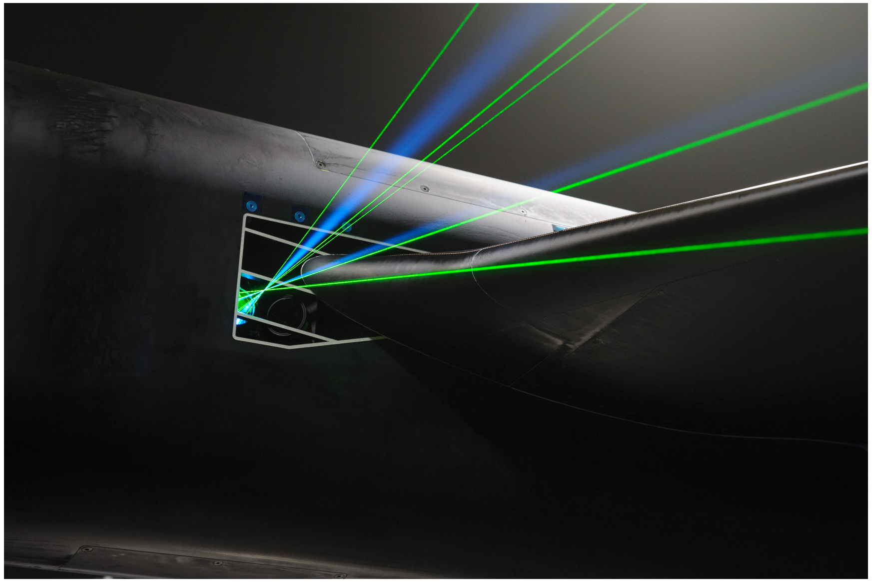
LDV Probe Head

- 90 mm working distance
- Green (532 nm) laser beams 1-5
  - Provide velocity measurements in 3 nonorthogonal directions
  - Measurement volume (MV) diameter and length of 140 μm and 960 μm, respectively
- Blue (488 nm) laser beams 6 & 7
  - Converging fringe pattern along the bisector of the two beams
  - Doppler frequency measured with this beam pair, in conjunction with velocity measured with green beams, can be used to deduce particle position along length of measurement volume
- Off-axis receiving optics
  - 110 mm focal length lens at 35 degrees to probe optical axis
  - Focuses scattered light onto 105 μm diameter multimode fiber
  - Effective length of MV is 180 μm

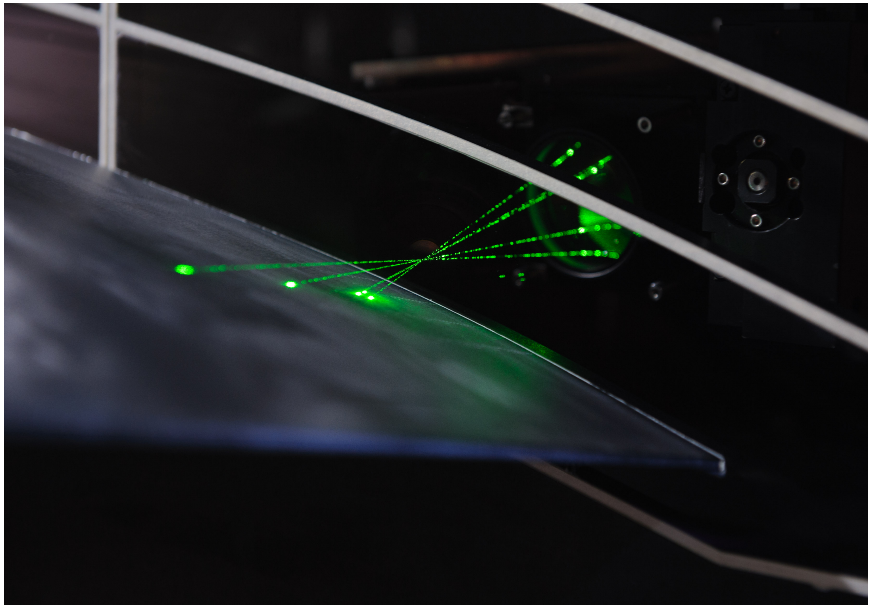




LDV Installations in the Junction Model



LDV system installed at the wing leading edge



LDV system installed at the wing trailing edge

Seeding for LDV Measurements

- Seeding was provided with a smoke generator located in the wind tunnel settling chamber

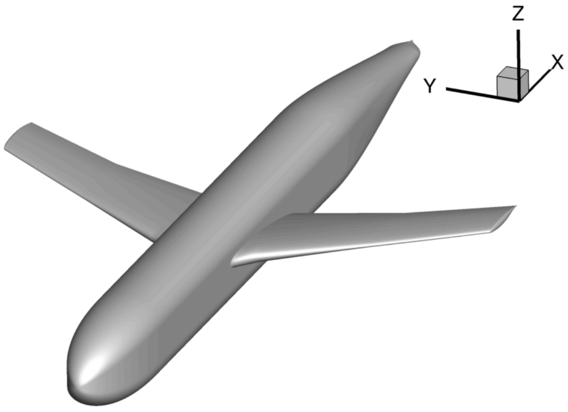
- Smoke generator uses a low-residue mineral oil that produces a narrow distribution of particle sizes with a nominal diameter of 0.94 μm

- The smoke generator was operated continuously during a wind-tunnel run to maintain adequate burst data rates

- Validated burst data rates of 100 bursts/s to 500 bursts/s were achieved

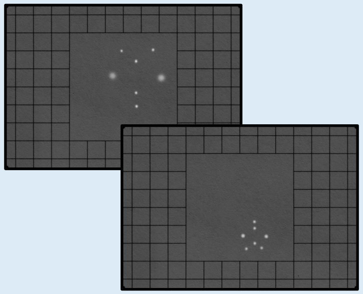
LDV Traverse System

- Traverse motion was performed in a body-fixed coordinate system with origin at model nose tip
- x- and z-axis travel of 152.4 mm, positional accuracy of 15 μm
- y-axis travel of 101.6 mm, positional accuracy of 10 μm

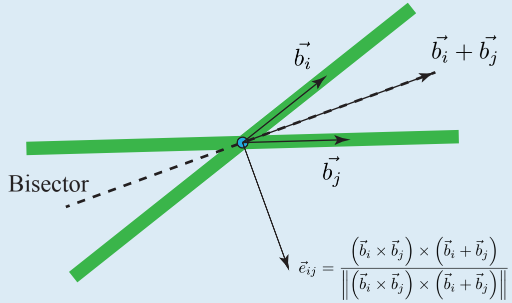


- To locate measurement volume relative to window surface
  - MV scanned through the window at low laser power & scattered light was measured
  - A peak in the scatter light occurs when the MV center is at the outer window surface
- Similar procedure used to locate MV relative to wing surface
- To find the x location, the MV was positioned relative to reference marks on windows at known locations from the model nose tip
- Located window and wing surfaces with wind on

Processing of LDV Data



Measure Beam Unit Vectors



$$d_{ij} = \frac{\lambda}{2\sin\left(\theta_{ij}/2\right)}$$

Measurement direction unit vectors and fringe spacings

$$u_{ij} = \vec{u} \cdot \vec{e}_{ij} = f_{ij} d_{ij}$$

Nonorthogonal velocity components

Histogram Clipping

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} e_{12(x)} & e_{12(y)} & e_{12(z)} \\ e_{34(x)} & e_{34(y)} & e_{34(z)} \\ e_{35(x)} & e_{35(y)} & e_{35(z)} \end{bmatrix}^{-1} \begin{bmatrix} u_{12} \\ u_{34} \\ u_{35} \end{bmatrix}$$

Transform to orthogonal body-fixed coordinate system

Histogram Clipping

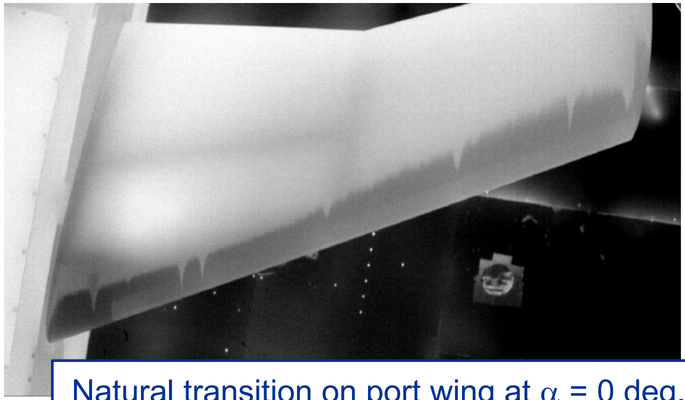
Calculate Statistical Moments

Statistical Moments

- To account for any velocity bias on statistical moments, each sample was weighted by the particle transit time (burst duration)
- Mean velocity: $$\overline{u} = \frac{\sum_i^N u_i \tau_i}{\sum_i^N \tau_i}$$
- Reynolds stress: $$\overline{u'v'} = \frac{\sum_i^N (u_i - \overline{u})(v_i - \overline{v})\tau_i}{\sum_i^N \tau_i}$$
- Velocity triple products: $$\overline{u'v'w'} = \frac{\sum_i^N (u_i - \overline{u})(v_i - \overline{v})(w_i - \overline{w})\tau_i}{\sum_i^N \tau_i}$$
- 30,000 samples were acquired at each point in a flow-field survey
  - For data rates of 100-500 samples/s, most of these samples were statistically independent
  - Large number of samples was sufficient to achieve converged statistical moments

Infrared Imaging

- IR imaging was used to characterize natural transition on the model and to verify turbulent flow on the model when using boundary-layer trip dots.
- Model was painted with a black lusterless polyurethane paint with thickness of 10-13 mils
- One IR camera was used to image port side of model
- Two IR cameras were placed above the test-section ceiling to view the upper wing surfaces
- Two IR cameras were placed below the test-section floor to view the lower wing surfaces
- IR cameras
  - Mid-wavelength infrared range of 3 to 5 μm
  - Detector resolution of 1460 by 852 pixels
  - Noise equivalent temperature difference less than 25 mK
  - Adjustments to overall exposure and contrast of images made during post-processing



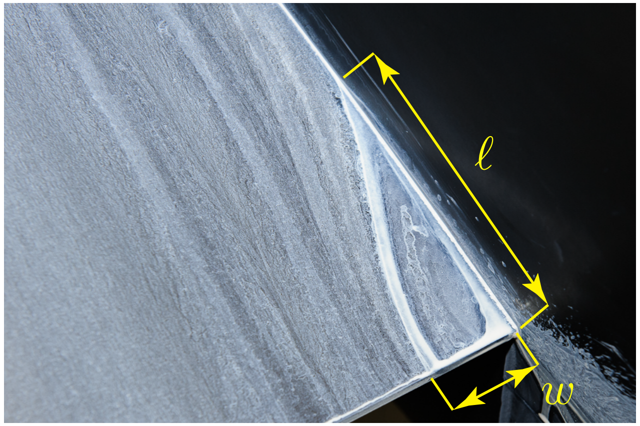
Natural transition on port wing at α = 0 deg.

Oil-Flow Visualization

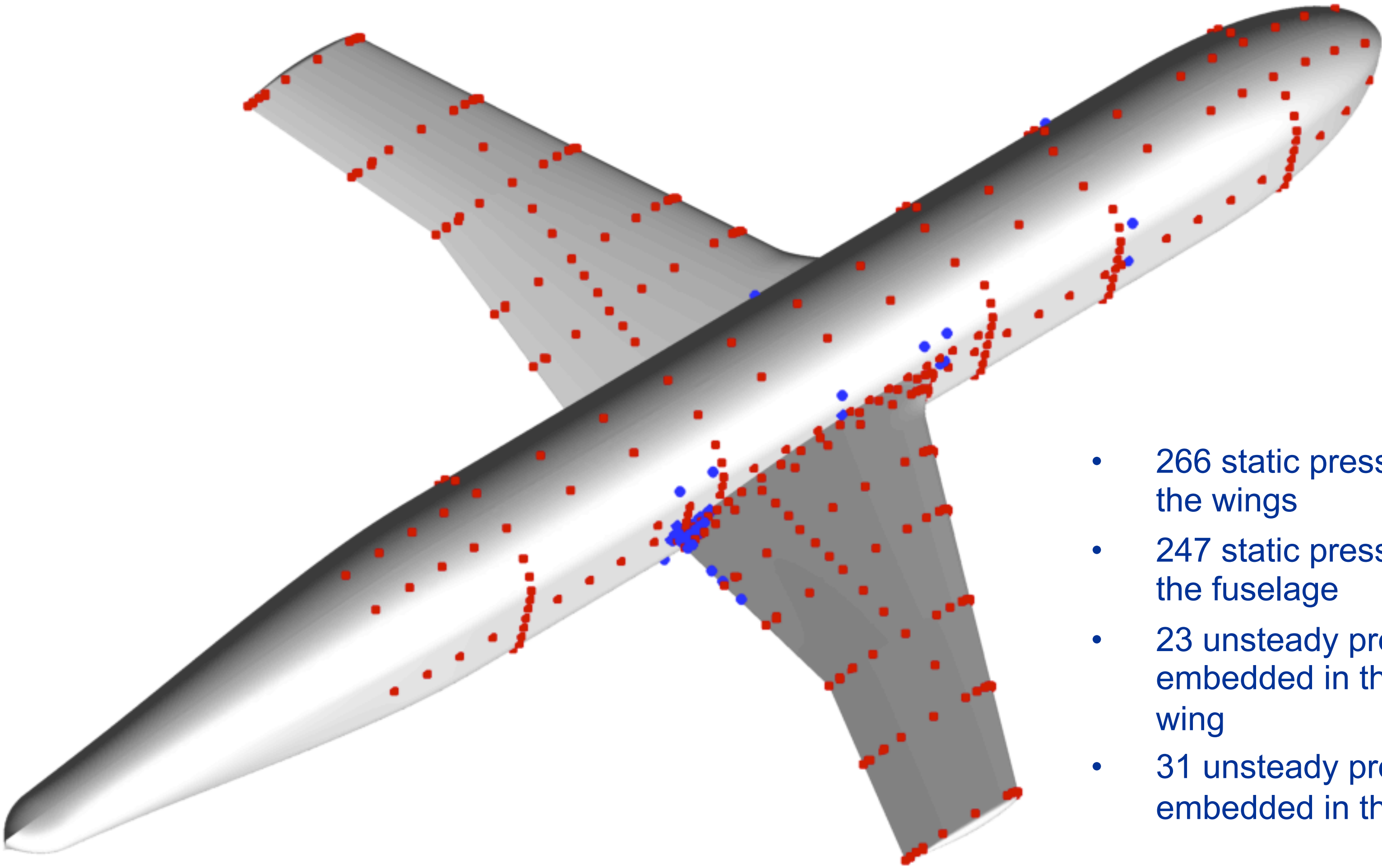
- Used to observe surface topology of TE corner-flow separation and its progression with model pitch angle
  - Guided selection of (x,y) locations for z-direction profile measurements
  - Measurements of corner separation length and width

- Used to observe surface topology in the LE region of the wing-fuselage junction
  - Guided selection (x,z) locations for y-direction profile measurements

- Video recordings of the oil-flow development during a run and post-test images were captured



Mean and Dynamic Pressure Measurements



- 266 static pressure ports on the wings
- 247 static pressure ports on the fuselage
- 23 unsteady pressure sensors embedded in the starboard wing
- 31 unsteady pressure sensors embedded in the fuselage

Red symbols: static pressure ports
Blue symbols: unsteady pressure sensors

Future Work

- A second entry in the 14x22 with the junction model is planned for January 2020

- Repeat measurements will be performed
  - Static pressure measurements on the model surface
  - Tunnel wall and boundary layer rake pressure measurements
  - Oil-flow visualizations
  - Laser scans of as-assembled model geometry
  - LDV profiles at selected repeat locations

- Augment LDV data set with new spatial locations and a new model pitch angle

- Detailed stereo PIV measurements in corner-flow region to complement LDV measurements

Summary

- Presented the methodology for a CFD validation experiment on a full-span wing-fuselage junction model
  - Model geometry exhibits a separated corner-flow region near the wing trailing edge that current RANS models are unable to reliably predict
  - Goal is to provide a publicly-available high-quality flow field and surface data set with quantified boundary conditions, geometry, and measurement uncertainties
  - Turbulence Modeling Resource Website: https:/turbmodels.larc.nasa.gov

- Performed flow-field measurements with internally mounted LDV systems
  - Measurements on the fuselage, near the wing leading-edge, and in wing trailing-edge corner-flow region
  - Measured all three components of mean velocity, all six independent components of Reynolds stress, and all ten independent components of the velocity triple products

- Performed supporting surface-based measurements (IR, oil-flow, mean and dynamic pressures)

Data set will be suitable for use in CFD workshop environments and will help CFD practitioners validate and improve their predictive capabilities for turbulent separated corner flows