High Reynolds Number Computational Aero-Optics

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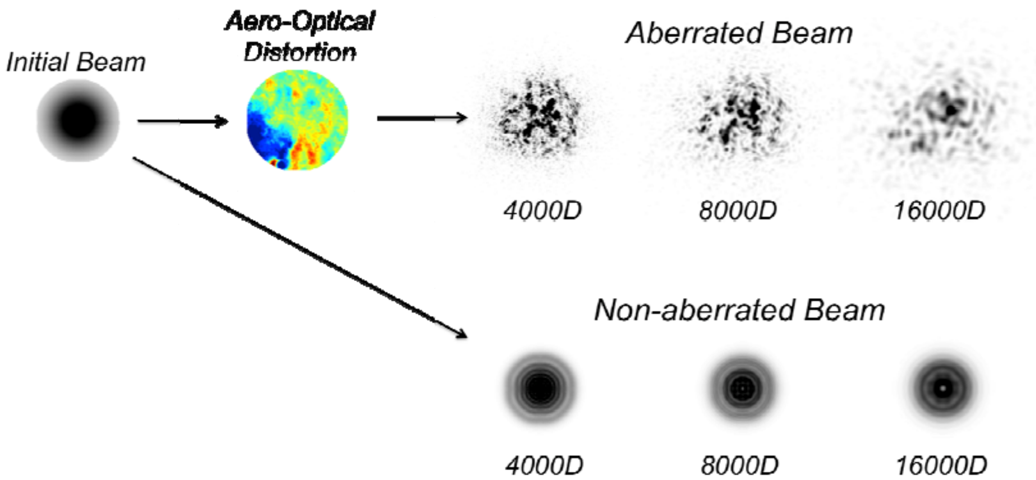
What is Aero-Optics?

- In short: The distortion of an optical beam caused by turbulent compressible flow



$$n(\mathbf{x}, t) = 1 + K_{GD}\rho(\mathbf{x}, t)$$

$$\mathrm{OPL}(x, y, t) = \int_{s_0}^{s_1} n(x, y, z, t)ds$$

$$\mathrm{OPD}(x, y, t) = \mathrm{OPL}(x, y, t) - \langle \mathrm{OPL}(x, y, t) \rangle$$

- Distortions are caused by non-uniform index-of-refraction field resulting from turbulent density fluctuations and small amplitude distortions in the near field can cause severe performance degradation in beam intensity and fidelity
- Major impediment to applications of airborne optical systems for communication, imaging, targeting, and directed energy systems

Current Work

- Want to use Computational Fluid Dynamics (CFD) to improve our understanding and our predictive capability of aero-optics systems at realistic Reynolds and Mach numbers

$$Re = \frac{\rho V D}{\mu} \quad Ma = \frac{V}{c}$$

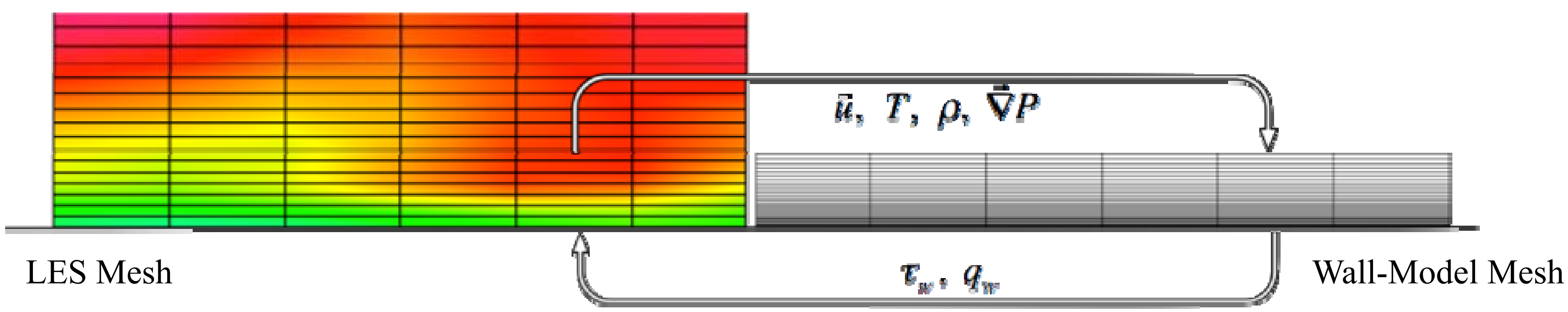
- Simulate the optical turret used on Notre Dame's Airborne Aero-Optical Laboratory (AAOL) using wall-modeled Large-Eddy Simulation (LES) at the actual flight Reynolds number of 2,300,000 and Mach number of 0.4
- Largest aero-optics calculation and highest Reynolds number wall-modeled LES to date, using over 200M control volumes

Challenges for Computational Aero-Optics

- Prediction of aero-optical distortions requires the capturing of optically relevant flow scales
- Mani et al. (2008) showed that this requirement can be fulfilled by adequately resolved Large-Eddy Simulation (LES)
  - LES solves the spatially filtered Navier-Stokes, continuity, and energy equations and provides modeling to account for the scales smaller than those resolved by the computational grid
- Resolving the turbulence near a wall in high Reynolds number flows is cost prohibitive in high-fidelity CFD (Choi and Moin, 2012)
  - $N_{total} \propto \mathrm{Re}_L^{37/14}$ for DNS
  - $N_{total} \propto \mathrm{Re}_L^{13/7}$ for wall resolved LES
  - $N_{total} \propto \mathrm{Re}_L$ to resolve outer scales of boundary layer in LES

Wall Model Method

- By solving the simplified Thin Boundary Layer equations on an embedded mesh, the wall shear stress τ_{wm} and heat flux q_w are imposed as approximate boundary conditions to the near-wall cell for LES calculations

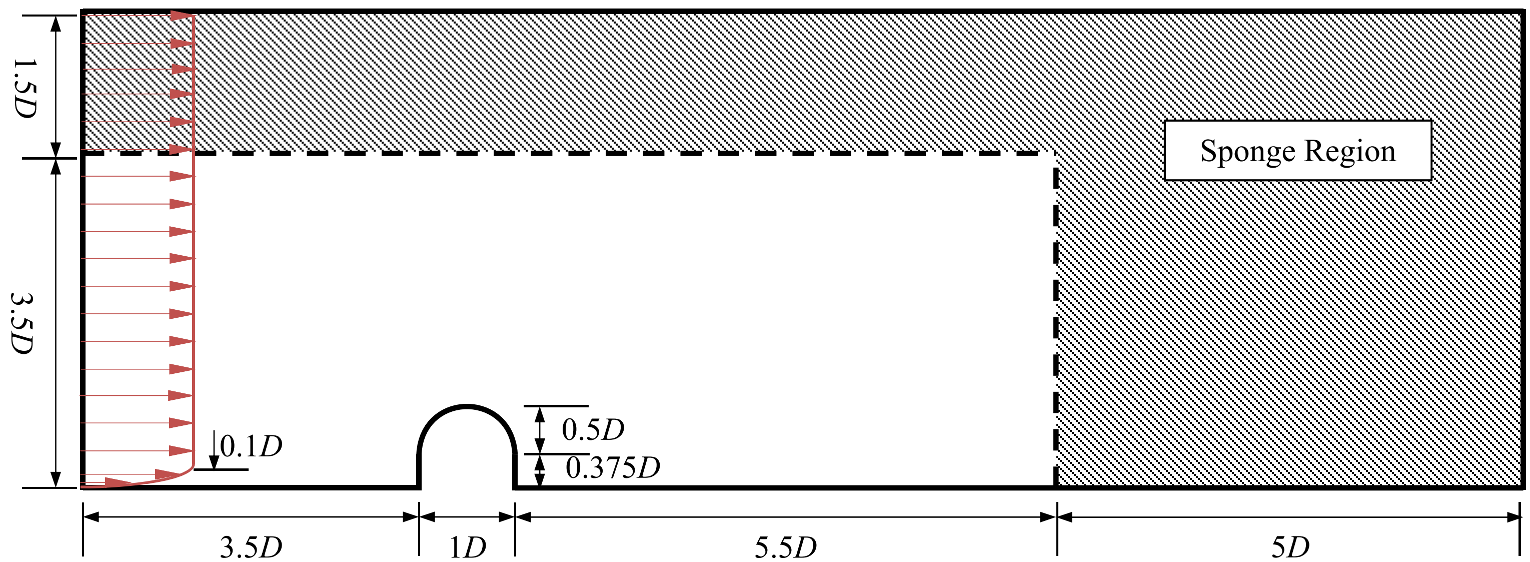


- In only resolving the outer scales of the boundary layer, LES at the Reynolds numbers of some engineering systems becomes possible where it was previously cost prohibitive

Flow Solver

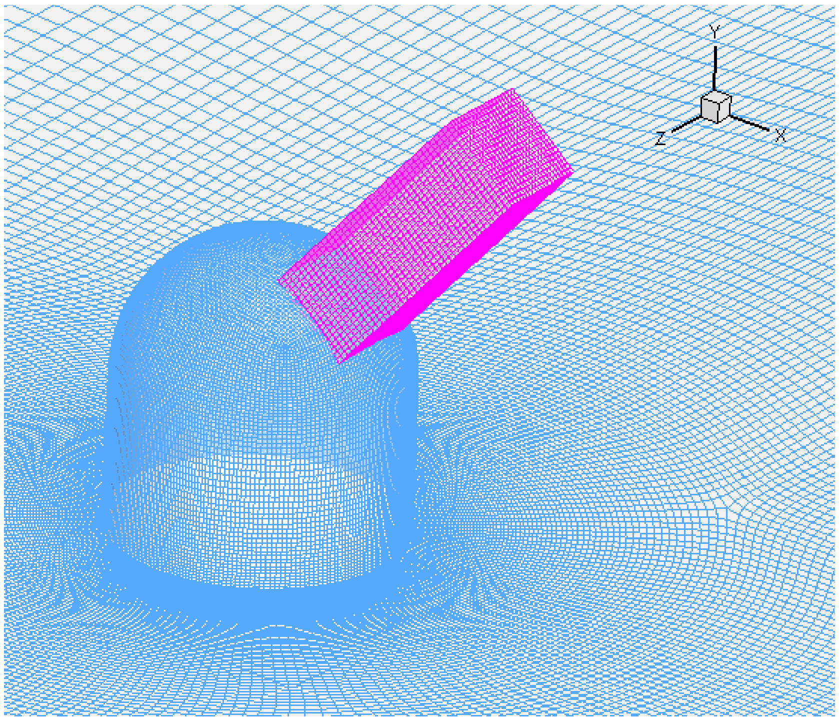
- Unstructured mesh, compressible LES code CharLES developed at Cascade Technologies Inc. (Khalighi et al. 2011)
- Low-dissipative finite volume for spatial discretization
  - Non-dissipative central flux blended with a dissipative upwind flux to provide computational stability when the mesh quality is not ideal
  - The amount of upwind dissipation is minimized and determined by local mesh skewness
  - Formally 2nd order but is 4th order in uniform Cartesian mesh
- Third-order Runge-Kutta in time
- Vreman model for subgrid-scale stress (Vreman 2004, You & Moin 2007)
- Parallelized using MPI

Simulation Domain



- Computational domain: 15*D* × 10*D* × 5*D*, 200.5 million CV's
- 0.1D Mean turbulent boundary layer profile provided at inlet
- Wall model applied on turret surface and bottom wall
- Sponge layer at the top and outlet damps out turbulent structures and acoustic waves
  - Running average is employed in sponge region and acts as boundary condition on both surfaces
- In spanwise direction, flow is periodic

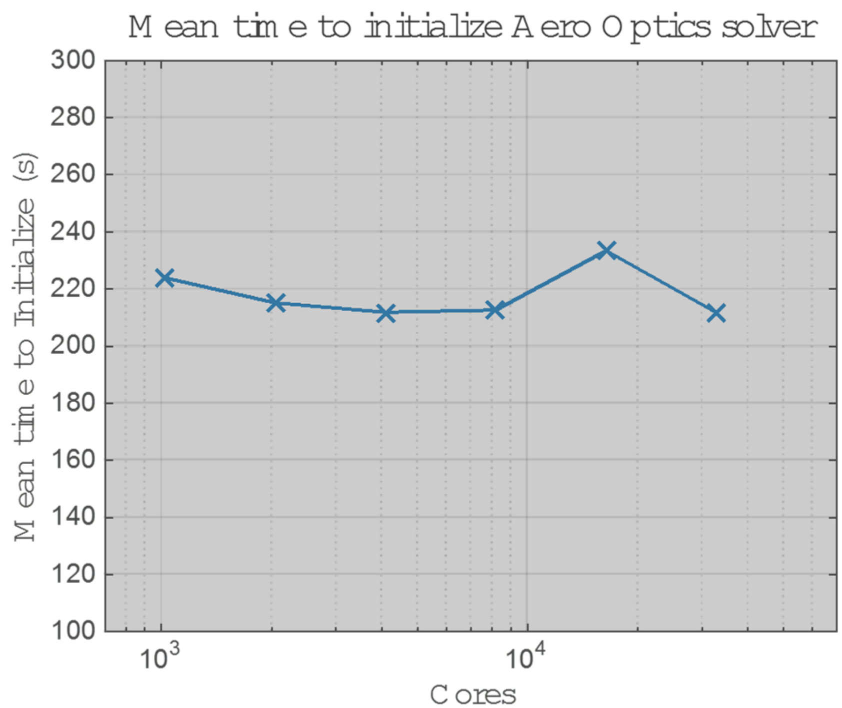
Optics Solver

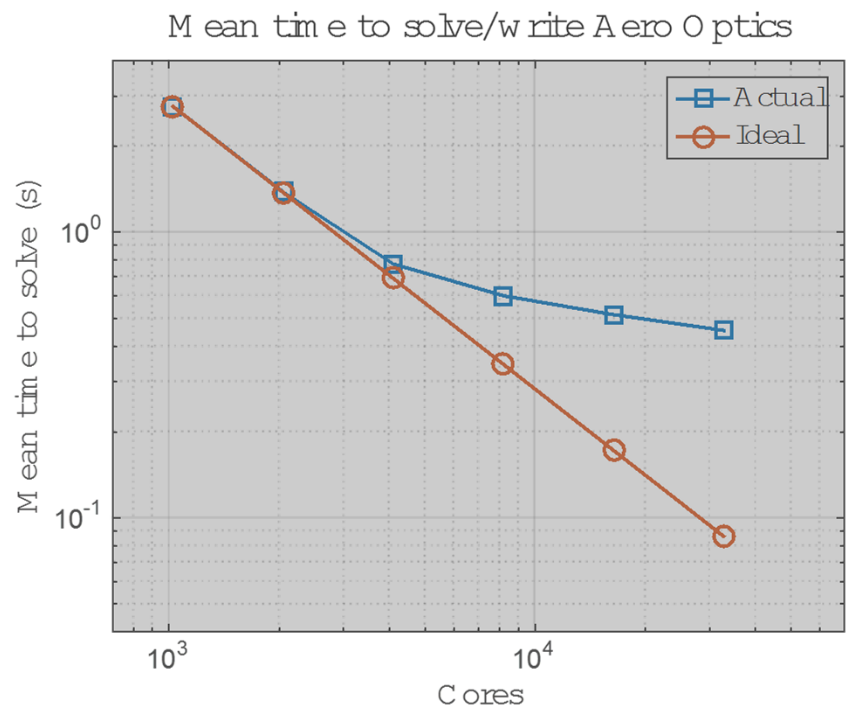


$$\mathrm{OPL}(x,y,t) = \int_{s_0}^{s_1} n(x,y,z,t)\,ds$$

- To compute the optics, separate beam grids are embedded in the computational mesh and computed using geometric optics
  - Each grid extends approximately 2*D* from the turret surface encompassing the entire optically active region of the flow
  - At each time step when the optics are calculated, the density is interpolated from the LES mesh using a second-order method, and the index of refraction is calculated and integrated along the beam propagation path
- Parallelized by integrating segments on each processor and compiling at the end using a collective communication

Optics Solver





- With Blue Waters, able to solve for nearly 300 viewing angles encompassing the entire turret viewing area.
- Each beam contained 5.4 million points – each time optics are calculated, ~1.5 billion points are interpolated and integrated. Generated ~1 TB of optical data in all.

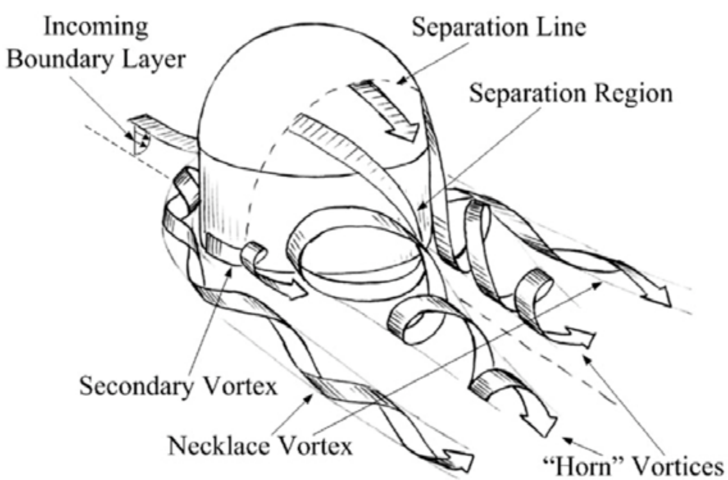
Flow Field Results - λ_2 in Turret Wake

Vortex structures visualized using λ_2. Blue structures denote strong coherent vortices (lower values of λ_2), red structures represent weaker vortices (higher values of λ_2).

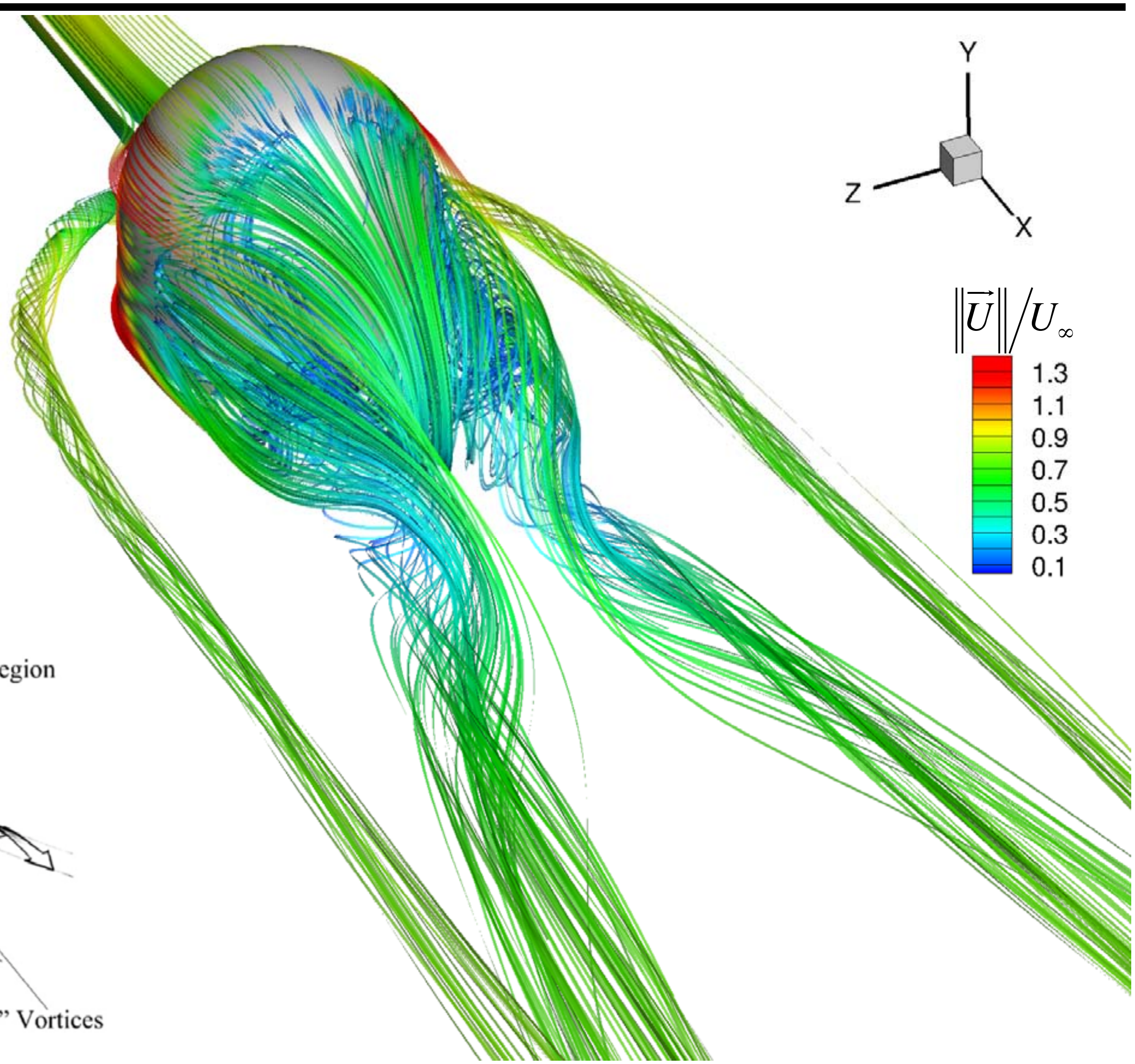
Fluctuating Pressure in Turret Wake

Isosurface of the fluctuating component of pressure, 0.7% lower than the local mean value.
Surface colored by value of fluctuating density, -2.5% (blue) – +0.5% (red) above local average.

Streamlines of Time-Averaged Velocity

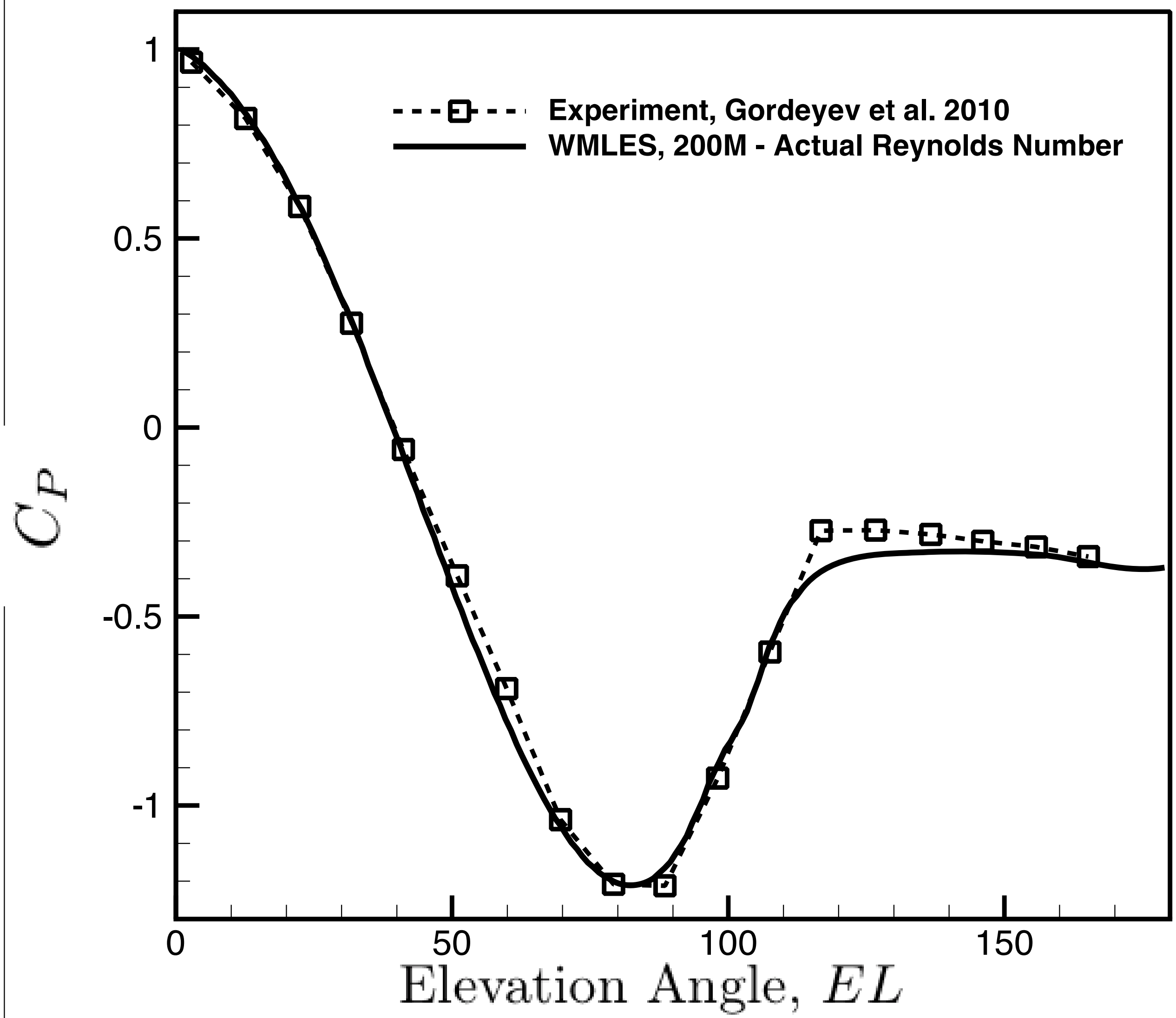


Gordeyev and Jumper.
"Fluid dynamics and aero-optics of turrets."
Progress in Aerospace Sciences. 2010.

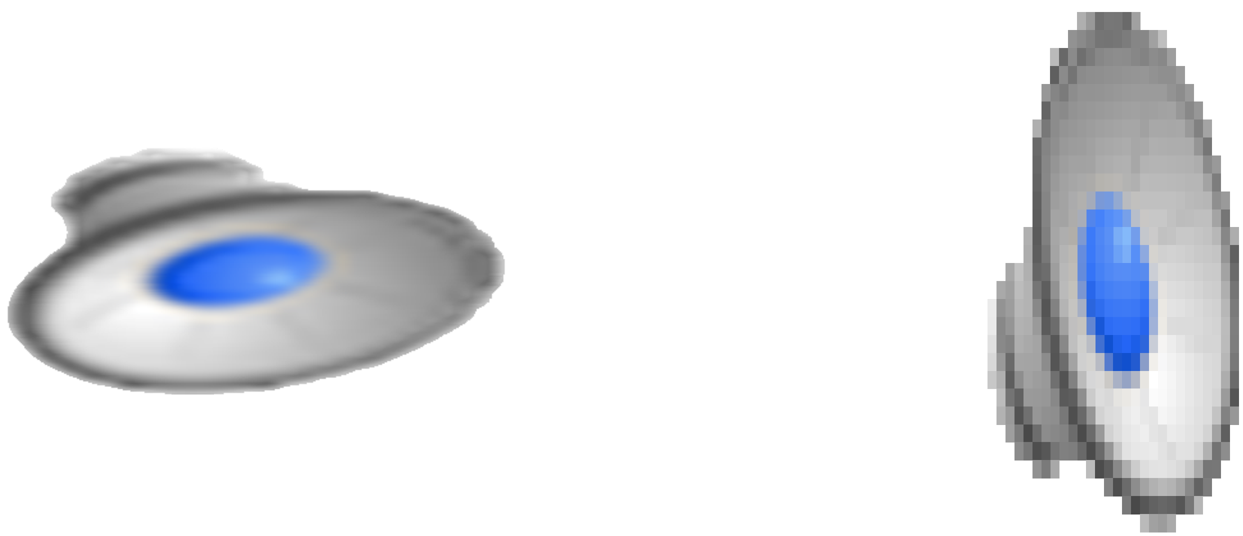


Pressure Coefficient in Turret Centerline

Coefficient of pressure along the turret centerline compared with wind tunnel measurements.

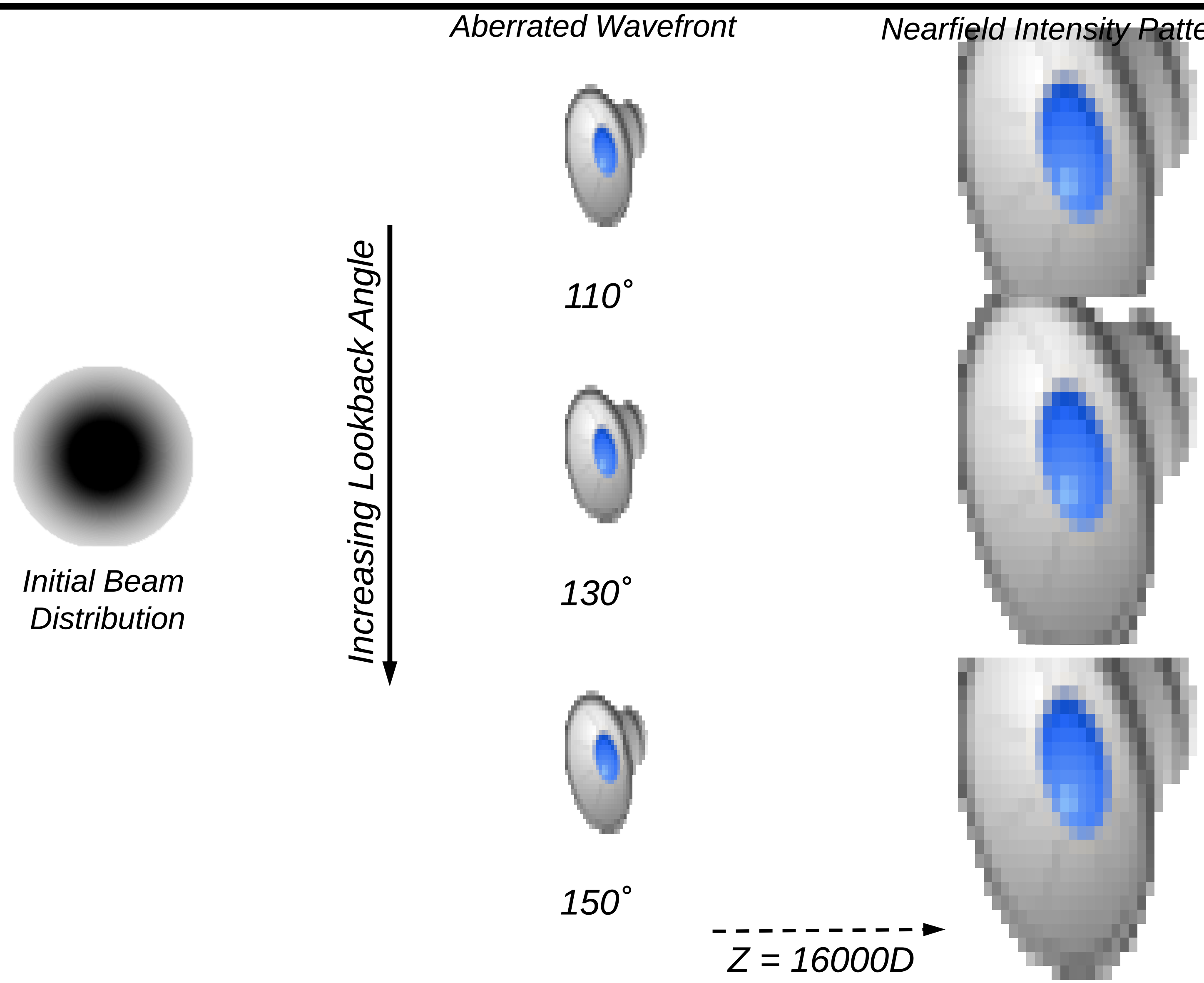


Density Fluctuations in Turret Wake

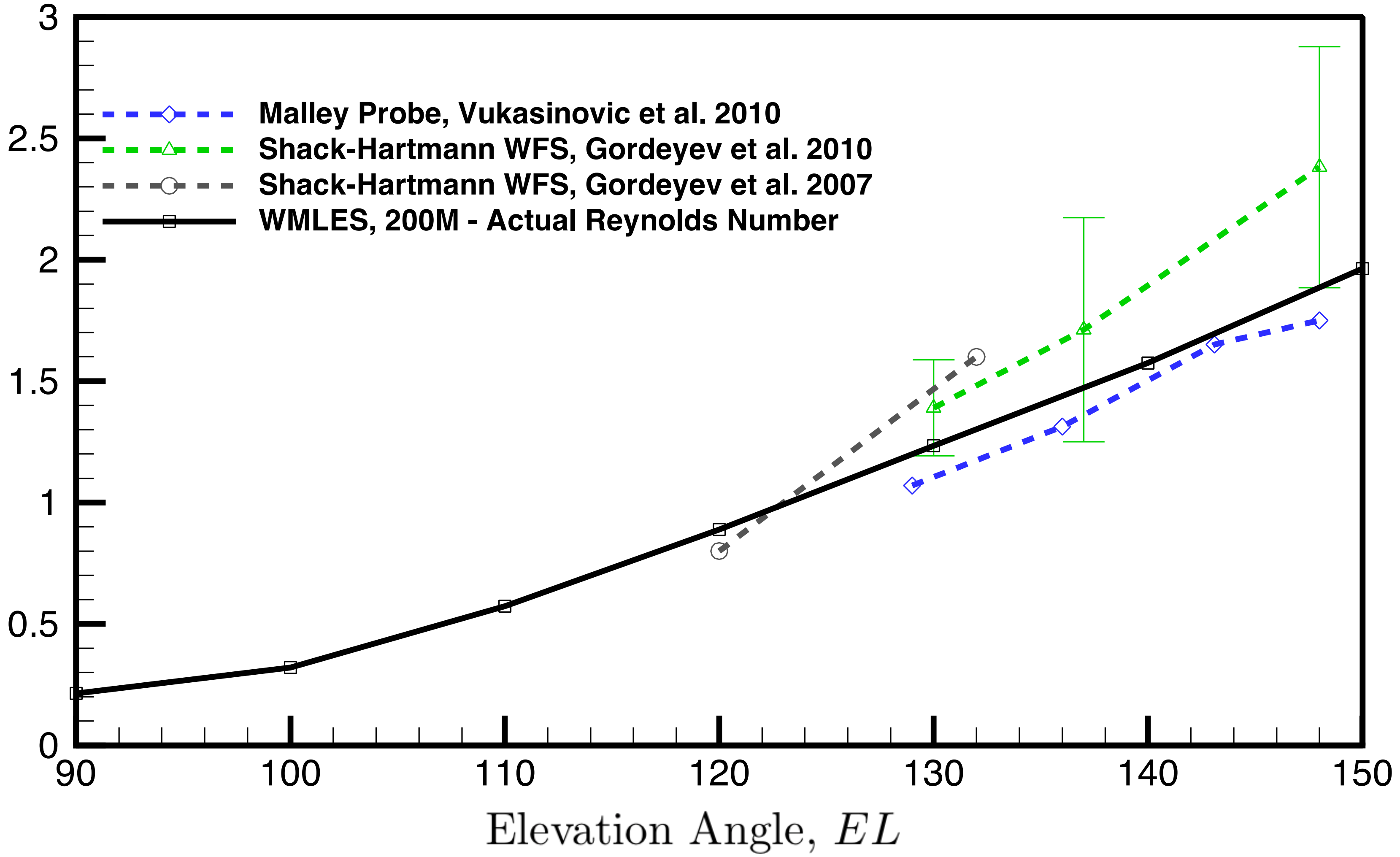


Contours of fluctuating component of density responsible for aero-optic effects.
Red and blue regions are 1.25% larger and smaller than the local mean, respectively.

Optical Results – Centerline in Wake

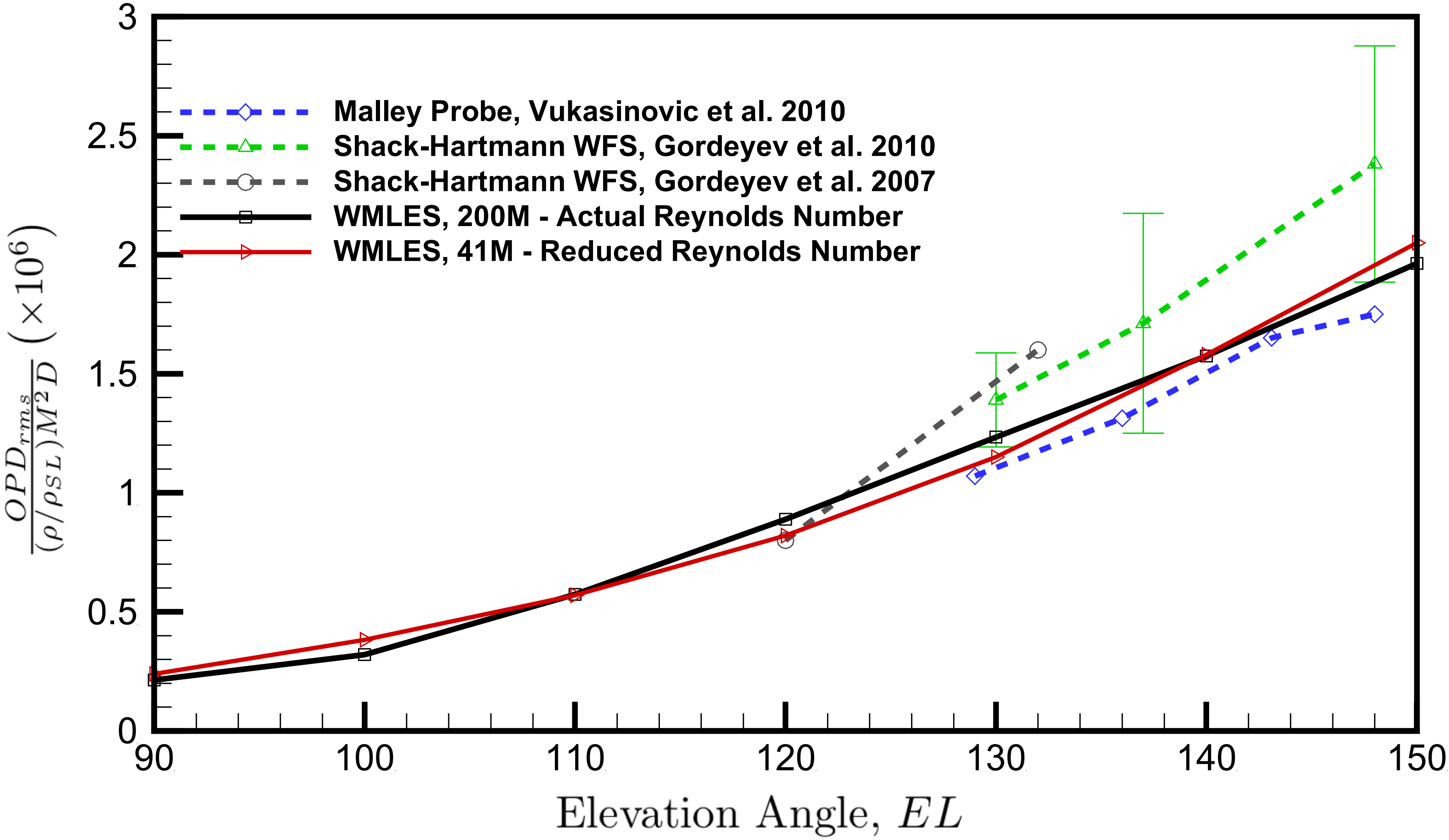


Comparison with wind tunnel measurements of the normalized OPD_{RMS}, a measure of optical distortion, along the centerline of the turret.



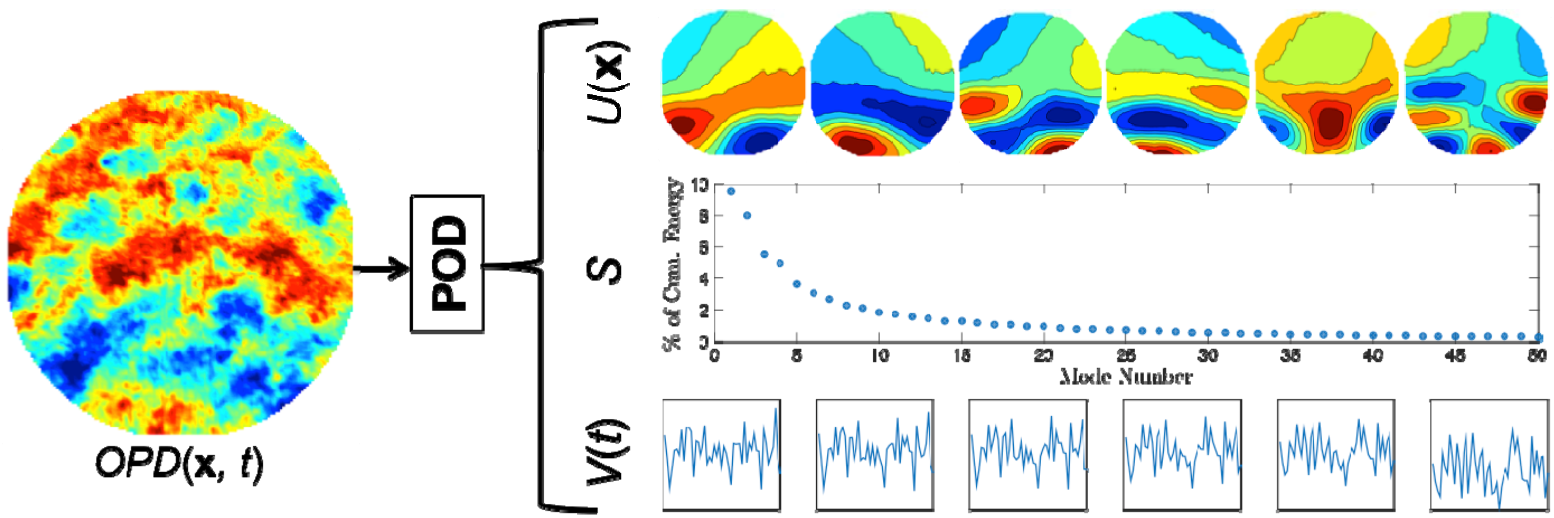
Optical Distorsion Measurements

Comparison with wind tunnel measurements of the normalized OPD_{RMS}, a measure of optical distortion, along the centerline of the turret.



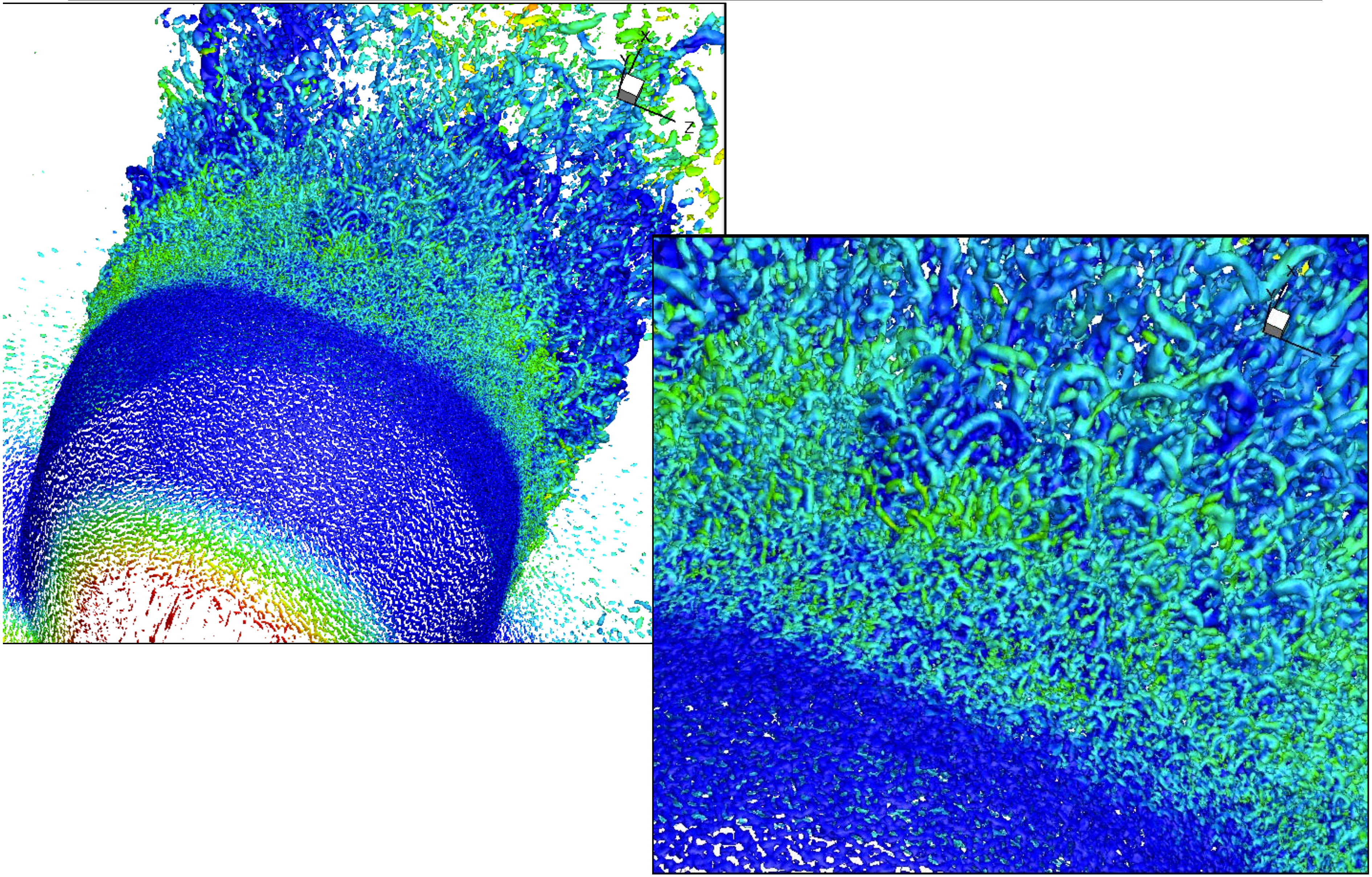
Future Work

- Processing the over 40 TB of flow field and optical data to extract information that can be used to guide the design of aero-optics mitigation strategies
- Beyond classical statistical approaches, looking to use data mining techniques like Proper Orthogonal Decomposition (aka PCA) and Dynamic Mode Decomposition
  - A scalable set of data mining tools specifically for fluid dynamics would be useful for experimentalists and CFD users

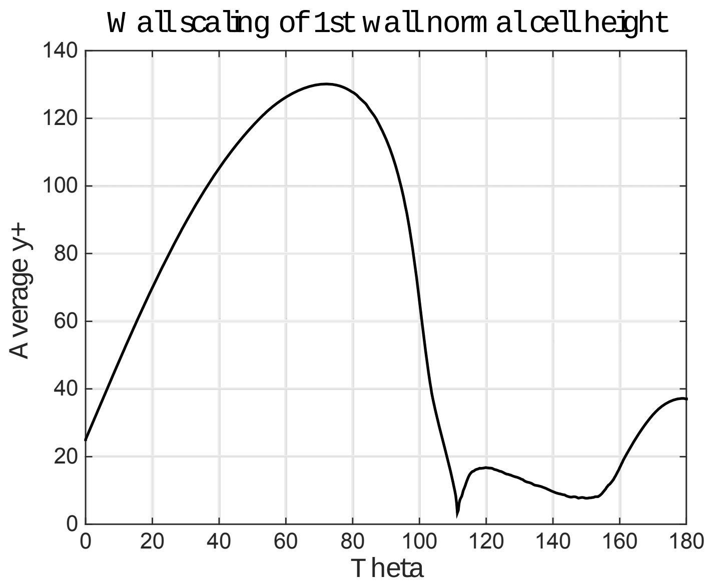


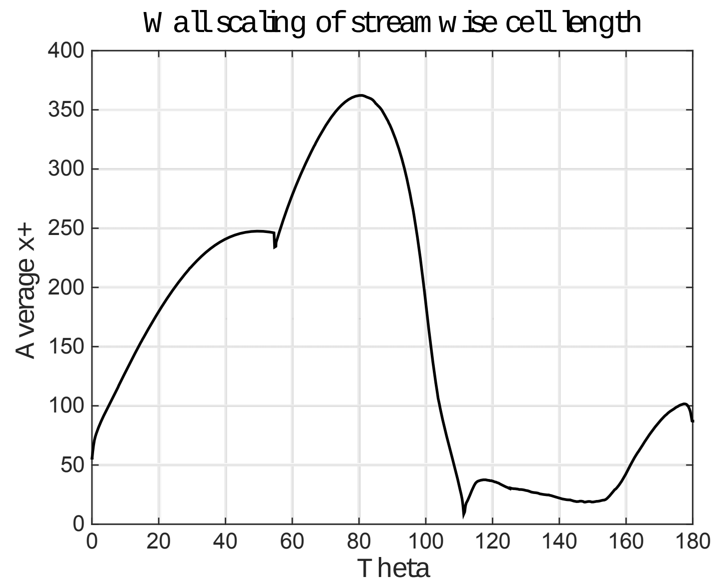
Extra Slides

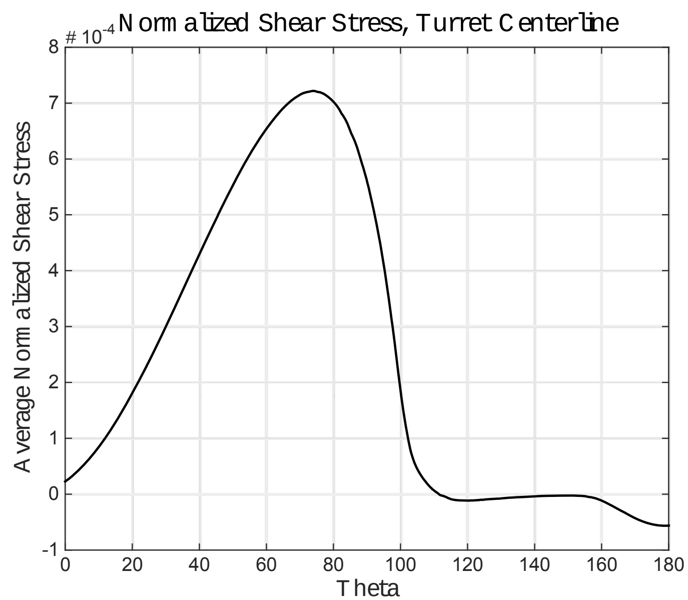
Separation Structures



Resolution of near wall mesh / Shear Stress







CharLES Scaling on Blue Waters