Laboratory verification of the Optical Turbulence Sensor (OTS): Particulate Volume Scattering Function and Turbulence Properties of the Flow

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LONG-TERM GOALS

Our goal is an extensive tank validation of the Optical Turbulence Sensor (OTS). This sensor uses a Hartman optical wavefront sensor to determine turbulence characteristics and to characterize the particulate field. The recent ocean trials indicate that the OTS surpasses in many ways current microstructure based instruments to quantify turbulence. Furthermore, it is able to measure particulate scattering for larger particles - particles larger >50 μm. In our effort we aim to develop methods to simultaneously quantify the flow turbulent parameters, scattering coefficient of embedded particulates and associated particulate flux.

OBJECTIVES

We have two-fold objectives:
Particle field characterization: to test new method to calculate particulate Volume Scattering Function (VSF) and the particulate scattering coefficient for particles larger >50 μm. The simultaneous measurement of the particle size distribution and the flow velocity, by a single measurement, allows for unprecedented determination of particle volume transport on very small scales and turbulence /particle interaction.

Turbulence characterization: In this part of the effort we compare independent and highly accurate thermistor and Particle Imaging Velocimetry (PIV) measurements of the turbulent kinetic energy dissipation rate and the temperature dissipation rate with concurrent OTS measurements of the same variables. These studies are performed in well-controlled fully turbulent convective tank.
In addition we plan on quantifying particle transport by coherent turbulent structures.

APPROACH

We carry out rigorous tank testing of the turbulent and optical quantities measured by the OTS and direct comparison with independent measurements.

- We in the process of directly measuring the following **turbulent quantities**: turbulent kinetic energy dissipation, temperature variance dissipation rate using 2D PIV setup and the fast thermistor FP07.

- We carry out direct measurement of the following **optical parameters**: particle VSF, beam attenuation and particle scattering coefficient. We use diffractometer to obtain the nearforward particle

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VSF concurrent (and independent) with OTS measurements and nephlometer for a sample VSF measurements.

- The OTS measurements yield the temperature dissipation rate and kinetic energy rate estimated either via either: the temperature spectra (with resolved dissipation peak) or a direct and instantaneous OTS measurement of flow shear.

- The OTS yields the flow Volume Scattering Function which can be split into the particulate VSF and the turbulent VSF.

- The OTS measured mean shear and flow velocity component are to be compared with concurrent PIV measurements of same quantities.

The work in this project is carried out by the PI and a PhD student Sarah Woods. In addition we collaborate with: Dr. M Jonasz (MJOpticalTech: particle optics, polarization, nephlometer measurements), Dr. A. Fincham (USC: PIV small scale measurements) and PhD student from Poland - W. Freda (IOPAN, Sopot: polarization measurements, Mie scattering calculations). Our laboratory setup of the diffractometer, PIV and OTS is presented on the Figure 1.

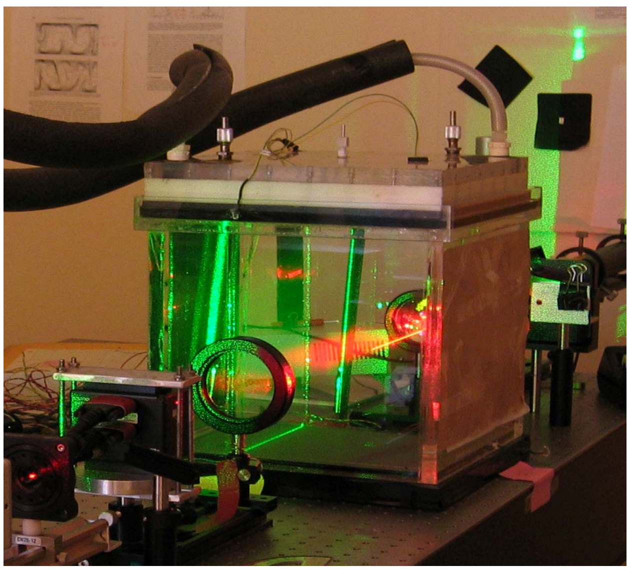

Figure 1. The laboratory experiment setup. Light beams in the convective turbulent tank. Particle Image Velocimetry PIV laser: green light sheet, the diffractometer light beam: thin red beam and the OTS light beam: wide red beam. At the top of tank: inserted fast thermistor. The bottom/top plates contain several imbedded thermistors to monitor the temperature gradient driving the steady fully turbulent convective flow (Ra>10^8).

WORK COMPLETED

We have completed 1 ½ year of the effort.

- **Completed experimental tasks - laboratory**:

- We have set up and calibrated the PIV system, the optical wavefront system, the nephlometer and the diffractometer.
-During the summer of 2008 we have carried out a set of experiments with varying flows of range of turbulent parameters. During experiments we have injected, into the steady turbulent flow, a set of particles of varying sizes between 10 μm to 1000 μm and measured the flow turbulent parameters and particulate forward scattering.
- The particulate VSF (concurrent with OTS) was measured using diffractometer with its optical path close to OTS sensing beam – Figure 1. The particles VSF was additionally measured by the benchtop nephlometer and results compared to Mie calculations.
- We have carried out OTS measurements without particulates to determine the optical turbulent scattering of the pure turbulent flow.
- We have used the diffractometer to measure the depolarization ratio for different turbulent flows with and without particles.
- Using PIV we have measured and calculated energy dissipation rates for the turbulent flows concurrent and collocated (Figure 1) with the OTS and the diffractometer measurements.

- **Completed experimental tasks –water samples from RSMAS beach**:

We have carried out wavefront measurements of oceanic water collected from the RSMAS beach. The aim of these experiments was to determine optical properties (using wavefront sensor) of the near bottom resuspended sediment samples. We have measured the sediment samples VSF using nephlometer and sediment size distribution using Coulter Counter and we run the Mie calculation to obtain the sediment VSF over the full set of angles: 0-180 deg.

- **Completed theoretical tasks**:

-Improved the OTS processing algorithm to obtain turbulent parameters in presence of large particles concentration. Improve discrimination between particulate and turbulent scattering in the OTS signal, we are in the process of establish bounds of particle diameter for which wavefront sensor can determine particles VSF.
- Established preliminary method of calculating the energy dissipation rates from the PIV data.
- Improved method of calculating temperature dissipation rate using PIV collocated with fast thermistor.

RESULTS

1. Improved OTS processing algorythm have increased OTS sensitivity. The recent OTS acquired data have revealed a frequent presence of coherent turbulent structures (Figure 2) resembling hairpin vortices or a vortex pairs. Such coherent turbulent structure can be potentially responsible for particle transport.

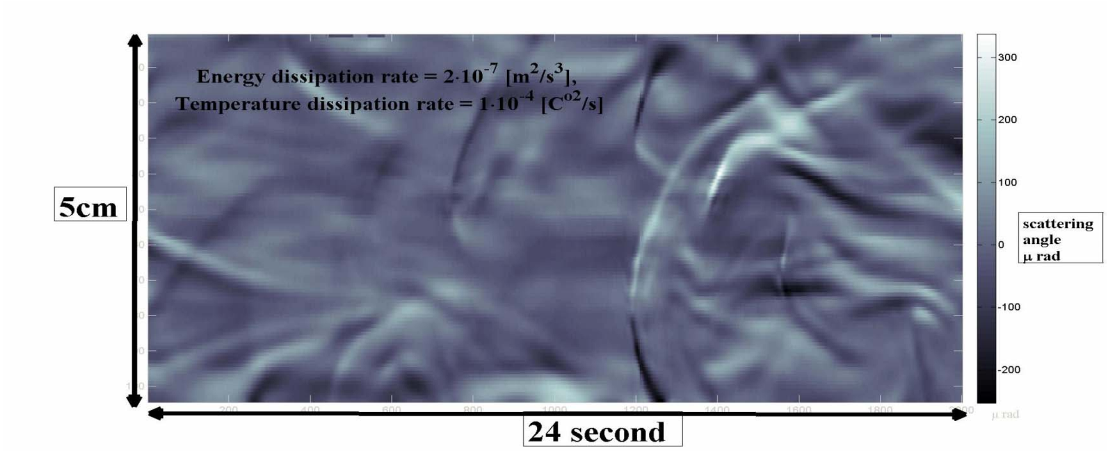

Figure 2. OTS measured time series of forward light scattering angle on the pure (no particles) turbulent flow – across 5 cm aperture. The hairpin-like turbulent coherent structure - center of the figure.

2. The tank experiments show good agreement between PIV measured energy dissipation rate and the one obtained from OTS – see Figure 3. Here – Figure 3 – panel A, we present the OTS measured energy dissipation rate when the convective cell temperature difference is set to ΔT =6.8 degC and ΔT =11.7 degC. The panel B shows PIV (for various interrogation window size – the smaller window – more accurate value) estimates of PIV during the ΔT =6.6 degC run. We have observed an (as expected) Gaussian distribution TKE values around the its mean value (Figure 3 – Panel A). The mean TKE value is in agreement with the PIV measurements (Figure 3 – Panel B) at selected the ΔT =6.6 degC.

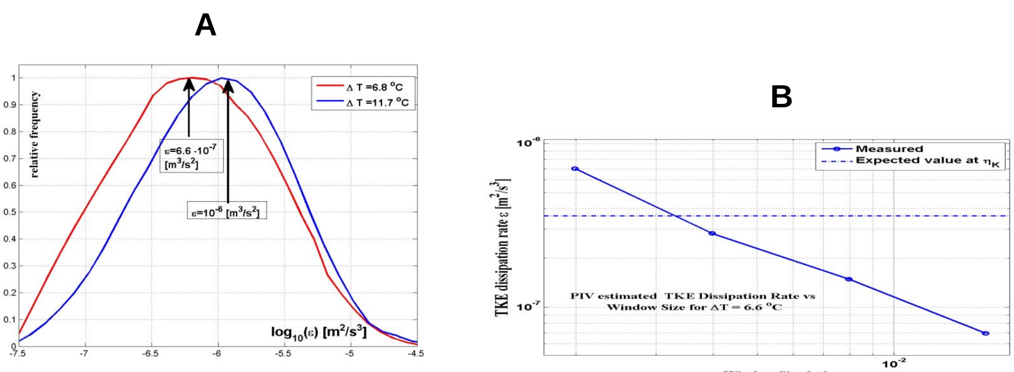

Figure 3. Comparison of OTS and PIV energy dissipation rates for T=6.7 -6.6 degC. Panel A- left – OTS measured histogram of energy dissipation during 120 seconds long run.
Panel B- right –PIV measure energy dissipation as a function of the interrogation window (smaller window = better accuracy) for same 120 sec long run – the estimated TKE in this experiment TKE= 7 10^{-7} m^2/s^3. The flow was seeded with 10 m particles and the OTS optical data were obtained in the presence of 10 m particles.

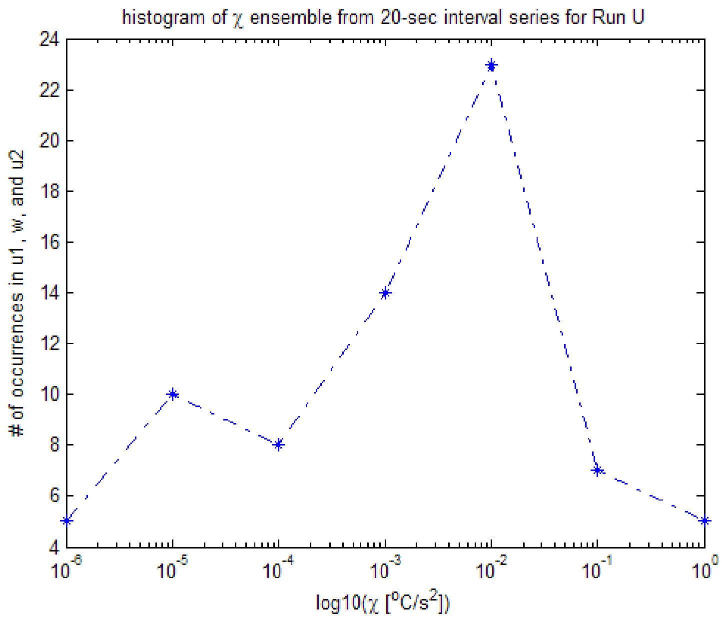

Figure 4. Histogram of measured temperature dissipation rates obtained from PIV/fast thermistor data for T=11.7 C.

Concurrently with OTS measurements we carry out measurements of energy dissipation rates Figure 3B and temperature dissipation rates – Figure 4.

3. From OTS measurements we have calculated the light scattering coefficient (b_turb) of the 'pure' turbulent flow under different turbulent conditions results are in Figure 5. The oceanic turbulent flows are a highly scattering medium – even the weakest reproducible in our laboratory experiment turbulent flow (turbulent kinetic energy dissipation rate= 10^{-9} m^2/s^3, temperature dissipation rate 10^{-7} C^2/s), had the scattering coefficient - b_turb= 0.8 [1/m]!. Such a weak turbulent flow can typically be encountered below the mixed layer depth. The values of energy and temperature dissipation rate within oceanic mixed layer depth frequently attain much larger values, thus are characterized by much larger scattering coefficient easily approaching 10 [1/m] (Figure 5)!!. Such conditions i.e. highly scattering flow frequently exist within the uppermost few meters of the water column, where the breaking waves can maintain the large values of energy/temperature dissipation rates. Such large values of scattering coefficients encountered in the aquatic environment have implications for active – lidar remote sensing [1].

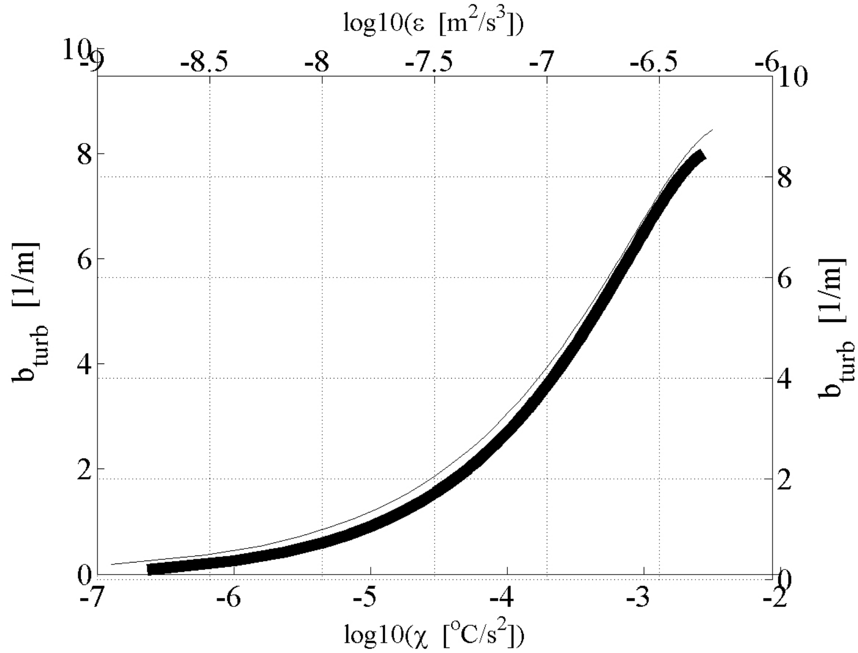

Figure 5. Measured turbulent scattering coefficient- b_turb, for under different turbulent conditions – NO particulates.

4. We are investigating the effect of oceanic particles light scattering on light wavefront measurements. Our implemented optical configuration (OTS) combined with used data processing allows to discriminate between turbulent and particulate the scattering for particle diameter the larger >50 μm. The Figure 6 presents the unprocessed wavefront sensor data under few lenslets without and with particles of varying sizes. Figure 7 presents a single data frame (1 sec long time series of light intensity under all lenslets) where part of the image contains a number of particles 180 -210 μm particles and part of the image corresponds to a turbulent flow without particles. For processing we have split the image into two parts: corresponding to the flow without and with particles. The results – VSF for the part of the image only with turbulent flow and for the part of the image turbulent flow + imbedded particles is shown in the Figure 7. We attribute the difference between the VSFs to the particulate scattering. The accuracy of such obtained particulate VSF is being analyzed via comparison with the benchtop nephlometer measurements and Mie calculations.

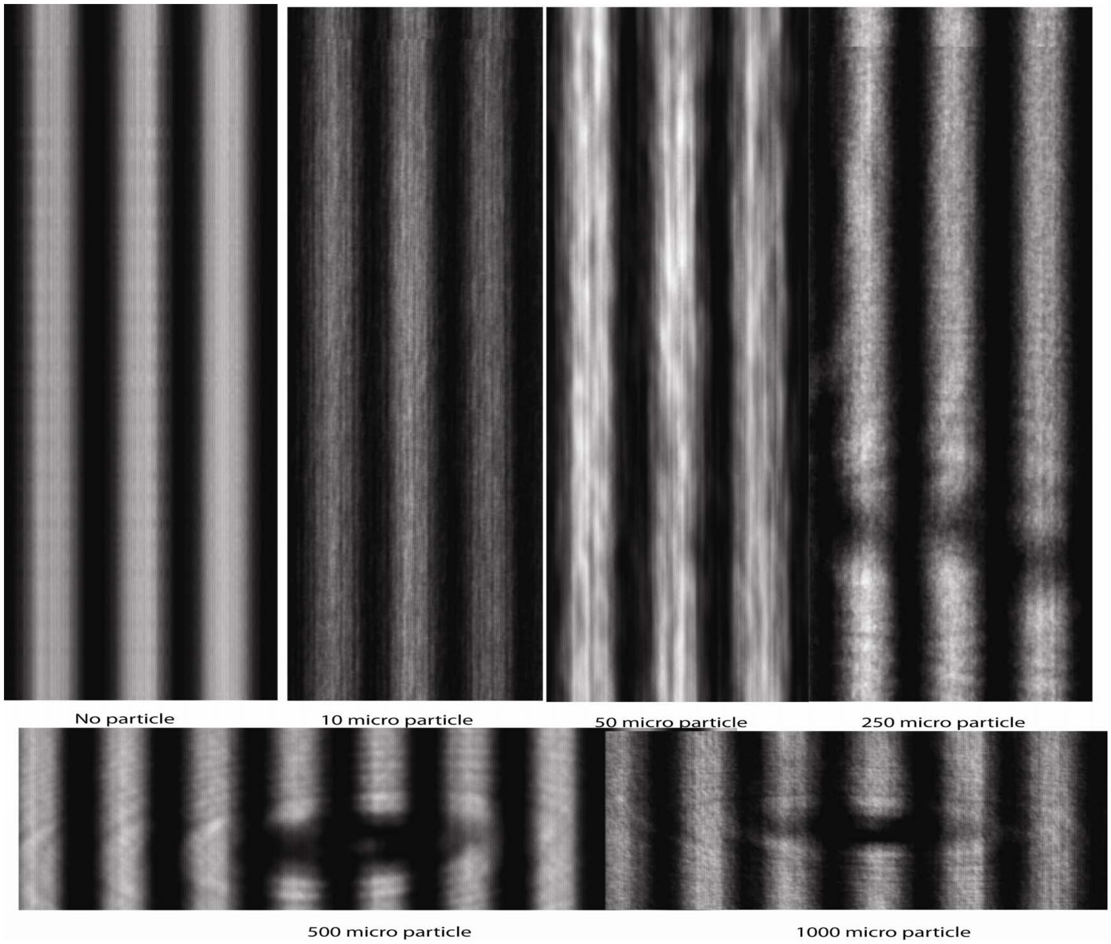

Figure 6. Effect of particulate scattering in OTS raw data image. The set of images correspond to same turbulent flow seeded with particles of different size. Top -left- no particles - pure turbulent flow. Bottom right 1mm particles.

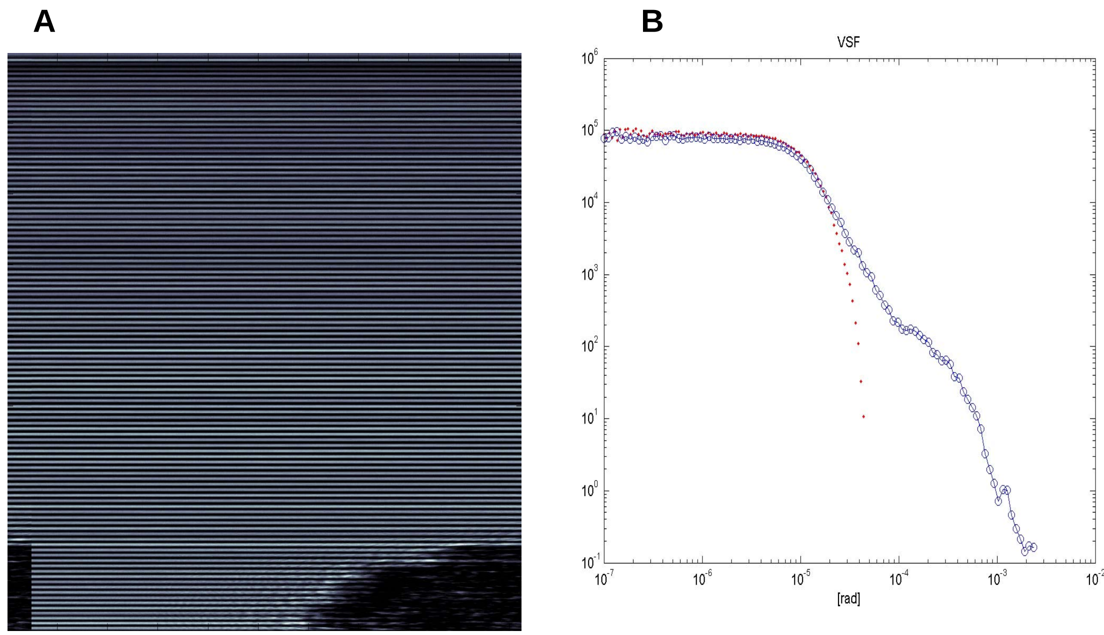

Figure 7. OTS measured VSF of purely turbulent flow and after adding 180 -210 m particles. Panel A. The raw OTS (time series of light intensity from all lenslets) data 1 sec long record. The left side panel A: no particulates, right side panel A: a cloud of 180 -210 m particles imbedded in the turbulent flow. Panel B. Derived from Panel A image: turbulent VSF of pure turbulent flow - red, the VSF of the turbulent flow with imbeded 180 -210 m particles – blue.

IMPACT/APPLICATIONS

- The OTS turbulent measurment verification i.e.: sensitivity, accuracy of Turbulent Kinetic Energy and temperature dissipation rates measurment with concurent PIV and fast thermistor data.

- Sediment transport process. Particles in the aqueous environment transport carbon and adsorb contaminants, are food source for biological organisms and contribute to the optical quality of the water column. Understanding particle transport has been the goal of oceans scientists and engineers for decades. Particles in suspension are packaged predominantly in porous agglomerations called - flocs. This repackaging of particles affects their transport rate, yet understanding of the controls on floc size remains rudimentary. It is generally assumed that the strength of background that small-scale turbulence is a relevant parameters controlling the floc dynamics but data to test in situ this assumption are lacking. The OTS combined and concurent turbulent/optical in situ measurments can shed sligh on particulate dynamics in the coastal environments.

- Role of coherent turbulent structures in particulate transport.

- Understanding of laser light beam propagation in the aquatic environment. OTS in situ estimates of the refractive index structure parameter C_n^2 will allow to estabilishing oceanic variability of the C_n^2 for example: within/below mixed layer or within bottom boundary layer. The oceanic variability of the

Fried coherence length (obtained from the OTS mean beam arrival angle) is one of the laser beam propagation parametrs and can now be routinely examined measured.

- The role of relatively strong depolarization of a light beam by a turbulent flow. The polarization effects can potentially be used for remote sensing applications such remote lidar polarimetric sensing of aquatic environment.

PUBLICATIONS

[1] D. J. Bogucki, J. Piskozub, M.-E. Carr and G. Spiers. Monte Carlo simulation of propagation of a short light beam through turbulent oceanic flow. Optics Express. 2007, 13988-13996

Conference:
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S. Woods, A. Fincham, D. J. Bogucki, Laboratory measurements of energy and temperature dissipation rates in Rayleigh-Bernard convective flow with Ra = $O(10^8)$ to $O(10^9)$. Accepted. American Physical Society Division of Fluid Dynamics 2008 Meeting.