- **Project Information**
    - Reducing jet aircraft noise by harnessing the heterogeneous XK nodes on Blue Waters
    - Professor Daniel J. Bodony, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign
    - Daniel Bodony (bodony@illinois.edu)

- **Executive summary (150 words)**

Reducing the jet exhaust noise from commercial and military aircraft will improve airport efficiency (by increasing the rate by which aircraft and land and take-off, especially at night), reduce noise-related environmental pollution near the airport, and reduce noise-related injuries to aircraft personnel. However, the source of the jet noise defies a simple engineering description and, instead, requires very large simulations to predict that are beyond petascale computing capabilities. The heterogeneous XK nodes on Blue Waters are being used as prototype hardware on which to develop a computational fluid dynamics prediction code that can harness on-node complexity at scale in preparation for forthcoming exascale computers.

- **Description of research activities and results**
    - *Key Challenges:* Without a guiding theory, reducing aircraft noise has been left to trial-and-error experiments and, more recently, simulations. The turbulence-induced sound is generated over a very large spatial region leading to a multi-scale nonlinear fluid dynamics problem where the relevant energy is contained over six-to-ten decades of spatial and temporal scales. Simulations that capture the full range of spatial and temporal scales are beyond current computing capacity but remain our best hope for quieter aircraft. A paradigm shift in computational science, enabled by the XK nodes on Blue Waters, is desperately needed to advance the fields of compressible turbulence and aeroacoustics to reduce the noise from jet aircraft.
    - *Why it Matters*: The project will have impact in three critical areas. By targeting the heterogeneous XK nodes on Blue Waters we will lead the development of power efficient, high performance computatioal fluid dynamics codes that can run across thousands of heterogeneous nodes and thus direct emerging programming models and numerical algorithms compatible with forthcoming hardware complexity at exascale. Second, the scale of Blue Waters will enable the largest simulations of compressible turbulent jet noise ever that will advance the science of flow-generated sound through carefully conducted simulations and guided post-processing of the 100s-1000s of TB of data generated. Third, new engine nozzle designs will be developed that will reduce turbulent jet noise and improve the quality of life of airport communities and military personnel.
    - *Why Blue Waters:* The research on Blue Waters concentrates on the heterogeneous XK nodes. When using all of the XK compute nodes the aggregate theoretical throughput is more than seven petaflops, roughly equal to the total throughput of the XE nodes. What is remarkable, however, is

that there is less than one-fifth the number of XK nodes as XE nodes; further, the XK nodes use less power. The future of large-scale computational science lies squarely on the more efficient and massive use of power-conservative computing elements that will enable 100-1000 times the performance of current computers while consuming the same amount of power. Harnessing the performance of the XK nodes across the entire Blue Waters machine requires significant research into the development new programming approaches that (a) incorporate node-level heterogeneity and (b) can be scaled across 1,000s of nodes. Single node examples are commonplace, but codes capable of effectively using massively parallel heterogeneous machines are not.

The research contains two components. The first is focused on algorithm development to take an existing large software application that has already demonstrated scaling up-to 100,000 cores on ORNL's Jaguar and transform it into a CPU-GPU application that runs across all 4+ thousand XK nodes with the ability to simultaneously use the CPU cores and Kepler GPUs that exist on the XK nodes. The code, which solves the partial differential equations that describe a compressible, viscous fluid, is currently based on MPI. To map the code onto CPU-GPU nodes, MPI is insufficient work at the GPU level. While the existing CUDA extension of C can be used to run on the Kepler GPUs, the run-time system is immature and cumbersome and not likely to yield success at Blue Waters scale. OpenACC, while currently a viable approach to including node-level task management for GPUs but with limited flexibility, is scheduled to become obsolete and incorporated into the OpenMP 4.0 standard. Emerging source-to-source transformation tools that can retarget code to different architectures are needed to (a) reduce repetitious code generation tasks and to (b) abstract away many of the challenges associated with computing on a device connected to a host. Source-to-source transformations represent a significant research task because there will be considerable inter-dependence on the memory utilization and localization, task pooling and scheduling, and bus contention on the XK.

The second component of the research utilizes the CPU-GPU enabled code on the XK nodes to conduct fundamental research on the reduction of jet noise from commercial jet aircraft engines. By building on existing AFOSR and ONR research support in this area, the heterogeneous code run across all of the XK nodes, simultaneously using the CPUs and GPUs, will permit the largest, most ambitious investigation into turbulent jet noise ever conducted and allow, for the first time, detailed links to be established between the jet engine nozzle shape, the turbulent noise sources and, ultimately, the radiated sound. The simulations will be conducted in two parts: first we will use the immense scale and i/o capability of Blue Waters to conduct the most detailed study of how turbulent jet noise is produced over the range of jet exhaust conditions (namely, velocity and temperature) most commonly encountered in aircraft. The databases for these simulations will approach 1 PB in aggregate and will provide unprecedented detail into the physics of noise generation; we will make these databases publically available. The second objective of the simulations is to design a quieter jet engine nozzle using an adjoint-based inverse design approach. At Blue Waters scale this design will be a watermark in the development of reduced jet engine noise because both the nozzle and flow will be included simultaneously. Because of the computational cost involved in adjoint-based design of fully turbulent flows, no such calculation has previously been attempted. Even at Blue Waters scale only one jet condition can be considered, and we will choose a high-subsonic dual stream jet exhaust typical of modern gas turbines, with a cool outer stream and hot inner stream. This simulation's objective is to identify what nozzle modifications are best suited for aircraft jet noise reduction. The societal impact of environmental noise pollution reduction is critical around airports, and a pacing issue for the health of military personnel operating on naval aircraft carriers. There are no computational resources available where several petaflops of computing resource can be utilized for a single calculation.

- *Accomplishments:* The first year of work didn't start until mid-2014 when a dedicated graduate student, Mr. Wentao Zhang (MechSE), arrived on campus and became familiar with the base code and Blue Waters. Once familiar he used TAU to profile the code on several platforms, including Blue Waters, and identified two limitations present: (1) the frequent use of small MPI-based communication prohibits the use of large data transfers between the host and device and (2) the data structure of the code was not conducive to effective vectorization on the Keplers. As a result the code has been heavily modified to remove both limitations and has only recently (January 2015) been verified for a wide class of problems.

List of publications and presentations associated with this work

ECSS Experience: Preparing a Production MPI Code for Hybrid Execution, by W. Zhang, J. Larson, D. Bodony, and L. Wilson, poster presented at XSEDE '14 in Atlanta, Georgia.

Foundational Shifts in Computing-Enabled Design & Engineering, by D. Bodony, keynote panel discussion on "Emerging Technologies of Importance to Aerospace" delivered at AIAA SciTech 2014 Meeting and Exhibit, January, 2014.

Plan for next year

Now that the MPI-based communication and data structures within the base code have been modified, we are ready to develop Kepler-specific code and start running on the XK nodes. To keep a common code base since we need to run on the AMDs and Keplers simultaneously, we will use a source-to-source transformation tool called MxPA, developed by Professor Wen-mei Hwu and his group at UIUC, to write the computational kernels in OpenCL (for running on the Keplers) and automatically port them to C (for running on the AMDs). We have demonstrated this procedure to work on a single XK node and now are extending the development to multiple XK nodes. Once implemented and verified, we will test the new code on a series of increasing complex jet noise problems that use grids with 5 million, 300 million, and 1.8 billion degrees of freedom.

We anticipate needing 200,000 XK nodes hours for 2015 and will split that between the four quarters as Q1: 10%, Q2: 20%, Q3: 20%, Q4: 50%. Our storage needs will be a modest 100 TB for the entire year.