FEDSM2006-98556

MICRO-OPTICAL SENSORS FOR BOUNDARY LAYER FLOW STUDIES (KEYNOTE PAPER)

Darius Modarress, Pavle Svitek, Katy Modarress
Measurement Science Enterprise, Inc. Pasadena, CA

Daniel Wilson
NASA Jet Propulsion Laboratory, Pasadena, CA

ABSTRACT
This manuscript describes optical MEMS (or MOEMS)-based microsensors for near wall boundary layer flow and particle field analysis. The sensors have been developed to measure a variety of parameters including flow velocity, surface speed, skin friction, and particle sizing. The surface mounted sensors measure flow velocity and/or flow velocity gradients as close as 70 microns from the wall. The sensors have been successfully used in a number of filed tests and flow facilities at different Reynolds numbers. They have also been used on-board full-scale vehicles. These compact and embeddable sensors incorporate specially designed diffractive optical elements and use single-mode optical fiber or integrated diode lasers for illumination.

INTRODUCTION
Small, portable, rugged yet accurate sensors have been devised using specially designed micro-fabrication techniques developed for MEMS and MOEMS sensors. The miniaturization of sensors has been achieved using diffractive optic elements. Some of the sensors developed by the authors are presented here.

NOMENCLATURE
f: Doppler frequency
k: slope of first non-vertical fringes
δ: fringe separation at y
σ: Fringe divergence rate
U: Streamwise velocity component
y: Distance from the wall

MICRO-OPTICAL SHEAR STRESS SENSORS:
The goal of this sensor is to determine the shear stress of a fluid within the first few hundred microns from a wall. Within this region, the velocity gradient is linear, where u is the velocity, is the shear stress, and y is the vertical coordinate.

Our diffractive optical micro-sensor generates a linearly diverging fringe pattern as illustrated in Figure 1. The fringe spacing can be expressed as δ=k y, where k is slope of the first non-vertical fringe.
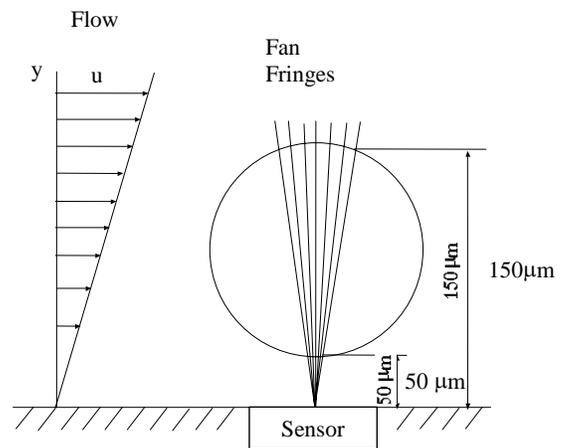

Figure 1- Schematic of the shear stress sensor principle

As particles in the fluid flow through the linearly diverging fringes, they scatter light to a detector with a frequency f that is proportional to the velocity and inversely proportional to δ. Using the relations for U and δ above, the measured frequency is directly proportional to the wall shear, $f = \dfrac{\sigma\, y}{k\, y} = \dfrac{1}{k}\sigma$

This technique was first presented by Naqwi and Reynolds using conventional optics [1]. A non-linearity of the velocity profile or the fringe pattern will translate into widening and skewness of the frequency distribution.

Design and modeling
A conceptual drawing of the micro shear stress sensor is shown in Figure 2. The diverging light from a diode laser is focused by a diffractive optical element (DOE) to two parallel

line foci. These foci are coincident with two slits in a metal mask on the opposite side of a quartz substrate. The light diffracts from the slits and interferes to form linearly diverging fringes to a good approximation. The light scattered by particles traveling through the fringe pattern is collected through a window in the metal mask. Another DOE on the backside focuses the light to an optical fiber connected to a detector.
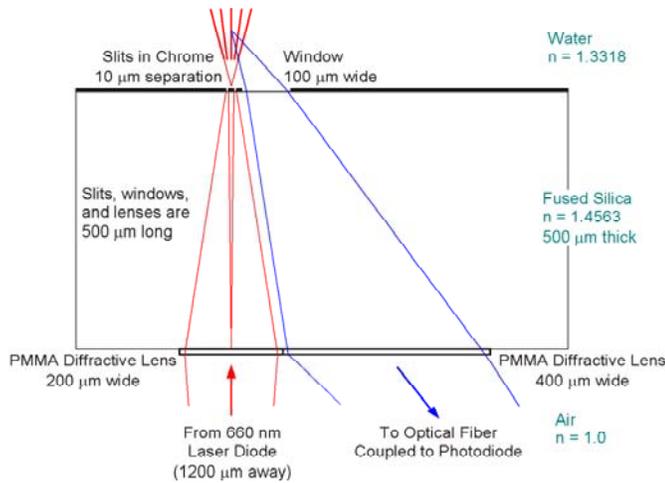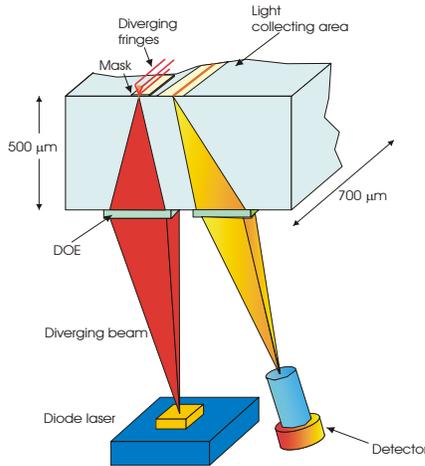

Figure 2- Schematic of the shear stress sensor assembly

A series of simulations were performed to aid in the design of the sensor. A finite-difference simulation of the fringe pattern for 2 mm wide slits separated by 10 mm is shown in Figure 3. The fringe pattern displays a suitable number of fringes for adequate measurements. The number of high-contrast fringes is determined by the slit width and the divergence of the fringe pattern is determined by the slit separation.
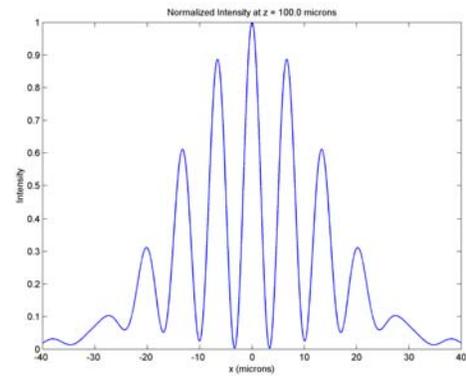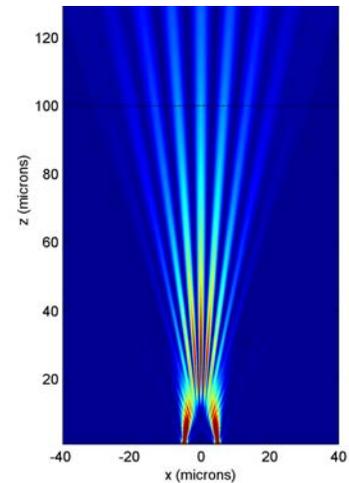

Figure 3- Fringe pattern resulting from two 2-mm slits separated by 10 mm

Fabrication and Testing

The main sensor element was fabricated by two-sided lithography on a 500 mm thick quartz substrate. The slits and collecting window on the front were fabricated by direct-write electron-beam lithography followed by wet etching of evaporated chrome. The polymethyl methacrylate (PMMA) diffractive optical elements on the back were fabricated by analog direct-write electron-beam lithography followed by acetone development [2]. A photograph and atomic force microscope scan of the dual-line focus-laser lens are shown in Figure 4.
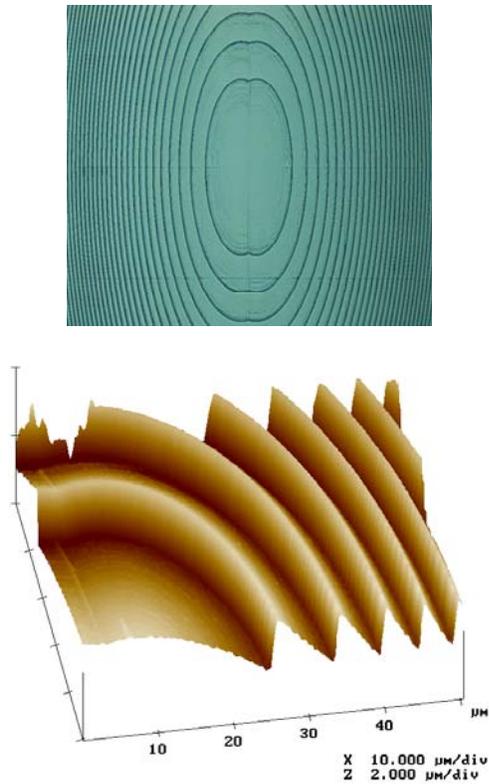
Figure 4- Photograph (top) and AFM scan (bottom) of the center of the dual-line-focus laser lens

The shear stress sensor's elements were assembled into a package (Figure 5) with a diode laser (660 nm) and a port for the collection fiber. The overall size of this prototype is 15 mm in diameter and 20 mm in length. The fringes were imaged with a CCD camera using a microscope objective and are shown in Figure 5. The fringe divergence was measured to be linear with a slope in close agreement with theory. The contrast is very satisfactory and preliminary tests using a moving surface through the fringe pattern yield a clear signal. Testing of the receiver side of the sensor element is underway.
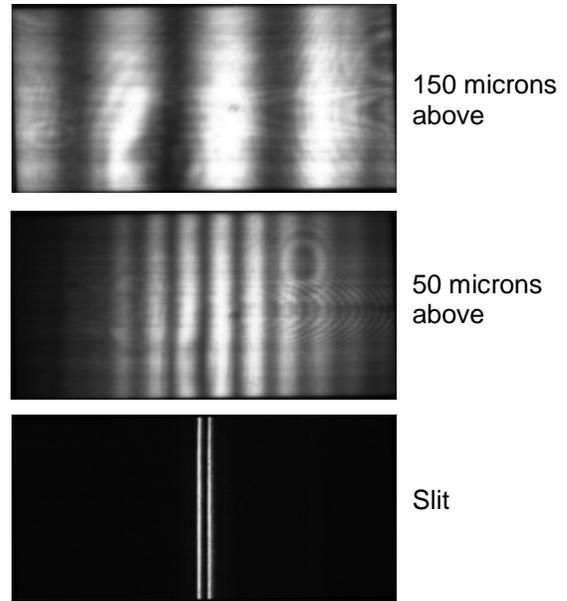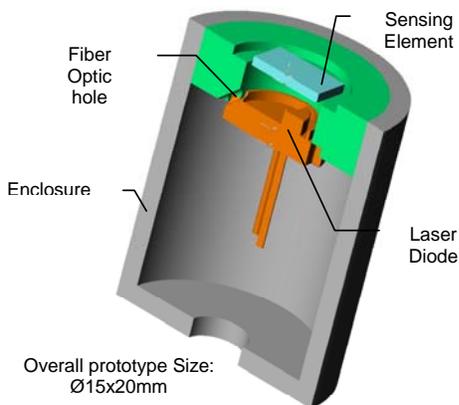

Figure 5- Shear stress sensor assembly (top) and photographs of the fringes at different heights above the surface (bottom)

Data have been collected in number flow facilities. Figure 6 shows the data collected over a flat plate comparing favorably with the wall shear stress values calculated from a co-located MiniLDV as well as the theoretical values. More comprehensive representation of the shear stress sensor performance are presented in [3] and [4].
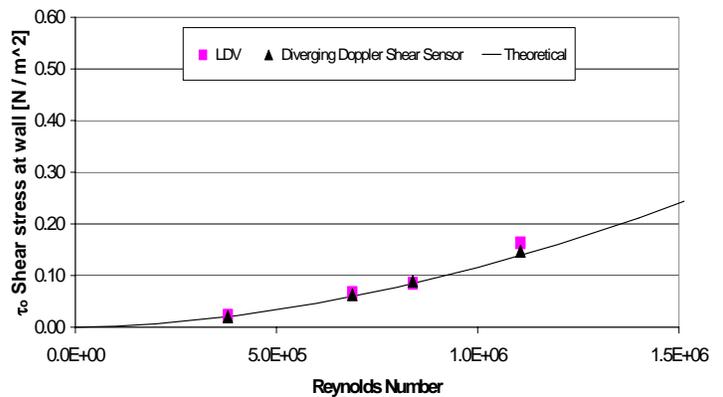

Figure 6- Wall shear data over a flat plate

TIME-OF-FLIGHT-MICRO VELOCIMETER

Similar technology was used to develop an integrated micro-sensor, called MicroV™, for direct measurement of particle velocity. The sensor consist of a diffractive optical element with one transmitting optics and two receiving optics written on one side of the doe. The transmitting optics transforms the laser beam into two parallel fringes located 7.5 mm in air (10 mm in water) from the surface of the doe.. A computed image of the transmitter beam is shown in Figure 7
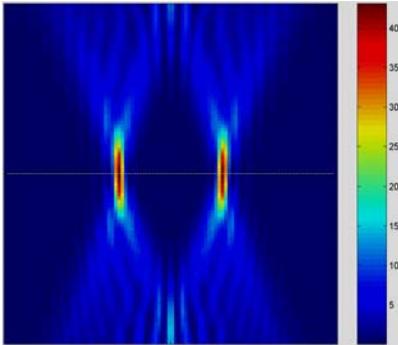

Figure 7- Transmitter beam configuration

Each fringe is approximately 5 microns thick, 300 microns long and 100 microns apart. The measurement region, defined by the two sheets are imaged onto two receiving fibers, each focused onto one of the two fringes. Care has been taken to minimize the cross talk between the two fringes. A schematic of a cross-correlation MicroV is shown in Figure 8. In this case, the probe volume distance from the sensor is 7.4 mm in air and 10 mm in water.
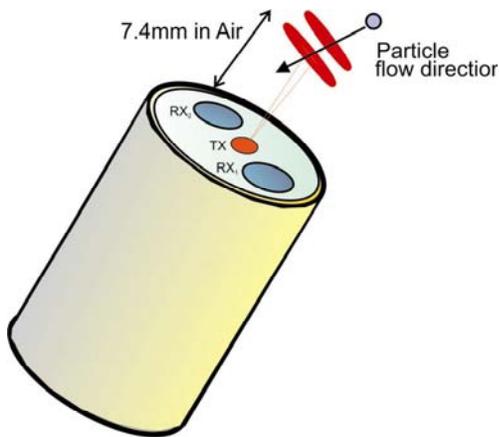

Figure 8- Schematic of a Cross-Correlation Micro V

To design the beam-shaping computer-generated hologram (CGH) phase function, we used a variation of the soft-operator iterative-Fourier transform algorithm. Starting with a 64 x 64-pixel gray-scale bitmap representation of the desired two-spot image, the algorithm was iterated approximately 5000 times to design the 128x128-pixel phase function shown in Figure 9 (1).

To produce a focus at 7.4mm from the surface, a 512x512 2-mm-pixel lens phase function was added to the CGH. The resulting 1 mm x 1 mm DOE shown in Figure 9 (2) was then fabricated in PMMA on a fused silica substrate using analog-dose electron-beam lithography [5, 6]. To characterize the performance, a HeNe laser coupled into a single-mode fiber was used to illuminate the DOE, and a bare CCD (no cover glass) recorded the image. Figure 9 (3) shows the simulated image and Figure 9 (4) shows the measured image. The measured image exhibits equal and uniform line intensities and diffraction-limited focusing.
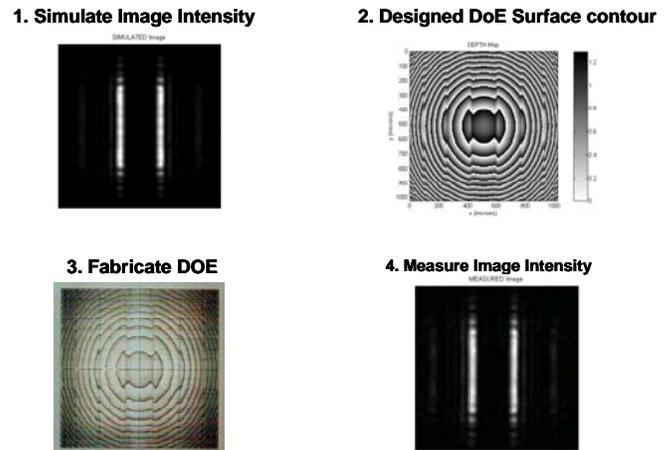

Figure 9- (1) Beam-shaping CGH phase, (2) Depth of CGH with lens added, (3) fabricated DOE, (4) measured image

Using similar design and fabrication procedures, we have created complete micro-velocimeter ("MicroV") sensors including transmitter and receiver DOEs and fiber-coupled sources and detectors. A fully packaged MicroV sensor is shown in Figure 10. It is designed to either be flush mounted in the wall of the device under test (flow tank, hydrofoil, etc.) to avoid disturbing the flow, or as a stand-alone watertight sensor for insertion into the flow. Such sensors typically exhibit detected signal to noise ratios of greater than 50:1.
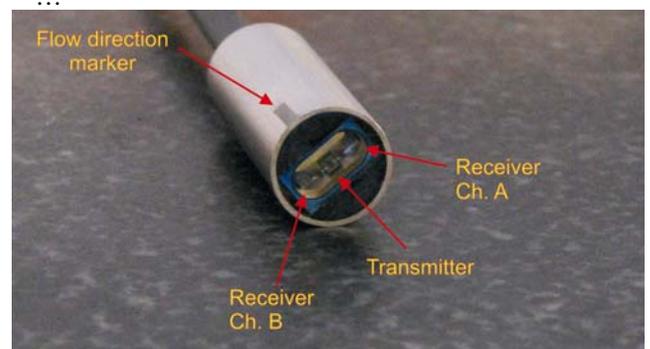
…

Figure 10- Photograph of a fully packaged MicroV sensor

The MicroV has been used in a variety of flow conditions. Figure 11 shows the analog output of the sensor for a small particle passing through each of the two beams. The speed of the particle is calculated from the measured time-of-flight, Δt, and the physical separation of the two fringes.
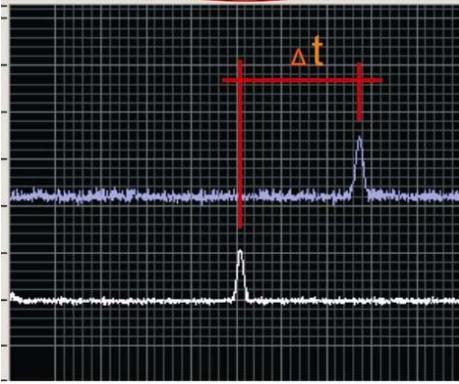

Figure 11- Traces of a single particle traversing the two beams of a MicroV sensor

A comparison of the data obtained by a MiniLDV and the MicroV in water tunnel is shows in Figure 12. Here, the MicroV was moved every 10 microns and the data agreed very well with the MiniLDV data.
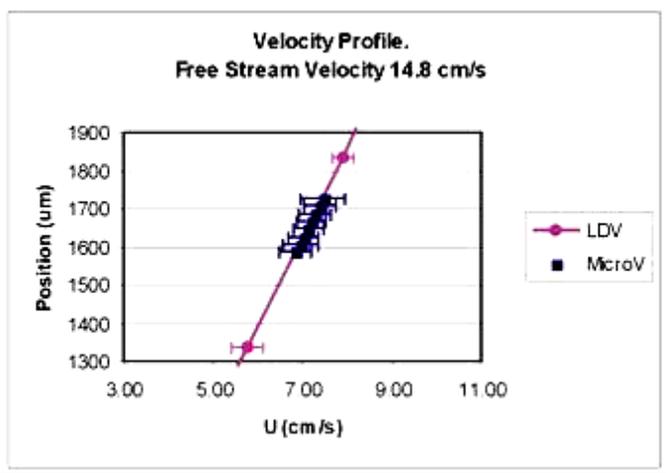

Figure 12- MicroV data compared with a co-located MinLDV

A variation of the Micro V was developed for particle sizing and particle concentration measurement. A new diffractive optical element was developed in the shape of an elongated donut. The cross-section of the sensor probe volume is shown in Figure 13. Here, the shape of the probe volume eliminates the probe volume dimension uncertainty, and hence provides an accurate estimate of the particle concentration.

The particle characterization sensor was developed in a forward collection mode. A schematic of the sensor components is also shown in Figure 13. Here, a laser or a fiber could be used as a source of the illumination. A separate doe is used to collect the scattered light at a number of different collection angles. Multiple collection of the scattered light eliminates the ambiguity in the Mie scattering collection.
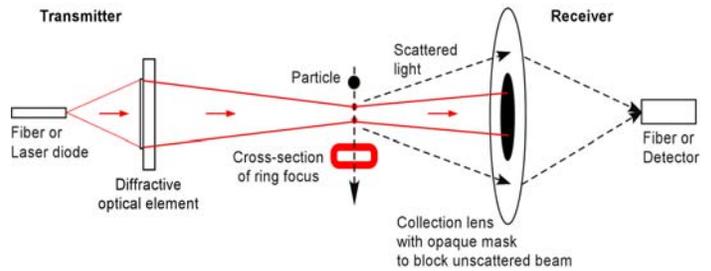

Figure 13- Particle Concentration and Sizing (PCS) sensor

The above sensor was incorporated into a standalone system for remote balloon testing. The sensor included a remote trigger capability and a remote data logger controlled by a central processing unit. The remote unit weighed just over one pound, including battery for an 8-hour standby and 10 minutes of continuous data collection.

MINIATURE LASER DOPPLER VELOCIMETER

The MiniDV[1] sensor developed by the authors uses specially designed diffractive optic elements for stationary and moving parallel fringe patterns. The optical design and the fabrication process ensure the uniformity of the fringes across the depth of field. An example of the MiniLDV is shown in Figure 14. The optical head contains the light source, miniature optics, receiving optics and detection system. In our present design, the diode laser does not require temperature stabilization. This portable device works in backscatter mode with a fixed probe volume distances between 34 to 240 mm. The overall dimension of the sensor head is 3 cm in diameter and 16 cm in length. Except for frequency shifting mechanism, it has no moving parts and requires no on-site alignment or calibration.

---

[1] Patent pending

Figure 14- Photograph of a MiniLDV optical sensor head

The optical quality of an LDV system is demonstrated by the visibility of the signal and the uniformity of the fringe separation along its probe volume. Figure 15 shows a digitized output of detector for an incense particle. The size of particle is estimated between 0.3 to 0.5 microns. The signal SNR is high and the visibility ratio of the Doppler signal is close to 100%.
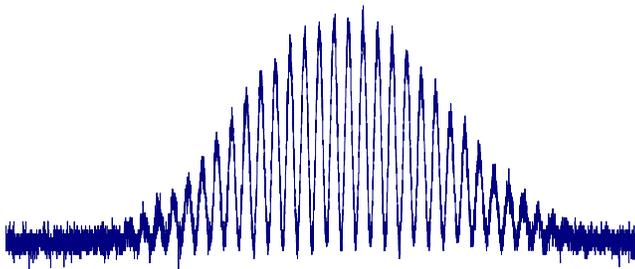

Figure 15- Doppler signal for an incense particle

Another important attribute of the MiniLDV is the uniformity of the fringe lines along its optical path. To measure the fringe spacing as a function of the position along the probe volume, a rotating disk with known diameter (±.01% uncertainty) was used. The MiniLDV was used to measure the perimeter of the disk. The distance between the sensor and the disk was changed and the measurement was repeated. The results are shown in Figure 16.
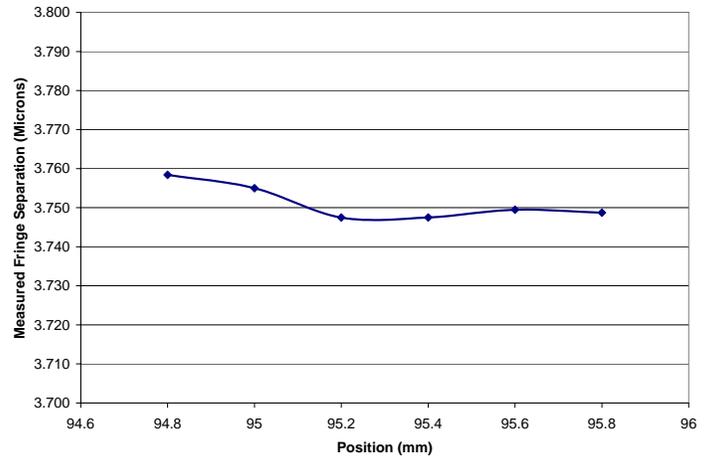

Figure 16- Variation of the fringe pattern along the probe volume

The data shows an absolute variation of 0.3% across the entire length of the probe volume, including the uncertainties of the calibration instrument and the processing technique.

MULTI-SENSOR CONFIGURATIONS

The size and the structure of the mini and micro sensors described in this manuscript lend themselves to multi-sensor instrumentation configurations designed for specific applications. Two of the configurations are presented here.

A MiniLDV was combined with two MicroS sensors in a water-tight housing for the measurement of the wall shear on a scaled submarine model. The MiniLDV was attached to a remote traversing unit for boundary layer profile measurement The three sensors and the traversing unit was housed inside a water tight enclosure and placed inside the test vehicle. A photograph of the integrated optical sensor is shown in Figure 17.
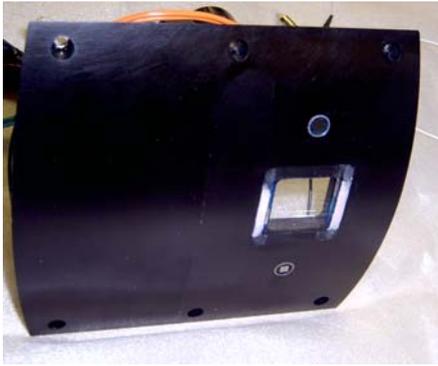

Figure 17- Housing for two surface-mounted shear stresses and an optical window for a traversing MiniLDV (not shown)

Similar, but smaller integrated units were fabricated for installation onboard a 140 ft ship for at-sea tests and measurements, as shown in Figure 18. Here, two wall mounted shear stresses and a traversing MicroV was installed inside a water-tight canister attached to the ship hull.

Figure 18- Integration of two MicroS shear stress sensors with a traversing microV for boundary profilometery within 2mm from the surface

Data were collected in the ocean north of Kauai Island in Hawaii. A sample data is shown in Figure 19.
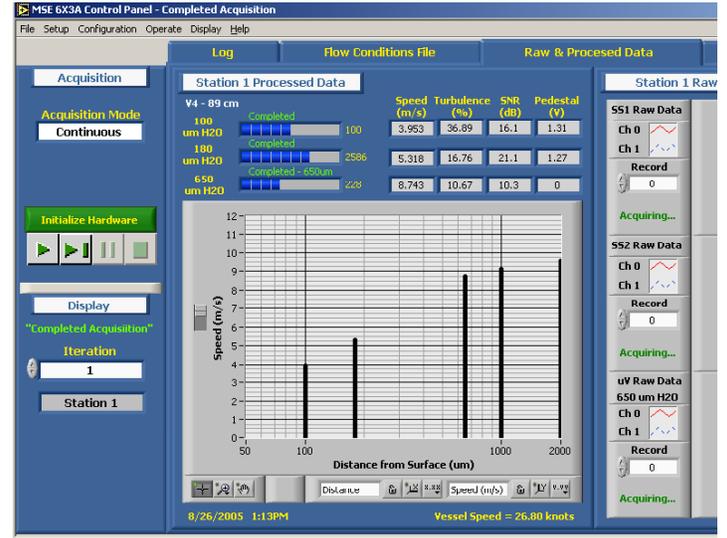

Figure 19- Sample data collected at sea

A total of twelve (12) set of sensor housing were installed in a 140 ft long vessel. Here, the mean velocity data at 100, 180, 600, 1000, and 2000 microns from the surface were collected.

CONCLUSION

A number of laser-based optical sensors for flow and particle characterization have been presented. The basic building blocks of the sensors are similar and in most cases, the processing requirements are also the same. The sensors presented are linear; do not have moving parts, they are designed to be rugged and operationally simple.

Through further refinements and modifications, the sensors will be able to detect smaller particles, providing higher data rates.

REFERENCES

[1] A. A. Naqwi and W. C. Reynolds, "Dual cylindrical wave laser-Doppler method for measurement of skin friction in fluid flow," Report No. TF-28, Stanford University (1987).

[2] P. D. Maker, D. W. Wilson, and R. E. Muller, "Fabrication and performance of optical interconnect analog phase holograms made be E-beam lithography," in Optoelectronic Interconnects and Packaging, R. T. Chen and P. S. Guilfoyle, eds., Proc. SPIE CR62, 415-430 (1996).

[3] D. Modarress, "Recent and future development of MEMS-based optical sensors", 5th International Symposium on MEMS and Nanotechnology, (2004).

[4] D. Fourguette, D. Modarress, F. Taugwalder, D. Wilson, M. Koochesfahani, M. Gharib, "Miniature and MOEMS flow sensors," AIAA 2001-2982 (2001).

[5] B. S. Rinkevichius, Laser diagnostics in fluid mechanics Begall House (1998).

[6] D. W. Wilson, J. A. Scalf, S. Forouhar, R. E. Muller, F. Taugwalder, M. Gharib, D. Fourguette, and D. Modarress, "Diffractive optic fluid shear stress sensor," in Diffractive Optics and Micro Optics, OSA Technical Digest (Optical Society of America, Washington DC, 2000), pp. 306-308.