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# Turbulent Boundary Layers Overlying Complex Roughness

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This grant supported the purchase of volumetric particle-image velocimetry (PIV) equipment that provides data acquisition in the kilohertz (kHz) range over volumetric fields of view for time resolved studies of the dynamics of complex turbulent flows, particularly on-going studies of realistic roughness effects in wall turbulence (AFOSR core grant FA9550-14-1-0101). While existing PIV equipment in the PI's lab provides extremely high spatial resolution for measurements of moderate Reynolds number turbulent flows, it does not afford similar resolution in the temporal domain, nor the ability to measure 3D aspects of these flow fields. Therefore, the equipment acquired with this funding was specifically selected to expand our capabilities in both of these domains to provide a step-change in our ability to interrogate complex, and inherently 3D, turbulent flows of relevance to a range of DOD applications.

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# Final Report for AFOSR DURIP Grant FA9550-15-1-0457

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## Federally-Funded Grants Impacted by this Funding

- **AFOSR Core Grant FA9550-14-1-0101:** *Turbulent Boundary Layers Overlying Complex Roughness: Advancing the Predictive Capabilities of Large-Eddy Simulation via Coordinated Experiments and Simulations* (K. T. Christensen, PI; C. Pantano (UIUC) and W. Anderson (UT-Dallas), co-PIs; Dr. Douglas Smith, Program Manager)
- **NSF Grant CBET 16-03211:** *Collaborative Research: Coordinated Experiments and Simulations of Near-Surface Turbulent Flow over Barchan Dunes: Informing Models of Dune Migration and Interaction* (K. T. Christensen, PI; J. Best (UIUC) and W. Anderson (UT-Dallas), co-PIs)

## Project Summary

This grant supported the purchase of volumetric particle-image velocimetry (PIV) equipment that provides data acquisition in the kilohertz (kHz) range over volumetric fields of view for time-resolved studies of the dynamics of complex turbulent flows, particularly on-going studies of realistic roughness effects in wall turbulence (AFOSR core grant FA9550-14-1-0101). While existing PIV equipment in the PI's lab provides extremely high spatial resolution for measurements of moderate Reynolds number turbulent flows, it does not afford similar resolution in the temporal domain, nor the ability to measure 3D aspects of these flow fields. *Therefore, the equipment acquired with this funding was specifically selected to expand our capabilities in both of these domains to provide a step-change in our ability to interrogate complex, and inherently 3D, turbulent flows of relevance to a range of DOD applications.*

## Fund Usage

The following equipment was purchased based on the original proposal:

- Four $2560 \times 1600$ 12-bit, Phantom V641 CMOS cameras operating at 1.5 kHz at full resolution from TSI, Inc.;
- One 50 mJ/pulse at 1 kHz, dual-cavity Nd:YLF laser from TSI, Inc. (Built by Northrop Grumman);
- Scheimpflug mounts and assemblies for the cameras;
- Optics for volume illumination;
- Software for image acquisition and data analysis.

The imaging portion of the system consists of four CMOS-based high-speed (HS) cameras with 12-bit digitization and a frame rate of 1.5 kHz for a $2560\text{k} \times 1600$ pixel array. These cameras provide excellent time resolution at full imaging resolution and even higher temporal resolution with reduction in the active imaging area up to 30 kHz. Each camera has 32 GB of on-board memory for acquisition of long time records with high temporal resolution. Figure 1 (left) shows the four cameras mounted

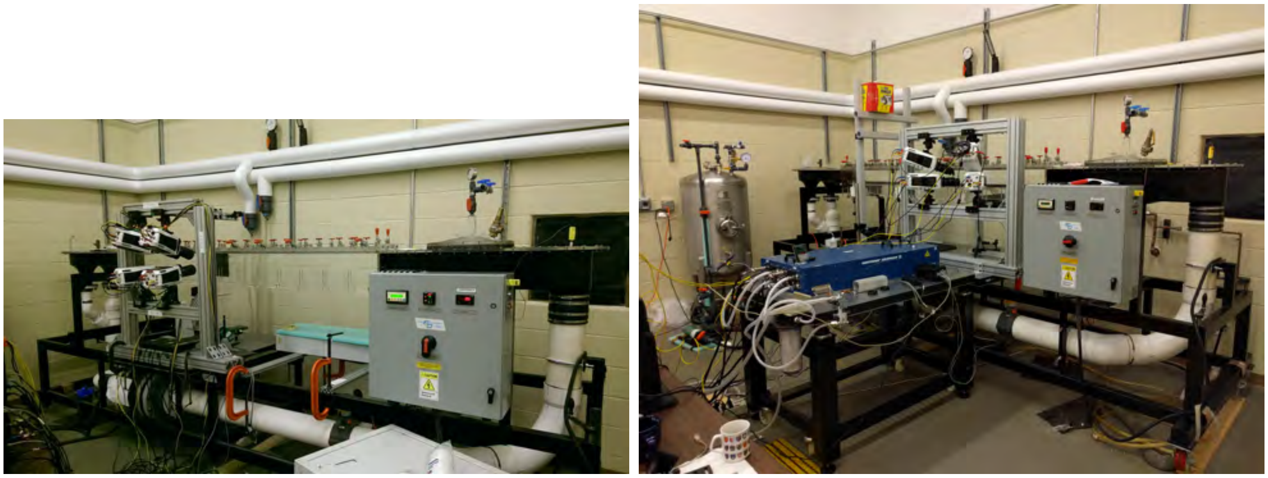

Figure 1: All four cameras installed on the PI's small-scale RIM facility in a volumetric imaging arrangement (left) and the new high-repetition PIV laser installed on the same facility (right).

in a volumetric imaging arrangement on a small-scale refractive-index-matched (RIM) flow facility in the PI's lab.

Illumination for this velocimetry system is achieved with a high-repetition, dual-cavity, frequency-doubled Nd:YLF (Neodymium-doped Yttrium Lithium Fluoride) laser. We had originally proposed to purchase a 30 mJ version of this laser which, at the time, was state of the art. Upon receiving this DURIP award, the PI was made aware from TSI, Inc. that a new line of PIV lasers was being released soon by Northrop Grumman, including a 50 mJ, dual-cavity, Nd:YLF laser at a cost comparable to the 30 mJ one. So the PI waited to purchase the system until this laser was commercially available and fully tested for stability and reliability. The extra 20 mJ/pulse is a huge improvement over the 30 mJ version and allows even larger image volumes to be measured without a loss of scattered light from the tracer particles. In addition, this laser can operate at higher repetition rates with an increasing cost in pulse energy, though for some applications this will likely prove advantageous for imaging smaller image volumes with higher temporal resolution. Figure 1 (right) shows the high-repetition laser in use in the PI's lab.

All components were purchased from TSI, Inc. in order to minimize the learning curve for the PI's research group as all other PIV equipment in the PI's lab is from TSI, Inc. TSI, Inc. provided on-site training for the PI and his entire research group and has been in continual contact with the PI's team as TSI improves its software for this new 3D velocimetry system that they are now selling while also assisting the PI's group in intricacies of implementing this system in both volumetric and planar measurements. In this latter regard, the system not only provides the ability to capture volumetric flow fields using all four cameras together, but can also be implemented to provide stereo PIV measurements on two planes simultaneously within a flow. Doing so requires splitting the laser pulses onto two different optical paths that generate light sheets in two different planes of the flow. The scattered light from each plane can then be imaged by a pair of cameras in a standard stereo PIV manner. The higher-energy laser purchased with this grant provides sufficient light to accomplish this sort of implementation in a wide range of flow scenarios.

**Finally, it should be noted that the estimated lifetime of this new PIV equipment is at least 10 years meaning it will have an extremely positive impact not only on the research discussed herein but also on the PI's research endeavors for at least the next decade.**

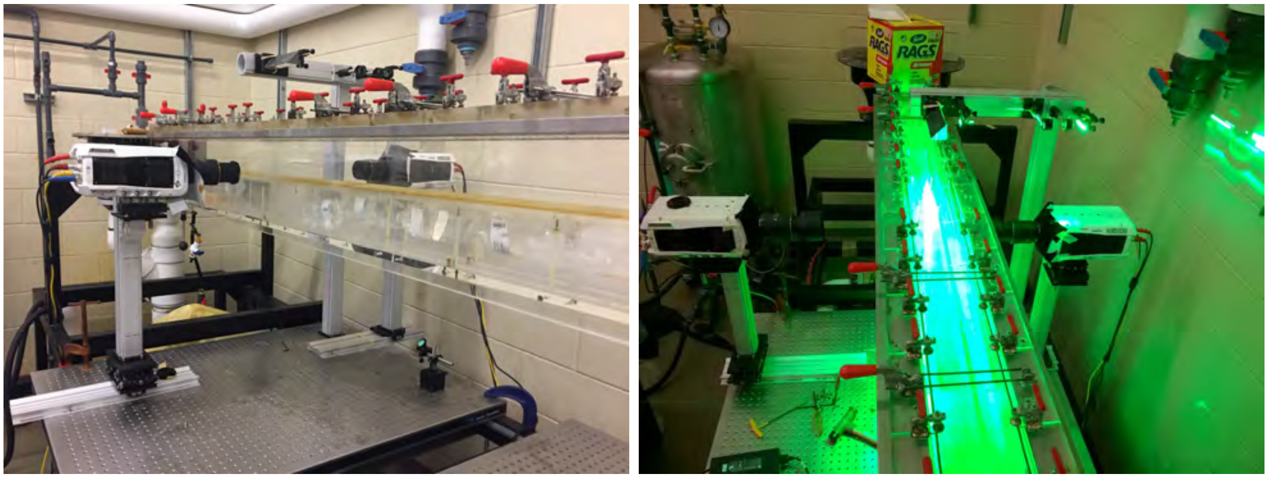


Figure 2: Photos of the new PIV equipment installed on the PI's small-scale RIM facility in a dual field-of-view arrangement as described in text.

## Impact on Current and Future Research

This new equipment is being initially deployed to study the dynamics of both smooth- and rough-wall turbulence. The aforementioned core grant, a collaborative research effort of Christensen, Pantano and Anderson, is focused on establishing the existence of the amplitude and frequency modulation phenomena in rough-wall turbulence, to explore its mechanistic underpinnings and to leverage this physics as a new approach for near-wall modeling of rough-wall turbulence. The experimental portion of this work is on-going in a refractive-index-matched (RIM) flow facility in which the rough surfaces, replicated from a turbine blade damaged by deposition of foreign materials, are built from acrylic and optically disappear when immersed in the sodium iodide working fluid. Such surfaces are quite distinct from roughness normally studied in lab environments as they are marked by a high degree of irregularity and a broad range of topographical scales. Our goal is to have sufficient temporal and spatial resolution to capture the small-scale flow physics while simultaneously capturing the evolution of the large scales which modulate the near-wall small scales. It is this linkage of the outer large scales modulating the near-wall small scales that is the basis of potential LES modeling advances and our efforts are the first to use PIV to explore this modulation phenomenon experimentally. Previous efforts, primarily by Marusic and co-workers, utilized hot-wires for this purpose as they are amenable to high spatial and temporal resolution and long time records, albeit at a single point in the flow. Even our initial research utilized hot-wires in this manner to establish the existence of this modulation phenomenon in flow over highly-irregular roughness in wind-tunnel studies. However, the real fruits of our labor are to utilize this unique PIV capability to explore the combined spatio–temporal features of this phenomenon.

Our first measurements have been planar PIV measurements over a hemispherical roughness topography to assess the ability of time-resolved PIV to capture these modulation influences. To do so, we imaged a single plane over the roughness in our small-scale RIM facility and utilized two cameras: the first imaged a large, ($\delta$-scale) field of view to capture the time evolution of the outer large scales, while the second camera imaged a smaller field of view close to the wall to capture the time evolution of the near-wall small scales. A photo of this imaging arrangement is shown in Figure 2. With these measurements, we have confirmed that PIV can in fact capture the relevant physics to quantify the degree of modulation present in these flows. However, in contrast to previous single-point hot-wire measurements, the PIV data acquired in this way gives us a simultaneous and instantaneous snapshot of the large scales responsible for this modulation. In this way, we can uniquely study the spatio-temporal physics of this process. We are presently conducting similar measurements for flow over the aforementioned highly-irregular roughness in the small-scale RIM facility.

Finally, the teaming of this unique PIV system with the PI's unique RIM flow facility in which flow models can optically disappear and thus allow unimpeded optical measurements near and within complex surfaces and models places the PI's group at the forefront of optical interrogation of complex turbulent flows, of which many exist in a range of DOD-relevant applications. Thus, the PI plans to leverage these unique capabilities to ensure that they have very broad impact across a range of applications.