Rockland Technical Note 024

— VMP Turbulence Profiler Measurements in a Tidal Channel—

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Contents

1 Objective

This application note describes the use of the Vertical Microstructure Profiler (VMP) for turbulence measurements in tidal channels.

2 Background

A recent case study conducted by TÜV SUD NEL Ltd. (Glasgow, UK) has identified turbulence measurements as a key requirement for optimizing designs of tidal-current turbines. There is a general consensus in the tidal energy sector that environmental turbulence significantly impacts the loading on turbines and their performance. In-situ turbulence measurements with a spatial resolution of 0.01–1m (i.e., the scale of the turbine blades scales) are required, yet existing acoustic methods for measuring flow velocities are not able to provide this information. The standard method for the measurement of ocean turbulence is with the shear-probe sensor, and this method can provide the environmental data required by the tidal-energy community.

3 Instrument Description

The Vertical Microstructure Profiler (VMP) is a widely used instrument for the measurement of microstructure[1] turbulence parameters in oceans, rivers, and lakes. The VMP is a free-falling device deployed from ships or from fixed platforms. Several models are available with varying depth ranges and sensor configurations, optimized for specific operating environments, such as coastal, offshore and deep sea. All VMP profilers carry microstructure velocity probes (shear probes) and high-resolution temperature sensors (thermistors) to measure turbulence parameters.

- The VMP-200 (Figure 1) is a coastal-zone profiler designed for operation from small vessels with limited deck space (e.g., Zodiacs), or where electrical power sources are limited or missing (e.g., ice camps). The VMP-200 records data internally on a memory card, eliminating the requirement for a deck-side power supply and data recording system. The battery and memory allow for up to 36 hours of continuous operation. Profiles can be repeated without recovering the profiler. At the end of a series of profiles, the recorded data are downloaded using a USB connection.
- The VMP-500 (Figure 2) is designed for coastal and shelf-region operation. Data are transmitted through a four-conductor cable and recorded with a ship-side data acquisition computer. Power to the profiler is supplied through the deployment cable, which allows for virtually unlimited deployment time. The VMP-500 can carry a variety of ancillary sensor, typically high-accuracy CTD sensors.

[1]Microstructure in this context is defined as the spatial scales where turbulent velocity fluctuations are damped out by the fluid's molecular viscosity, typically on the order of millimetres to centimetres. These scales are also called the dissipation range.

Figure 1: The VMP-200 about to be deployed from a small sailboat.

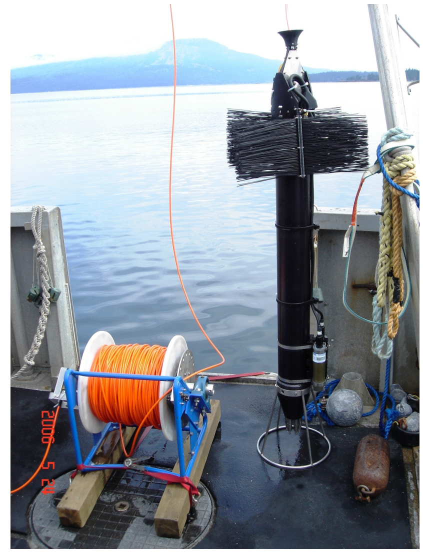

Figure 2: The VMP-500 Profiler and a small hand-winch to manage its electro-mechanical tether.

4 Turbulence Profiling Procedures

The VMP is deployed in a“tethered free-fall” mode, where the profiler is connected to the ship by a cable or line that is paid out at a rate slightly faster than the sum of the profiler’s fall speed and its rate of horizontal advection away from the ship. Due to the slack tether, the fall speed is constant and independent of ship motions. Brushes at the top end of the profiler provide drag, slowing the profiler to a constant fall speed of approximately $0.8\,\mathrm{m\,s^{-1}}$. This speed is a trade-off between the operational desire to conclude a profile as quickly as possible and the requirement to profile slowly to avoid generating vibrations or instabilities in the motion of the profiler. During the profile, the ship typically drifts with the current or the wind. The profiler is launched from the upwind side so that the ship drifts away from the tether cable to avoid snagging it beneath the ship. The person deploying the profiler feeds the line into the water at a rate that will result in a certain amount of slack cable being visible at the water surface. Instead of drifting, the ship can also steam ahead slowly at a rate of $0.5–1\mathrm{m\,s^{-1}}$ – the main limitation being the length of the tether and its maximum rate of deployment.

5 Turbulence Sensors

Turbulence sensors are mounted on the nose of the VMP, pointing downward. In this position, the sensors are not affected by any turbulence created by the profiler itself. The primary sensor for the measurement of turbulence is the shear probe (Figure 3), which consists of a piezo-ceramic element, 12 mm long and 1.5 mm wide, that is embedded halfway into a hollow stainless steel support sting. The free end of the piezo beam is encased in a flexible silicone rubber tip that has the shape of an axially symmetric airfoil.

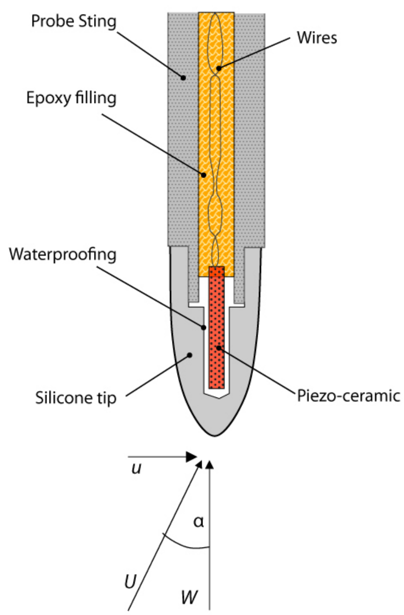

Figure 3: Shear probe schematic. W is the apparent vertical velocity due to profiling, u is the horizontal velocity fluctuation due to turbulence, U is the total velocity, and α is the angle of attack.

Figure 4: Chart of Sansum Narrows, located approximately at 48.80 °N, 123.55 °W.

As the probe moves axially through the water at a speed W (the fall-rate of the profiler), the horizontal component of the turbulent velocity, u, induces a lift force over the airfoil. The piezo-ceramic element translates this lift force into an electric charge, which is differentiated by the VMP's signal conditioning electronics to yield a voltage, $E = sW\partial u/\partial t$. With Taylor's hypothesis, the time derivate of u is converted into a spatial derivative, to yield the vertical shear of horizontal velocity, $\partial u/\partial z = W^{-2}s^{-1}E$, where s is the sensitivity of the probe, which is established during calibration[2]. The shear probe is sensitive to only a single component of velocity oriented at right angles to its axis. Therefore, two shear probes in parallel, with one rotated by 90 ° around its axis, can provide both components of vertical shear, $\partial u/\partial z$ and $\partial v/\partial z$. When the

[2]Details on the shear probe operating principle, calibration, and data processing are given in the RSI Technical Note TN-005, available under Support at www.rocklandscientific.com.

shear probe is used in a horizontal configuration (such as towing or on a gliders), the probe measures the horizontal shear of two velocity components, namely $\partial w/\partial x$ and $\partial v/\partial x$, where x is the quasi-horizontal direction of profiling.

The smallest spatial scale resolved by the shear probe is determined, to first order, by the length of the probe tip, which is approximately 1 cm. The largest resolved spatial scale is determined by the stability of the profiler as it moves through the water column. The profiler body is inert to turbulent eddies with scales much smaller than the profiler length. However, large eddies with sizes comparable to (and larger than) the length of the profiler will move the profiler and attenuate the velocity detected by the shear probes. That is, a freely falling vertical profiler acts as a high-pass filter to velocity fluctuations with scales larger than the length of the profiler. The VMP-200/500 are approximately 1.5 m long and the largest spatial scale that can be resolved is 1 m.

The other outstanding characteristic of the shear probe is that it is extremely sensitive and can detect velocity fluctuations smaller than $1\,\mathrm{mm\,s^{-1}}$. In practice, the signal resolution is limited by profiler vibrations, and this holds true for all relative velocity sensors.

6 Data examples from tidal channel

Profiles of turbulent vertical shear were collected with a VMP-500 in Sansum Narrows (Figure 4), which is a swift tidal channel near Victoria, British Columbia, Canada, separating Vancouver and Saltspring Islands. The profiles were collected downstream of a sill when the flooding tide was running northward through the channel with typical speeds of 2 m s^{-1}. The ship was drifting with the current while the VMP descended at a rate of 0.65 m s^{-1}. Data for this profile were collected on 24-May-2006 at 13:26 local time (file VMP_012_005). The VMP was equipped with two standard velocity shear probes (SPM-1000), one high-resolution temperature probe (FP07-1000), and one high-resolution conductivity sensor (SBE7-1000).

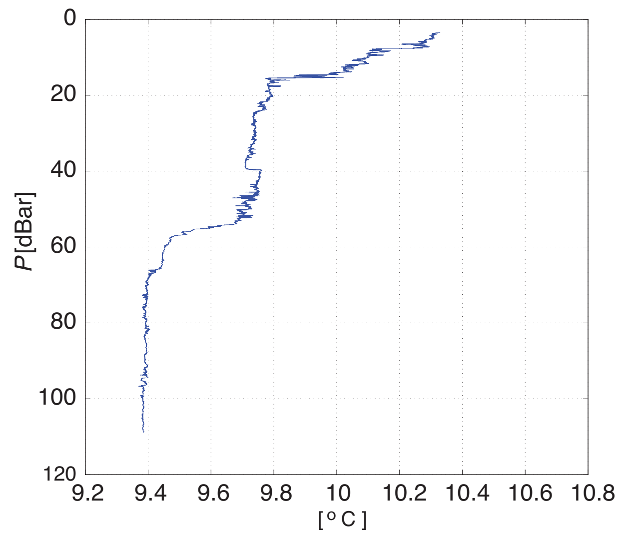

Figure 5: Temperature profile from Sansum Narrows collected with the high-resolution thermistor on the VMP-500.

All vertical axes in the figures presented here are expressed as pressure, in units of dBar. One unit of pressure is almost identical to a depth change of 1 m. Consequently, oceanographers use pressure and depth interchangeably, unless the difference is important. The shape of the temperature profile (Figure 5) shows a water column that is, for the most part, stably stratified with temperature decreasing from 10.3 °C at the surface to 9.4 °C at 100 m depth. A seasonal thermocline between the surface and 15 m depth overlays a weakly stratified mixing layer that extends down to 55 m. Between 55 m and 65 m there is a another thermocline, and below 65 m the water column is nearly homogeneous (well mixed). The temperature profile was taken with the fast-response thermistor, so it also reveals numerous temperature inversions on submetre scales that are caused by turbulent overturns. For example, the abrupt increase of temperature at 40 m and the numerous fluctuations between 45 and 55 m give a clear, but indirect, indication of turbulence.

During the deployment of the profiler, vigorous turbulent mixing was evident in the form of surface boils of smooth and nearly wave-free water (local updrafts) and convergences of very choppy waves (local downdrafts). Figure 6 shows the vertical profile of shear, the gradient of temperature and electrical conductivity (mostly due to salinity). Only one of the shear sensors is shown here for clarity. Clearly, the entire water column is turbulent, with the exception of a 10 m thick quiescent layer between 55 and 65 m, corresponding to the depth of the deeper thermocline. The small-scale velocity shear (blue line) reaches levels of around 2.5 s^{-1} in the surface layer and around 10 s^{-1} in the lower turbulent layer. The high-resolution profiles of the vertical gradients of the two scalar turbulent components, $\partial T/\partial z$ (green line) and $\partial C/\partial z$ (red line), also reflect the vertical variations of the turbulence in Sansum Narrows. Panel (b) in Figure 6 presents a high-resolution detail of the shear profile over a 40 cm depth range starting at 103 m, that shows the sub-centimetre resolution of the shear probe.

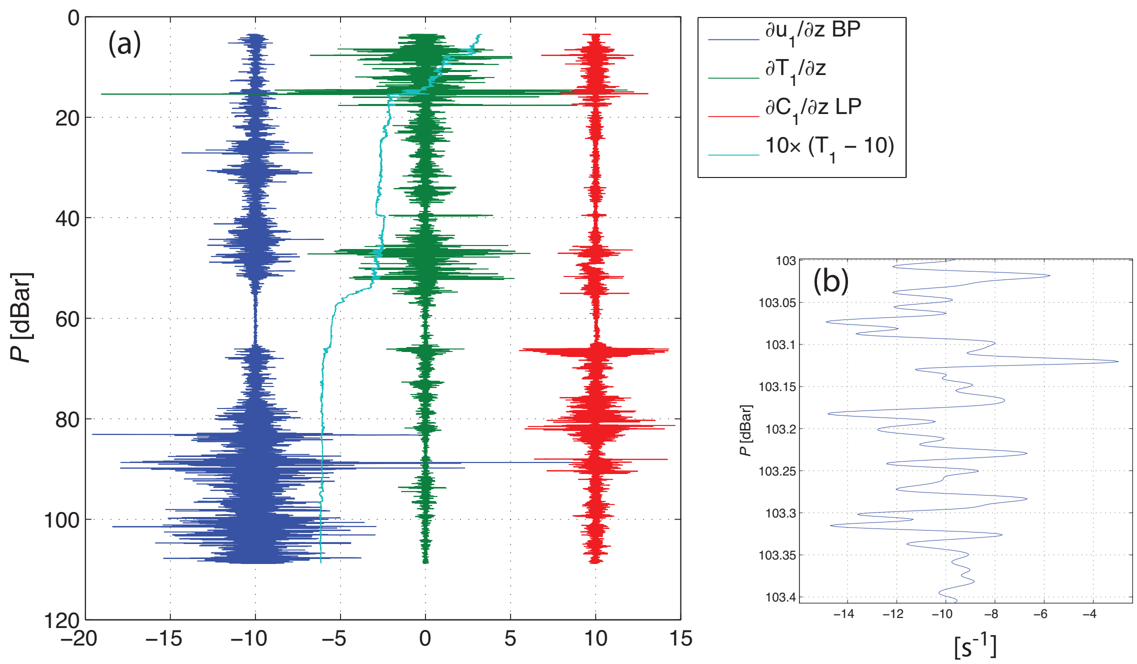

Figure 6: (a) Profiles of shear (blue) and the vertical gradients of temperature (green) and conductivity (red). The data are band-pass filtered between 0.4 and 50 Hz for display purposes only. A scaled version of the temperature profile (cyan) is shown for reference. The shear and the conductivity gradients have been shifted left and right by 10 units for clarity. (b) A 40 cm detail of the shear starting at 103 m depth highlights the centimetre-scale variations resolved by the shear probe.

A standard parameter that is used in oceanographic research to describe the strength of turbulence is the rate of dissipation of turbulent kinetic energy (TKE), which can be calculated from the variance of the measured velocity shear using

$$\epsilon = \frac{15}{2}\nu\overline{\left(\frac{\partial u}{\partial z}\right)^2}. \tag{1}$$

where ν is the kinematic viscosity of water and the over-bar denotes a vertical (or depth) average (typically taken to be 0.5–1m). Figure 7 shows the profile of the rate of dissipation of TKE, computed from the shear data. The vertical depth bins were approximately one meter. The rate of dissipation can vary by many factors of ten in a tidal channel. For Sansum Narrows the range is almost 10^5 , during this profile.

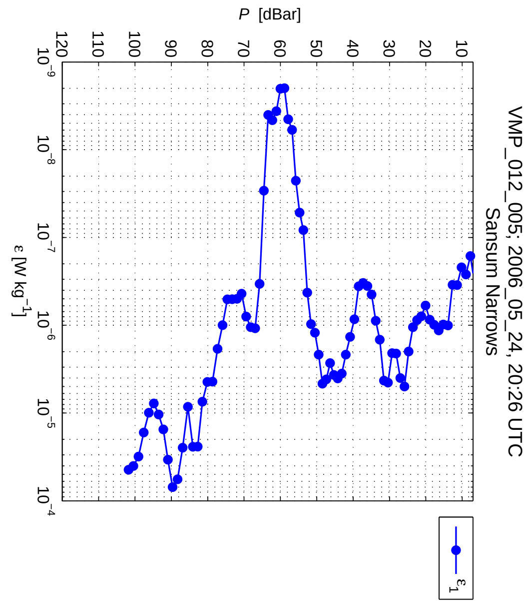

Figure 7: The vertical profile of the rate of dissipation of TKE. The estimates are spaced approximately 1.25 m vertically.

Finally, the shear probe signal can be numerically integrated to give a direct expression of the small-scale velocity fluctuations, u. For the shear profile in Figure 6, the velocity profile is shown in Figure 8, with the inset graph showing a detail of the profile. The high spatial resolution of the shear probe signal is evident in the detail, with velocity fluctuations on scales of $\approx$1 cm being resolved.

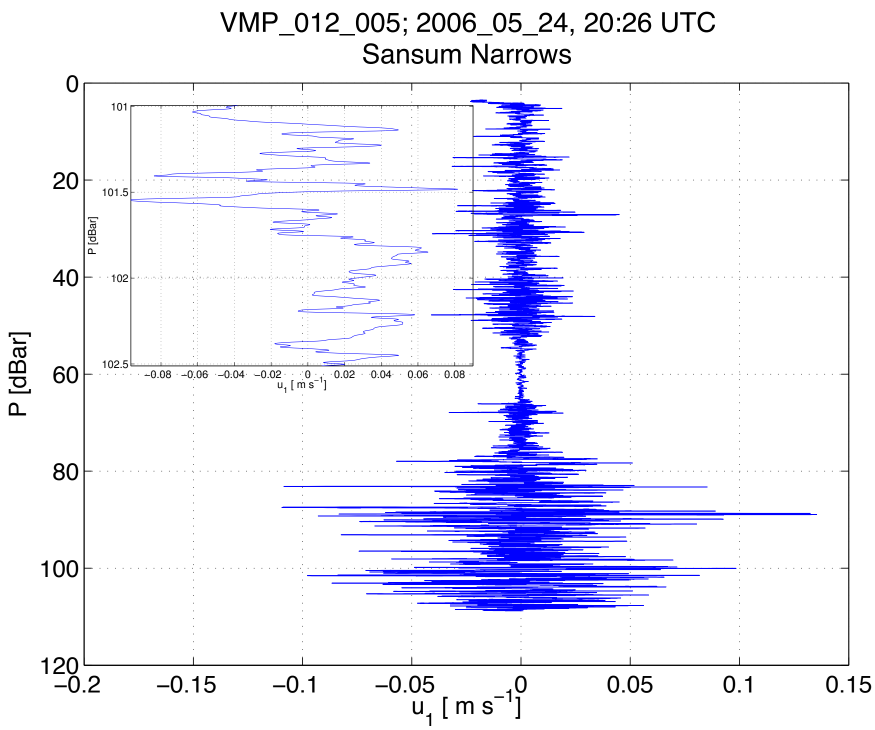

Figure 8: (a) Profiles of turbulent horizontal velocity computed by numerically integrating the vertical shear.
(inset) A 1.50 m detail of the velocity starting at 101 m depth highlights the centimetre-scale variations resolved by the shear probe.

7 Summary

- Turbulent velocity measurements with fine spatial resolution are a key requirement for the operation and design of tidal-energy turbines. The VMP can satisfy this requirement.
- The VMP is a standard instrument for measuring turbulent velocity fluctuations and is used routinely by the academic research community for in-situ observations. The key sensor of the VMP is the shear probe, which resolves turbulent velocity on scales between 0.01–1m and does so with extremely low noise.
- Data from a deployment of a VMP in a swift tidal channel demonstrate the application of the instrument in a tidal regime. Turbulent parameters of velocity, velocity shear and energy dissipation rate are well resolved. In addition, high-resolution gradients of temperature and conductivity can provide additional information about the turbulent structures in the water column.

8 Further Reading

- Lueck, R. G., 2010: Converting Shear Probe, Thermistors and micro-conductivity signals into physical units, Technical Note, Rockland Scientific Inc. TN-005, available at www.rocklandscientific.com.
- Wolk, F., H. Yamazaki, L. Seuront, R. G. Lueck, 2002: A New Free-Fall Profiler for Measuring Biophysical Microstructure. *J. Atmos. Oceanic Technol.*, **19**, 780–793.
- Lueck, R. G., F. Wolk and H. Yamazaki, 2002: Ocean velocity microstructure measurements in the 20th century. *Japan J. of Oceanogr.*, **58**, 153–174.
- Lueck, R. G., 2005: Horizontal and vertical turbulence profiling. Marine Turbulence: Theories, Observations and Models. Ed. H. Baumert, J. Simpson and J. Suendermann. Springer-Verlag. Berlin

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