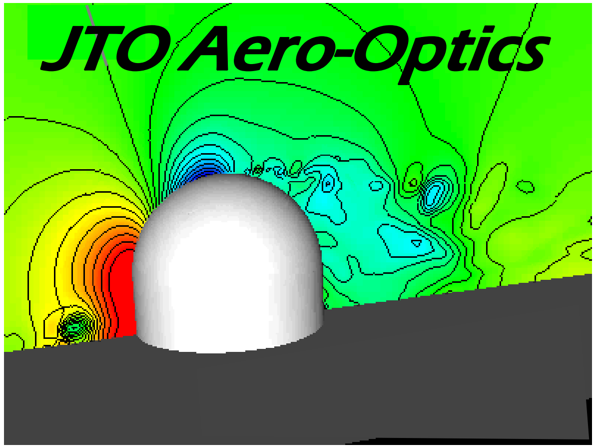

Wind Tunnel Validation of Computational Fluid Dynamics-Based Aero-Optics Model

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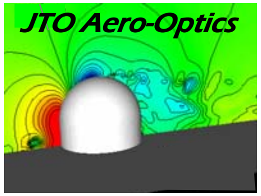


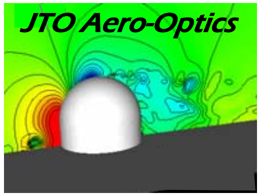
Outline

- Program summary
- Background: Phase I summary

Phase II

- Turret requirements & configuration
- CFD code, computational grid, & OPD calculation
- Typical CFD flow solutions & OPD maps
- Validation

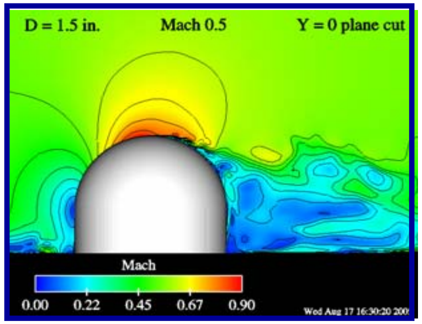
- Summary & conclusions



Program Summary

Need

- Validate CFD-based aero-optics model to analyze optical performance of larger, more realistic airborne system



Objectives

- Validate CFD-based OPD model using wavefront sensor data from wind tunnel experiments
- Exercise CFD model to assess performance of larger, more realistic configuration with conformal window
- Determine wavefront control system requirements

Approach

- CFD validation
  - Wind tunnel WFS measurements of phase over scaled turret with conformal window
  - Compare with CFD-based model at 1:1 scale including wind tunnel boundaries & inlet flow profile
- Large scale analysis
  - Assess performance of larger turret with conformal window
  - Evaluate wavefront control requirements

Status

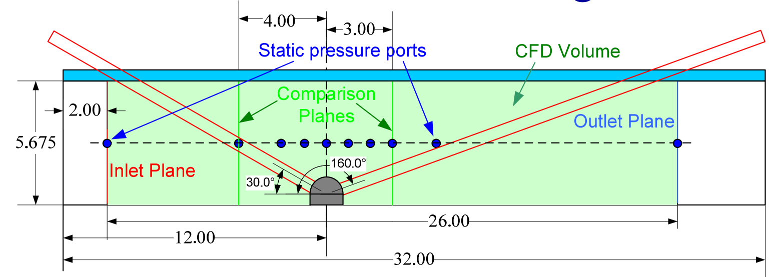
- Program successfully completed
  - Turrets designed & fabricated
  - Wind tunnel tests conducted
  - WFS data collected
  - CFD-based aero model validated
  - Large scale analysis & wavefront control requirements completed

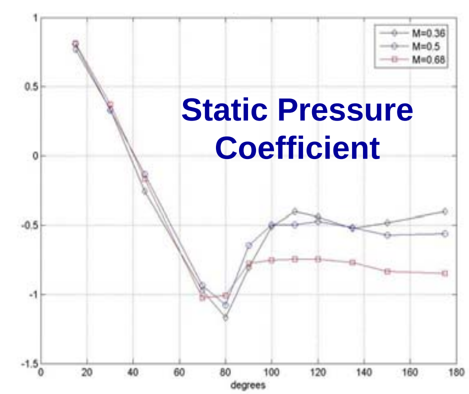
Phase I Results – Wind Tunnel Test

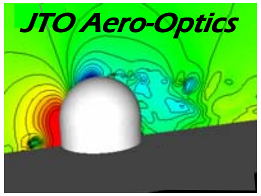
1.5" Diameter Turret with Conformal Window

- **Successful Phase I wind tunnel tests conducted at Notre Dame**
  - **Configuration: 1.5" turret with conformal window**
  - **Mach number**
    - **M0.36, 0.5, 0.6, & 0.68**
    - **M0.5 basis for validation**
  - **Lines-of-sight**
    - **Azimuth = 0° (overhead pass)**
    - **Elevation = 30° to 160°**
  - **Fluid measurements**
    - **Steady & unsteady pressure**
    - **Velocity**
  - **Optical measurements**
    - **Malley probe (1D phase in flow)**
    - **2D Hartmann WFS**

Test Section Configuration



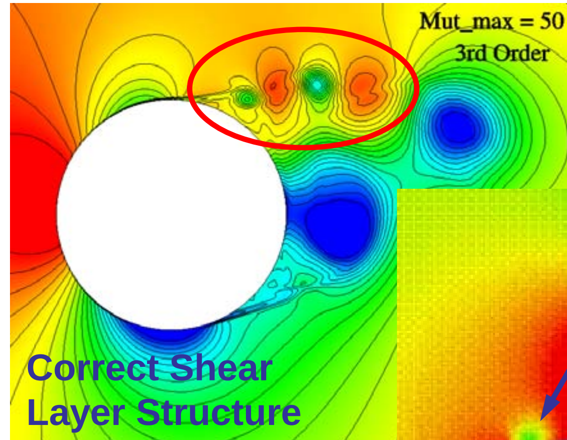




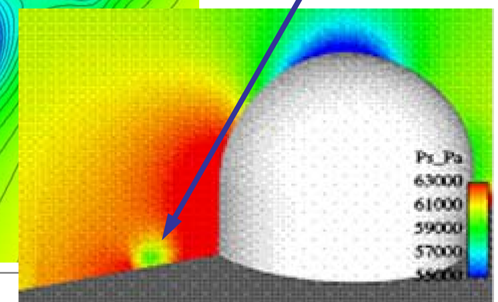
Phase I Results – CFD Validation

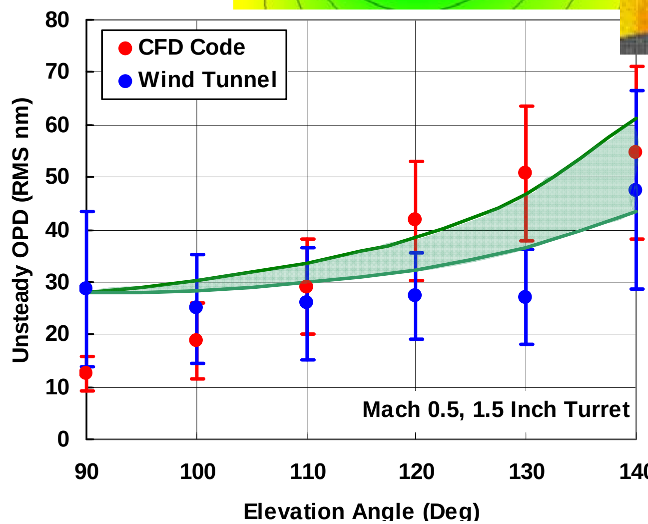
Validated Over Realistic Lines-of-Sight

- **Updated CFD-based aero-optical model**
  - **Increased node density to resolve turbulent bdy layer, free shear layer, & necklace vortex**
  - **Implemented Partially Averaged Navier-Stokes (PANS) technique in k-ε turbulence model**
- **Figures-of-merit**
  - **Tilt-corrected OPD**
  - **In-flow phase correlation length**
  - **Time-averaged mean & standard deviation**

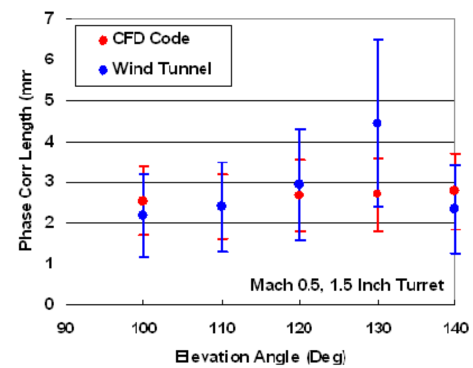


Resolved Horseshoe Vortex





Optical Path Difference

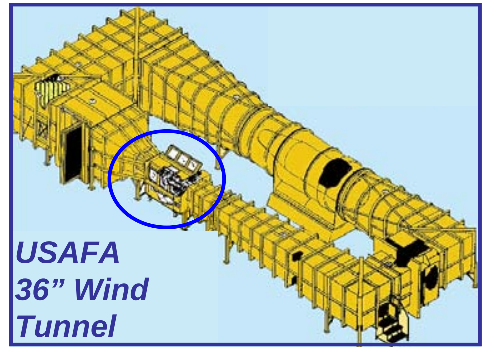


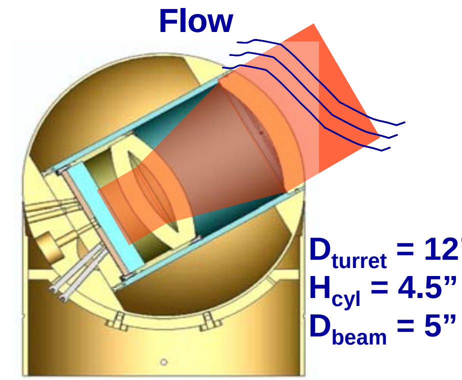
Phase Correlation Length

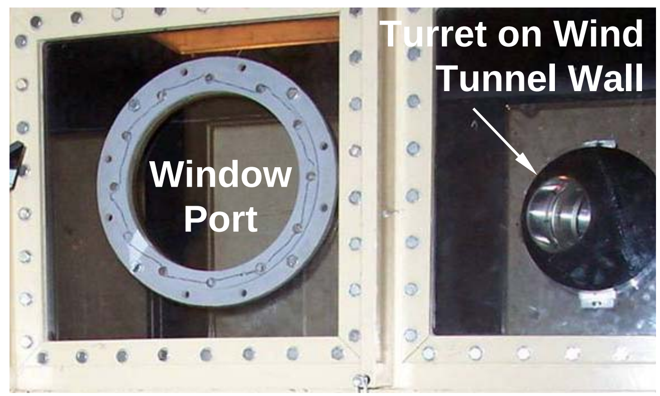
Phase II Turret & Lines-of-Sight

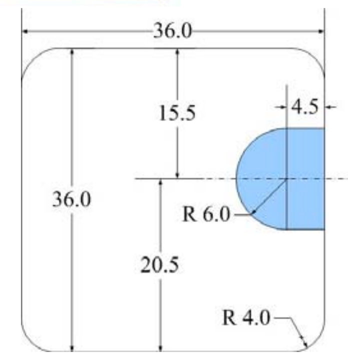
12” Diameter Turret with Conformal Window

- **Configuration: 12” turret with conformal window**
- **Mach number**
  - **M0.35, 0.4, & 0.45**
  - **M0.4 basis for validation**
- **Lines-of-sight**
  - **Azimuth = 0° (overhead pass)**
  - **Elevation = 45° to 130°**
- **Fluid measurements**
  - **Steady & unsteady pressure**
  - **Velocity**
- **Optical measurements**
  - **Malley probe (200 KHz in-flow 1D phase)**
  - **2D Hartmann WFS (10 Hz)**

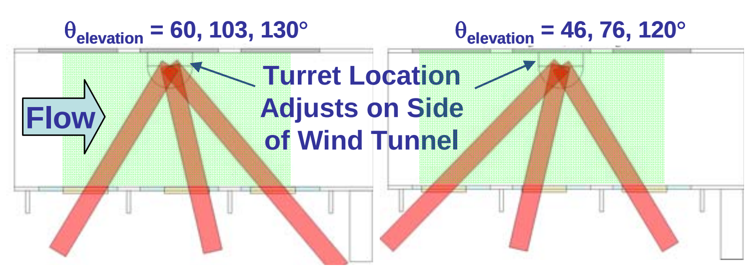




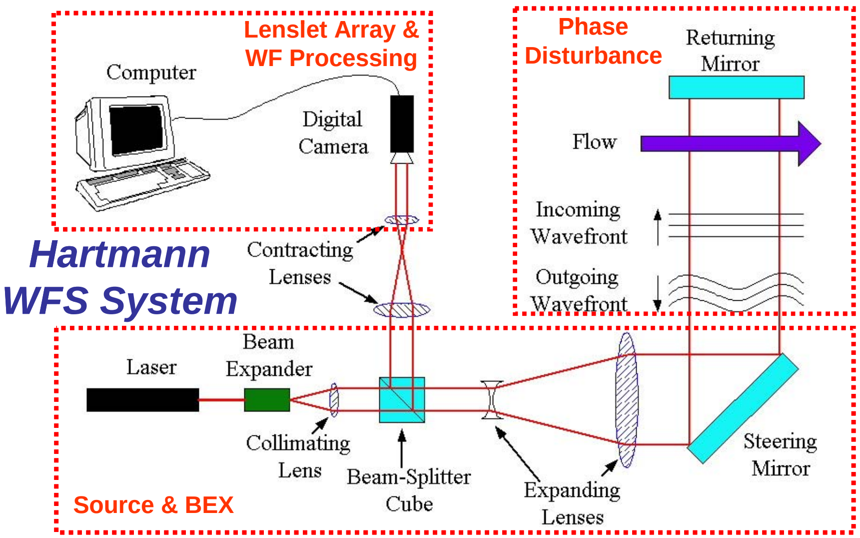




WT Section

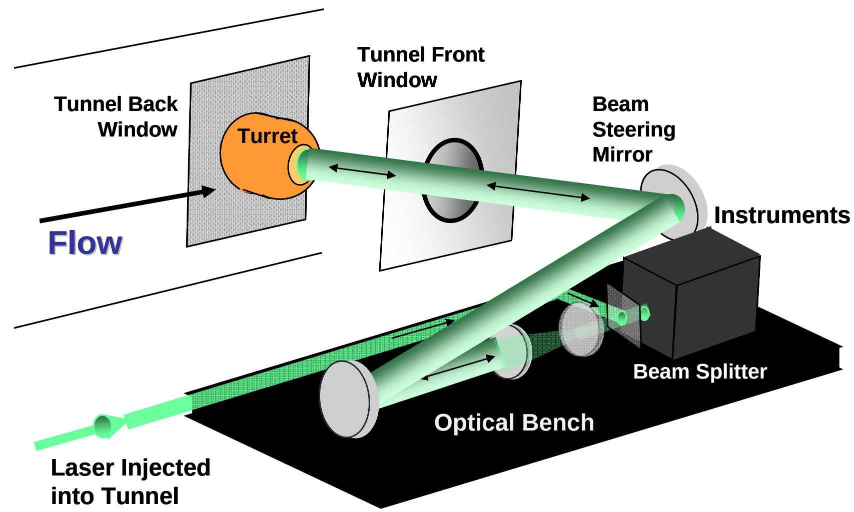


Beam Train & WFS Configuration



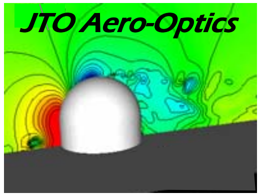
System Configuration

- Laser & beam expander
- Turret generating phase disturbance
- WF sensor & processing



AFA Implementation

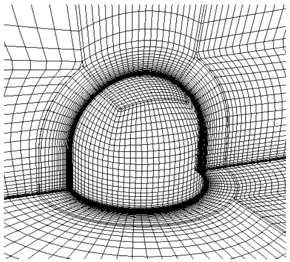
- Laser beam injected thru wind tunnel front window
- Turret on opposite vertical *wall* of wind tunnel



CFD Analysis Approach

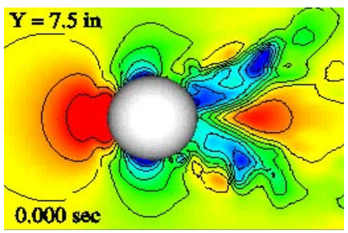
Grid Generation, Flow Solution, & Path Integration

- **Generate computational grid**



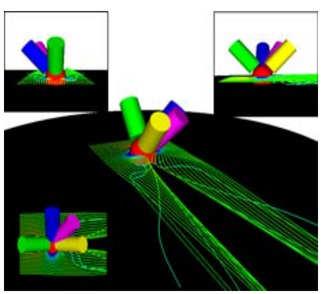
  - **Node array for flow solution**
  - **Varying zones & grid density**

- **Initialize CFD code & run**

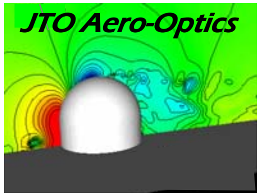


  - **Steady-state soln from Navier-Stokes eqns**
  - **Unsteady flow solution**

- **Integrate density variations**

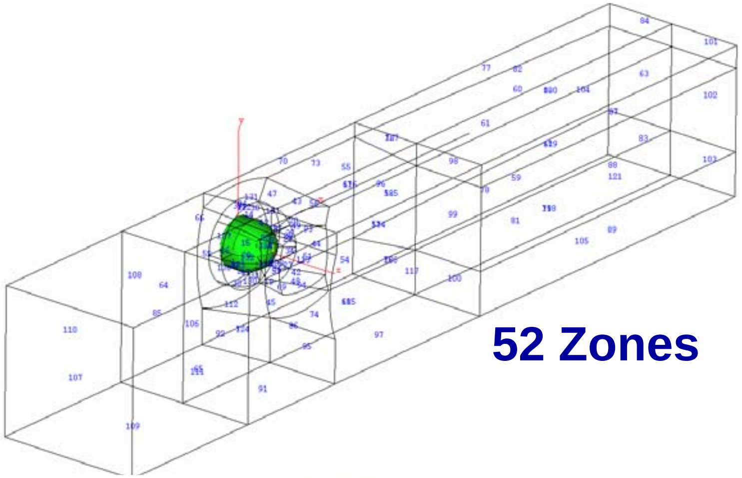


  - **Interpolate flow soln to OPD array**
  - **Integrate density to yield OPD(time,LOS)**



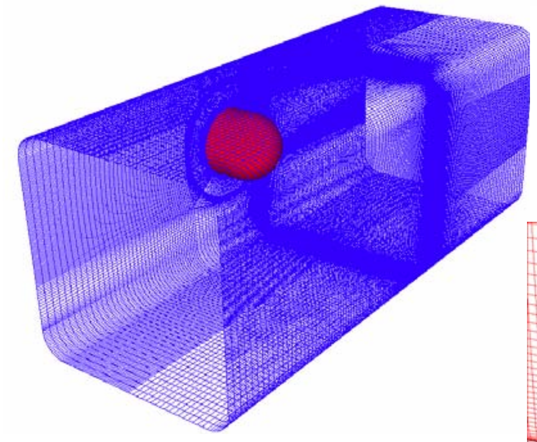
Grid Development

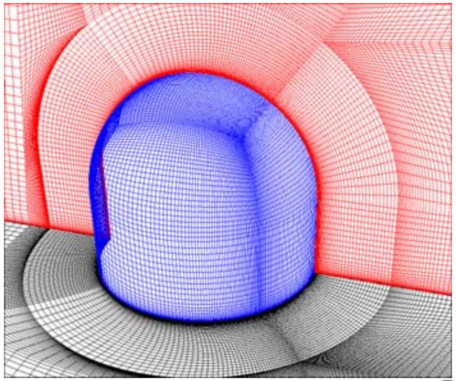
Zones & Nodes Define Computational Boundaries



52 Zones

2.7M Nodes





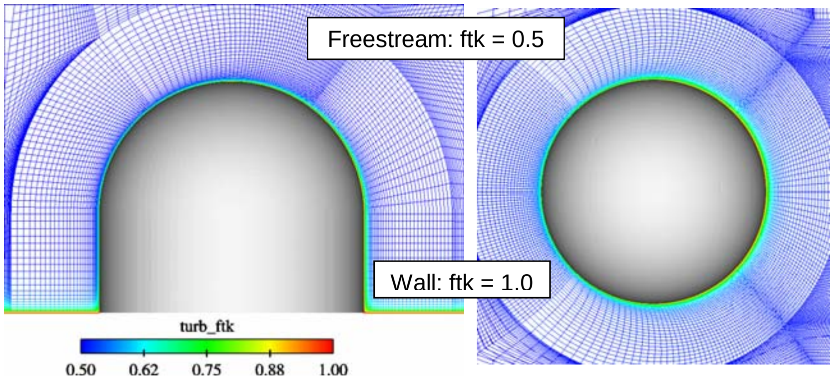
Zone & Node Density About Turret

- CFD model includes turret, wind tunnel walls, & inlet flow profile
- Conformal window flow symmetry allows single grid for all Mach numbers & LOS angles
- Structured grid
- Grid density increased in boundary & shear layers
- Extends 45” upstream to 150” downstream
- 52 zones
- 2.7 million nodes

Flow Solver & Conditions

Time Iterative Density/pressure-based Algorithm (TIDAL)

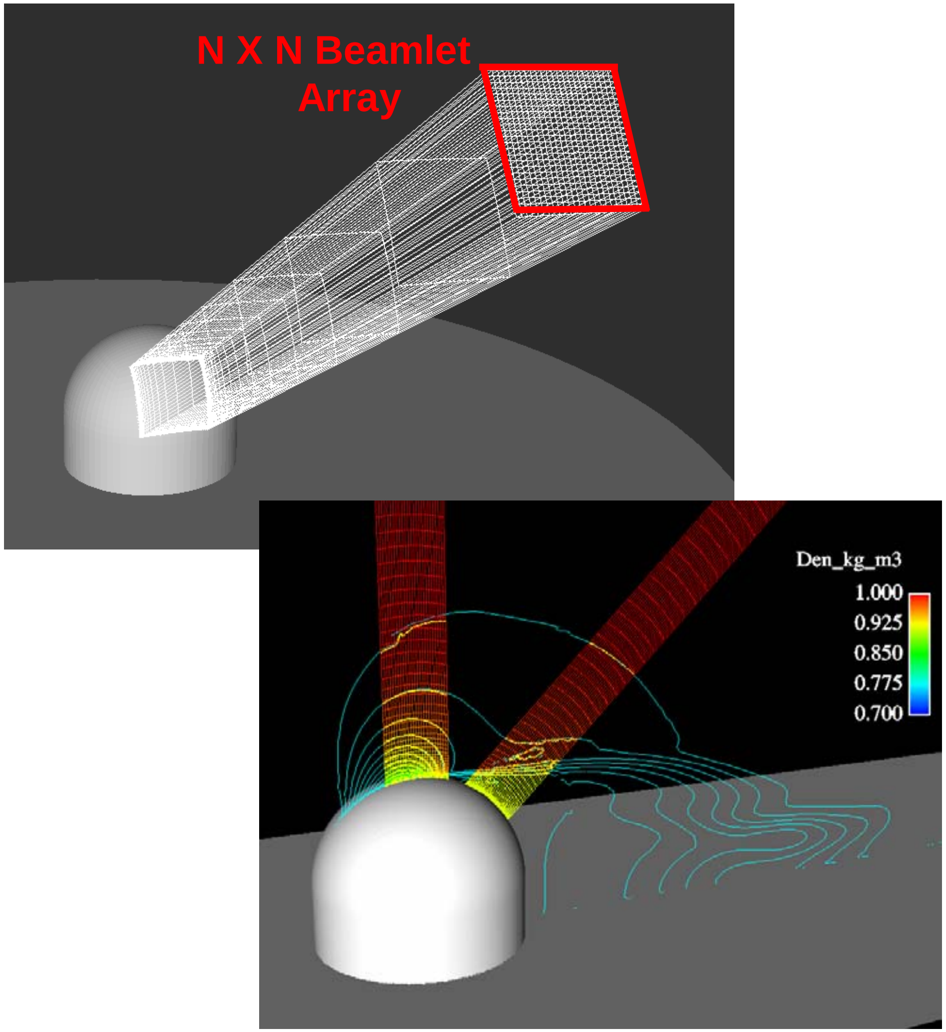
- **Code features**
  - **Generalized 3D flow solver**
  - **Finite 3D volume with multi-zone method**
  - **Structured grid**
  - **Steady & unsteady flow**
  - **Dual time stepping for time-accurate calculations**
  - **Partially Averaged Navier-Stokes (PANS) k-ε model**
- **Values**
  - **5 μsec time step**
  - **Solution saved at Δt = 50 μsec**
  - **300 frames saved (15 msec) for wavefront analysis**
  - **ftk = 0.4 ~ 1.0**



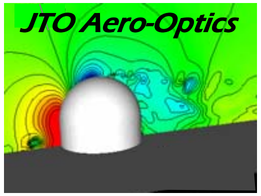
Variable ftk

JTO Aero-Optics

OPD Calculation

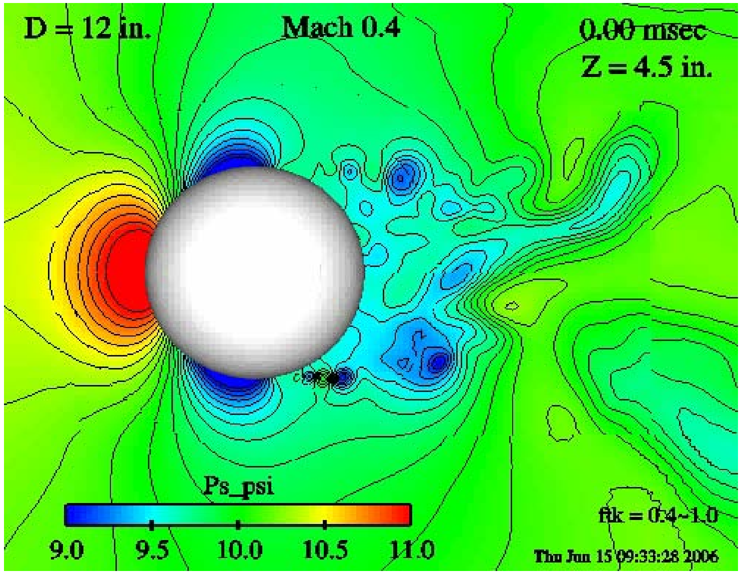


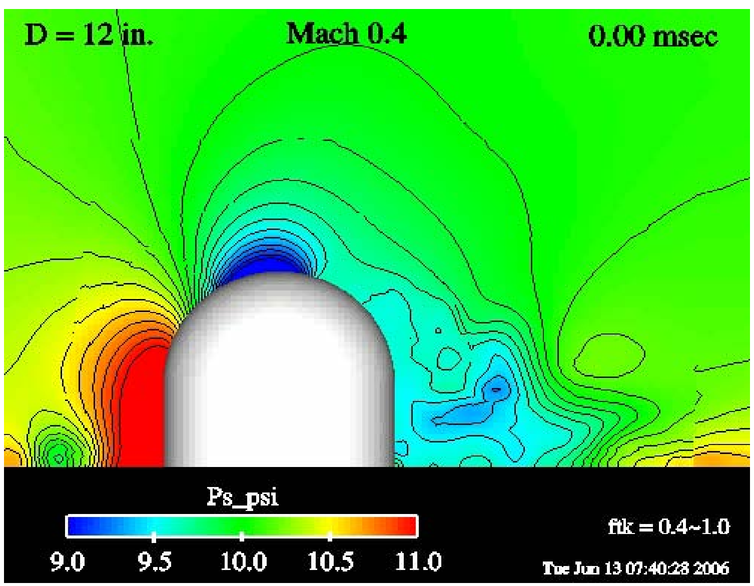
- **Generate beam grid**
  - **25 x 25 mesh**
  - **~ 12.7 x 12.7 x 120 cm^3**
- **Beam grid extends from turret window to tunnel wall**
- **Interpolate flow density to beam grid**
- **Integrate density or index along beam direction (grid line) to obtain OPL**
- **Use ambient density inside turret & outside of tunnel**



Typical Flow Solutions

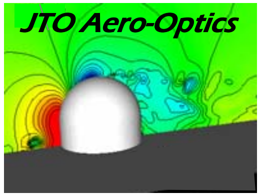
Solution Shows Required Features





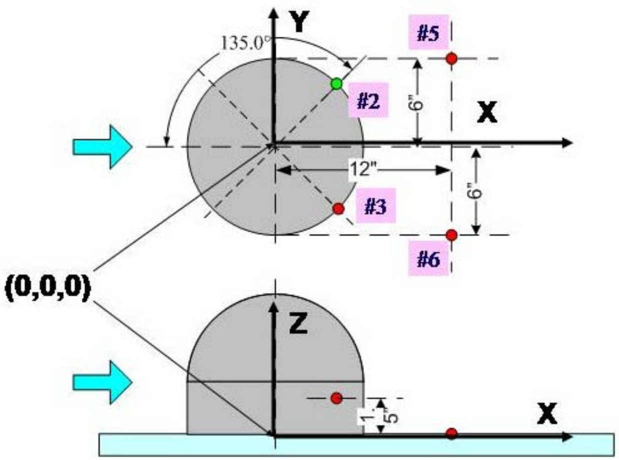
- **Instantaneous realizations of central plane & shoulder plane sections**
- **Low pressure aft result of wake**
- **Low pressure, circular area forward at base is core of necklace vortex**
- **Instability in shear layer rolls into vortices**
- **Pressure within vortices shows oscillatory behavior as in PIV**

Resolution of shear layer vortices is critical to accurate simulation of aero-optical effect

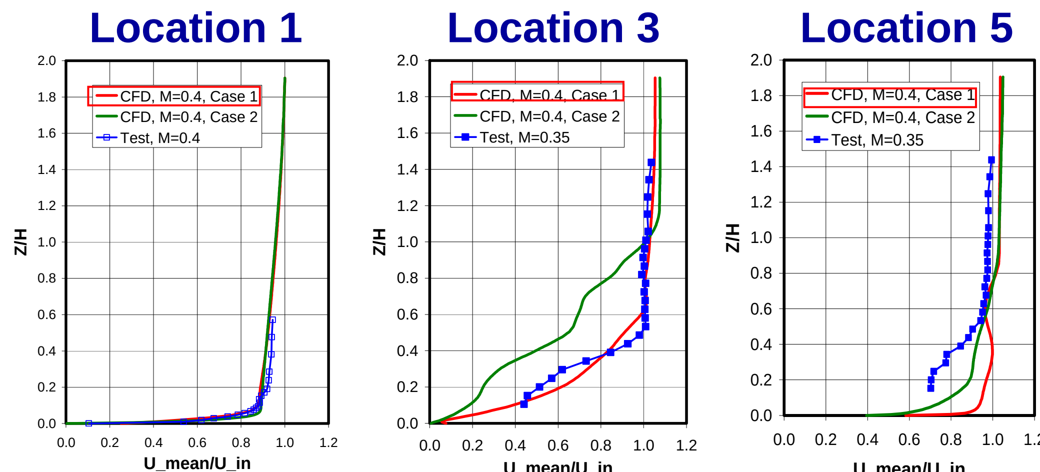


Fluid Mechanical Validation

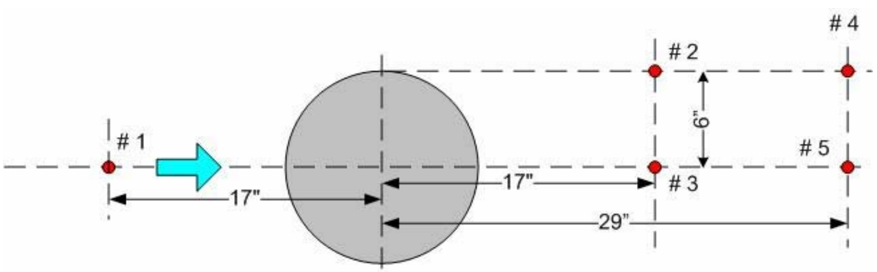
First Match Fluid Properties



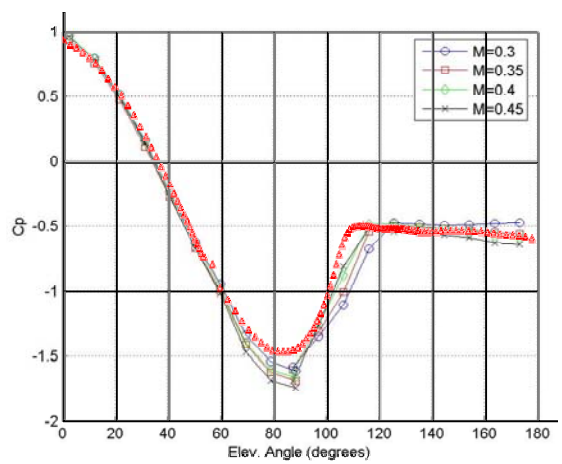
Locations of unsteady pressure sensors



CFD-based & measured velocity profiles (Case 1 is selected model)



Locations of velocity profile sensors

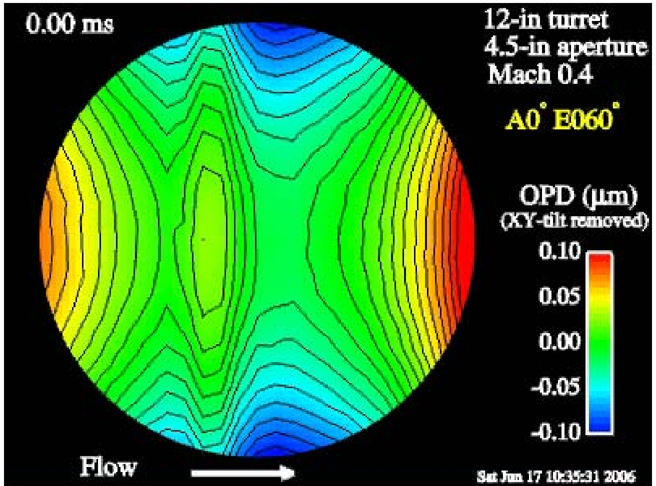


CFD & measured C_P over elevation angle

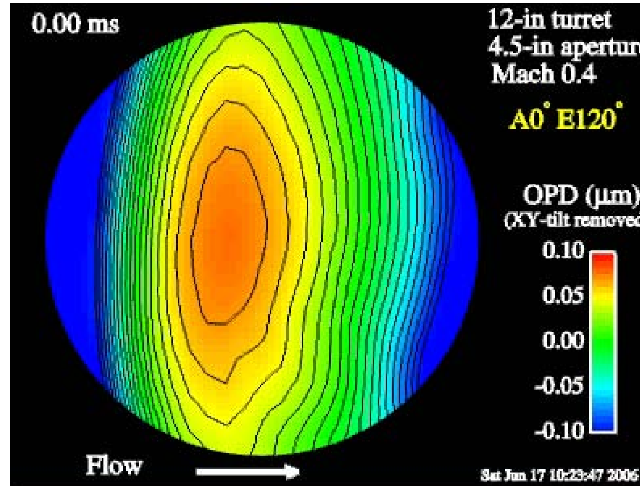
JTO Aero-Optics

OPD Maps in Time

Piston & Tilt Removed OPD at 60°, 90°, 120° & 132° Elevation



C1_OPD_notilt_A000E060_c.avi



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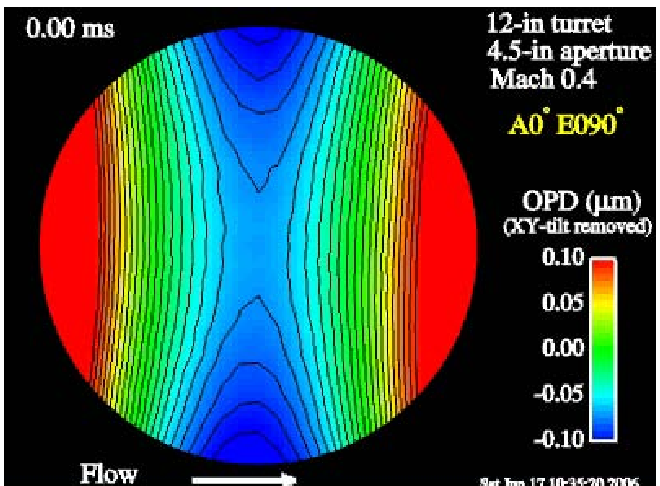

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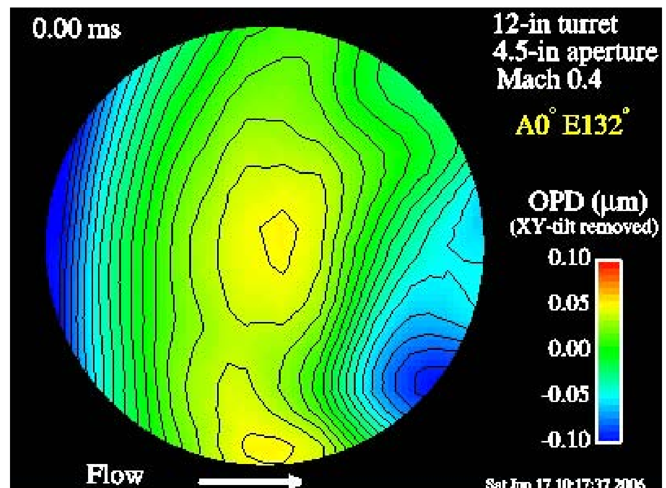

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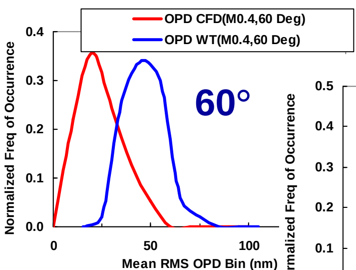
BOEING

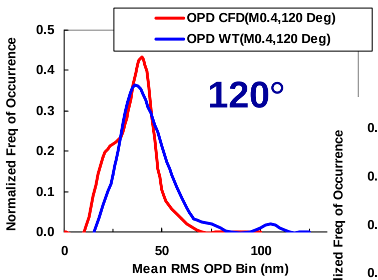
JTO Aero-Optics

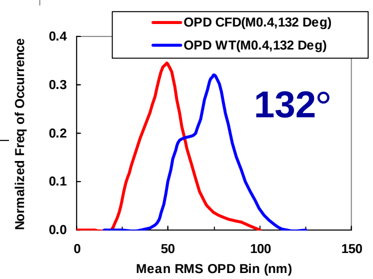
Optical Validation

FOM: RMS Wavefront Error & Phase Correlation Length

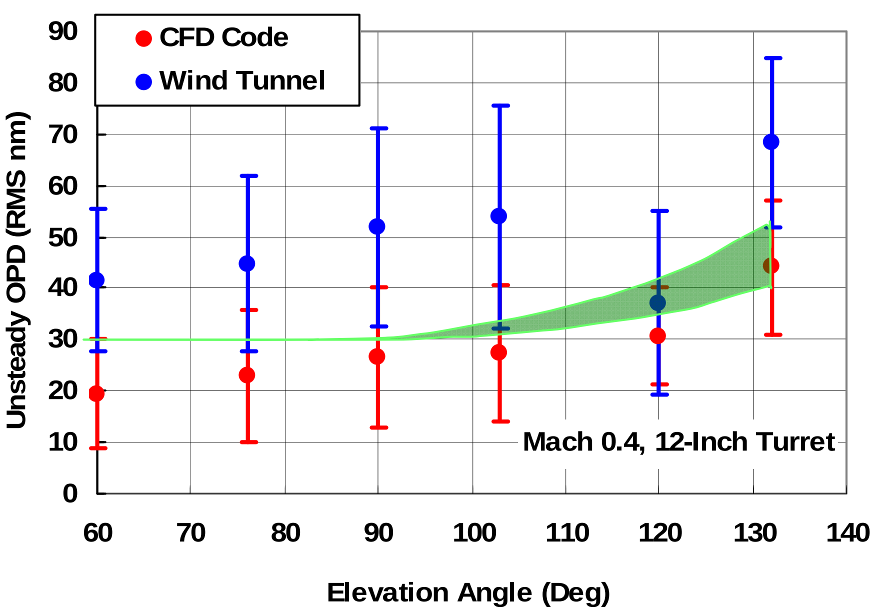
Wavefront Error



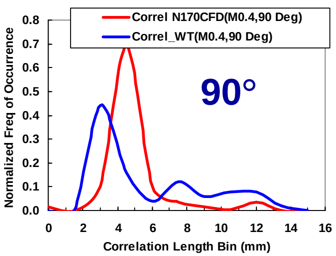


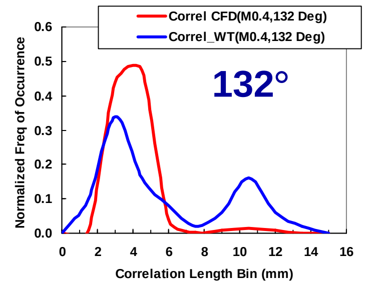


Measured & CFD-based PDF for RMS OPD at each elevation

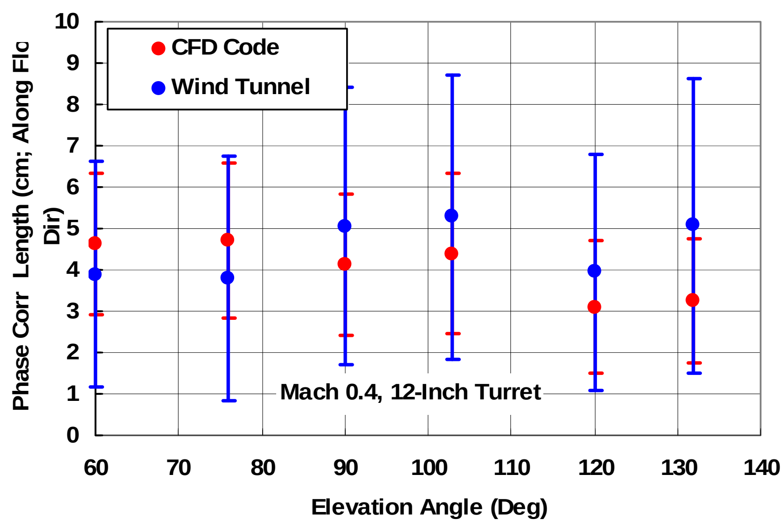


Phase Correlation Length





Measured & CFD-based PDF for phase correlation length at each elevation



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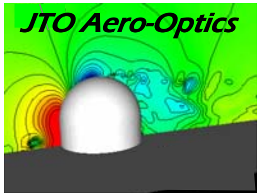

Summary & Conclusions
Successful Model Validation

- **Aero-optical effects beyond separation point can be a significant performance degrader in airborne systems**
- **Wind tunnel testing is expensive, time-consuming, & subject to scaling limitations; exercising CFD is cost effective**
- **JTO program successfully validated CFD-based aero-optical model based on fluid & optical FOMs**
- **Good agreement using reasonable turret & window configurations over practical range of LOS angles**
- **Lessons learned: Grid generation (resolution vs CPU time), turbulence model, & scaling limits**
- **WFS data useful for validation in future CFD development**