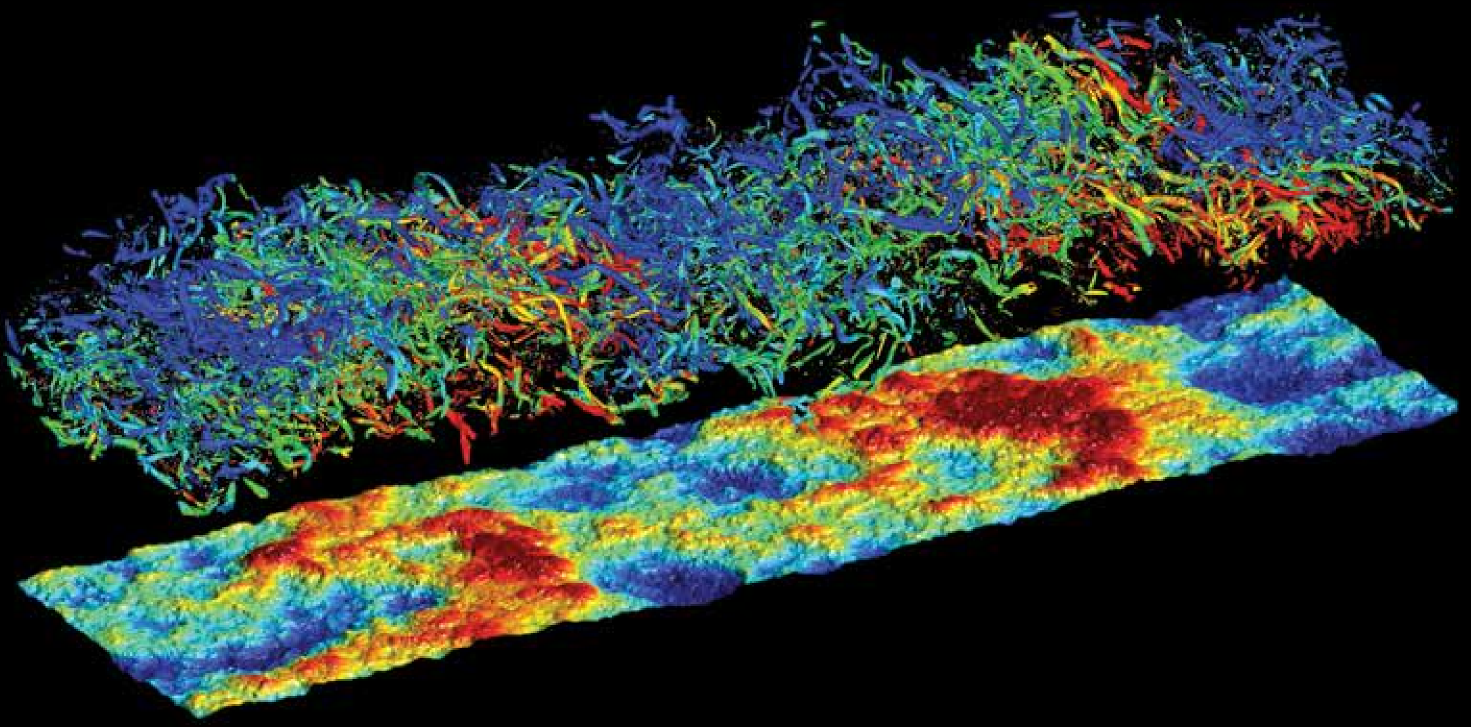

LARGE EDDY SIMULATIONS OF AERO-OPTIC DISTORTIONS

Edwin Matthews, University of Notre Dame
2014-2015 Graduate Fellow

RESEARCH SUMMARY

The distortion of an optical beam caused by turbulent air surrounding a projecting or receiving aperture, known as aero-optics, is a major impediment to applications of airborne optical systems for communication, imaging, targeting, and directed energy systems. When an initially planar optical wavefront is transmitted through a compressible turbulent flow, it is distorted due to the non-uniform speed of light resulting from density fluctuations. These distortions can greatly affect the fidelity and coherence of an optical beam as it propagates to far distances, rendering some airborne optical systems effectively unusable.

In the past year, research using large-eddy simulations (LES) of compressible flows to investigate aero-optic phenomena has progressed on two fronts. First, the numerical investigation of a hemisphere-on-cylinder optical turret at the experimental Reynolds number of 2.3 million has continued to advance. To better converge statistical quantities, the runtime of the finest resolution simulation has been doubled and over 90 TBs of optical and flow field data have been collected to study the aero-optic environment. Also, a coarse mesh simulation of the same configuration was calculated to investigate the sensitivity of the solution to grid resolution. By analyzing nearly 400 optical viewing angles calculated from the simulation database, our knowledge about the effects of turbulent wake structure, viewing angle, and aperture size on optical distortions found in a common beam transmission platform has greatly improved.

In addition, a parallel solver to compute data-driven decompositions like Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD) was developed to explore the dynamics of the turret flow and aero-optics. Their computation requires the calculation of the economy singular value decomposition (SVD) of a large dense matrix, requiring the memory and I/O capabilities of Blue Waters. POD calculations of the density field using the solver have scaled well up to 1,024 XE nodes using 2,000 time instances each composed of 200.5 million data points.

Finally, to study the spectral behavior of aero-optic phase distortions, high-fidelity LES of weakly compressible mixing layers with different initial conditions were computed. The spectral behavior of aero-optical distortions is of fundamental interest to the field, helping to understand the role of different length scales of turbulence in aero-optic phenomena and aiding in the development of adaptive-optic methods. Optical results from the simulations were compared with theoretical expressions derived for the spectral behavior of optical phase distortions and confirmed a direct relationship to the spectral behavior of density fluctuations. Density fluctuations can then be shown to be dependent on the conditions of the top and bottom streams of the mixing layer. Depending on flow conditions, simulation results show that small-scale density fluctuations can be strongly dependent on temperature fluctuations, pressure fluctuations, or a combination of both.

WHY BLUE WATERS

A unique aspect of Blue Waters has been the ability to generate massive simulation databases, move them quickly between near-line storage to scratch space, and then efficiently read and write the data in post-processing. Capacity to handle data in large volumes combined with the quick queue times allows for a much higher level of productivity compared to other systems. Blue Waters can run through tens of terabytes of data in post-processing, moving all of the data needed in hours, not days. This aspect has enabled our research to progress quickly, taking an idea for data processing through to realization within a day.

PUBLICATIONS AND DATA SETS

Mathews, E., K. Wang, M. Wang, and E. J. Jumper, LES of an aero-optical turret flow at high Reynolds number. Proceedings of the 54th AIAA Aerospace Sciences Meeting, AIAA SciTech, San Diego, California, January 4-8, 2016.

Mathews, E., K. Wang, M. Wang, and E. J. Jumper, LES prediction and analysis of the aero-optical environment around a 3-D turret. 68th Annual Meeting of the APS Division of Fluid Dynamics, Boston, Massachusetts, November 22-24, 2015.

Mathews, E., K. Wang, M. Wang, and E. J. Jumper, Numerical investigation of aero-optical distortions over a hemisphere-on-cylinder turret with gaps, AIAA Aviation, Dallas, Texas, June 22-26, 2015.

FIGURE 1 (LEFT): Coherent turbulence structures in a weakly compressible mixing layer are visualized by isosurfaces of the q-criterion and colored by fluid density. An initially planar optical wavefront propagating through the mixing layer will be distorted by changes in the refractive index due to turbulent density fluctuations. The result is an aberrated wavefront as shown on the surface under the turbulent structures.

Edwin Matthews is in his fifth year as a Ph.D. student studying Aerospace Engineering at the University of Notre Dame. Edwin plans to finish his degree in 2017 and wishes to pursue a career in industry or at a national laboratory.

"The use of high-fidelity computational fluid dynamics methods, like LES and hybrid LES/RANS, is becoming more commonplace in the design of engineering fluid systems. Blue Waters has allowed me to gain experience with these methods using a world-class high-performance computing system while learning to manage large volumes of data and to program with scalability in mind."