

Near-wall 3D Lagrangian particle tracking over a 6:1 prolate spheroid

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ABSTRACT

Wall-bounded turbulence is a common application in fluid mechanics. Turbulence models are commonly used in computational fluid dynamics. However, they need to be validated and improved through near-wall experimental data. The High-Reynolds Number Prolate Spheroid program was developed, with a focus on providing high-fidelity measurements on a 6:1 prolate spheroid. The 3-meter anodized aluminum model can be pitched from 0 to 20° angle of attack and rolled from +180 to −180°, making it an ideal canonical shape to mimic the bodies of vessels typically operated in air or sea. Tests were conducted in a towing tank at the Naval Surface Warfare Center Carderock Division. The target Reynolds number based on the length ranges from $1 - 12 \times 10^6$. At the highest Reynolds number, the viscous lengthscale is on the order of 10 μm . Our goal is to resolve the time-resolved wall shear stress from the velocity gradients within the viscous sublayer. The length and time scales impose stringent resolution requirements. We implemented three-dimensional Lagrangian Particle Tracking (LPT) using a novel, single-camera plenoptic 3.0 imager (Yamakaitis et al., 2025). Polystyrene tracers are locally injected upstream of the measurement region, while a double-head 527-nm pulsed Nd:YLF laser, routed via optical fiber to a custom fiber-optic ring light, provides volumetric illumination for the first 1.2 mm wall normal region. The testing spanned a two-week rigging and testing period. Close to 275 test runs were completed, comprising just under 170 TB of data. We currently have preliminary results, including flow visualization of streamlines from various data sets. Due to the complexities in our system, existing LPT software is not suitable for processing the acquired data and progress on a new particle tracking algorithm is reported.

1. Introduction

Wall-bounded turbulence pervades a wide range of fluid mechanics applications. In hydrodynamics, any vessel translating through a fluid above a critical speed develops a turbulent boundary layer along its hull. The properties of this boundary layer dictate the hydrodynamic performance of the vessel as well as the governing effects, such as flow separation and re-attachment. Capturing the parameters of the boundary layer is difficult even for well-established computational methods. Direct simulation of complex high-Reynolds-number flows remains intractable as a result of its

computational expense. Computational approaches instead rely on empirical closure models for the boundary layer. Such models are calibrated against simulations and laboratory measurements, typically acquired on simple geometries. Meaningful improvement of these methods, therefore, demands diagnostic techniques capable of delivering fully-resolved near-wall measurements over more complex bodies.

We obtain such fully-resolved measurements along the solid boundary of a canonical geometry by employing Lagrangian particle tracking (LPT), a diagnostic that yields three-dimensional measurements of all three velocity components. Both the wall proximity and the spatial resolution of the technique enable estimates of time-resolved wall shear stress from velocity gradients evaluated within the viscous sublayer as well as near-wall flow.

The selected geometry is a 3 m 6:1 prolate spheroid. While geometrically simple, this shape presents a doubly curved surface representative of streamlined bodies routinely operated in air or water. Acquisitions are made at a fixed axial location of 24.3% from the front tip across several pitch angles, with rolling of the model providing access to a complete circumferential dataset. Imaging and illumination are routed through a single viewport flush with the surface of the model, enabling the high-magnification measurements demanded by the technique. Optical distortions introduced by the curved interface are eliminated by employing a polymer with a refractive index matched to that of water. Dense seeding, essential for detailed flow-field reconstruction, is achieved through local particle injection upstream of the measurement region.

The High-Reynolds Number Prolate Spheroid (HIPRO) program was an ONR-funded, multi-institution effort. Alongside the LPT system described here, a complementary set of conventional and advanced diagnostics was fielded in parallel, comprising measurements of loads, moments, static pressure, dynamic pressure, and stereo-PIV. The load and moment instrumentation was jointly developed and operated by the University of Michigan and the Naval Surface Warfare Center Carderock Division (NSWCCD). Pressure instrumentation was led by the University of Michigan, while the stereo-PIV system was designed and operated by Johns Hopkins University. All testing took place at NSWCCD. These parallel diagnostics provide global consistency between the present measurements and those previously reported in the literature for both experimental and computational studies.

The full LPT system was required to be contained entirely inside the model. Because the model was shared between multiple diagnostic platforms, the measurement hardware had to be packaged into an interchangeable hatch (shown in Fig. 1), with the available installation volume limited to $125 \times 333 \times 127 \text{ mm}^3$. Every sub-system was consequently custom-engineered, incorporating new enabling technologies to meet the geometric and optical constraints set by the model. This paper details the design and implementation of the principal subsystems: particle seeding, the refractive-index-matched viewport, laser-fiber coupling, dark-field illumination, and the plenoptic 3.0 imager. An initial qualitative inspection of the acquired data is provided, together with a

preliminary look at the quantitative results.

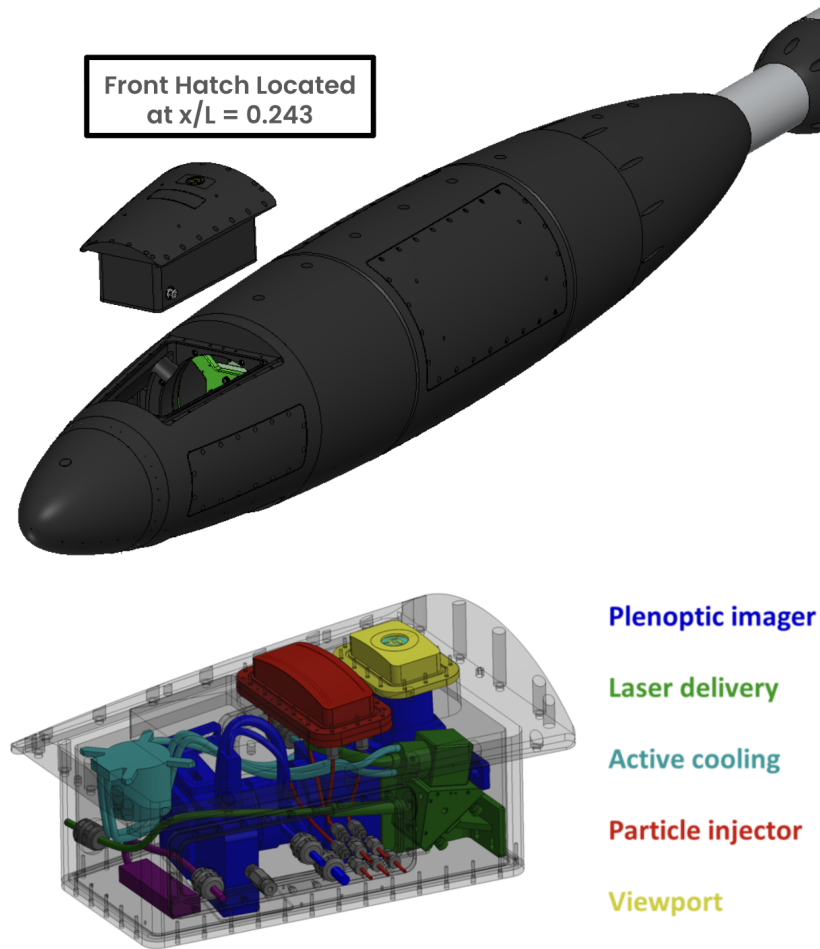


Figure 1. CAD model of the prolate spheroid, in addition to the hatch we used and the systems housed inside.

2. Experimental Setup

2.1. Model and Facility

The experimental campaign was carried out at NSWCCD Carriage 1. Figure 2 shows the facility, which is purpose-built for large-scale hydrodynamic testing of both surfaced and submerged models. The installation comprises the towing carriage itself, two movable dry docks, and the basin. All runs in this campaign were performed in the deep-water portion of the basin, which is 889 feet (271 m) long, 51 feet (15.5 m) wide, and 22 feet (6.71 m) deep. Carriage 1 can tow models at speeds ranging from 0.03 to 6.17 m/s (0.0625 to 12 knots). In the HIPRO configuration, the model was rigidly mounted to the carriage with a total assembled weight of 350 kg.

The HIPRO test article is a 6:1 prolate spheroid with a nominal length of 3 m (9.84') and a nominal

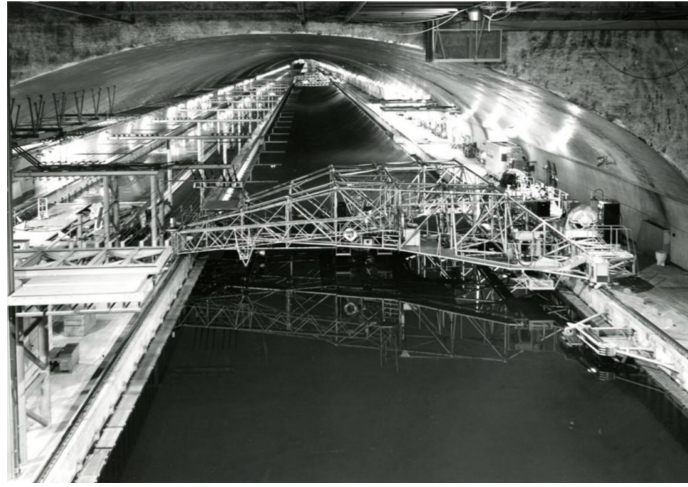


Figure 2. Carriage 1 testing facility in the David Taylor Model Basin at NSWCCD. Courtesy of the U.S. Naval Institute Photo Archive, 1943.

diameter of 0.5 m. Figure 1 presents a simulated model of the article with the GW experimental hatch detached, while Fig. 3 shows the physical model in the test facility. The body was machined from 6061 aluminum and features a dry interior purpose-designed to house a dense suite of high-fidelity instruments. Its design was a collaborative effort between NSWCCD Code 863 and the three academic teams. Geometric scans confirmed that the as-built body lies within 0.03 % of its design dimensions, providing the accuracy needed for the archival-quality datasets used in CFD validation.

To enable high-resolution flow measurements over the entire surface of the body, the model is fitted with an actuation system that allows it to be pitched and rolled during the campaign. A roll mechanism rotates the body through its full range of azimuthal angles. It is driven by a stepper motor coupled to a 256:1 planetary gearbox, enabling a single set of internally mounted instruments to scan the entire flow field for reliable cross-comparisons. The model is also attached to a pitching strut by way of a 16-inch-long, 6-inch-diameter sting, supporting tests at angles of attack up to 20° .

2.2. Plenoptic 3.0 Imager

Our objectives are to recover the time-resolved wall shear stress from the velocity gradients within the viscous sublayer and the near-wall flow. The associated length and time scales place stringent demands on the measurement resolution. For this reason, three-dimensional LPT is performed using a novel, single-camera plenoptic 3.0 imager (Yamakaitis et al., 2025). A high-speed camera (IDT Phoenix HD) provides a sensor resolution of 1920×1440 pixels at a pixel pitch of $10.4 \mu\text{m}$. Operating at full resolution, the camera records at 15 kHz and streams directly to local hard drives to support long acquisitions. The imaging system delivers a magnification of 2.1, a field of view of

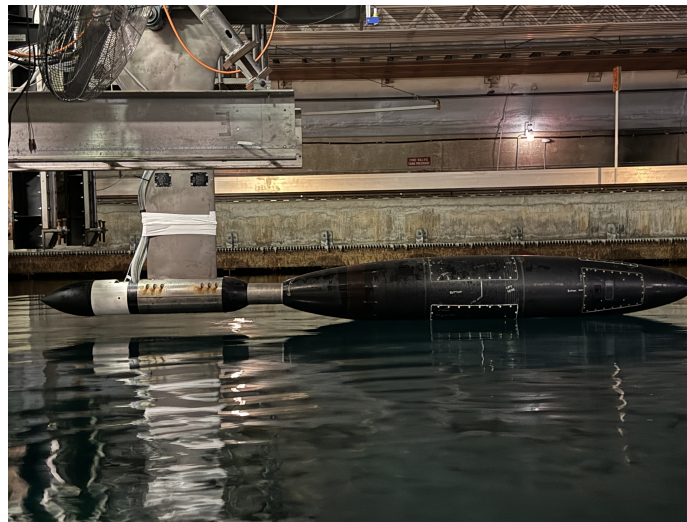


Figure 3. Model raised above the water surface while mounted on the towing rig in Carriage 1.

$5 \times 3 \text{ mm}^2$, and a wall-normal depth of field of 1.50 mm. Given the spatial constraints of the hatch, a near-90-degree bend had to be incorporated into the lens assembly, as shown in Fig. 4.

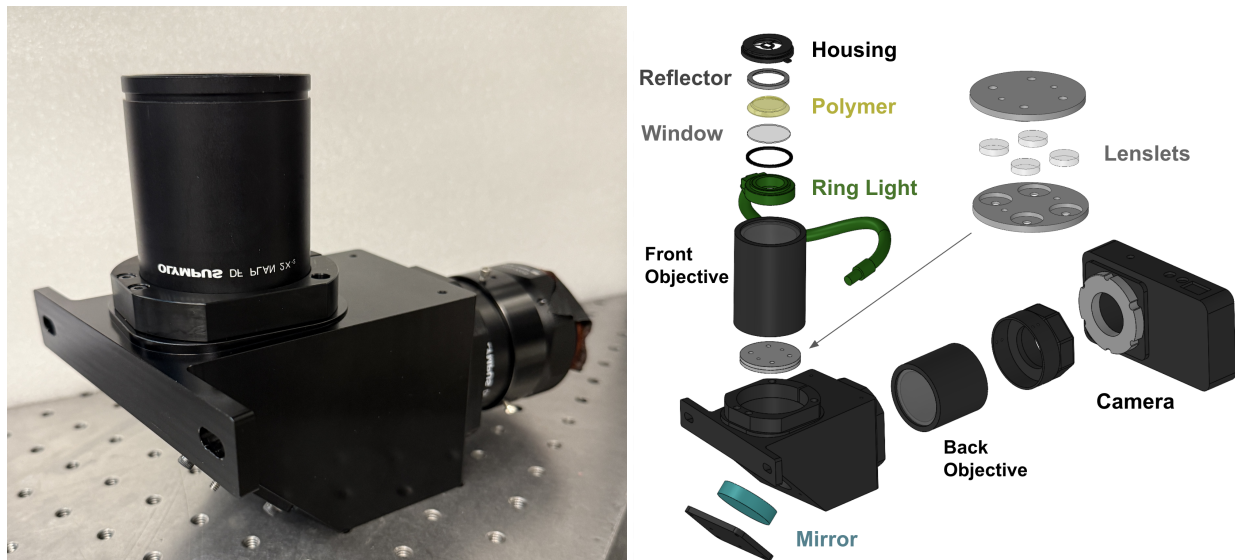


Figure 4. Plenoptic 3.0 lens assembly used in the campaign (left) alongside the exploded view (right).

The optical specifications of the imager are verified through several stages of calibration. Initial imaging of a standard grid and resolution target in the GW laboratory confirms that the system attains its design magnification of 2.0 to within 5%. The lateral resolution is measured to be $10 \text{ }\mu\text{m}$, and the viewing angle is verified at 35° by translating the grid target along the common optical axis of the imager. The resulting triangulation accuracy for particle tracking is $1 \text{ }\mu\text{m}$ laterally and $3 \text{ }\mu\text{m}$ axially, which is adequate to resolve the velocity gradients at the wall. The nominal depth of field is 0.15 mm, although particles outside this range can also be tracked. To support such

tracking, a custom calibration target has been designed and fabricated to accurately profile the intensity distributions of out-of-focus particles and enable their detection. Particles throughout the full 1.2 mm depth illuminated by the dark-field source can thus be recovered. After the optical system is installed within the hatch, fine focus adjustments are performed. A dedicated target at the window verifies correct focus. Once focus is confirmed, the complete optical assembly is rigidly clamped to the hatch at multiple points, preventing any motion that could compromise the focus or calibration. The plenoptic lens assembly has no moving parts and is insensitive to vibrations.

The camera is synchronized to the laser's illumination pulse via a TTL digital delay/pulse generator. The camera's sync output is also fed into the data acquisition system, which records the force, moment, and pressure signals. Power is delivered to the camera through a dedicated cable, while image data is transmitted on an optical fiber link; both 30 m cables were custom-fabricated by IDT. The camera streams directly to hard drive at the full acquisition rate. Typical recordings consisted of 2 min of continuous time-resolved data at $Re = 1$ M and 40 s at $Re = 12.6$ M. The collected frame sequences span thousands of boundary layer turnover times; this extended acquisition ensures convergence of the near-wall statistics.

2.3. Particle Injection

Polystyrene tracers with a diameter of $1.7\ \mu\text{m}$, supplied by NASA, are injected locally upstream of the measurement location. Depending on the test condition, seeding was delivered either through an array of $100\ \mu\text{m}$ diameter holes located 63 mm upstream or through $400\ \mu\text{m}$ diameter holes located 97 mm upstream. The total injection area is held constant between the two arrays. The larger holes are slightly more intrusive geometrically but operate at lower exit velocities for a given flow rate ($< 3\%$ of the free-stream velocity), reducing jet momentum and mitigating clogging. Each array is accompanied by a reservoir plumbed with two dedicated 1/8-inch OD tubes of 30 m length—one to drive tracers into the flow and the other to purge them from the cavity. Photographs of the injection plates and their holes are presented in Fig. 5.

2.4. Laser-Fiber Coupling

Illumination is supplied by a double-head, frequency doubled 527-nm pulsed Nd:YLF laser. For the majority of the campaign, a single cavity was operated at 3 mJ per pulse and 7.5 kHz. When both cavities are employed, the system can deliver up to 5 mJ per pulse at 20 kHz, although in practice the acquisition rate of the camera in 10-bit mode at full resolution sets the limiting throughput.

The laser is positioned on the carriage outside of the model. The open-water test basin produces a highly humid environment, which presents an operational risk due to condensation. The laser is



Figure 5. Particle injection plate with a zoom-in view of the 100 μm diameter holes.

therefore enclosed within the sealed housing shown in Fig. 6. To defend against carriage-induced vibrations, the laser is mounted on a vibration-damping rack inside the enclosure. The enclosure itself rests on pneumatic isolation bumpers, providing additional decoupling from structural vibrations during carriage motion. Light is delivered from the laser head to the hatch by a 30 m optical fiber with a 200 μm core diameter. All of the optics required to guide the laser beam into the fiber are contained within the sealed environment. The coupling alignment is fine-tuned remotely using motorized optomechanical mounts.



Figure 6. Climate-controlled enclosure housing the laser mounted to the central strut of the carriage. The yellow cable exiting the box on the right of the image is the 30-m-long optical fiber used to deliver laser light. A chiller with lines going to the laser can be seen on the left of the image. The housing is mounted onto a vibration-damping rack.

2.5. Dark-Field Illumination

In an ideal LPT arrangement, only the particles inside the measurement volume are illuminated. Restricting illumination in this way minimizes contributions from out-of-plane particles, which would otherwise appear defocused and degrade the image quality. Since the region of interest is confined to the first millimeter from the wall, a shallow depth of illumination is required. Accomplishing this is non-trivial because both imaging and illumination must share the same access window in the model.

To meet this constraint, an on-axis light delivery system was developed to project collimated light into the measurement volume at a steep inclination angle. The resulting beam forms an inverted hollow cone whose apex sits on the wall and which diverges rapidly away from the surface. This geometry localizes illumination to the near-wall region while suppressing far-field exposure.

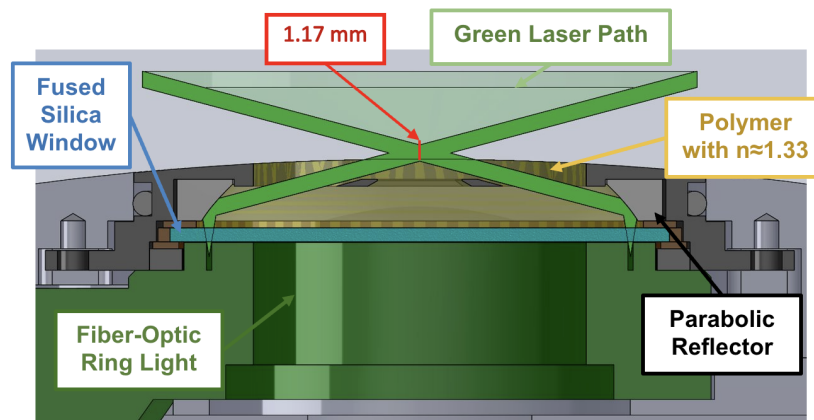


Figure 7. Cross Section of the viewport, including the components of the on-axis light delivery system.

The illumination scheme is achieved by coupling the 30 m optical fiber to a custom fiber-optic ring light capped with a parabolic reflector. The oblique illumination profile enables a dark-field imaging scheme in which only the light reflected and refracted by the particles is collected by the imager, so that the particles appear as bright spots against a dark background. The light delivery assembly sits directly beneath the surface and is arranged concentrically with the final imaging objective. A cross-sectional view of the light delivery system inside the viewport is provided in Fig. 7, and an exploded view is shown in Fig. 8.

A central challenge in coupling the optical fiber to the ring light was coupling efficiency of the light into the fiber ring. Nearly 50% of the incident laser power is lost at the bundle entrance due to interstitial gaps between the circular fibers, producing substantial localized heating of the epoxy that bundles the fibers together. At the 15 W of optical power required for high-speed imaging, the epoxy reached its maximum temperature 350°C in a few seconds. Therefore, we had to implement a continuous water-cooling of the fiber entrance. The warmed coolant was subsequently routed into the surrounding aluminum model structure, which served as the ultimate thermal sink.

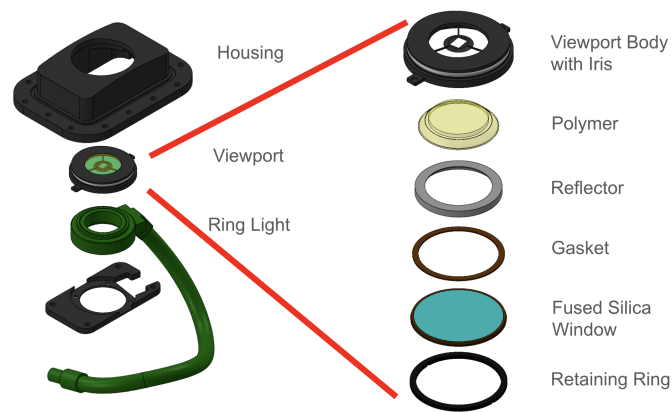


Figure 8. Exploded view of light delivery system within the viewport.

2.6. Refractive-index-matched viewport

To follow the curvature of the model while minimizing optical distortion, the outer layer of the viewport is fabricated from a polymer whose refractive index is matched to that of water (Fort & Bardet, 2021). The polymer is molded in place by pouring its liquid uncured form into the viewport cavity and pressing it against an acrylic mold machined to the corresponding curvature. After UV curing, the material solidifies into the final optical surface.

The viewport housing itself is an aluminum part 45 mm in diameter and 6 mm in thickness. A fused silica window is sealed at its base, presenting a rigid optical interface against which the refractive-index-matched polymer is bonded. On either side of this window sit elements of the light delivery system: the ring light is mounted below the window, and the parabolic reflector is positioned above it. During casting, the reflector becomes embedded within the polymer, which simultaneously secures the reflector and mechanically locks the cured polymer in place. Embedded alongside it is a spider aperture that defines the imager's field of view.

3. Results

Originally set to span 4 weeks, the GW entry was condensed into a two-week rigging and testing period. In 5.5 days of data collection, we were able to collect 275 datasets totaling 167 TB of data. Of those sets, 241 were unique test conditions, with 34 being repeat runs of the conditions of interest. A critical factor in the data collection effort was the high-speed streaming camera we used, which is able to capture quality images for runs as long as ten minutes at 7.5 kHz. The time needed for converged statistics was greatly reduced, allowing for multiple roll angle conditions to be recorded in a single carriage pass. Figure 9 is a diagram representing the data sets collected during the campaign.

With the complexities in our optical configuration and imaging geometry, existing LPT processing

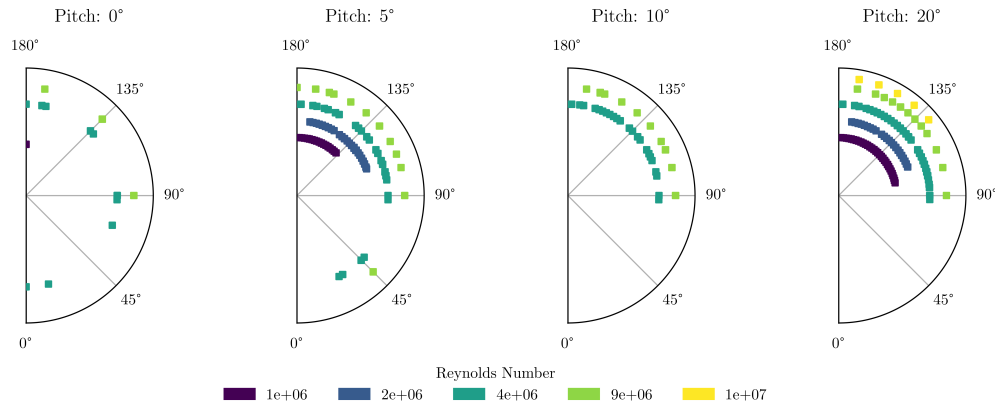


Figure 9. Diagram showing all 241 unique test cases obtained during the campaign at each of the four determined pitching angles, spanning 5 Re conditions.

frameworks are not directly applicable to the acquired data. Thus, we are currently developing a dedicated processing pipeline tailored to the present measurement configuration. The most recent developments in the algorithm include particle detection, a sample of which is shown in Fig. 10. As progress continues, processed results and details of the underlying algorithms will be reported as this effort progresses.

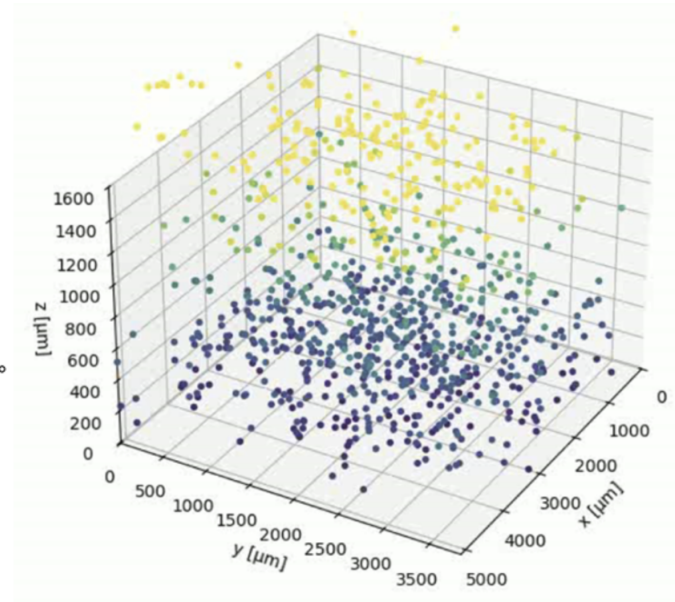


Figure 10. Results of the particle detection section of the plenoptic LPT algorithm.

In parallel to the algorithm development, we have taken sections of selected datasets to create preliminary flow streamlines. Arrays of streamline visuals for given test conditions are shown in Fig. 11. This simple analysis gives us insight into the direction of the flow in a given condition. In

particular, we focused on Re of 4.2×10^6 and 8.4×10^6 at a 20° angle of attack. Doing so allows us to validate our results against that of the experiment of Kreplin et al. (1985), which used a 6:1 prolate spheroid of similar dimensions. The experiment involves measuring wall shear stress on an inclined prolate spheroid inside the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) 3m $\times$ 3m Low Speed Wind Tunnel in Göttingen, Germany. Surface hot film probes were used to capture both the magnitude and direction of the local wall shear stress at various angles of attack up to 30° . The most comparable condition in this study was the 6.35×10^6 Re case at 20° angle of attack. A plot of our two conditions and the two closest streamwise locations from the DFVLR data is shown in Fig. 12. All cases demonstrate a similar trend in flow angle as the roll angle increases.

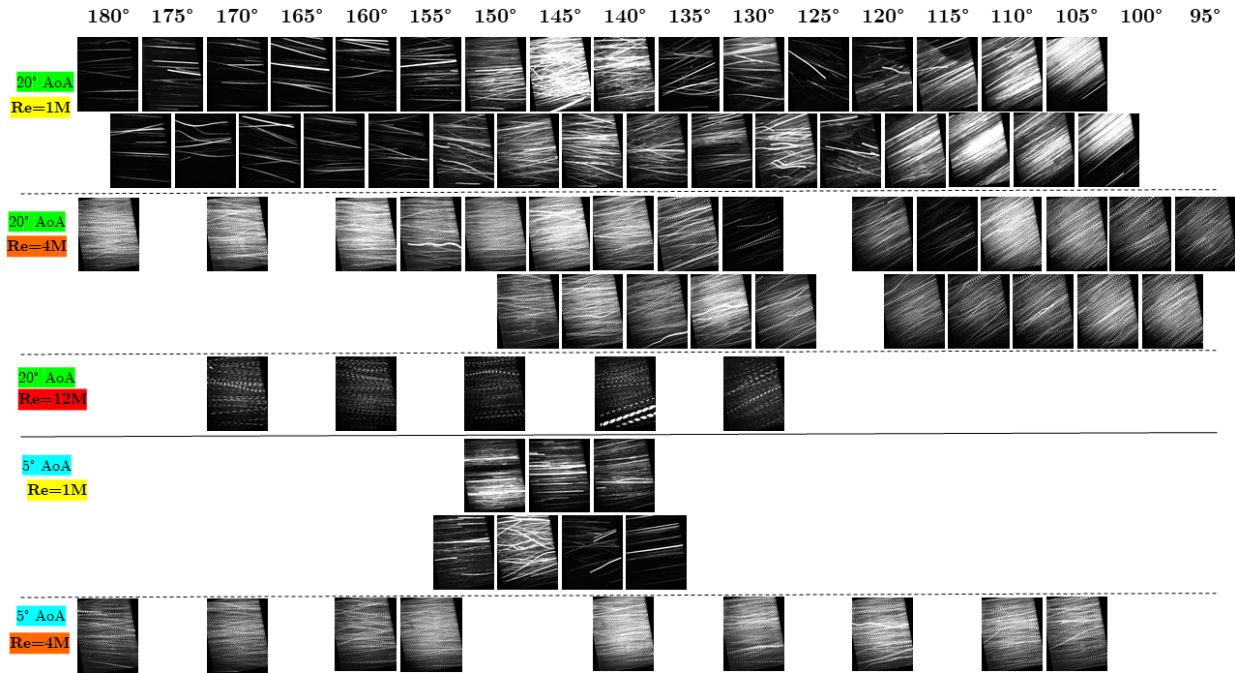


Figure 11. Graphic of streamlines from given test cases across multiple roll angles.

In addition to the comparison with the DFVLR wall-shear-stress measurements of Kreplin et al. (1985), the present results will also be compared with the experimental study of Wetzel (1996) and Wetzel et al. (1998) at Virginia Tech, which examined separation-line behavior on a prolate spheroid at $Re = 4.2 \times 10^6$ over a range of angles of attack. This comparison is particularly relevant because it provides an experimental reference for the separation-line topology at a Reynolds number matching one of the HIPRO test conditions.

The inferred streamline patterns are also qualitatively consistent with the numerical simulations performed within the HIPRO program (Plasseraud et al., 2023; Plasseraud & Mahesh, 2025; Du & Zaki, 2025), showing similar broad trends in near-wall flow direction and circumferential streamline development. These comparisons are intended here as qualitative consistency checks; more

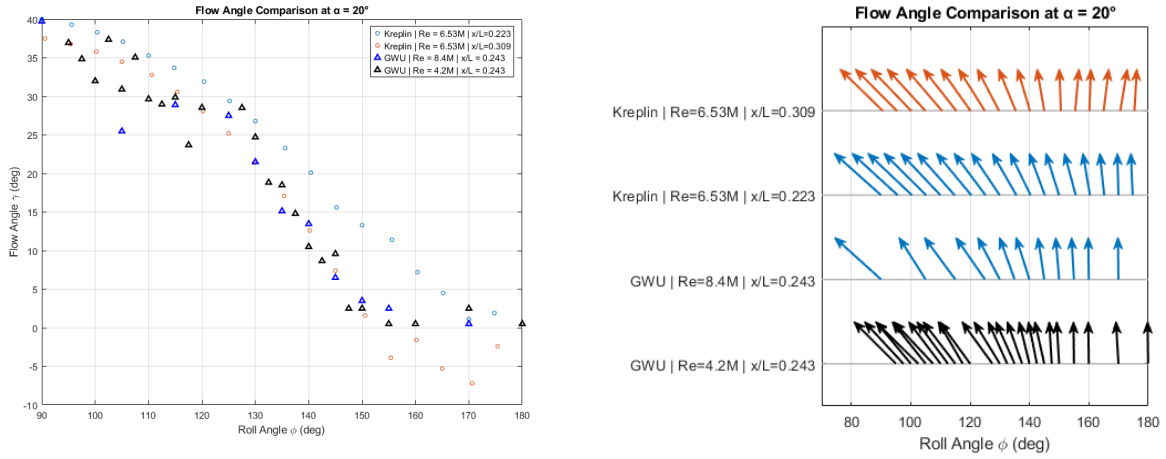


Figure 12. Two plots depicting a flow angle comparison between our 4.2 and 8.4 Million Re conditions and two runs from the DFVFR.

detailed quantitative comparisons with both the Virginia Tech measurements and the HIPRO simulations will be pursued in future work.

4. Conclusions

The acquired dataset is positioned to serve as a benchmark for high-fidelity diagnostics of near-wall turbulence within a boundary layer that evolves rapidly under pressure gradients and surface curvature. Development of the LPT algorithm will continue in an effort to extract all relevant statistics from the datasets. In the meantime, the streamline analysis compared to similar experiments previously conducted depicts a strong coherence and gives us great confidence in the validity of our datasets.

The campaign established the feasibility of conducting microscopic measurements from inside a test specimen in a large-scale facility. While the present measurements targeted near-wall turbulence in a single-phase incompressible flow with a Newtonian fluid, the diagnostic platform demonstrated here can be readily adapted to investigate a wide range of additional microscopic phenomena occurring in the presence of complex flows, materials, or geometries.

Acknowledgments

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