The NASA Juncture Flow Test as a Model for Effective CFD/Experimental Collaboration

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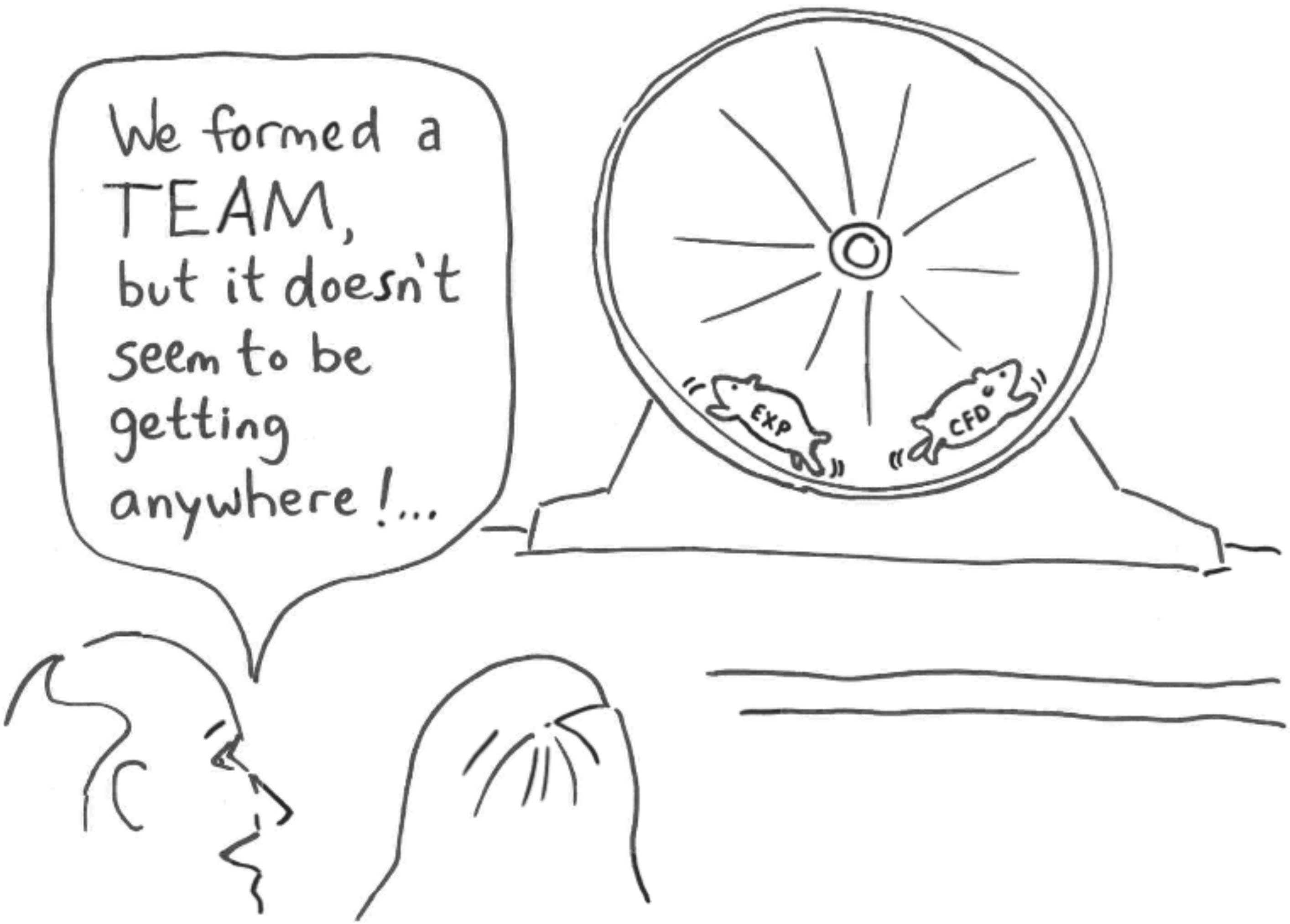
Outline

- Introduction
- History
- Juncture Flow (JF) Team
  - Organization and Structure
  - Team Functioning
  - Goals Document
  - Accomplishments to Date
- What's coming
- Summary

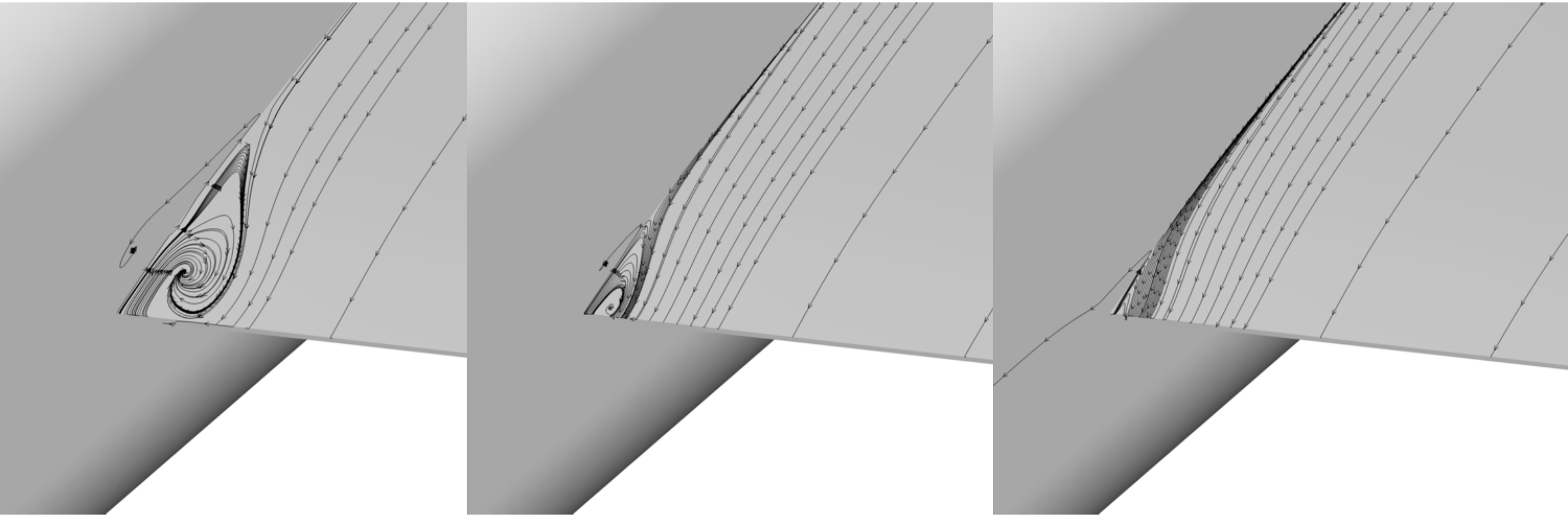
JF Team


We formed a TEAM, but it doesn't seem to be getting anywhere!...
EXP
CFD

JF Team – CFD and EXP

Introduction

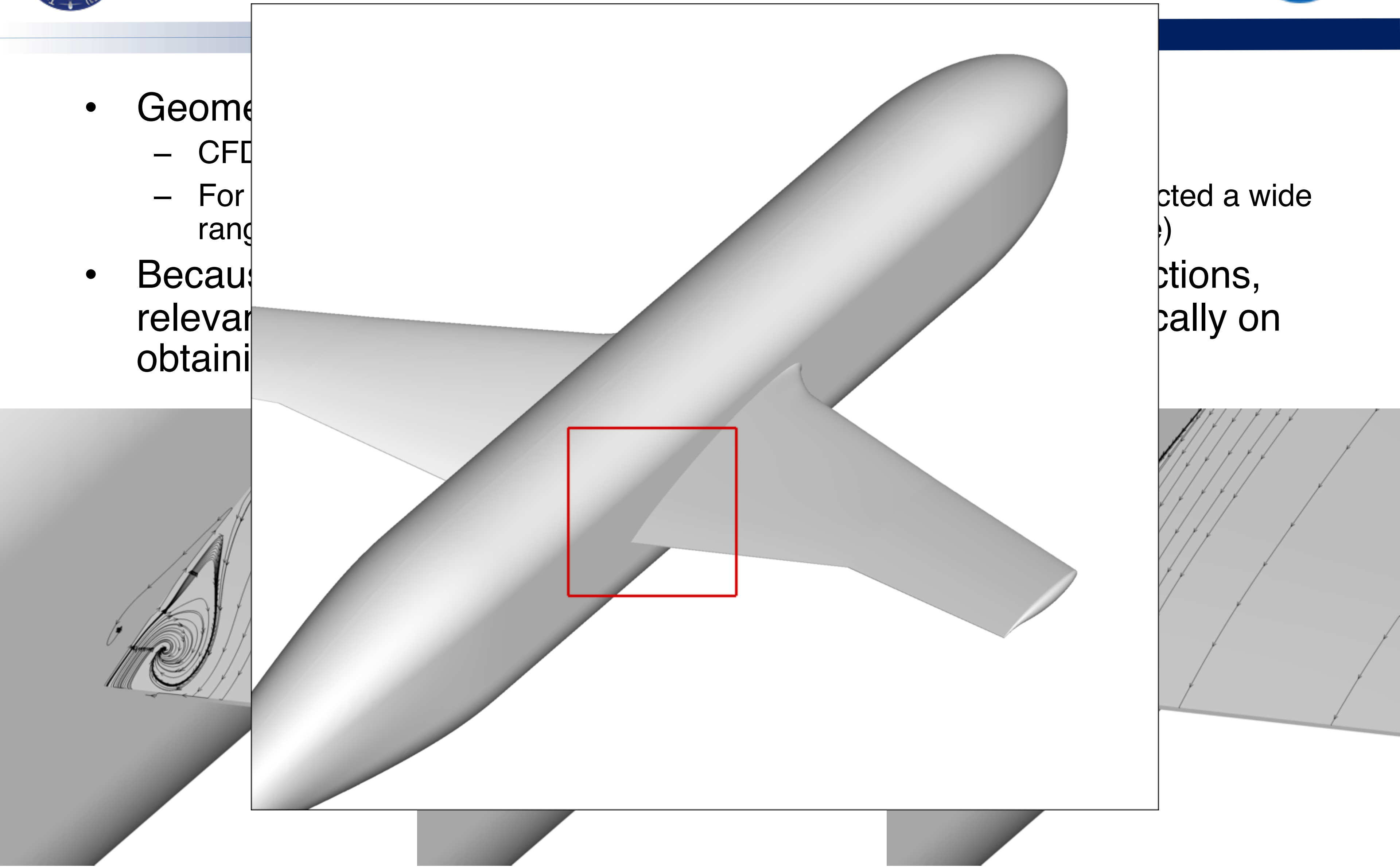
- Geometric junctures (corners) are common on aircraft
  - CFD predictive capability is currently uncertain
  - For example, in Drag Prediction Workshops (DPW), participants predicted a wide range of wing-body corner separation bubble sizes (none to very large)
- Because of the high degree of uncertainty in the CFD predictions, relevant separated corner flow experiments focused specifically on obtaining high-quality data for CFD validation are needed



* Example JF computations using 3 different turbulence models (SA, SA-RC-QCR, and RSM models)

Introduction

- Geome
  - CFD
  - For … cted a wide rang …)
- Becaus … ctions, relevar … cally on obtaini



* Example JF computations using 3 different turbulence models (SA, SA-RC-QCR, and RSM models)

Introduction, cont'd

- "CFD Validation-Quality" experiment
  - Experiment should include the measurements of all information necessary for a thorough and unambiguous CFD validation study, including boundary conditions, geometry information, and quantification of experimental uncertainties
  - See, e.g., Aeschliman & Oberkampf (AIAA J 36(5):733-741, 1998)
- Main purpose:
  - Collect data to help assess/improve the ability of existing CFD models to predict the onset and extent of the three-dimensionally separated flow near the wing juncture trailing edge region of a full-span wing-body configuration
- Experimental campaigns in NASA's 14x22 wind tunnel:
  - Late 2017 and Spring 2018 (completed)
  - Late 2019
  - Early 2021

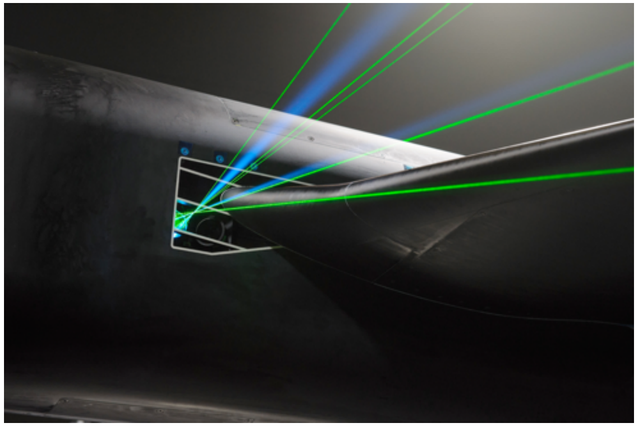
Introduction, cont'd

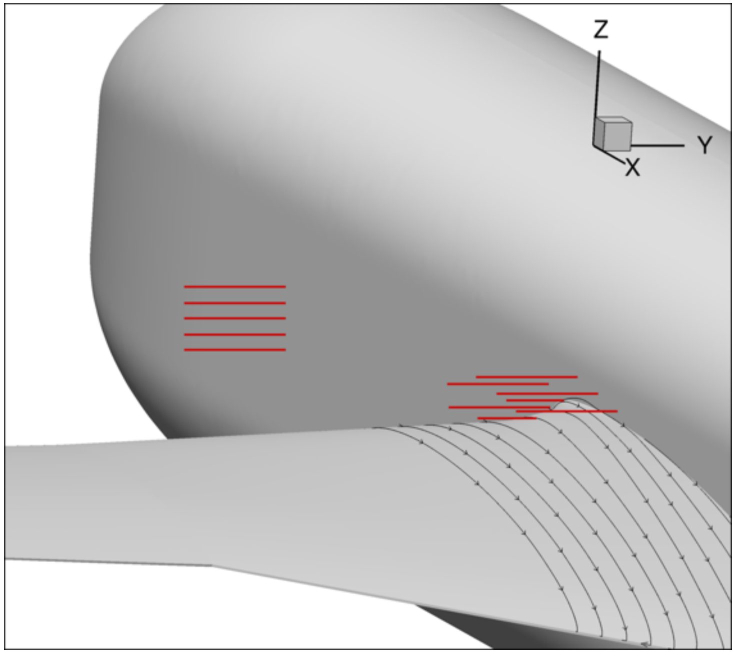
- Use of advanced surface and flowfield instrumentation
  - Internally-housed laser-Doppler velocimeter capable of measuring the velocities near the juncture corner (SBIR Phase 3, AUR Inc.)*
  - Unsteady pressure sensors
  - Unsteady shear stress sensors (JF serves as a test-bed for evaluation, SBIR Phase 3, ICC)*
  - Internal PIV also being explored*
  - Infrared thermography for BL transition detection and placement of trip dots

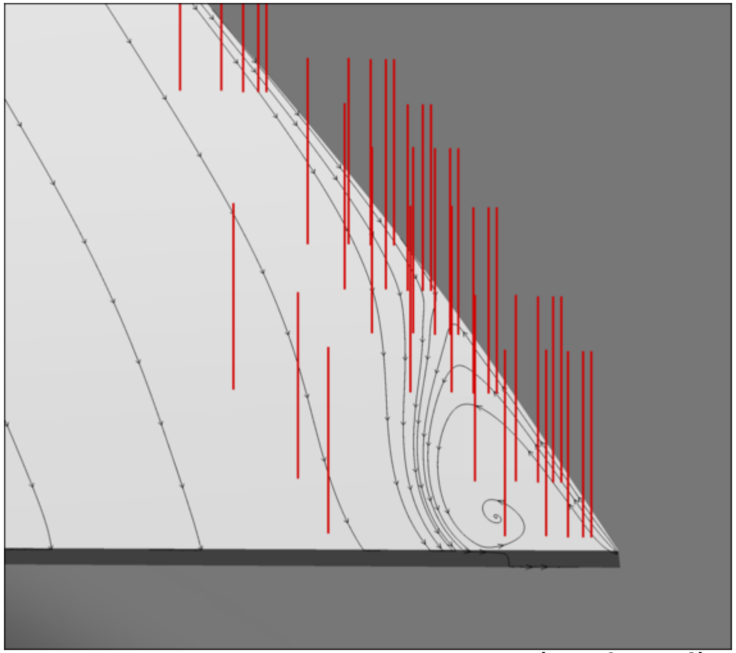
*First time for these capabilities in the 14x22 (<u>high risk</u>)

Introduction, cont'd

- LDV Expected Results
  - At fuselage nose, several lines of LDV data are taken normal to the fuselage (-y direction in body axis coordinate system)
  - At wing LE, lines of LDV data are taken normal to the fuselage
  - At wing TE, lines of LDV data are taken in lines above the wing (+z direction in body axis coordinate system)
    - u,v,w
    - 6 components of Reynolds shear stress
    - Higher moments are possible, but would have larger uncertainty



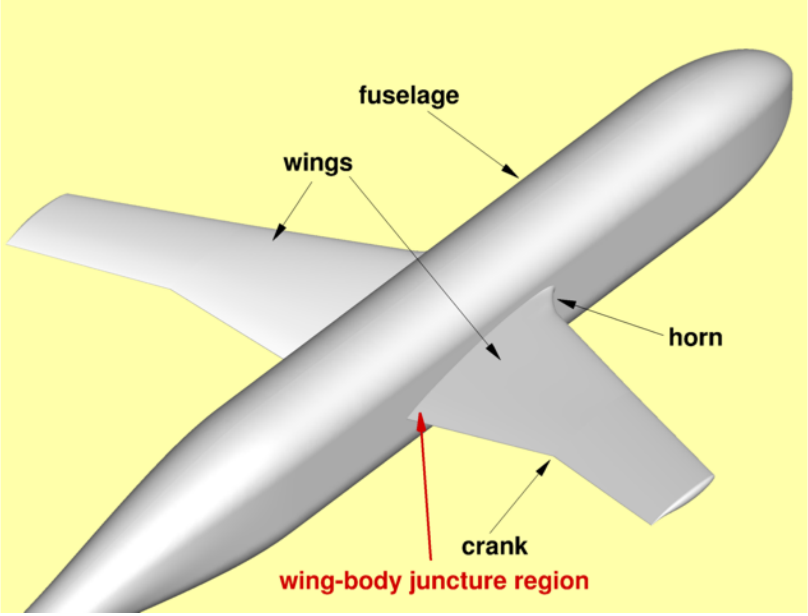


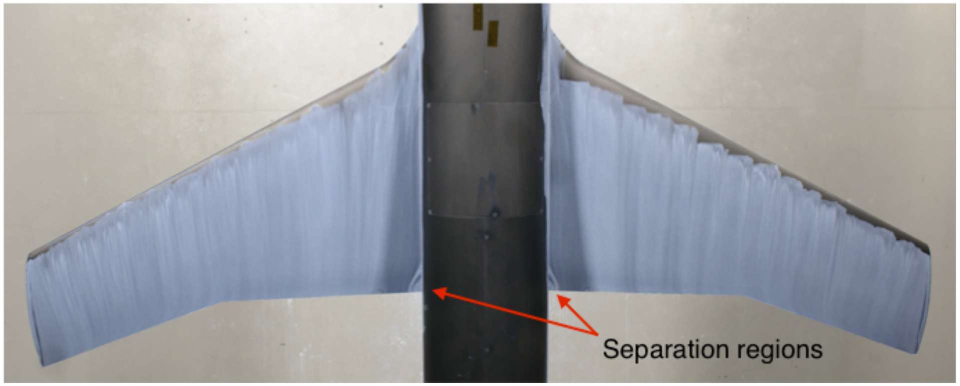


(notional)

History

- The NASA JF experiment was originally conceived by members of the Drag Prediction Workshop (DPW) steering committee
  - Prediction of onset and progression of corner separation
- Enables the accurate prediction of unsteady separated flows as outlined in the CFD 2030 Vision (contributes to “accuracy” pillar of RCA research)
- Funded by NASA’s Transformational Tools and Technologies (T^3) project
- There is also collaboration / tie-in with NASA’s Aerosciences Evaluation and Test Capabilities (AETC) Project (wind tunnel characterization effort)





History, cont'd

- Summer 2014-Spring 2015: attempt to use CFD to design the experiment
- 2015 & 2016: use of "risk reduction experiments" to help pick configurations and help determine locations of instrumentation
  - CFD was not considered reliable for making this decision
  - We wanted to be sure to achieve the desired corner separation
  - 5 wing shapes tested, 2 built: F6-based wing achieves separation, 0015-based wing achieves incipient separation
  - No-horn and with-horn variants of both wings built
  - 2 fuselage nose lengths also built
- 2016 & 2017: preparation for final test and exploration of inflow freestream
  - Inflow explored using PIV and Boeing's QWSS probe
  - Can the tunnel inflow nonuniformities be characterized for use by CFD?
  - Analysis ongoing
- 2017 – present: full model test (primarily LDV with some PIV)
  - F6-based wing with separation

The JF Team

JF Team

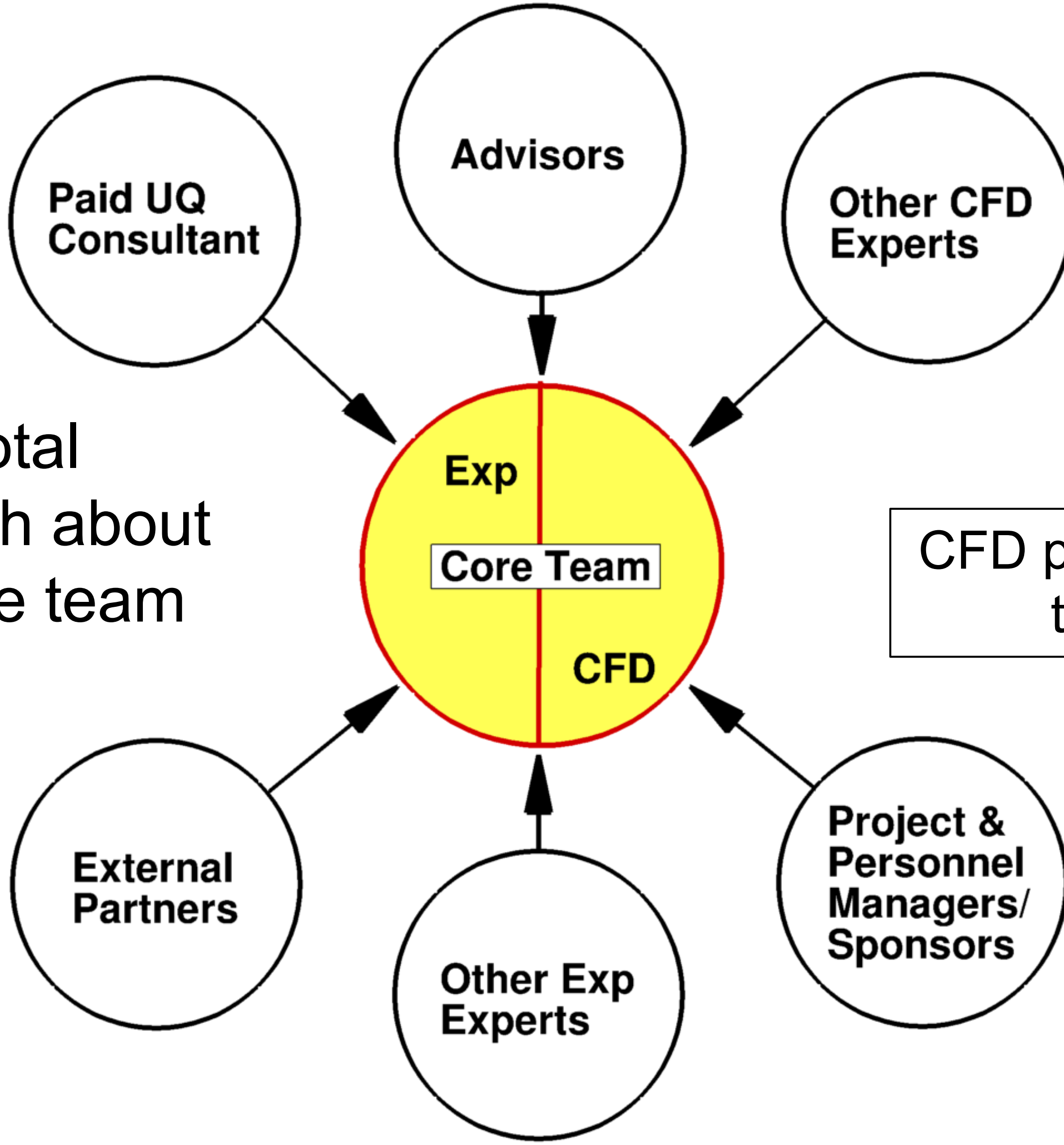
- Coming together is a beginning. Keeping together is progress. Working together is success. (*Henry Ford)*

- The best teamwork comes from people who are working independently toward one goal in unison. (*J.C. Penny*)

- The strength of the team is each individual member. The strength of each member is the team. (*Phil Jackson*)

- It's a very important thing to learn to talk to people you disagree with. (*Pete Seeger*)

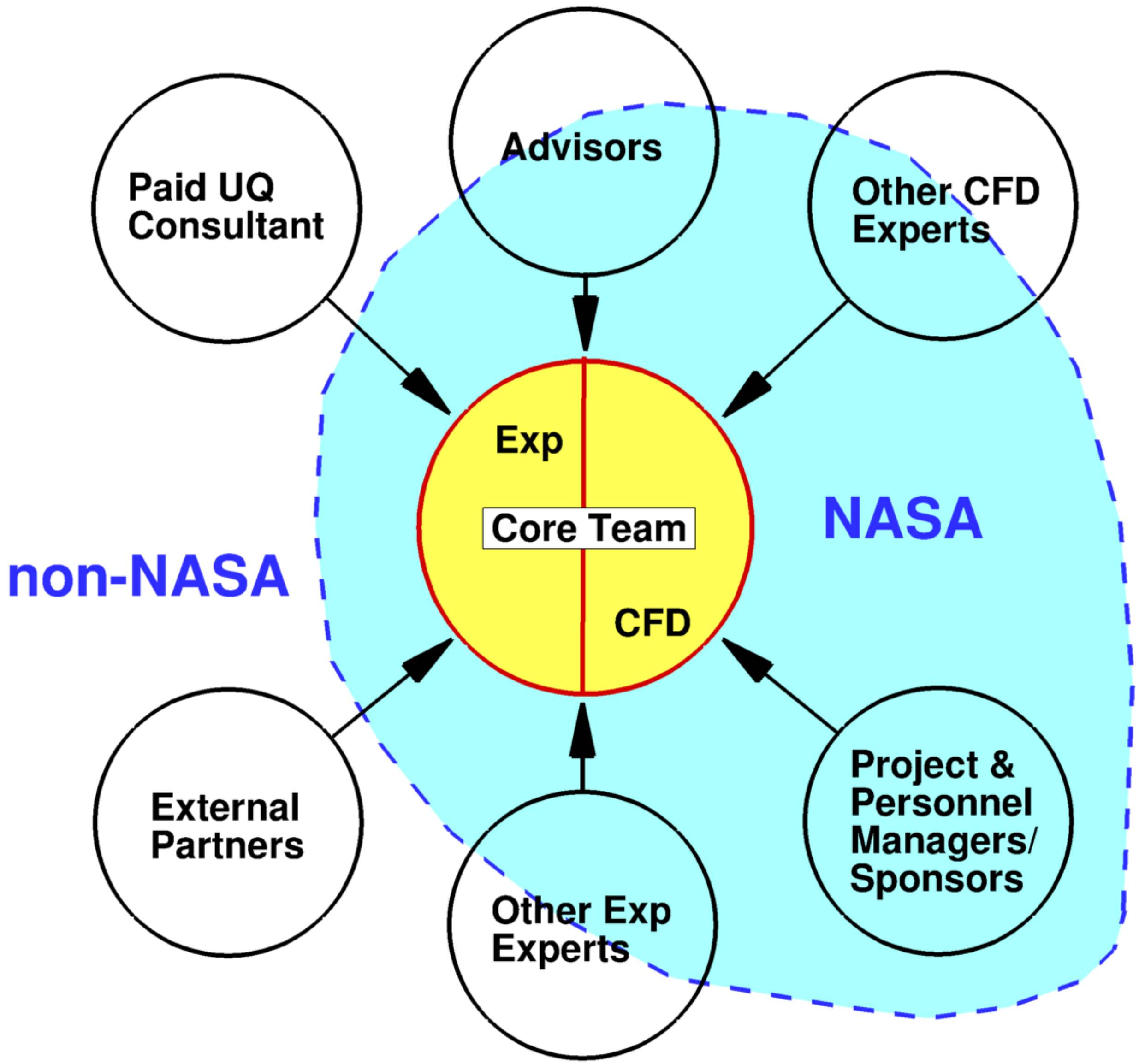
JF Team – Organization and Structure



Roughly 25 total members, with about 5-6 in the core team

CFD person leading the effort

JF Team – Organization and Structure



JF Team – CFD and EXP

- **Team meetings by Webex™ every 2 weeks (core team also met additionally as needed)**
- **Computationalists and experimentalists worked together throughout**
  - **Beneficial: cross-fertilization, seeing different sides, every team decision was made with consideration of both CFD and experimental aspects**
  - **Challenging: cultures have been historically different**
  - **Take-away: the more you work together, the easier it gets (builds trust)**
- Team inclusion of auxiliary members from outside the home organization
  - Beneficial: different perspectives, fresh ideas, external viewpoints
  - Challenging: remote, not always consistent participation, lack of “team cohesion”
  - Take-away: not easy, but benefits outweigh challenges
- Goals document established in the beginning
  - Clarified purpose and information needed for unambiguous CFD validation
  - Established priorities
  - Helped unify the team and aided with decision making
  - Full document included in the appendix of the written paper

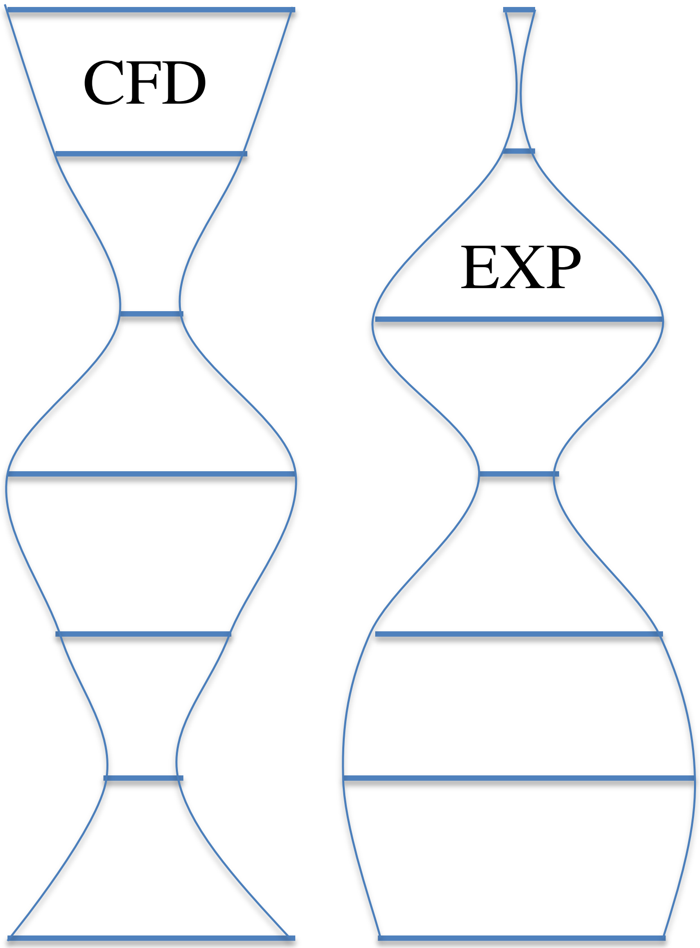
JF Team – CFD and EXP

- CFD perspective
  - Helped to keep experimental focus on fact that this is a “CFD validation experiment”
  - Continual focus on need for measurements of BCs (e.g., well upstream of region of interest), geometries, etc.

- EXP perspective
  - Helped to keep computational focus on “reality”
  - Reminder of measurement capabilities & limitations

Approximate Process, CFD and EXP

- Initial CFD efforts
- Shift to design ideas
- Preliminary “risk-reduction” testing
- Design downselect and additional CFD
- Empty tunnel tests & prep for final test
- Final test
- Data reduction and CFD comparisons



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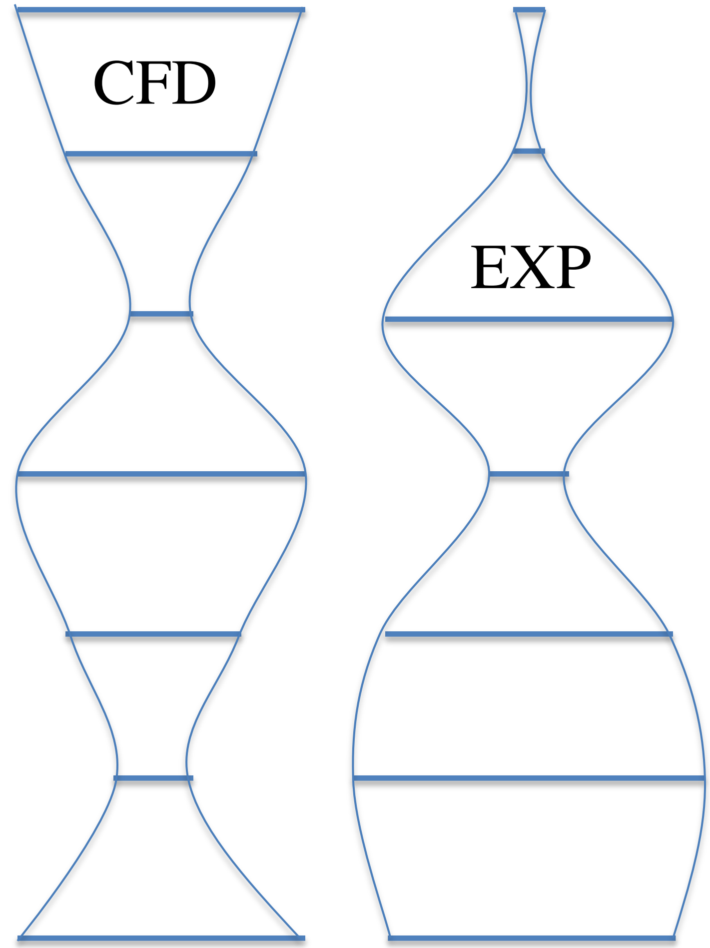

CFD and experiment have been generally serving complementary roles throughout the project’s life

JF Team – CFD and EXP

JF Team – External Members

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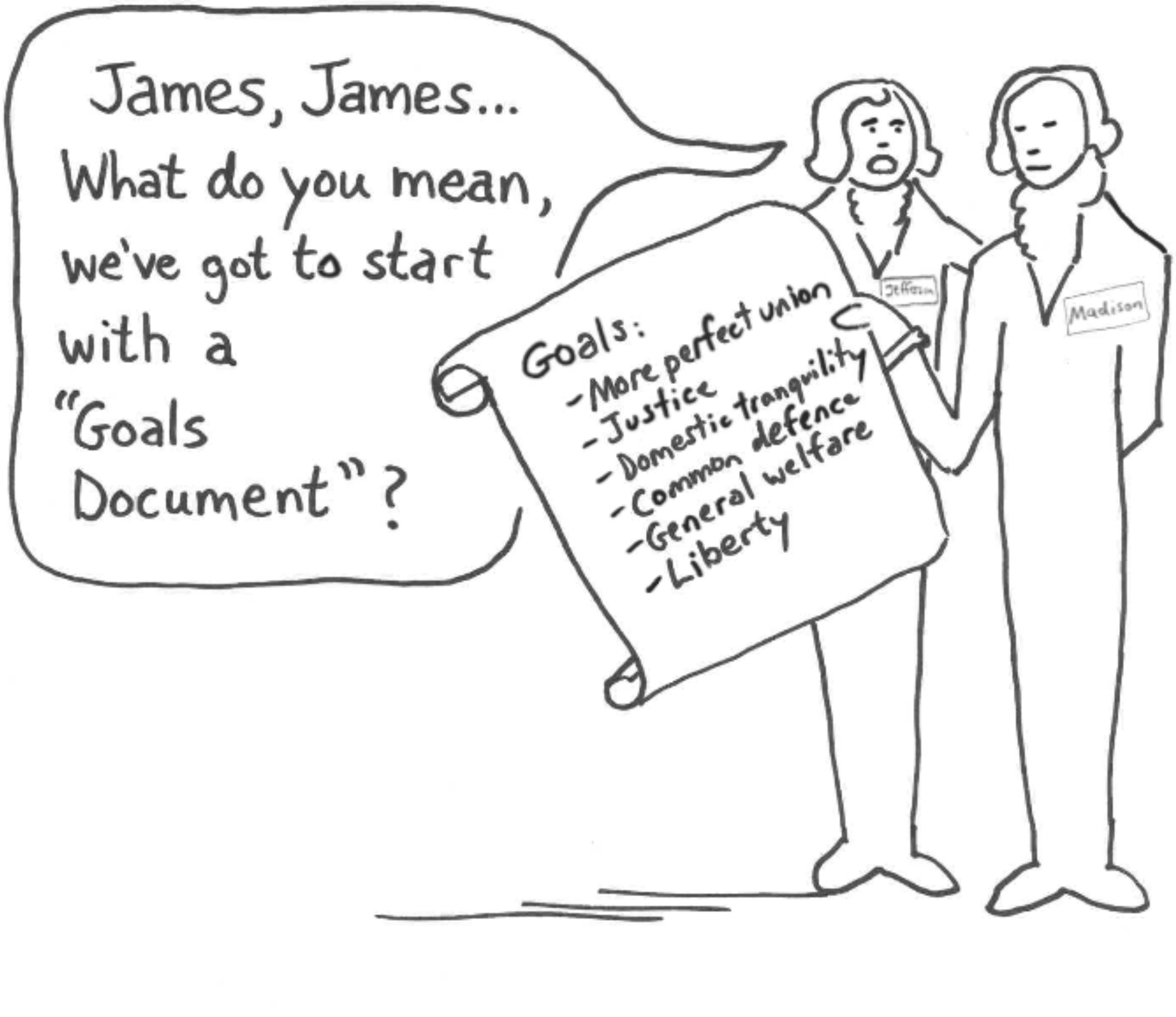
JF Team – Goals Document



JF Team – Goals Document

- Goals:
  - Understanding and assessing experimental uncertainty
  - Assess ability of models to predict:
    - Juncture separated flow in terms of topology
    - Time-averaged velocity near juncture region
    - Time-averaged Reynolds stresses near juncture region
    - Time-averaged surface pressures
    - Others…
- Prioritized data:
  - Documentation of as-built geometry
  - Documentation of tunnel BCs
  - Mean velocity near the juncture region and upstream
  - Reynolds stresses near the juncture region and upstream
  - Surface pressures
  - Documentation of trips
  - Documentation of wind tunnel geometry
  - Documentation of mounting hardware geometry
  - Others…

JF Team – Accomplishments to Date

- High-quality flowfield and surface data has been acquired toward goal of CFD validation of juncture flow
- Breakthrough use of on-board LDV and PIV laser measurement systems in a major NASA production wind tunnel
- Data:
  - Surface pressures, some unsteady pressures and unsteady shear stress measurements
  - LDV: mean velocity and Reynolds stresses in three areas (200 μm from upstream windows and 500 μm from windows near wing)
  - PIV planar data: still exploratory, mean velocities expected
- Improving the input data for the purpose of CFD validation:
  - Laser scans of as-built shape
  - Laser scans of mast/sting configurations relative to tunnel walls
  - Photogrammetry to determine wing shapes under load
  - Test section pressures along walls and ceiling; diffuser pressures along floor
  - Wall rakes on walls and ceiling to record BL thicknesses and growth
  - IR thermography to verify trip effectiveness
  - Attempts made to measure details of tunnel's incoming freestream
  - On the model itself, flow measured well upstream on the fuselage nose

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- Data:

Quality of data will be extraordinary

- Improving the input data for the purpose of CFD validation:

Usefulness of data will be shaped by our efforts to capture this additional information

Challenges

- Trying to ensure that CFD and experiment are “apples-to-apples”
- Characterizing sources of uncertainty
  - Flowfield inflow (currently using repeat measurements with model inverted)
  - Measurement (currently using repeat runs, standard techniques)
  - Geometric (currently using laser scanning, photogrammetry)
  - Plan to make more use of CFD parametric studies
  - What influence do the uncertainties have on near-corner data?
- Communication – continuing to encourage persistent and effective collaboration between CFD and experiment
  - Understanding of the capabilities and limitations of each discipline is important
  - Ultimately we want the combination of CFD and experimental methods to help overcome the limitations of each used alone

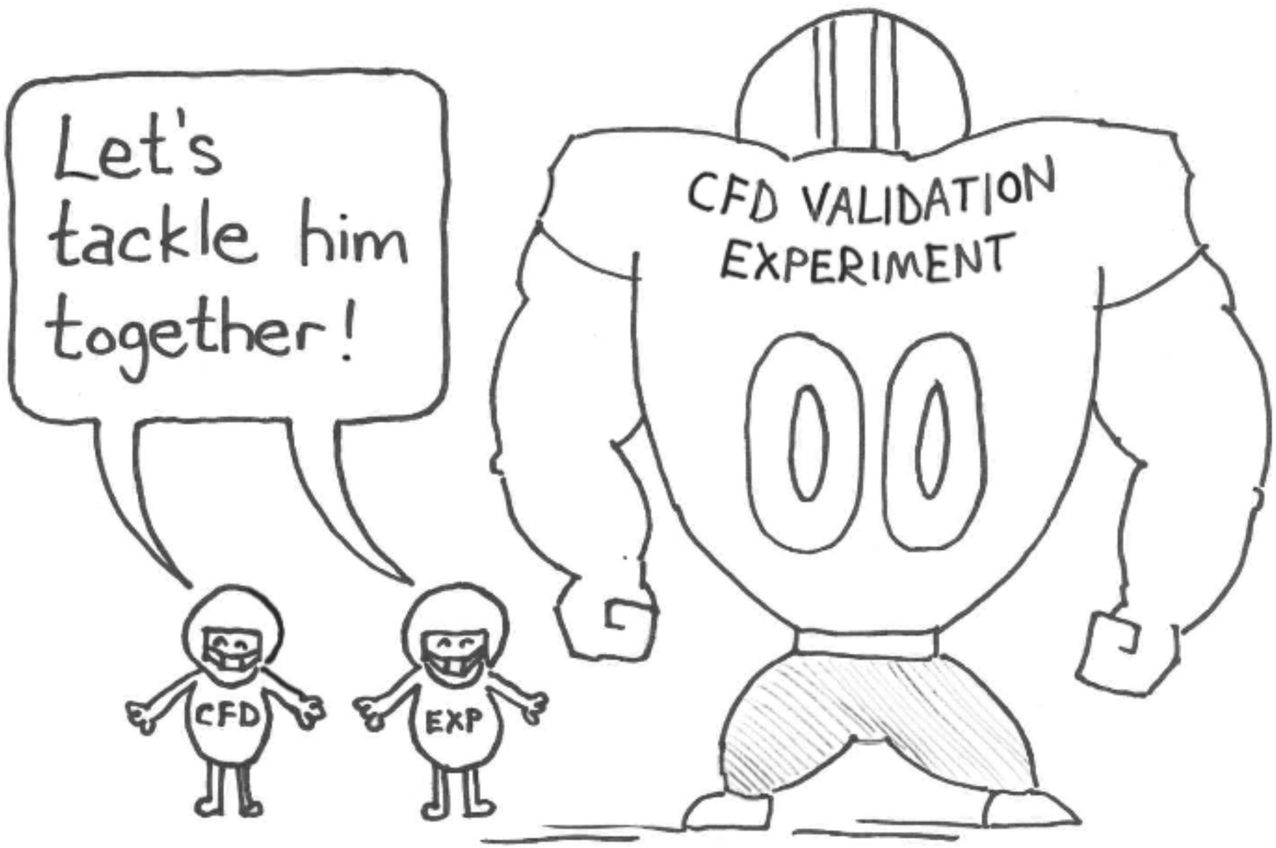
What's Coming

- January 2019
  - NASA documentation of experimental results (e.g., NASA TM)
  - Special session at SciTech (San Diego) with JF-related papers: experiment (LDV and PIV) and comparison with CFD
- 2018-2019
  - Posting of data to website
  - More analysis (Improvement of turbulence models needed? Is there particular data still missing?)
- End of 2019
  - Next phase of experimental testing (More on F6? Other wing? More focus on PIV?) Details TBD

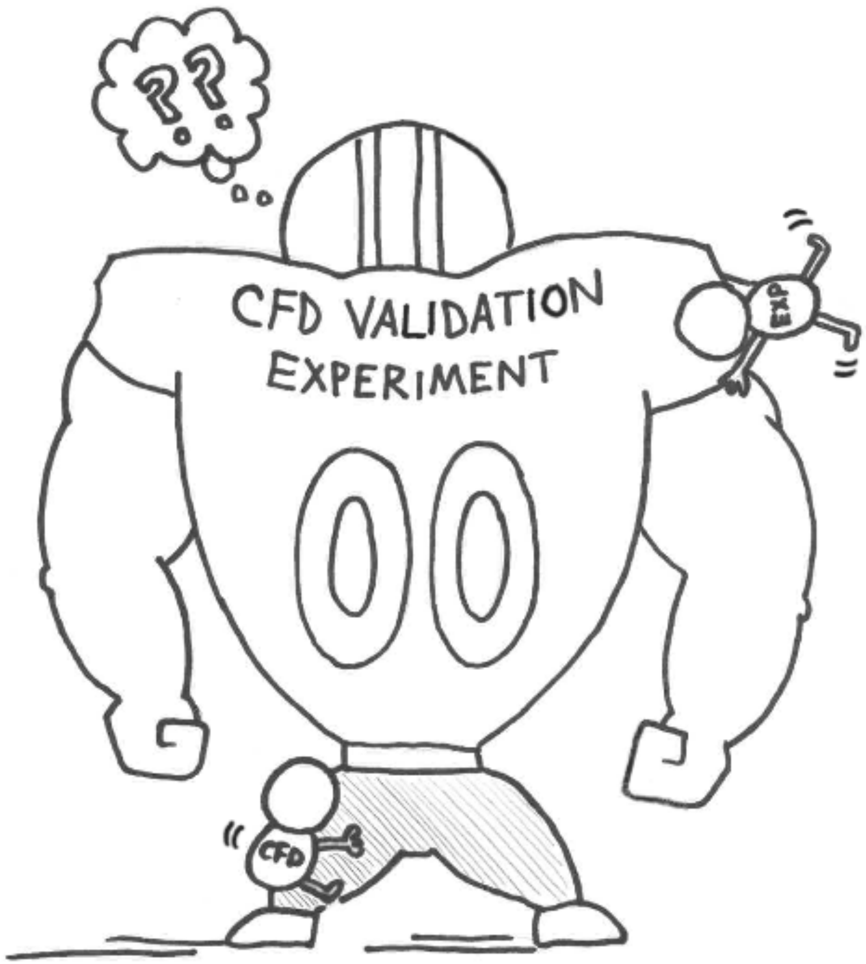
Summary: Team Perspective

- Teamwork can be challenging across different disciplines and organizations
- But close integration of CFD and experiment experts on the same team brings a lot of benefits
- More input ultimately improves the final product: Including external “auxiliary” members, consultants, advisors, partners on the team adds more debate and ideas
- Establishing a Goals Document near the start of any project is recommended

Summary: Team Perspective



Summary: Team Perspective



Cartoons in this presentation are original artwork by the author

(all in good fun)

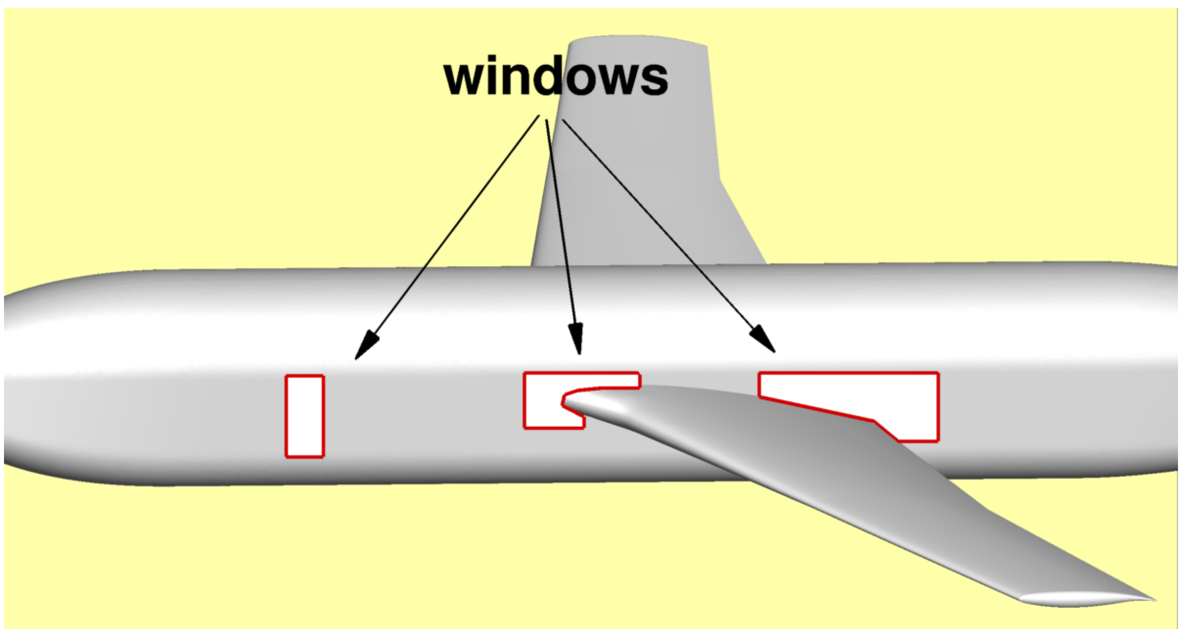
Backup Slides

Current Team Members

- Chris Rumsey (LaRC)
- Dan Neuhart (LaRC)
- Mike Kegerise (LaRC)
- Judi Hannon (LaRC)
- Luther Jenkins (LaRC)
- Chung Sheng Yao (LaRC)
- Mark Fletcher (LaRC)
- Scott Bartram (LaRC)
- Jan-Renee Carlson (LaRC)
- P. Balakumar (LaRC)
- Tom Pulliam (ARC)
- Henry Lee (ARC)
- Roger Simpson (AUR, Inc.)
- Gwibo Byun (AUR, Inc.)
- Bill Oberkampf (WLO)
- Sandy Webb (LaRC)
- Mark Cagle (LaRC)
- Joe Morrison (LaRC)
- Bil Kleb (LaRC)
- Cathy McGinley (LaRC)
- Mujeeb Malik (LaRC)
- Ashley Dittberner (LaRC)
- Brian Mahan (LaRC)
- James Bell (ARC)
- Philippe Spalart (Boeing)
- John Vassberg (Boeing)
- Tony Sclafani (Boeing)
- Ashley Jones (Boeing)
- (Others involved in the past but no longer active are not mentioned here)

Status

- Currently: testing of the F6-based wing with separation
  - Primary focus at AoA=5 and -2.5 deg
  - Both with and without horn
  - Re=2.4 million based on crank chord
  - Boundary layer is tripped (fuselage, upper & lower wing surfaces)
  - LDV off-body measurements (velocity, moments) in 3 regions

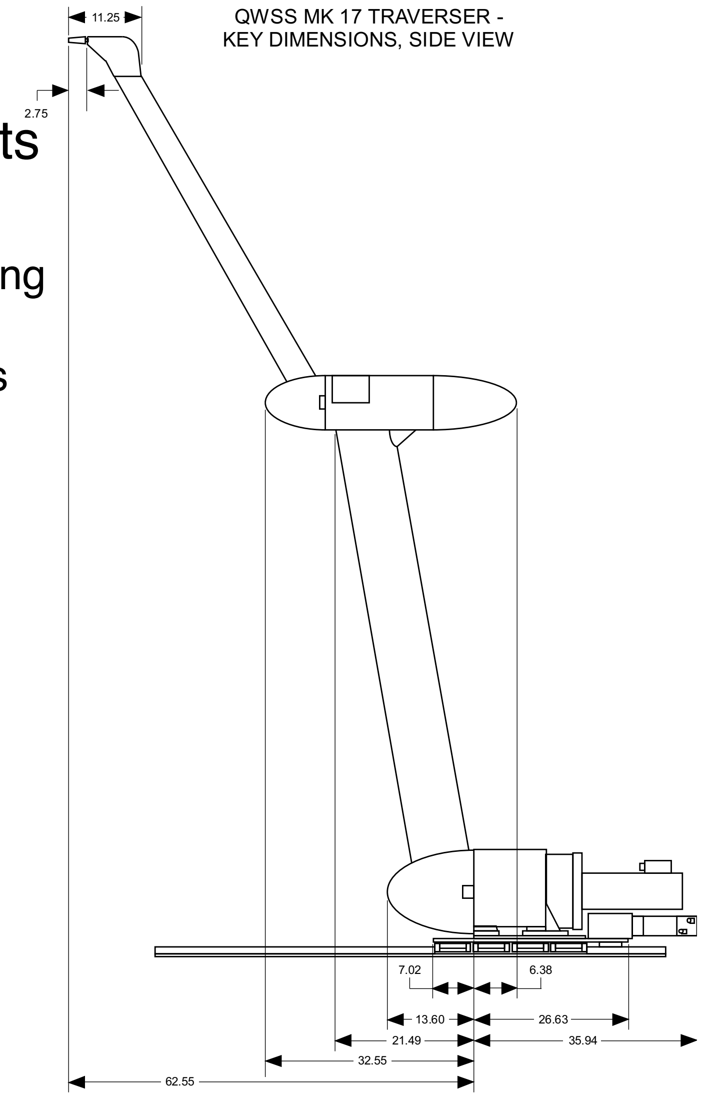


Status, cont'd

- Data
  - Off-body velocities and moments (LDV and some PIV)
  - Model surface pressures, unsteady surface pressures and unsteady surface shear stress measurements
- Boundary conditions
  - Over the body: measurements at front window
  - Pressure rail in tunnel diffuser
  - Three wall rakes in test section
  - Test section wall pressures
  - Infrared thermography for transition detection
  - Tunnel inflow (measured with Boeing's QWSS in separate tests)
- Geometry
  - Laser scans of tunnel walls, model, and mast/sting/cabling details
  - Photogrammetry to document wing deflections under load

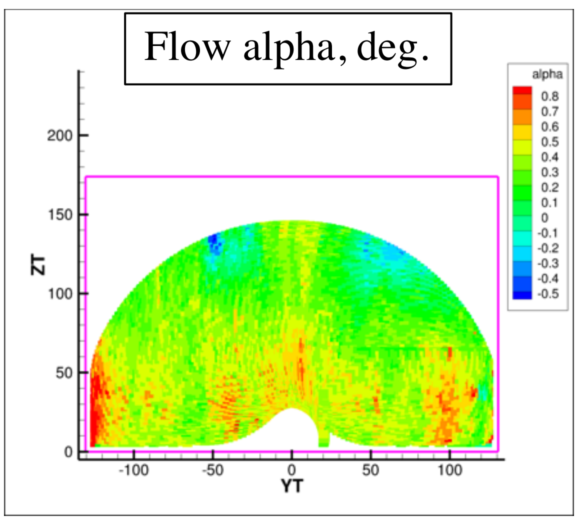
Progress Toward Inflow BC Characterization

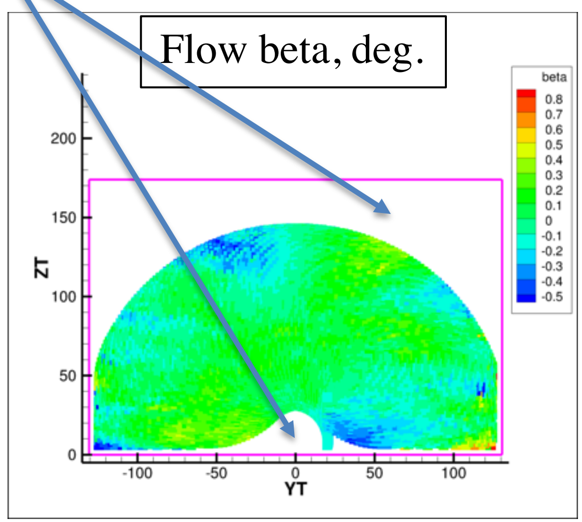
- Boeing's Quantitative Wake-Survey System (QWSS) used in two recent tests in 14x22
  - Although not its intended use, we are exploring whether something like the QWSS can measure freestream flowfield nonuniformities at inflow to test section
  - Answer appears to be only a qualified "yes"
- PIV was also tried in 14x22
  - Limited access
  - Difficult to get large field of view along with high accuracy



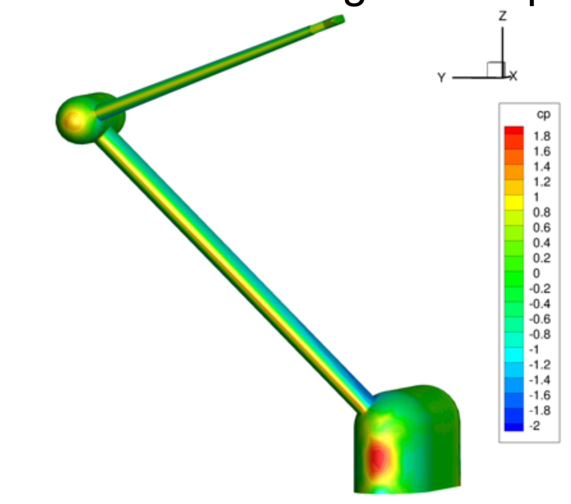
Progress Toward Inflow BC Characterization

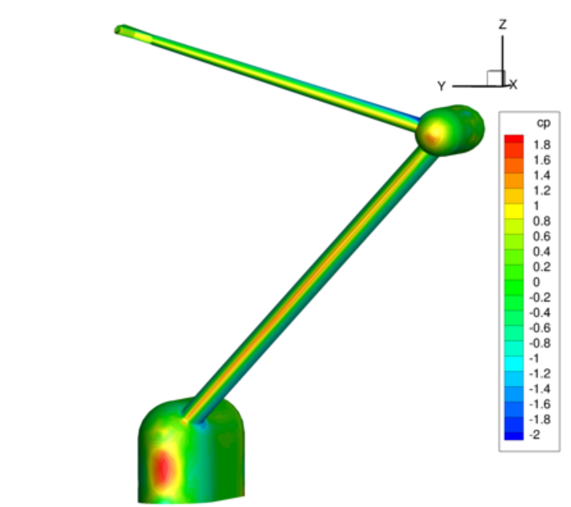
- CFD studies indicate that the QWSS influences what it is measuring (to the level of accuracy we are interested in)
- Very small probe misalignment has same effect
- But QWSS can measure same points with different arm positioning; this allows error to be assessed and corrected (using assumption that flowfield is steady in the mean)
- Nonetheless, without significantly more testing, it is not clear what are <u>consistent characteristics</u> of the tunnel, and what will change from run to run
- We are not yet sure if/how CFD can use this information
- Some areas are missed





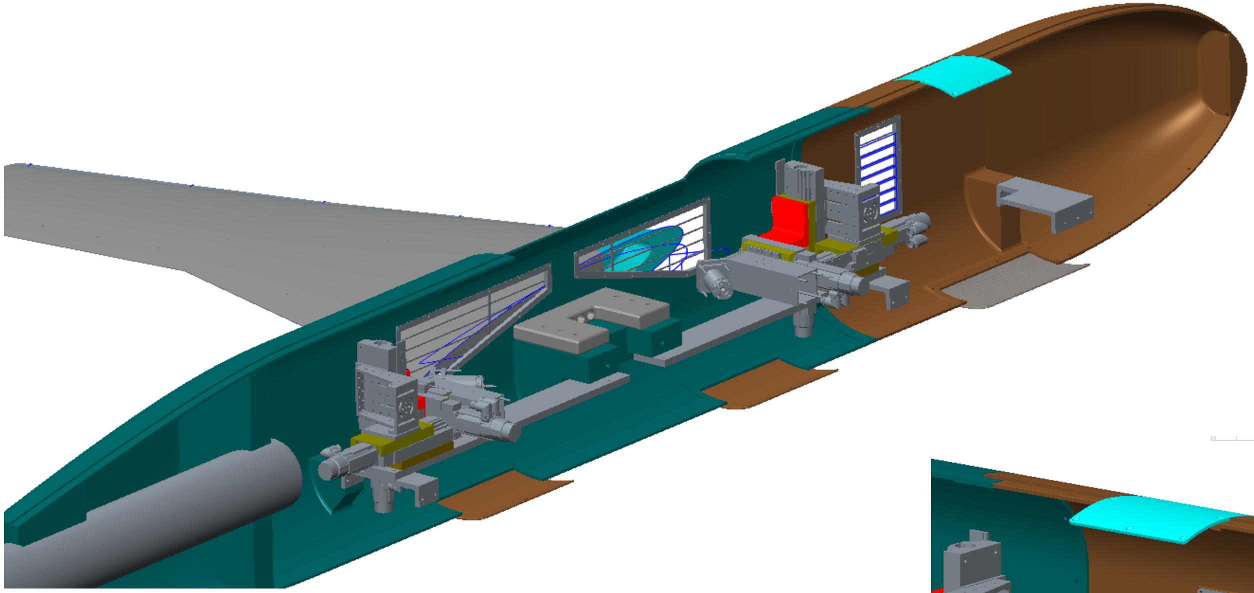
2 arms measuring same spot

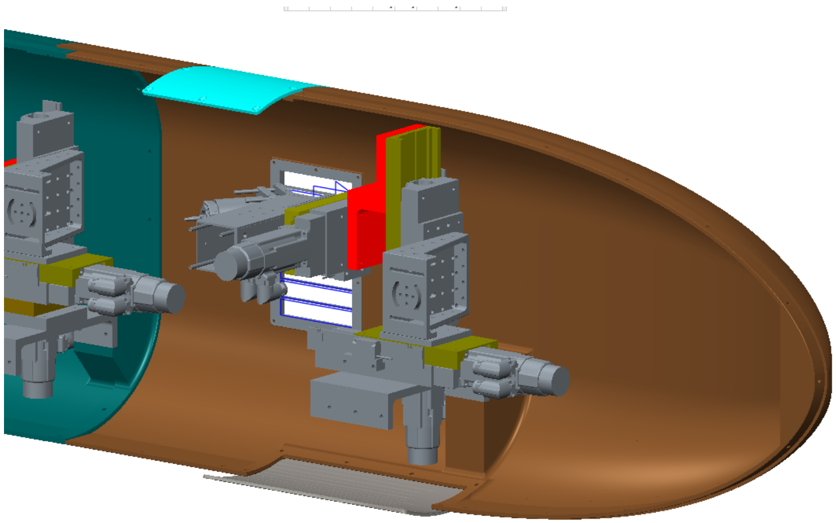




(CFD used idealized hub shape)

LDV Placement in Fuselage





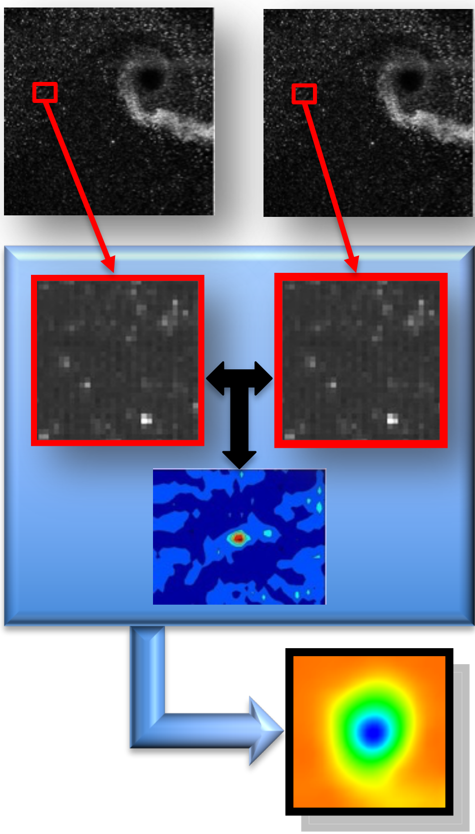
Embedded Laser Doppler Velocimeter

- Two miniaturized, fiber-optic based LDV probes are located inside the model, behind windows in the fuselage*
- Each probe is mounted to a 3-axis traverse system
- The LDV probes provide simultaneous measurements of three velocity components
  - Data are post-processed to yield the 3 mean velocity components and all 6 components of the Reynolds stress
- The embedded LDV systems afford
  - Precise positioning of the measurement volume (MV)
  - High spatial resolution
  - Velocity measurement uncertainty of around 1%
- Since LDV is a point measurement technique, data are collected as a series of profiles
- On window surfaces, the MV can be placed 200 μm off the surface
- On the wing surface, the MV can be placed 500 μm off the surface

*The LDV probe were designed and delivered by Roger Simpson and Gwibo Byun of AUR, Inc.

PIV Details

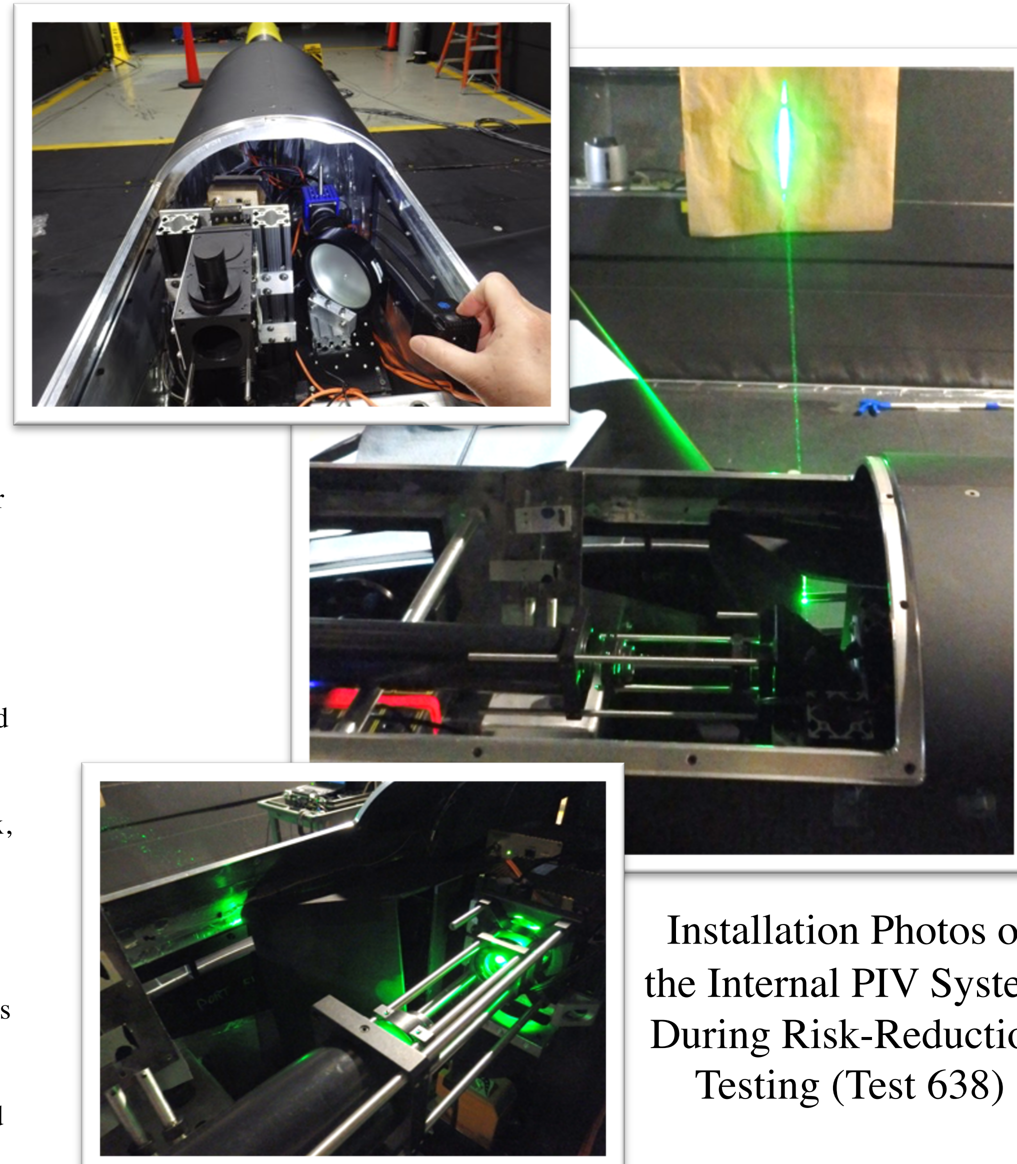
How does Conventional PIV work?



Particles in the flow are exposed by two laser pulses separated in time and imaged using CCD or CMOS cameras.

Images are discretized and the cross correlation is computed to determine particle displacements (dx, dy) over the entire image.

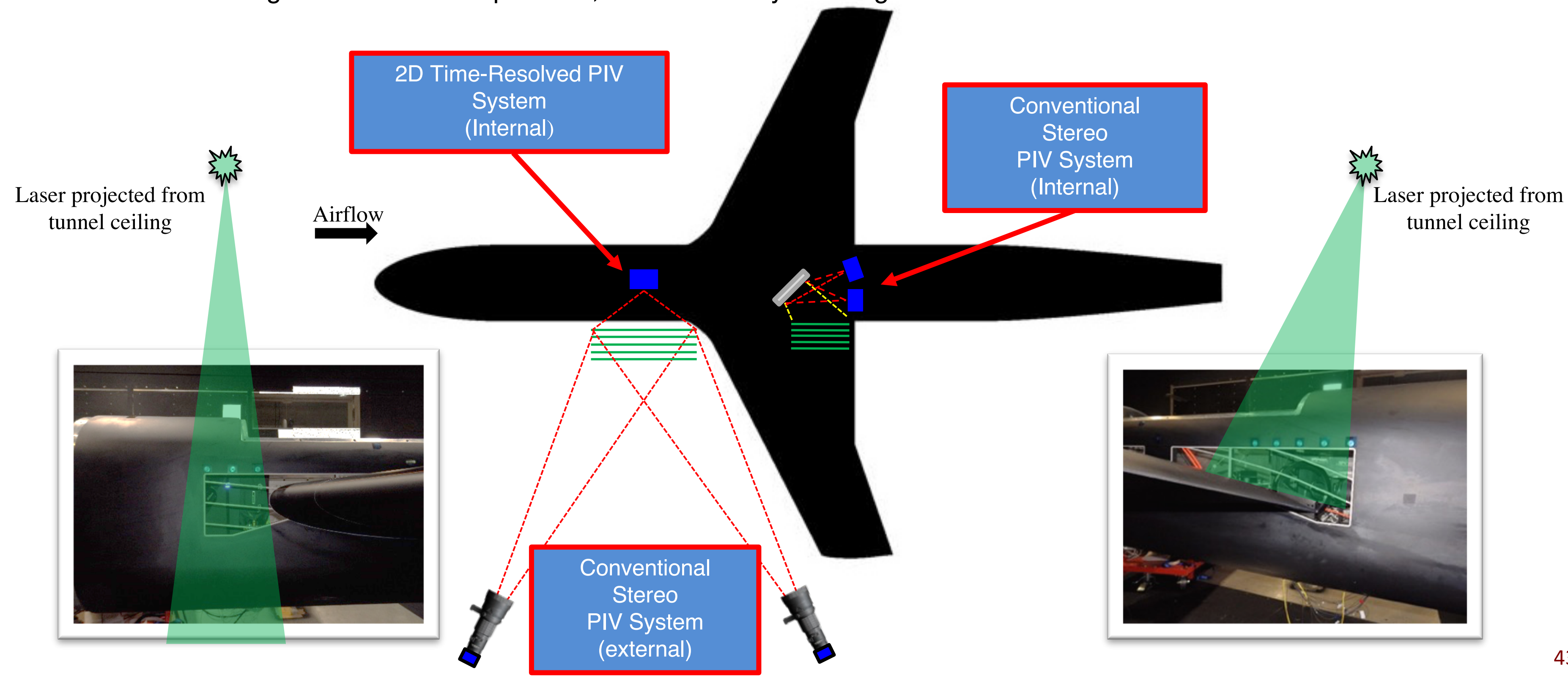
The particle displacements and time between laser pulses are then used to compute the velocity field for the entire image.



Installation Photos of the Internal PIV System During Risk-Reduction Testing (Test 638)

PIV expected results

- At wing LE, multiple planes of PIV data will be acquired parallel to the fuselage (xz plane in body axis coordinate system)
- At wing TE, several planes of PIV data will be acquired above the wing (xz plane in body axis coordinate system)
- Expected results
  - Planar measurements of u, v, w
  - Instantaneous and time-averaged flow structure
  - Higher moments are possible, but uncertainty will be greater



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