MEASUREMENT OF SMALL–SCALE OCEANIC TURBULENCE USING AN AUV

Manhar R Dhanak and Ken Holappa

Department of Ocean Engineering
Florida Atlantic University
Boca Raton, FL 33431, USA

ABSTRACT

Small–scale turbulence measurements in up to 150m deep waters, using Florida Atlantic University's small autonomous underwater vehicle, *the Ocean Explorer*, are described. Cross–stream components of the fluctuating velocity were measured using two shear probes mounted on the nose of the vehicle as it travelled through shallow tropical waters off the coast of Florida and in the Gulf Stream. The turbulence measurements are of good quality and correspond to energy dissipation rates in the range $\epsilon = O(10^{-7} - 10^{-9})\mathrm{m}^2\mathrm{s}^{-3}$. Supportive measurements, using on–board sensors, of current profiles and in–situ electric conductivity and temperature were also obtained. The mobile measurement platform and the measurements will be described.

INTRODUCTION

Free from limitations of a traditional laboratory environment, the ocean offers a good opportunity to study small scale turbulence. Assuming a turbulence dissipation rate ε in the range $10^{-5} - 10^{-9}$ $\mathrm{m}^2\mathrm{s}^{-3}$ and the kinematic viscosity $\nu \simeq 10^{-6}$ $\mathrm{m}^2\mathrm{s}^{-1}$, we expect from the theory of locally isotropic turbulence that the minimum length scale, $(\nu^3/\varepsilon)^{1/4}$, of turbulence to lie in the range 0.5mm – 1cm. Further, the minimum time scale of the field, $(\nu/\varepsilon)^{1/2}$, on this basis is expected to be 0.3 – 35s. Traditionally, small–scale turbulence measurements are carried out with probes mounted on tethered vehicles (Lueck, 1987) or on fixed platforms on the sea–bed or suspended from buoys (Gregg, 1977). A small, reliable autonomous underwater vehicle (AUV) provides an alternative platform, which is mobile, low cost and uncoupled from the low frequency motions of surface support ships. Such motions frequently induce platform vibrations which lie in the frequency range of interest and can significantly corrupt flow measurements. Significant advances have been made in recent times in the development of reliable low cost AUV's so that their use in routine oceanographic surveys is now possible. These small AUVs offer the possibility of making four–dimensional space–time measurements, potentially during a storm when processes such as sediment transport and turbulent mixing occur with great intensity and are expected to induce major changes to the bed form and the water column. Low risk deployment in storms is possible if the vehicles can be deployed from underwater docks. Application of AUV platforms in making small scale turbulence measurements has been demonstrated, for example, by Levine and Lueck (1996) and Dhanak and Holappa (1999). Since the AUV is a self propelled vehicle, an important concern in making these measurements is the vibrational noise which is transmitted from the vehicle machinery to the vicinity of the probes. Further limitations may be induced by body motions induced by vehicle controls. The vibrational noise is usually monitored by accelerometers mounted locally in the vicinity of the measurement probes. Noise which is narrow banded in the frequency range may be filtered out from measurements during post processing (Gargett 1982). However, quiet often the vibrations induced by the vehicle thruster are fairly broad banded, the noise levels depending upon the characteristics of the vehicle components. Reliable flow measurements are then possible provided the signal to noise level ratio is sufficiently high. In Dhanak and Holappa(1999), it is shown that, with sufficient care in isolating the turbulence package from the body of the vehicle and the body, in turn, from the tail section of the vehicle, high quality small scale turbulence measurements corresponding to rates of energy dissipation in the range $\epsilon = O(10^{-8} - 10^{-9})\mathrm{m}^2\mathrm{s}^{-3}$ may be achieved with the *Ocean Explorer* AUV (OEX) developed at Florida Atlantic University (Smith et al 1995). Here we describe deployment of the OEX in in the Gulf Stream for measurement of small scale turbulence and distribution of rate of energy dissipation. The OEX is described briefly in section 2 and a brief analysis of the measurements is presented in section 3.

THE *OCEAN EXPLORER* AUV

The OEX is 2.4m long (Fig. 1a,b) with a maximum diameter of 0.53m. It carries a CTD package and an acoustic Doppler current profiler (ADCP) as well as a Watson Block self motion package and a GPS satellite positioning system. In the Gulf Stream mission, the turbulence package consisted of two shear probes (see Lueck 1987, for example), a micro–structure thermistor and three locally mounted accelerometers housed in a single pressure case, located about 0.3m ahead of the bow of the vehicle to minimize flow disturbances associated with the motion of the latter. Mean current speed was measured with a Marsh–McBirney electromagnetic current meter although since then use is made of the on–board ADCP to measure the speed of the vehicle through the water. The turbulence package also utilizes the CTD and self–motion packages in the rear section of the submarine to get estimates of the local density, depth and vehicle attitude. The pressure vessel also contained electronic conditioning packages for the probes, a small on–board PC with 540Mbyte hard–disk capacity used for data acquisition and storage, with ethernet capability, and a battery power supply for the computer. Since the mission, a second turbulence package has been developed which is essentially independent of the particular AUV used, although the vibrational noise associated with the vehicle will determine performance.

TURBULENCE MEASUREMENT MISSIONS OF FEBRUARY 29, 1996 AND JULY 16, 1997.

The mission of 2/29/96 was carried out at the location 26^0 19.1'N, 80^0 03.8'W, off the coast of Boca Raton, Florida, in a region on the edge of the Gulf Stream, where the water depth is $\simeq$18m. Here, currents are frequently induced by large eddies which spin off the Gulf Stream. A southerly wind of 5 knots and an approximate 2s swell of less than 1/3m were apparent in the region. During the mission, the AUV traveled north at a speed of 1m/s, diving to a depth of $\simeq$10m, cruising at that depth for 40s and returning to the surface. A horizontal distance of 164m was covered over the mission.

The measured time series of CTD and mean velocity, recorded at a sampling rate of 4Hz, are shown in figure 2 and are discussed in detail in Dhanak and Holappa (1999).

The time variation can be related to the spatial variation on the basis of Taylor's hypothesis, $\partial/\partial t = -U\partial/\partial x$, where U is the mean speed of the vehicle ($U \simeq 1$m/s) relative to the water column; U is much larger than the magnitude of the fluctuating components of velocity which are of O(0.01 m/s). Thus the wavenumber can be written $k_1 = -f/U$, where f is the frequency in hertz. The time series for the derivatives $\partial v/\partial x = \frac{1}{U_x(t)}\partial v/\partial t$ and $\partial w/\partial x = \frac{1}{U_x(t)}\partial w/\partial t$, where v and w are respectively the y and z (cross–stream) components of the water velocity, and the corresponding time series for the signals a_y and a_z recorded by the locally–mounted accelerometers are given in Dhanak and Holappa(1999). The data were recorded at 322Hz. The coherency functions $\gamma_v^2(k_1)$ and $\gamma_w^2(k_1)$ between $\partial v/\partial x$ and a_y and between $\partial w/\partial x$ and a_z respectively revealed that for the most part, the coherence between the shear probe signals and the accelerometer signals was fairly low, indicating a low level of self noise contamination over the range 1–100Hz. The vibrational noise was filtered from the shear signals using $\phi_{(clean)}(k_1) = (1-\gamma^2(k_1))\phi_{(meas)}(k_1)$, where $\phi_{(clean)}$ and $\phi_{(meas)}$ respectively refer to the filtered and unfiltered dissipation spectra. The velocity spectra $\Phi_v(k_1)$ and $\Phi_w(k_1)$, corresponding to $\phi_{v(clean)}(k_1)$ and $\phi_{w(clean)}(k_1)$ may be obtained using the relation $\Phi(k_1) = \phi(k_1)/(2\pi k_1)^2$. In order to see the local *in situ* variations in turbulence levels, the turbulence and accelerometer data were processed over 10s segments. The dissipation rate $\epsilon^{(i)}(i = 1, 2, ..., 12)$, was estimated in each case by integrating the spectra over the range 0–90(cpm) and taking the average $\epsilon^{(i)} = (\epsilon_v^{(i)} + \epsilon_w^{(i)})/2$. Normalized velocity spectra $\Phi(k_1\eta)/(\epsilon\nu^5)^{1/4}$, are shown in figure 3a and an ensemble average given by $\overline{\Phi}(k_1\eta) = \frac{1}{10}\sum_{i=1}^{11}\Phi^{(i)}(k_1\eta)/(\epsilon^{(i)}\nu^5)^{1/4}$, is shown in figure 3b and is compared with the corresponding Nasmyth spectrum; the Nasmyth spectrum is a curve fit to a collection of empirical observations in strongly turbulent tidal channels(Oakey, 1982). Here $\eta\ (= (\frac{\nu^3}{\epsilon})^{1/4})$ is the Kolmogorov length scale. A very good agreement between the data and the Nasmyth spectrum is evident. Clearly, the measured data are of superior quality, free from vibrational contamination. The p.d.f.s of $\partial v/\partial x$ and $\partial w/\partial x$ plotted in figure 4 and compared with the Gaussian distribution show good correspondence between the two, both significantly deviating from the Gaussian at the tails; the rms values being $(\partial v/\partial x)_{rms} \simeq (\partial w/\partial x)_{rms} \simeq 0.06s^{-1}$, the skewness factors being $S_{\partial v/\partial x} \simeq 0.02$ and $S_{\partial w/\partial x} \simeq 0.15$, and the kurtoses being $K_{\partial v/\partial x} \simeq 6.0$ and $K_{\partial v/\partial x} \simeq 7.4$.

The mission of 7/16/97 was carried out in the Gulf Stream at the location 26^0 20.04'N, 80^0 01.16'W, off the coast of Boca Raton, Florida, where the water depth is $\simeq$150m. A SE wind of 5–10 knots and an approximate 2s swell of less than 1/3m and a surface current of 3.1 knots at 8^0 were apparent in the region. During the mission, the AUV traveled in a general southerly direction, against the current, at a relative water speed of $\simeq$1.4m/s for $\simeq$48 minutes, diving, in steps, to a depth of $\simeq$126m and returning to the surface. A horizontal distance of $\simeq$1200m was covered over the mission.

The depth, salinity and temperature determined from the recorded CTD data are shown in Fig. 5 a–d. The salinity data indicate occurrence of a broad salt layer at around 80m. There is good correspondence between salinity and temperature variations, the later varying, across the seasonal thermocline, by 15^{0}C over the depth covered. The speed of the vehicle through the water is shown in Fig. 5e, measured using the on–board

ADCP. Acoustic tracking revealed that in view of the strong surface current, extending down to 80m, the AUV followed a bearing of 120^0, but in deeper waters where the current is markedly less, it followed a bearing of 170^0.

For this mission, only the shear probes and the accelerometers were utilized. Analysis suggests that good quality turbulence data were obtained over the dissipation range $O(10^{-7} - 10^{-8} m^2 s^{-3})$ and significant information will result from the measurements. The micro–structure data were recorded at 422Hz. In order to see the local *in situ* variations in turbulence levels, the turbulence and accelerometer data have been processed over 8s segments. Details of the variation of the dissipation rate over the entire region traversed will be described elsewhere. Here we briefly consider the velocity shear spectra over 52 segments of the rise section (2190 – 2738s) of the time series which were computed. The velocity spectra $\Phi(k_1\eta)/(\epsilon\nu^5)^{1/4}$ and its ensemble average $\overline{\Phi}(k_1\eta) = \frac{1}{52}\sum_{i=1}^{52}\Phi^{(i)}(k_1\eta)/(\epsilon^{(i)}\nu^5)^{1/4}$ is shown in Fig. 6 a,b and the letter is compared with the corresponding normalized Nasmyth spectrum, as before. The measured data are again of high quality, the measurements being in good agreement with the Nasmyth spectrum over a substantial wavenumber range. The p.d.f. of $\partial v/\partial x$, plotted in figure 7 and compared with the Gaussian distribution, is comparable to those shown in figure 4; in this case the rms value $(\partial v/\partial x)_{rms} \simeq 0.15 s^{-1}$, the skewness factor $S_{\partial v/\partial x} \simeq -0.01$ and the kurtoses $K_{\partial v/\partial x} \simeq 7.2$. The variation of the dissipation rate over the analyzed time–series section is shown plotted against vehicle depth in Fig. 8a, together with the mean velocity data measured over a 9m region beneath the AUV by the on–board ADCP. Figures 8 (b)–(d) are based on measurements from the downward–looking on–board ADCP (1200kHz, in 12 0.75m bins). The vertical axes in (b)–(d) are on the same scale as the horizontal axis. V_x and V_y are horizontal components and V_z points vertically upwards. V_x points in the direction of heading, V_y towards starboard. The constant mean vehicle speed through the water, shown in Fig. 5e, has been subtracted from the ADCP measurements, so that the velocity shown is relative to this; the ground speed was only available over a section of the mission only, when the vehicle was sufficiently close to the bottom, so that values of absolute currents are not available. However, the the data is very useful in establishing presence of velocity shear in the flow. The occurrence of maximum dissipation rate corresponds well with the region of large–scale horizontal velocity feature observed in the ADCP data at around 80m depth. This also corresponds with the edge of the salt layer observed in Fig. 5b.

SUMMARY

Turbulence measurements of superior quality have been made off the east coast of Florida, using an AUV, over the 1 – 100 cpm wavenumber range in the shallow water and over 0.8 – 100 cpm range in the deeper Gulf stream mission. The CTD data of 2/29/96 shallow–water mission suggest the existence of local winter shear layers in the Boca Inlet region surveyed and the variation of the estimated dissipation rate over a 164m long region was determined. Measurements in the Gulf Stream were made across the summer thermocline, with the temperature dropping by around 15^0C over a depth of 126m. The AUV encountered a broad salt layer at a depth of around 80m, in the vicinity of which high rates of turbulence dissipation were measured. A brief analysis of the measured data is given here. Further details will be given in a journal article currently in preparation.

Other missions include one during recent cold winter fronts over shallow South Florida waters and a joint mission with the Southampton Oceanographic Centre involving a study of Langmuir circulation in Scottish waters in Summer 1999.

ACKNOWLEDGEMENTS.

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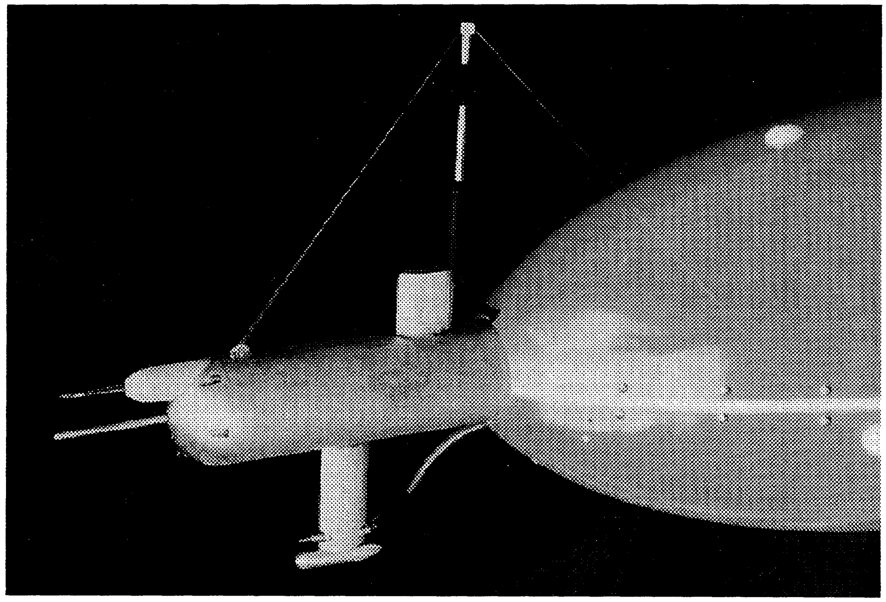

Figure1a. The OEX AUV measurement platform

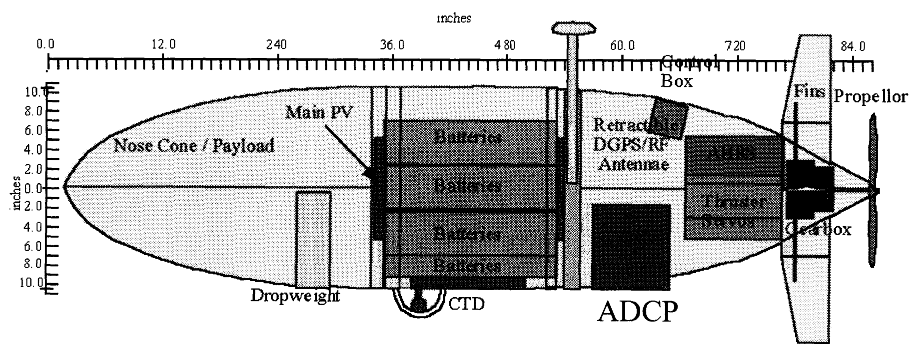

Figure 1b. Schematics of the *OEX*–series AUV showing the location of the CTD and the ADCP.

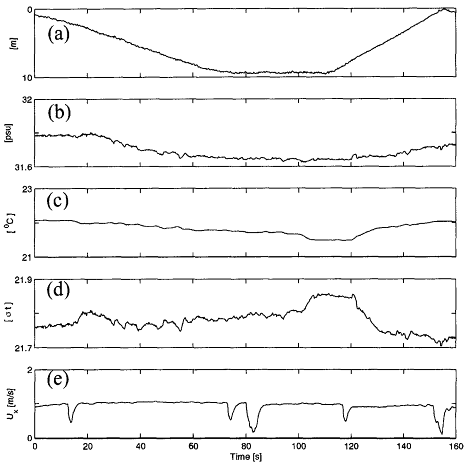

Figure 2. Time series of the mean data for 2/29/96 mission determined from the CTD and mean velocity measurements, sampled at 4Hz: (a) Vehicle depth, (b) salinity, (c) temperature, (d) density, (e) streamwise (x) component of velocity.

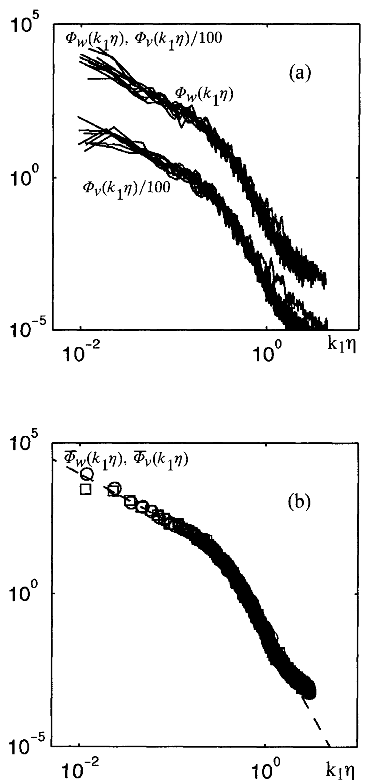

Figure 3. (a) Normalized velocity spectra for both cross–stream components 2/29/96 mission. (a) Spectra from 5m segments (b) Average of $\Phi v(k_1\eta)$ ('squares') and of $\Phi w(k_1\eta)$ ('o') are compared with the Nasmyth spectrum (dashed line).

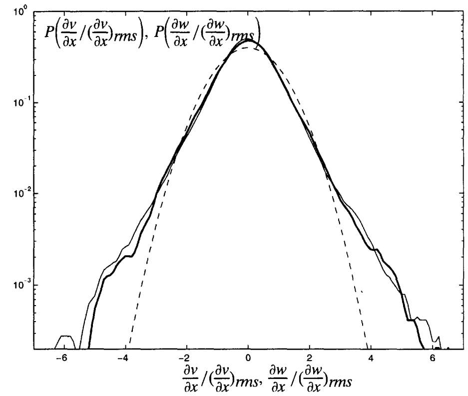

Figure 4. P.d.f.s of $\partial v/\partial t$ (thick line) and $\partial w/\partial t$ (thin line) compared with the Gaussian distribution (dashed line); 2/29/96 mission.

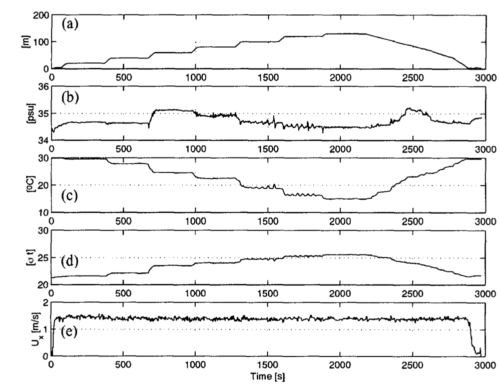

Figure 5. Time series of the mean data for 7/16/96 mission determined from the CTD and mean velocity measurements, and turbulence spectra: (a) Vehicle depth, (b) salinity, (c) temperature, (d) density, (e) streamwise (x) component of velocity,. Oxyz is a frame of reference fixed with respect to the AUV. When the AUV is traveling horizontally, Ox points to the North.

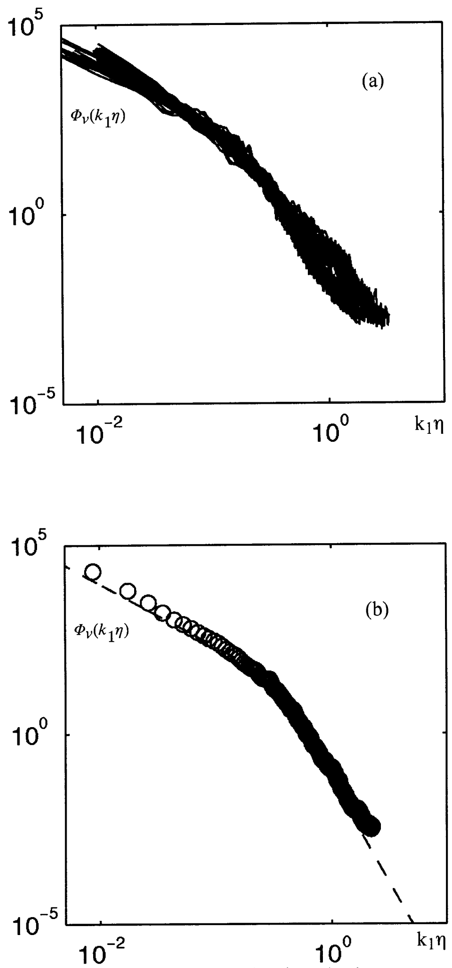

Figure 6. (a) Normalized velocity spectra $\Phi_v(k_1\eta)$ during 7/16/97 mission. (a) Spectra from 5m segments (b) Average of spectra compared with the Nasmyth spectrum (dashed line).

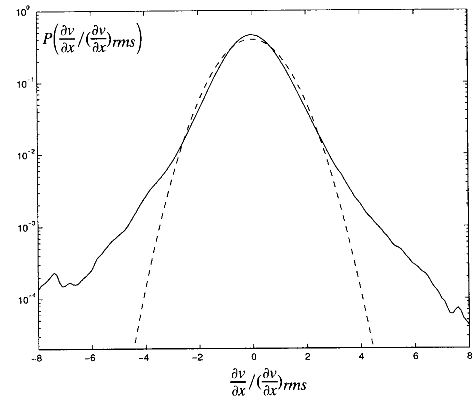

Figure 7. P.d.f.s of $\partial v/\partial t$ compared with the Gaussian distribution (dashed line); 2/29/96 mission.

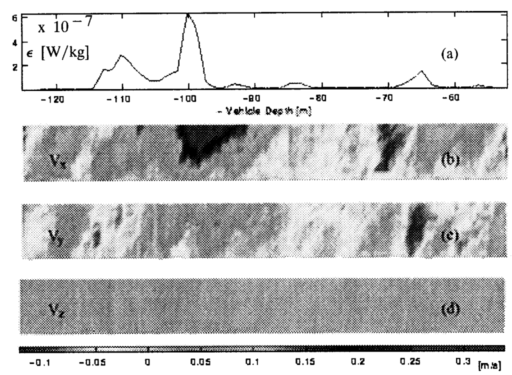

Figure 8.(a)Variation of dissipation rate, and (b)–(d) water velocity for region beneath the AUV plotted against instantaneous vehicle depth during the Gulf Stream mission of 7/16/97.